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Aquatic fauna and water chemistry of the mound springs and wetlands of Mandora Marsh, north-western Australia

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Abstract

The Mandora Marsh system, adjacent to Eighty-mile Beach, in the northwest of Western Australia supports many mound springs as well as several other permanent and seasonal wetlands. Although listed under the Ramsar Convention, little was known of the non-waterbird ecological values of the system. A survey of the water chemistry and aquatic fauna of the wetlands and springs was conducted in October 1999, which identified a new species of fish and bathynellid syncarid, occurrence of stygofauna, as well as a relatively diverse aquatic invertebrate fauna. Overall, the aquatic fauna is of considerable conservation value. The survey also identified pressures from cattle, feral camels and possible future developments adjacent to the Marsh, which could threaten the future ecological health of these mound springs if not managed appropriately.

Keywords: aquatic fauna, mound springs, wetlands, endemism, Mandora Marsh

Introduction

Mound springs and spring-swamps are known from several parts of the world but are most significant when located in deserts. Notable arid-zone systems are the artesian Nubian Aquifer in north-eastern Africa, the carbonate aquifers of eastern Nevada and the Great Artesian Basin (GAB) in north-eastern Australia (Ponder 1986, 2003; Nobel *et al*. 1998). The GAB underlies approximately one-fifth of Australia and is the best studied within that continent. However it is not the only spring fed system within Australia. There are many other smaller systems known to support permanent springs, including the Canning Artesian Basin and the North Kimberley Mounds in the north of Western Australia, and the Gnangara Groundwater Mound, a superficial aquifer overlying deeper confined aquifers in the south-west (Jasinska *et al.* 1996; Knott & Jasinska 1998; Kern *et al*. 2004). Permanent springs are particularly important because they provide long term, stable habitat in which aquatic fauna may survive periods of aridity. As a result, the aquatic fauna of such springs is often characterised by relictual species, with these populations representing remnants of a more widespread distribution in earlier geological times (Leys *et al.* 2003; Murphy *et al.* 2009). The springs may also contain locally endemic species (Ponder 1986). For instance, springs in Mexico and western parts of the United States are notable for their endemic aquatic invertebrate fauna (Ponder 1986; Erman 1998). Similarly, species have been found that are apparently restricted to springs, as reported for those on the edge of the GAB in South Australia (Mitchell 1985; Ponder 2003) and Queensland (Ponder & Clarke 1990), as well as those on the Gnangara Groundwater Mound in south-west Western Australia (Jasinska *et al.* 1996; Jasinska & Knott 2000) and in the Pilbara region of north-west Western Australia (Pinder *et al.* 2010).

Springs can occur in many physical settings, including that of mound springs that appear as low (1–3 m high) mounds from which water seeps. The mounds are formed over thousands of years by the deposition of fine clay brought to the surface by the water and by the long term accumulation of organic material derived from vegetation dependent on the water source. The types, modes of formation, physical, chemical and geological characteristics of artesian springs have been described by Ponder (1986). While many detailed studies have been conducted in South Australia (see Ponder 2002), there have been few comprehensive assessments of spring systems in other states, including Western Australia. The Mandora Marsh area, in the arid north-west of Western Australia, is characterised by numerous wetlands, the majority of which are well vegetated mound springs fed by artesian water. Little is known of the aquatic invertebrate fauna of the wetlands and mound springs of Mandora Marsh, but as noted by Kay *et al.* (1999), permanent springs would be expected to have high conservation importance because they support richer faunas than ephemeral water-bodies. Therefore, as part of a larger survey to document terrestrial fauna and flora, as well as wetland-dependent flora of the Marsh (see Graham 1999), the aquatic invertebrate fauna and water chemistry of a representative suite of springs and wetlands were sampled in October 1999. The aims of the aquatic sampling were to determine water quality, species composition, conservation significance and effects of current land use.

Study Area

The Mandora Marsh system (105 000 ha) lies within the La Grange South groundwater subarea of the Canning Basin, on the northern edge of the Great Sandy Desert. It is 140 km south-south-west of Broome, approximately 40 km inland from Eighty-mile Beach, and lies at the transition between the Pilbara and Kimberley regions (Fig. 1). It is part of a larger palaeo-drainage system that extends from the Northern Territory, through Lake Gregory in the eastern Kimberley, to Eighty-mile Beach on the west coast (Wyrwoll *et al.* 1986). Mandora Marsh is located on what is considered to be the palaeo-estuary for this system.

The climate of the region is semi-arid monsoonal with hot, wet summers (mean daily max./min. temperatures approximately 35/25°C) and warm, dry winters (mean daily max./min. temperatures approximately 28/12°C). Mean annual rainfall is 390 mm, however, as reported by Halse *et al*. (2005), annual rainfall is highly variable, ranging from ~ 30 mm in dry years to > 1500 mm in wet years, with rainfall mostly derived from cyclonic events which occur with a high frequency. Since 1910, 22 cyclones have crossed the coast in the vicinity of Eighty-mile Beach, and at least one cyclone occurred each year between 1994 and 1999; Cyclone Annette (1994), Gertie and Chloe (1995), Kirsty (1996), Rachel (1997), Thelma and Les (1998), and Gwenda (1999). When total annual rainfall exceeds 800 mm, widespread flooding usually results. These wet years appear to lead to substantial recharge of shallow groundwater aquifers around Mandora Marsh so that moderate rainfall in years following a major flood will also result in flooding (Halse *et al*. 2005).

The marsh is listed in the Directory of Important Wetlands of Australia (Environment Australia 2001), and also forms part of the Eighty-mile Beach Wetland of International Importance listed under the Ramsar Convention (Jones 1993). Ramsar nomination was based principally on the number of migratory birds utilising Eighty-mile Beach, but also for the landform values of Mandora Marsh (Jones 1993). It has subsequently been shown that the marsh periodically also supports very high waterbird values (Halse *et al*. 2005). The marsh consists of Mandora Lake (which is a large saline pan), samphire flats, an endoreic salt water creek (Salt Creek), salt and freshwater mound springs, and the underlying aquifer. Mandora Lake (known as Walyarta in the traditional Karajarri language) forms a broad, open basin up to 10 km wide that holds shallow water (< 0.5 m) following substantial rainfall in the catchment.

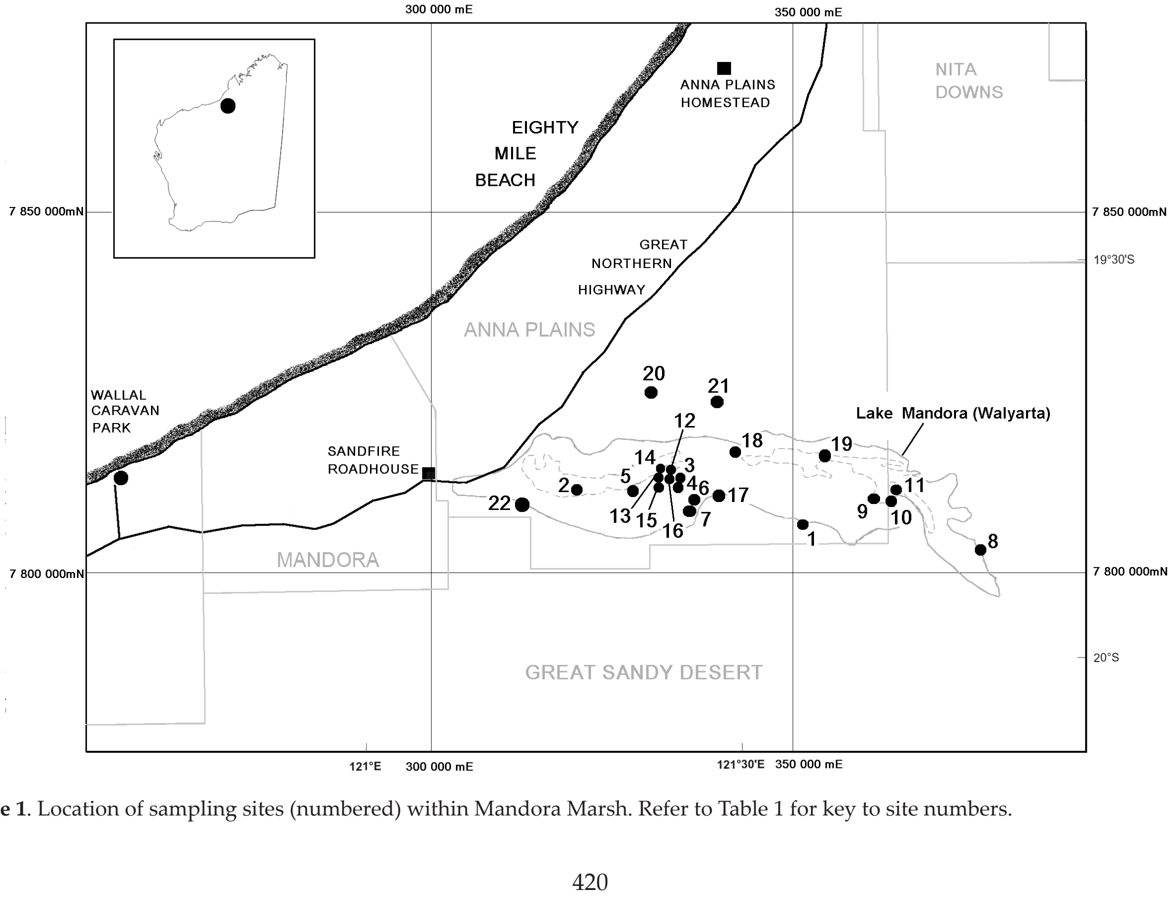

Figure 1. Location of sampling sites (numbered) within Mandora Marsh. Refer to Table 1 for key to site numbers.

Episodic inundation to a depth of ca. 1 m occurs when cyclones pass close to the lake. The area around the lake supports samphire vegetation (*Halosarcia indica* [Willd.] Paul G.Wilson, *H. halocnemoides* [Nees] Paul G. Wilson and *Frankenia* sp.) and *Sporobolus virginicus* (L.) Kunth grassland. Salt Creek, a small permanent saline creek seeps into the eastern end of Mandora Lake and features the most inland occurrences of mangroves (white mangrove, *Avicennia marina* [Forssk.] Vierh.) in Western Australia. The creek is 10–20 m wide, 1–2 m deep, 5 km long and is supplied by groundwater discharge and saline seeps from adjacent claypans.

Scattered along Mandora Marsh is a series of permanent springs that form mound springs and small swamps. Eil Eil Spring, also referred to as Mandora Soak (Jones 1993) and Mandora Swamp (Wyrwoll *et al*. 1986), is the most spectacular of these spring-swamps. It takes the form of a 'raised bog' rising 2 m above the surrounding country and supports a 20 m high forest of silver cadjeput, *Melaleuca argentea* W. Fitzg. over a tussock grassland of *Fimbristylis ferruginea* Vahl (Wyrwoll *et al*. 1986). A 3.3 m thick accumulation of organic sediment overlies a sand substrate, and carbon dating suggests it began accumulating 7000 yrs B.P. (Wyrwoll *et al*. 1986). Other plants occurring in the spring-swamps include dragon flower trees, *Sesbania formosa* (F.Muell.) N.T. Burb., the rush *Schoenoplectus litoralis* (Schrad.) Palla, the bulrush *Typha domingensis* Pers. and the mangrove fern *Acrostichum speciosum* Willd. Cyclonic winds are known to physically damage the vegetation in the spring-swamps. For example, Cyclone Annette crossed the coast at Mandora Station in December 1994, with wind speeds of 217 km hr^{-1} (Australian Bureau of Meteorology) and de-crowned *Sesbania* trees in Saunders Spring (Storey pers. obs.). Surface water tends to be limited in the springs, typically consisting of small areas of shallow water (5–10 cm) amongst the vegetation and organic debris on top of the mound spring, and a shallow (~ 20 cm deep) moat around the perimeter of the mound.

Methods

A total of 22 sites (Table 1) were sampled between the 18th and 21st of October, 1999. Sites were selected with the emphasis on mound springs, but to help interpret the significance of the mound-spring data, sampling was also undertaken at Mandora Lake, saline springs feeding Salt Creek, a seasonal claypan (Coolabah Claypan), and the underlying aquifer accessed by collection at outflows from windmills on bores/wells (Friday and Lyngett Well). At each site, a basic suite of water chemistry variables was measured *in situ* using a Yeo-Kal Model 611 multiprobe water quality analyser. Variables included temperature, pH, dissolved oxygen (DO % saturation), total dissolved solids (TDS g L^{-1}) and electrical conductivity (mS cm^{-1}) (Table 1). Water samples were also collected from 12 of the sites for more comprehensive laboratory analysis of water chemistry, *i.e.* total soluble nitrogen (TN), nitrate ($N\text{-}NO_3$), ammonia ($N\text{-}NH_3$), total soluble phosphorous (TP), soluble reactive phosphorus (PSR), ionic composition, total soluble iron (Fe), silica (SiO_2), colour (TCU), alkalinity, hardness and turbidity (NTU). Samples for nutrient analysis were pre-filtered in the field through

Table 1

Sites sampled in Mandora Marsh, grouped by wetland type, with GPS-determined latitudes and longitudes, indicating if sampled for a basic or comprehensive suite of water chemistry variables, and if aquatic macro- and/or microinvertebrates were sampled.

Site no.	Type	Site name	Latitude S	Longitude E	Basic water chemistry	Detailed water chemistry	Macro-inverte-brates	Micro-inverte-brates
1	Claypan	Coolabah Claypan	19° 48' 50"	121° 30' 38"	✓	✓	✓	✓
2	Main lake	Mandora Lake (Walyarta)	–	–	✓	–	–	–
3	Mound spring	Fern Spring	19° 46' 01"	121° 23' 29"	✓	✓	✓	✓*
4	Mound spring	Melaleuca Spring	19° 46' 15"	121° 23' 15"	✓	✓	✓	✓
5	Mound spring	Saunders Spring	19° 47' 05"	121° 20' 15"	✓	✓	✓	✓*
6	Mound spring	Little Eil Eil Spring	19° 47' 40"	121° 26' 33"	✓	✓	✓	✓*
7	Mound spring	Eil Eil Spring	19° 47' 53"	121° 26' 49"	✓	✓	✓	✓*
8	Mound spring	Linear Spring	19° 49' 07"	121° 37' 53"	✓	✓	✓	–
9	Mound spring	Top Spring	19° 48' 48"	121° 36' 52"	✓	✓	✓	–
10	Mound spring	Sump 300m from Top Spring	–	–	✓	–	–	–
11	Mound spring	Sporobolus Spring	19° 48' 18"	121° 37' 30"	✓	–	–	–
12	Mound spring	Stockyard Main Spring	19° 45' 34"	121° 23' 06"	✓	–	–	–
13	Mound spring	Small spring with mangrove at stockyard	19° 45' 34"	121° 23' 06"	✓	–	–	–
14	Mound spring	Mangrove/*Typha* spring 100m W of stockyard	19° 45' 34"	121° 23' 06"	✓	–	–	–
15	Mound spring	Small spring 200m ESE of stockyard	19° 45' 34"	121° 23' 06"	✓	–	–	–
16	Mound spring	Spring with *Typha* and moat 150m W of stockyard	19° 45' 34"	121° 23' 06"	✓	–	–	–
17	Riverbed spring	Bretts Spring	19° 47' 23"	121° 27' 06"	✓	✓	✓	✓
18	Salt creek	Salt Creek Claypan Spring	19° 44' 03"	121° 28' 41"	✓	✓	✓	✓
19	Salt creek	Salt Creek Stromatolite Pool	19° 44' 36"	121° 32′ 29″	✓	–	–	–
20	Windmill	Friday Well (bore)	19° 42' 44"	121° 20' 24"	✓	✓	✓	✓
21	Windmill	Lyngett Well (bore)	19° 42' 27"	121° 27' 42"	✓	✓	✓	✓
22	Windmill	Coolgardie Well	19° 47' 15"	121° 13' 25"	✓	–	–	–

* Denotes microfauna was also extracted from a shallow core sunk into the peat.

a 0.45 μm Millipore™ filter. For interpretations of biological significance, concentrations of major cations and anions were converted to milliequivalents (meq L^{-1}) prior to statistical analysis. The concentration of bicarbonate (and carbonate) ions was estimated as the difference between the equivalent sum of the cations and that of chloride and sulphate ions.

Aquatic macroinvertebrates and microinvertebrates were each sampled at 12 of the 22 sites, with both components sampled at 10 sites (Table 1). Macroinvertebrates were sampled using a standard 250 μm mesh net to kick/sweep over a discontinuous 50 m distance, with the aim of maximising species collected. Microinvertebrates (Protozoa, Rotifera, Copepoda, Ostracoda & Branchiopoda) were sampled using a 53 mm mesh plankton net passed through the water column without disturbing benthic sediments. Sampling the mound springs was difficult due to the limited area and shallow nature of surface water, with sampling conducted in shallow pools on the top of the mounds and in the surrounding moat. To collect invertebrates from the groundwater aquifer, plankton nets were suspended under the outflow pipes of windmills. Nets were left in place for at least 24 hrs. Hyporheic fauna was sampled at four of the mound springs. This was achieved by extracting a one metre deep core of the consolidated peat using a 40 mm diameter PVC pipe corer. The resultant hole was allowed to fill with porewater and was then pumped through a 110 mm net using a bilge pump, and the material retained for sorting. All samples were fixed in 5% formalin.

Fish were collected opportunistically throughout the study area by a combination of sweep (FBA pond net with 1 mm mesh aperture) and cast netting (213 cm diameter net, with 2 cm stretched mesh). Specimens that could not be identified in the field were fixed in 5% formalin and forwarded to the Western Australian Museum (Dr Gerry Allen) and/or the Museum of the Northern Territory (Dr Helen Larson) for identification.

Analysis

Relationships between sites in terms of physico-chemical characteristics and fauna assemblages were analysed using multivariate procedures in the PRIMER (v6) software package (Clarke & Gorley 2006). Sites were assigned to categories according to salinity (as TDS; < 1 g L^{-1}, 1 – 4.5 g L^{-1}, > 4.5 g L^{-1}). Mutually correlated physico-chemical variables were identified using Spearman rank correlation (SPSS software version 17.0) and strongly correlated ($\rho \geq 0.95$) variables were excluded from further analyses: electrical conductivity (μS cm^{-1}; correlated with salinity g L^{-1}), hardness (mg L^{-1}; correlated with Ca^{+}) and Mg^{2+} (correlated with salinity, hardness and ion equivalents Ca, K and SO_4). Physico-chemical data were transformed where appropriate and normalised as recommended for multivariate analysis on mix-type variables (Clarke & Warwick 2001). Physico-chemical data and invertebrate presence/absence data were examined using both hierarchical agglomerative clustering (UPGMA) and non-metric multidimensional scaling (MDS) ordination (Clarke & Gorley 2006). Cluster and ordination based on Euclidean distance was used in preference to Principle Components Analysis (PCA) for physico-chemical data so that the hypotheses of differences in habitat types could be tested using the ANOSIM ($p < 0.05$) procedure in PRIMER. Cluster and ordination based on Bray-Curtis similarity matrices (Bray & Curtis 1957) was used to analyse species data, with infrequently occurring species (species occurring in < 5% of samples) omitted to avoid 'low-occurrence' taxa having a disproportionate effect on the results (Gaugh 1982; Belbin 1995). The SIMPROF (similarity profile) routine within PRIMER was used to test the significance ($p < 0.05$) of CLUSTER site groupings while ANOSIM was used to test the significance ($p < 0.05$) of the separation of salinity groupings in MDS ordination space. Similarity percentage analysis (SIMPER) was used to determine those species contributing most to the similarity/dissimilarity between sites. Similarity matrices from physico-chemical and species data were correlated using RELATE analysis. The relationship between abiotic and biotic data was further assessed using the BIOENV routine within PRIMER to calculate the smallest subset of physico-chemical variables that explained the greatest percentage of variation in the taxa ordination pattern, as measured by Spearman rank correlation (ρ) (Clarke & Warwick 1998). Unless indicated, default values or procedures otherwise recommended by Clarke and Gorley (2006) were employed for PRIMER routines.

Results

Physico-chemistry

Wetlands varied in several physico-chemical parameters. Salinities ranged from fresh (< 1 g L^{-1}) at Coolabah Claypan, Bretts Spring and Top Spring to saline (27.2 g L^{-1}) at Mandora Lake, Salt Creek Claypan Spring (38.5 g L^{-1}) and Salt Creek Stromatolite Pool (> 60 g L^{-1}) (Table 2). The mound springs ranged from fresh to brackish (ca. 0.5–5.8 g L^{-1}), with the brackish sites tending to be lower in the landscape and closer to the lake. Analyses of ionic composition indicated Na and Cl to be the dominant ions in most waters (Table 2), accounting for 60–87 % of the total cation and anion equivalence (Table 3). The exceptions were the freshwater Linear Spring, Top Spring and Coolabah Claypan, where HCO_3^- was the dominant cation. At Coolabah Claypan, HCO_3^- constituted 72 % of the anion equivalence. The dominance or sub-dominance of HCO_3^- and the sub-dominance of Ca^{2+} suggested ionic composition of waters at most sites to be influenced by limestone aquifers rather than accumulation and concentration of marine derived salts alone. Mg^{2+} and SO_4^{2-} were subdominant in waters with TDS ≥ ~ 5 ‰ and SO_4^{2-} was also relatively high at Bretts Spring (Tables 2 and 3). The Ca^{2+}:HCO3- ratio was typically < 1, but higher ratios were recorded for Fern Spring (1.3) and Salt Creek Claypan Spring (4.3) (Table 3). The Na^{+}:Cl^{-} ratios typically ranged from 1.0 to 1.5, but with a ratio of 2.1 at Coolabah Claypan.

In most instances waters were alkaline (pH 7.21–9.61). The open, shallow and unvegetated sites (*i.e.* Salt Creek Claypan Spring, Mandora Lake, Saunders Spring and Melaleuca Spring) had high daytime water temperatures ranging from 33.7 °C to 36.3 °C. When combined with high nutrient levels, as at Saunders Spring (5.2 mg L^{-1} TN, 0.71 mg L^{-1} TP) and Melaleuca Spring (17 mg L^{-1} TN, 2.0 mg L^{-1} TP), this often resulted in extremely high

Table 2

Physico-chemical analyses for each of the 22 sites sampled in Mandora Marsh.

Site no.	Site name	Temp °C	pH [H^+]	DO %	EC mS cm^{-1}	TDS g L^{-1}	Na mg L^{-1}	Ca mg L^{-1}	K mg L^{-1}	Mg mg L^{-1}	Cl mg L^{-1}	HCO_3[A] mg L^{-1}	SO_4 mg L^{-1}
17	Bretts Spring	30.3	9.17	136.0	1335	0.74	294	28	9	12	390	132	107
1	Coolabah Claypan	27.1	8.58	101.2	303	0.14	70	29	12	8	52	240	3
7	Eil Eil Spring	29.1	7.60	49.4	2541	1.4	539	72	20	37	660	488	191
3	Fern Spring	26.0	7.46	85.7	10500	5.78	1910	201	82	123	2900	461	766
20	Friday Well (bore)	33.6	7.05	70.5	2480	1.46	384	105	82	61	600	521	172
8	Linear Spring	20.6	8.41	99.9	1105	0.62	187	54	20	31	210	408	61
6	Little Eil Eil Spring	25.3	7.46	31.3	2112	1.22	446	67	17	29	620	350	112
21	Lyngett Well (bore)	28.0	7.21	47.6	2366	1.30	463	74	61	40	570	507	206
4	Melaleuca Spring	36.3	9.61	>200.0	7342	4.71	1750	96	63	59	2500	344	538
18	Salt Creek Claypan Spring	34.5	8.44	>200.0	57400	38.50	14700	286	1740	608	21000	200	7320
5	Saunders Spring	35.8	9.21	>200.0	2200	1.27	353	48	26	24	460	237	169
9	Top Spring	19.1	8.32	106.0	975	0.54	178	35	12	17	180	320	42
22	Coolgardie Well	39.3	7.76	52.9	907	0.49	–	–	–	–	–	–	–
2	Mandora Lake (Walyarta)	33.7	8.84	108.4	42200	27.20	–	–	–	–	–	–	–
19	Salt Creek Stromatolite Pool	35.6	7.81	>200.0	>80000	>60.00	–	–	–	–	–	–	–
11	Sporobolus Spring	19.4	8.66	92.8	2099	1.25	–	–	–	–	–	–	–
12	Stockyard Main Spring	24.6	8.85	134.9	6825	4.39	–	–	–	–	–	–	–
13	Small mangrove spring	21.9	7.89	30.8	6000	3.83	–	–	–	–	–	–	–
14	Spring100m W of stockyard	26.8	7.97	55.0	12300	7.02	–	–	–	–	–	–	–
15	Spring 200m ESE of stockyard	25.4	6.81	18.0	6333	4.04	–	–	–	–	–	–	–
16	Spring 150m W of stockyard	22.7	8.15	64.4	7711	5.02	–	–	–	–	–	–	–
10	Sump 300m from Top Spring	18.1	8.14	69.7	1257	0.72	–	–	–	–	–	–	–

> Denotes *in situ* value outside the measurable range for hand–held field meters;

[A] Estimated from the difference between the equivalent sum of the cations and that of Cl^- + $SO4^{2-}$.

Table 2 continued

Site no.	Site name	Alkalinity mg L^{-1}	Hardness mg L^{-1}	Turbidity NTU	Colour TCU	Fe mg L^{-1}	SiO_2 mg L^{-1}	TN mg L^{-1}	N-NO_3 mg L^{-1}	N-NH_3 mg L^{-1}	TP mg L^{-1}	PSR mg L^{-1}
17	Bretts Spring	100	120	4.1	21	<0.05	19	0.4	0.07	0.04	0.05	0.04
1	Coolabah Claypan	170	100	5.2	27	0.06	8	2.2	<0.02	0.02	0.10	<0.01
7	Eil Eil Spring	335	330	12.0	170	<0.05	95	2.7	<0.02	0.14	0.15	0.06
3	Fern Spring	243	1000	2.5	160	0.13	40	1.4	0.03	0.02	0.21	0.21
20	Friday Well (bore)	333	520	<1.0	8	<0.05	66	13.0	9.70	0.02	0.02	0.02
8	Linear Spring	308	260	48.0	95	<0.05	100	5.2	0.15	<0.02	0.67	0.03
6	Little Eil Eil Spring	225	290	2.2	110	<0.05	54	2.0	0.04	0.31	0.49	0.27
21	Lyngett Well (bore)	355	350	<1.0	6	0.30	75	16.0	16.00	0.03	0.04	0.04
4	Melaleuca Spring	268	480	46.0	270	0.08	36	17.0	0.06	0.14	2.00	0.04
18	Salt Creek Claypan Spring	240	3200	6.4	7	<0.50	29	2.8	1.20	0.29	0.06	0.03
5	Saunders Spring	198	220	32.0	66	<0.05	3	5.2	0.11	0.02	0.71	0.01
9	Top Spring	243	160	16.0	120	<0.05	77	5.4	0.05	0.02	0.58	0.04
22	Coolgardie well	–	–	–	–	–	–	–	–	–	–	–
2	Mandora Lake (Walyarta)	–	–	–	–	–	–	–	–	–	–	–
19	Salt Creek Stromatolite Pool	–	–	–	–	–	–	–	–	–	–	–
11	Sporobolus Spring	–	–	–	–	–	–	–	–	–	–	–
12	Stockyard Spring	–	–	–	–	–	–	–	–	–	–	–
13	Small mangrove spring	–	–	–	–	–	–	–	–	–	–	–
14	Spring 100m W of stockyard	–	–	–	–	–	–	–	–	–	–	–
15	Spring 200m ESE of stockyard	–	–	–	–	–	–	–	–	–	–	–
16	Spring 150m W of stockyard	–	–	–	–	–	–	–	–	–	–	–
10	Sump 300m from Top Spring	–	–	–	–	–	–	–	–	–	–	–

< Denotes value less than analytical detection limit.

daytime dissolved oxygen levels (> 200% saturation), indicative of eutrophication. The presence of dung and pugging from cattle and wild camels on the mounds, and in the surrounding moats, suggested stock and feral animals were most likely the cause of high nutrient levels. Nutrient enrichment was most obvious at Friday and Lyngett wells, both of which had excessively high nitrate (> 9.7 mg L^{-1}) and total nitrogen (> 13 mg L^{-1}) concentrations, suggesting groundwater contamination in the vicinity of the bores. Turbidity ranged widely with highest levels (> 30 NTU) encountered at Linear, Melaleuca and Saunders springs. Silica levels were mostly within the range 29–100 mg L^{-1}, with relatively low levels recorded from Saunders Spring (3 mg L^{-1}) and Coolabah Claypan (8 mg L^{-1}).

Cluster analysis on physico-chemical data did not

Table 3

Ionic composition (% meq L^{-1}) and equivalent ratios.

Site no.	Site name	%Ca	%K	%Mg	%Na	%Cl	$\%SO_4$	$\%HCO_3$	Ca:Na	Ca:Mg	$Ca:HCO_3$	Na:Cl	Na:K	$HCO_3:Cl$	$Cl:SO_4$
17	Bretts Spring	9.1	1.5	6.4	83.0	71.4	14.5	14.1	0.1	1.4	0.6	1.2	55.5	0.2	4.9
1	Coolabah Claypan	26.5	5.6	12.1	55.8	26.9	1.1	72.0	0.5	2.2	0.4	2.1	9.9	2.7	23.5
7	Eil Eil Spring	11.7	1.7	9.9	76.6	60.9	13.0	26.1	0.2	1.2	0.4	1.3	45.8	0.4	4.7
3	Fern Spring	9.5	2.0	9.6	78.9	77.7	15.1	7.2	0.1	1.0	1.3	1.0	39.6	0.1	5.1
20	Friday Well	18.0	7.2	17.3	57.5	58.2	12.3	29.4	0.3	1.0	0.6	1.0	8.0	0.5	4.7
8	Linear Spring	19.4	3.7	18.4	58.6	42.6	9.1	48.2	0.3	1.1	0.4	1.4	15.9	1.1	4.7
6	Little Eil Eil Spring	13.1	1.7	9.3	75.9	68.4	9.1	22.5	0.2	1.4	0.6	1.1	44.6	0.3	7.5
21	Lyngett Well	12.9	5.4	11.5	70.2	56.1	15.0	29.0	0.2	1.1	0.4	1.3	12.9	0.5	3.7
4	Melaleuca Spring	5.5	1.8	5.6	87.1	80.7	12.8	6.5	0.1	1.0	0.8	1.1	47.2	0.1	6.3
18	Salt Creek Claypan Spring	1.9	6.0	6.7	85.5	79.2	20.4	0.4	0.02	0.3	4.3	1.1	14.4	0.01	3.9
5	Saunders Spring	11.8	3.3	9.7	75.3	63.6	17.3	19.1	0.2	1.2	0.6	1.2	23.1	0.3	3.7
9	Top Spring	15.6	2.7	12.5	69.2	45.4	7.8	46.8	0.2	1.2	0.3	1.5	25.2	1.0	5.8

reveal strong grouping of sites according to salinity categories (Fig. 2A). Four significant ($p < 0.05$) cluster groupings were identified: group 1 comprised the most saline site, Salt Creek Claypan Spring; group 2 comprised the mound springs at Melaleuca, Saunders and Bretts springs; group 3 comprised Coolabah Claypan, and group 4 comprised Friday and Lyngett wells together with all other mound springs for which there was detailed water chemistry (Fig. 2A). MDS ordination revealed a similar pattern, again with the distinct separation of Salt Creek Claypan Spring (Fig. 2B). ANOSIM detected no significant differences between salinity groups in ordination space (Global $R = 0.194$, $p = 0.094$).

Aquatic invertebrates

Excluding the two bores, 134 taxa were recorded from 10 sites (Appendix). Approximately half are known to be described species and at least some of the larvae not formally identified are likely the same species as represented by adults. Many of the microinvertebrate specimens however, likely represent undescribed species. The aquatic invertebrate fauna of the Mandora wetlands was dominated by Insecta, which comprised ~53 % of the total fauna. Coleopterans were the richest of the insect groups (23.7 %), followed by dipterans (13.7 %) and hemipterans (8.6%). Microinvertebrates comprised 23 % of all taxa collected, predominantly rotifers (11.5 %) and rhizopods (10.1 %). Microcrustacea were also relatively species rich; ostracods (5 %), copepods (5 %) and cladocerans (3.6 %). Only one species of macro-crustacea was collected, a bathynellid syncarid, subsequently described as a new genus and species of stygofauna, *Kimberleybathynella mandorana* (Cho *et al*. 2005). Other rare components included a new species of assimineid snail, *Assiminea* sp. nov., present at Fern and Linear springs. Ephemeropterans, odonates and trichopterans were also under represented and mostly restricted to Bretts Spring, Coolabah Claypan and Linear Spring.

The greatest number of taxa (48) was collected from the freshwater Coolabah Claypan and the fewest (15) from the saline Salt Creek Claypan Spring. An average of 30 taxa was collected for sites at which both macro- and microinvertebrates were sampled. Fifty-eight percent of taxa were recorded from single sites only. Both bores were depauperate with Lyngett Bore containing a juvenile unionicolid water mite, and two ostracods; *Cypretta baylyi* McKenzie and *Limnocythere ?dorsosicula* (juvenile specimen). Friday Well contained juvenile cyclopoid copepods and the new bathynellid syncarid. The fauna of the cores was also depauperate in comparison with surface waters at the same sites (Appendix), containing less than 29 % of the taxa richness of the corresponding wetland. A total of 10 taxa were collected from the cores, three of which were not recorded in the surface water samples; *Arcella* sp. B, *Difflugia* cf *ventricosa* and an indeterminate foraminifera.

Five species appeared restricted to the saline Salt Creek Claypan Spring, including the rhizopod *Arcella* cf *discoides*, the copepod *Ameira* sp., the ostracod *Diacypris spinosa* De Deckker, the chironomid *Tanytarsus barbitarsus* Freeman and an unidentified empidid. There were 40 species that were only collected from freshwater (< 1 g L^{-1}) sites, including seven of the eight rotifers, two rhizopods, four of the six branchiopods, two ostracod species, five chironomid species, three odonates and all four trichopteran species.

Classification of invertebrate data (Fig. 3) produced three significant ($p < 0.05$) site groupings: group 1 comprised the saline (38.5 g L^{-1}) Salt Creek Claypan Spring, group 2 comprised the saline mound springs (Melaleuca 4.7 g L^{-1}, Fern ~ 5.8 g L^{-1}) together with the freshwater Saunders Spring (~ 1.3 g L^{-1}), and group 3 comprised the remaining freshwater mound springs (Eil Eil 1.4 g L^{-1}, Little Eil Eil 1.2 g L^{-1}, Bretts ~ 0.7 g L^{-1}) and Coolabah Claypan (~ 0.1 g L^{-1}). Analysis of similarity profiles (SIMPROF) revealed significant differences between salinity groups 2 and 3. However, the average Bray-Curtis pairwise similarity was generally low; ~ 36 % within the group 3 freshwater mound springs and ~ 51 % within the group 2 springs. Low similarity levels were not unexpected given the large number of singletons collected. Between-group similarity levels were ~ 20–33%. Salinity groupings were not significantly different in ordination space (ANOSIM, $R = 0.374$, $p = 0.10$), however similarity matrices for physico-chemical and invertebrate data were correlated (RELATE, $\rho = 0.581$, $p = 0.002$). Water quality variables that best explained the variance in invertebrate community composition among sites were dissolved oxygen concentration (% saturation), salinity

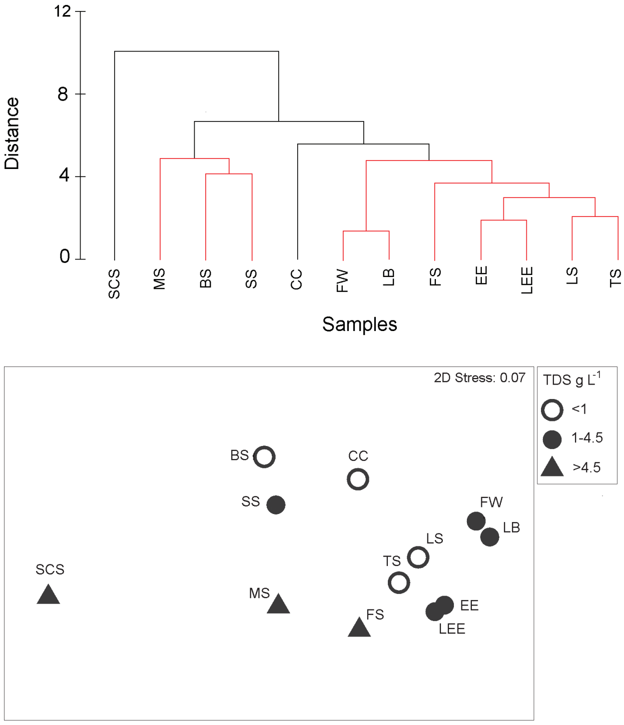

Figure 2. UPGMA classification dendogram (A) and MDS ordination plot (B) on physico-chemical data for all sites for which there were comprehensive water chemistry data (n = 12). Sites or groups of sites joined by a red line on the cluster dendogram are not significantly different (SIMPROF, p >0.05). Ordination is in two dimensions indicating salinity (TDS g L^{-1}) groupings. Site codes: BS = Bretts Spring; CC = Coolabah Claypan; EE = Eil Eil Spring; FS = Fern Spring; FW = Friday Well; LEE = Little Eil Eil Spring; LS = Linear Spring; MS = Melaleuca Spring; SCS = Salt Creek Claypan Spring; SS = Saunders Spring; TS = Top Spring.

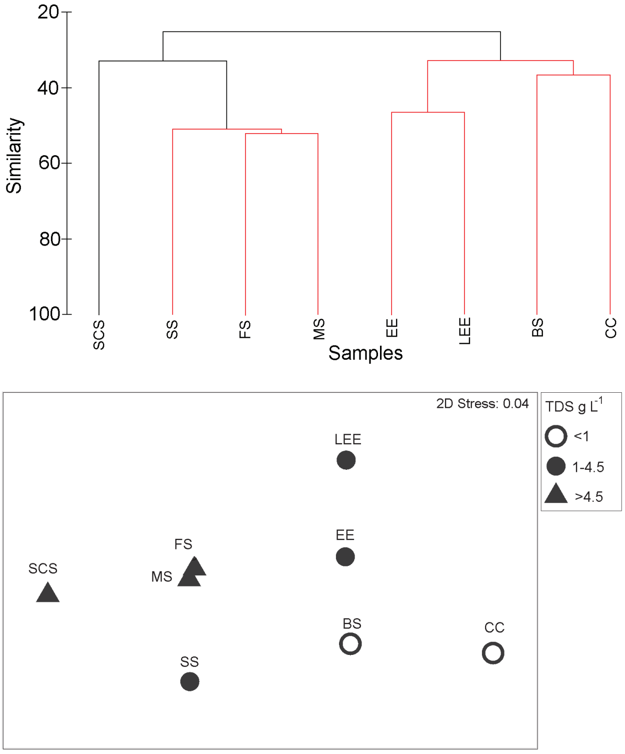

Figure 3. UPGMA classification (A) and MDS ordination plot (B) on invertebrate species presence/absence data for all sites at which both macro- and microinvertebrates were sampled (n = 8). Sites or groups of sites joined by a red line on the cluster dendogram are not significantly different (SIMPROF, p >0.05). Ordinations in two dimensions indicating salinity (TDS g L^{-1}) groupings. Site codes: BS = Bretts Spring; CC = Coolabah Claypan; EE = Eil Eil Spring; FS = Fern Spring; LEE = Little Eil Eil Spring; LS = Linear Spring; MS = Melaleuca Spring; SCS = Salt Creek Claypan Spring; SS = Saunders Spring; TS = Top Spring.

($\log_{10}$ transformed TDS) and %HCO_3^- (BIOENV, $\rho = 0.771$). Of these variables, salinity appeared the most influential on the number of species found at each site, with 30 % of species apparently restricted to freshwater springs.

Fish

Two native fish species were recorded from the Salt Creek system, spangled perch *Leiopotherapon unicolor* (Günther) and a new species of goby *Acentrogobius* sp. nov. Spangled perch were abundant in the Salt Creek channel and in Mandora Lake. Large numbers of dead fish were also observed in dry channel pools to the east. The goby was taken from amongst mangrove pneumatophores in small pools in a channel running from a saline spring into Salt Creek. The habitat was difficult to sample and only a limited number of juveniles and adults were caught[1]. No fish were observed in any of the springs, bores or Coolabah Claypan.

Discussion

Fauna composition

In terms of total number of invertebrate taxa (138), Mandora Marsh may be considered relatively rich when compared with other Australian spring systems. Similarly, the proportion of Insecta (~ 50%) is comparatively high for Australian inland waterways, although microcrustacea may be under-represented because sampling for microinvertebrates was restricted due to the shallow, organic-rich water. The Department of Environment and Conservation subsequently surveyed the invertebrate fauna of Saunders Spring in May 2008 (Daniel *et al.* 2009), as part of resource condition monitoring of the Eighty-mile Beach Wetland of International Importance (Ramsar site). Forty-five macroinvertebrate taxa were recorded from three sampling locations within the Spring. The macrofauna was dominated by cosmopolitan dipteran, coleopteran and hemipteran species. Microfauna were not sampled.

Mitchell (1985) sampled 13 mound springs in northern South Australia and recorded 59 taxa, comprising 27 Crustacea and 32 Insecta, however, not all groups were taken to species level, and microfauna other than

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[1] On 11th August 2001, Sally Black, Tim Willing and David Dureau (Department of Environment and Conservation) collected additional specimens of *Acentrogobius* sp. nov. from the Salt Creek palaeochannel, 15 km east of the current study site (location 19°44'33" S, 121°37'20" E).

microcrustacea were not sampled. Therefore, the fauna likely supports additional taxa, but even so, it appears less rich than the Mandora wetlands. Halse *et al*. (2000) sampled three peaty spring sites in the Carnarvon Basin, with taxa richness ranging from 15, in a very small site with virtually no free water, to 38. These sites had a high proportion of Insecta (*i.e.* up to 90%), reflecting the difficulty in sampling the shallow, peaty habitat. Halse *et al*. (2002) collected 159 species during a one-off sampling of five springs in the Pilbara region of north-west Western Australia, with an average richness of 60 species per spring and an average proportion of Insecta of 61%. The springs, however, were not mound springs but were on river channels, subject to frequent wet season flushing, resulting in a coarser substrate and deeper surface flow. The sites were also widely distributed across the Pilbara region (*i.e.* separated by 100s of kilometres), and across catchments which would increase the suite of species that could be present.

Pinder *et al.* (2010) similarly surveyed a comprehensive diversity of wetland habitats across the Pilbara, including 18 flowing springs/spring fed creeks. Between 2003 and 2006, a total 189 samples were collected from one-off sampling of 100 sites in spring and autumn. Average richness per sample was 94, with microinvertebrate richness ranging from 3 to 57 and macroinvertebrate richness ranging from 4 to 170. Insects comprised 42% of all taxa collected. By comparison, average richness from the 36 samples collected at springs/spring-fed creeks was 94, with microinvertebrate richness ranging from 5 to 45 and macroinvertebrate richness ranging from 45 to 144. Insecta were again dominant, comprising 61% of the total fauna of the springs/spring-fed creeks. Pinder *et al.* (2010) found numerous endemics (*e.g.* amphipods, isopods, riffle beetles) and rare non-endemics (*e.g.* assimineid snails, leptophlebiid mayflies, species of water mite) that appeared restricted to a sub-set of the springs/ spring-fed creeks. One of these groups, the assimineid snails, was also present in Mandora Marsh, represented by a new species, *Assiminea* sp. nov.

Further south, Pinder *et al*. (2006) surveyed seven tumulus mound springs in the northern Wheatbelt Region of Western Australia, recording 88 taxa in March and 80 taxa in August 2001, giving a total of 103 taxa. The fauna of the springs comprised common and widely distributed insects, some regionally rare and a suite of groundwater-dependent species including a bathynellid syncarid, an amphipod, and several species of ostracod and copepod. The fauna was dominated by Insecta (58 %), with the conservation value lying with the restricted groundwater-dependent fauna, as well as some species that were considered uncommon in the region, being more characteristic of the wetter south-west (Pinder *et al*. 2006).

Tumulus mound springs on the Gnangara Groundwater Mound, north of Perth have been sampled more frequently, with taxa richness ranging from 40 species from King's and Muchea springs (Jasinska & Knott 2000), 43 from King's, Muchea and Egerton springs (Pinder, unpub. dat.), and 72 from repeated seasonal sampling of Muchea and Egerton springs (Jasinska & Knott 1994).

When compared with other arid-zone non-spring wetlands, the Mandora system is again comparable in terms of richness. Halse *et al*. (1998) undertook invertebrate sampling of Lake Gregory – a large (380 km^2), mostly fresh, semi-permanent lake on the edge of the Great Sandy Desert, with similar methods to those used in this study and considered the 174 taxa (42% Insecta) recorded over three sampling occasions to represent a highly diverse fauna for inland waters. Sampling, however, spanned a range of salinities as the lake evapoconcentrated, which would encourage different species to inhabit the lake. Storey & Creagh (unpubl. data) collected 124 taxa (37 % Insecta) from freshwater pools during one-off sampling of the highly ephemeral Jones Creek in the northern Goldfields of Western Australia. Timms *et al.* (2007) recorded more than 100 invertebrate taxa over four sampling occasions from saline and fresh wetlands (> 750 km^2) in the episodically filled Lake Carey complex in the eastern Goldfields, though their study did not target rotifers or micro-crustaceans. Amongst other substantially larger, more extensively surveyed arid systems, riverine waterholes of the Lake Eyre basin reportedly support 136 macroinvertebrate taxa (Costelloe *et al*. 2004) and at least 400 microinvertebrate taxa (Shiel *et al.* 2006), and arid-zone wetlands on the Paroo River floodplain in south-west Queensland support at least 200 invertebrate taxa (Timms & Boulton 2001; Hancock & Timms 2002).

The considerable richness of Mandora Marsh was considered due to the different types of permanently inundated wetlands within the one system. This concurs with the suggestion by Halse *et al.* (1998) that increased richness will occur in inland systems when there is regular, prolonged inundation coupled with waters of varying solute composition. Faunal composition of the Mandora wetlands was closely linked to salinity, though even within freshwater sites, spatial variation in community assemblage was high. However, it is likely the current survey underestimates species diversity and number of restricted species, as not all sites were sampled for microinvertebrates, but also the shallow, peaty seeps on the mound springs were difficult to sample, especially for microinvertebrate fauna.

Fauna endemism

The macroinvertebrate fauna of the Mandora Marsh was dominated by highly vagile predators capable of traversing the region and easily able to move between wetlands within the marsh. Dispersion within the marsh of less mobile elements of the aquatic fauna would be facilitated by widespread flooding that regularly occurs following cyclonic activity. Taxa that appeared endemic to the springs (*e.g.* the snail *Assiminea* sp. nov.) are likely to have habitat requirements that restrict their occurrence. Ponder (unpubl. data) undertook a survey of 30 springs in the northwest of Western Australia in September 1987, sampling Salt Creek, Eil Eil Spring and three unnamed springs at Mandora. The most significant fauna recorded was *Assiminea* sp., which appeared to be restricted to the springs of Mandora Marsh. Insecta were not identified below ordinal level, however all orders recorded by Ponder were present in this survey.

Though the cores contained taxa not recorded from adjacent surface waters, the rate of occurrence of these taxa was low and comparable to elements of the microfauna taken from each wetland. These taxa were therefore considered to be rare, rather than restricted to the pore water of the peat mounds. The presence of groundwater species such as the bathynellid syncarid *Kimberleybathynella mandorana*, copepods *Mesocyclops brooksi* and *Metacyclops mortoni* Pesce *et al*. and the ostracods *Vestalenula marmonieri* Rosetti & Martens and ?*Candona* sp., does suggest the potential for more stygal material from this aquifer. The Pilbara region has previously been found to be rich in stygal species (Halse *et al.* 2002; Eberhard *et al.* 2005; Cooper *et al.* 2007).

Rhizopoda

Rhizopods are ubiquitous in damp situations, from soil and moss to fully aquatic environs. Taxonomy has historically been based on test morphology. Because testates were long-thought to be cosmopolitan, names applied have been 'cosmopolitan' on all continents, even when the bearers are only superficially (or not at all!) similar. Australasian Rhizopoda are poorly known, particularly those of Western Australia. The only detailed work in any Australian region remains that of Playfair (1917) in NSW. The group needs critical revision by modern standards using biometry, scanning electron microscopy and genetic analysis. Evidence from widespread collections across southern Australia (Meisterfeld & Tan 1998; Shiel & Tan unpubl. data), shows that the Australian Rhizopoda have a cosmopolitan component, a Gondwanic component and an endemic component, but, given the poor taxonomic resolution of the rhizopods in Australasia, the extent of each component remains unknown. Only 14 taxa in five families were encountered in the Mandora Marsh samples, most from the genera *Arcella*, *Centropyxis* and *Difflugia*, with *Arcella* sp. A and *Centropyxis aculeata* (Ehrenberg) the most common (present at four sites). Richness was similar to that reported by Pinder *et al.* (2010) for other springs and spring-fed creeks within the Pilbara region. However, richness and density per site were very low relative to collections from eastern Australia (Meisterfeld & Tan 1998), although collecting methods may be partly responsible for this. Most Mandora Marsh rhizopods either could not be identified from current literature, and may well be undescribed, or resembled to some degree known species, but in-depth population analysis is needed to confirm the identification. Only two species were unequivocally the nominate (cosmopolitan) species.

Rotifera

Rotifers are among the smallest metazoans and are largely associated with freshwater, although a few species are adapted to athallasic saline or oceanic waters. They were long thought to be cosmopolitan, however recent detailed studies on all continents have demonstrated regionalism in rotifer faunae. Australia has approximately 15% endemicity in the known Rotifera (~ 700 spp.) (Shiel & Koste 1986). The few reports of rotifers from Western Australia suggest that it has a higher degree of endemicity than found in eastern Australia, with some Tasmanian affinities in southwest Western Australia and Indo-Malaysian affinities in the northwest of the state (*e.g.* Halse *et al.* 1998; Shiel & Williams 1990; Storey *et al*. 1993). At least 16 rotifer taxa in seven families were recognised in the Mandora Marsh samples. More are likely in view of the difficulty of identifying bdelloid rotifers from preserved material. Nevertheless, the number of 'hidden' species is likely to be few and the total estimated (~ 20) is low relative to other Western Australian sites. For example, Pinder *et al*. (2010) recorded 105 taxa from springs/spring-fed creeks across the Pilbara, Halse *et al.* (1998) recorded ~ 40 species at Lake Gregory, and Shiel *et al*. (2006) recorded 20 to 30 species per site for arid zone waters in central Australia. These rotifer numbers in turn are low relative to well-watered billabongs of eastern Australia, where > 100 rotifer species have been recorded from single net tows in Murray-Darling billabongs (Shiel *et al.* 1998). In terms of novelty, only two of the Mandora rotifers are new (a *Brachionus* related to the cosmotropical *B. budapestinensis* Daday, and a *Cephalodella* close to the South American *C. boettgerii* Koste). The estimated 10% endemicity for the Mandora rotifers probably reflects the small sample size and perhaps incomplete collecting. It is less than the continental endemicity and the estimated 12% for Western Australia. Notably, the remaining Mandora Marsh rotifers are all cosmopolitan taxa.

Branchiopoda: Anomopoda / Ctenopoda (cladocerans)

With only five taxa identified from Mandora Marsh, the cladoceran representation in the microfauna is poor relative to other Western Australian studies (cited above) and Australia in general. Four of the five taxa occurred once, with only *Ceriodaphnia cornuta* Sars at more than one site. The three indeterminate species are probably Australian endemics. For example, the Australian form of *Moina micrura* Kurz, collected from Coolabah Claypan, has been shown by genetic analysis to be distinct from the nominate species (Petrusek *et al.* 2004) but the regional distribution of this, and other indeterminate species, remains unknown. About half of the described Australian cladocerans (~ 200 spp.) are endemic.

Other Microcrustacea

Like other microinvertebrate groups, the ostracod and copepod faunas of Mandora Marsh were relatively depauperate. More than 150 species of surface water ostracods are known from Western Australia, although fewer than half are described (Halse 2002). Up to 10 ostracod species per site were recorded from seasonal pools in semi-arid areas on the mid-west coast (Halse *et al*. 2000), and up to 12 were recorded at individual Pilbara springs (Pinder *et al*. 2010), whereas a total of only five living species were recorded from Mandora Marsh as a whole, with a maximum of three at a site. The marsh sites contained a mixture of stygal (?*Candona*, *Vestalenula*, *Metacyclops*) and epigean species, with most of the named species having widespread occurrence in Australia or beyond. Three of the four described copepod species collected are widespread in Australia (Halse *et al*. 2002; Pesce *et al.* 1996b); *Metacyclops mortoni* was the exception, having previously been collected only from deep groundwater near Cape Range on the northwest coast and the Ashburton River on the mid-west coast (Pesce *et al*. 1996a).

Oligochaeta

All species of oligochaetes recorded are widespread in Australia. *Allonais ranauana* (Bolt) frequently occurs in arid and tropical sites (including Coopers Creek, South Alligator River and Lake Gregory), but has not been recorded from southeastern or southwestern Australia. Worldwide, *A. ranauana* is fairly widespread, but particularly common in Africa. *Pristina longiseta* Ehrenberg and *Dero furcata* Müller both are worldwide, cosmopolitan species (A. Pinder, Dept. Environment and Conservation, pers. comm.).

Gastropoda

Two gastropod species were recorded; the planorbid *Gyraulus* sp. and the assimineid *Assiminea* sp. nov., which is new to science. Further survey effort is required to determine whether or not it is endemic to these springs. It was present at both saline Fern Spring (5.78 g L^{-1}) and freshwater Linear Spring (0.62 g L^{-1}). *Gyraulus* sp. is probably widespread across northern Australia (W. Ponder, Australian Museum, pers. comm.) and it too was present in both saline and freshwaters.

Arrenuridae / Eylaidae / Hydrachnidae

The identified species of water mites are common across the north of Australia. It is likely that many of them parasitise adult dragonflies, providing an efficient means of distribution (Harvey 1998).

Coleoptera / Hemiptera

The hemipteran fauna of the springs was relatively rich but dams and soaks often provide good habitat for *Anisops*, of which seven species were present. The fauna contained typical northern Australian species (Lansbury 1969; Wroblewski 1970, 1972). The occurrence of *Micronecta lansburyi* Wroblewski is of interest because it has rarely been recorded. The beetle fauna consisted of at least 27 species and was substantially richer than that at many other north-western Australia wetlands (Halse *et al*. 1996, 1998; Pinder *et al.* 2010). It was comprised mostly of widespread species of Dytiscidae and Hydrophylidae (Watts 2002).

Diptera

The species of Chironomidae recorded from the Mandora sites are all cosmopolitan in distribution. *Tanytarsus barbitarsus* Freeman is a halobiont species, and was only recorded from the Salt Creek Claypan Spring (38.5 g L^{-1}). Other species of chironomid appeared restricted to freshwater sites, though some at least are known to have a range of tolerances, *e.g. Procladius paludicola* Skuse and *Chironomus* aff. *alternans* Walker. Of other dipterans that could be identified to species, the culicid *Culex bitaeniorhynchus* Giles has a generally northern distribution and is known to breed in wetlands and creeks, and is most common following wet season rains (Liehne 1991). *Culex annulirostris* Skuse is common and widely distributed across Australia.

Trichoptera / Odonata

There are many undescribed *Ecnomus* and *Oecetis* species across the north of Australia, and given the mobility of the adults, these species are likely to be common. *Triplectides ciuskus seductus* Morse & Neboiss is also common across the north of Australia (J. Dean, Victorian EPA, pers. comm.). The odonate fauna was depauperate and consisted of widespread species (Watson 1962).

Biogeography

Though the marsh was comparatively taxa-rich overall, the aquatic invertebrate fauna of individual sites was taxa-poor in comparison with other temperate and tropical wetlands in Western Australia (*e.g.* Davis *et al.* 1993; Storey *et al*. 1993; Edward *et al*. 1994; Halse *et al.* 1996, 2000, 2002; Pinder *et al*. 2004). It must, however, be noted that sampling the shallow seeps was problematic, and one-off sampling will have underestimated the richness of the Mandora wetlands given the high degree of temporal variability in Australian inland waters (Sheldon *et al.* 2002).

The insect species at the marsh were characterised by strong-flying adult stages, promoting efficient dispersal. Unsurprisingly, the macroinvertebrates of the wetlands consisted of few taxa with limited distributions or endemic to the area. The majority of endemic taxa were recorded from the microinvertebrate fauna, but richness and levels of endemism were mostly low compared to other detailed fauna surveys (Halse *et al*. 1998, 2000; Meisterfield & Tan 1998; Shiel *et al*.1998; Pinder *et al.* 2010).

Approximately 15 M yr BP, the Mandora system was part of a large drainage system known as the Wallal Palaeoriver. A gradual shift toward more arid climatic conditions caused the drainage valley to fill with alluvial and aeolian material (Watkins *et al.* 1997). By about 10 000 yr BP, the system was part of a shallow marine system. Carbon dating of peat sediments in Eil Eil Spring (Wyrwoll *et al.* 1986) suggest the wetlands that exist today formed some 7 000 years ago, and have changed little in that time. The relatively short life of the springs could further explain the low levels of endemism in the aquatic fauna.

That the Mandora area once was an estuary could also explain the presence of inland mangroves, mangrove fern, a new species of *Acentrogobius* gobiid, and the endemic assimineid gastropod. *Acentrogobius* is a poorly defined genus currently including marine and estuarine species, widespread in the Indo-west Pacific (H. Larson, NT Museum, pers. comm.). Gastropods of the genus *Assiminea* also are regarded as marine. The presence of new species of these ‘marine’ genera and isolated occurrences of mangrove plant species in the Mandora system probably reflects isolation at the start of the Holocene, some 9 000–10 000 yr BP (Ridpath *et al.* 1991) with subsequent genetic and morphological divergence.

Conservation and Management

Mound springs of Australia are widely recognised as having high conservation significance, particularly in arid zones, where their permanent water provides refugia for flora and fauna. They are known to support remnant populations of species with a once wider distribution, as well as new and endemic species, resulting from speciation of isolated populations. Upwelling flows originating from subterranean habitats may also bring short-range endemic and more broadly distributed stygofauna to the surface.

The Mandora system contains a variety of wetland types, with closely adjacent sites ranging in salinity from fresh to saline despite only small variations in topography. This would indicate a complex groundwater system with fresh and saline aquifers likely at different depths, feeding different parts of the system. The saline spring-wetlands are likely driven by an aquifer containing stored marine salts from pre-Holocene. However, it is currently not known if the freshwater springs are driven by deep artesian water, or unconfined near-surface groundwater recharged by local rainfall. This diversity in wetland types within the one system is partly why Mandora Marsh was listed under the Ramsar Convention (Jones 1993).

Pressure from stock and feral animals appears to be a major threat to the wetlands. Elevated nutrient levels in the two wells suggests nutrient enrichment of the shallow groundwater aquifer at these locations, which is likely, given the heavy stock usage of the bores, shallow depth to groundwater (~ 3 m below surface) and sandy nature of the soils. However, the spatial extent of any enrichment is not known, given the low density of bores for sampling. Cattle and feral camels have already adversely affected the ecological health of the mound springs. Apart from the physical damage caused by stock trampling the mounds and grazing the regenerating vegetation, the tendency of stock to remain at the springs for long periods during hot weather, is degrading the vegetation and water quality. Sampling was conducted at the end of the dry season, when wetlands in general, and particularly those in arid zones, tend to recede and evapoconcentrate. Even so, the occurrence of algal blooms in the shallow moats around Melaleuca and Saunders springs, combined with highly elevated nitrogen levels at these sites relative to others, indicates nutrient enrichment. Interestingly, Mitchell (1985) recorded highly elevated dissolved nitrate levels from mound springs in northern South Australia which was attributed to defecation by stock, and considered that stock would eventually result in the destruction of the wetlands. Halse *et al*. (2005) acknowledged that domestic stock degrade wetlands through pugging and grazing, with most damage occurring in the second half of the dry season as temperatures increase and water and fodder are scarce, with cattle camping around natural (and man-made) waterholes. But Halse *et al.* (2005) also suggested cattle may have little influence on episodic wetlands such as Mandora Lake, unless the wetlands are part of a landscape subject to widespread overgrazing. The permanently inundated mound springs of Mandora Marsh concentrate domestic stock and feral camels, as they provide a reliable water source in an arid environment, and it appears this pressure is damaging the springs.

In recognition of the damage by stock and feral animals, Saunders Spring was fenced in November 1997 by the holders of Anna Plains pastoral lease, in association with the Broome Botanical Society, using funds from the Commonwealth Natural Heritage Trust. Part of the strategy was to leave a man-made pool outside the fenced area to provide for stock. The fencing appeared to be of immediate benefit as understorey vegetation within the fenced area was visibly regenerating and the moat was well shaded, with no algal activity. However, algal growth was extreme in the pool outside the fence which was subject to heavy stock use (Storey pers. obs.). Mitchell (1985) and Halse *et al*. (2002) recommended fencing of springs to exclude stock and feral animals and so prevent eutrophication and physical damage. The increase in taxa richness at Saunders Spring between 1999 (current study) and 2008 (Daniel *et al.* 2009) suggests progressive improvement in ecological health following fencing of the site in 1997, but further sampling would be required to corroborate any causal link.

Change in hydrology is also a major threat to mound springs. To the north-east of Mandora, trials were conducted in the late 1990s to grow irrigated cotton using groundwater extracted from the La Grange sub-basin. Although these trials have not progressed, they may in future (Hale & Butcher 2009), and water extraction from the aquifers feeding the springs at Mandora would be extremely detrimental to these springs and would probably lead to their loss. Maintenance of a natural hydrological regime is seen as a critical management issue for most arid-zone wetlands (Harris 1992; Kingsford & Thomas 2004; Halse *et al.* 2005). Mitchell (1985) also identified over pumping from artesian bores as a threat to the existence of mound springs in northern South Australia, with reduced flows in some springs attributed to over pumping at adjacent bores.

The aquatic fauna of the wetlands at Mandora Marsh may not be unique, but the system is worthy of conservation as it represents one of only a few permanent arid zone wetlands and contains new and restricted species. Mitchell (1985) sampled 13 mound springs in northern South Australia and separated the aquatic invertebrate fauna into two components, the insects with good powers of dispersal and therefore a wide distribution, and non-insects, with low powers of dispersal and no drought-resistant stages in their life cycle (*i.e.* hydrobiid gastropods, phreatoicid isopods, an amphipod and a gobiid teleost). Together with some endemic ostracods, Mitchell (1985) considered these non-insect elements to be the unique mound spring faunal assemblage. The aquatic fauna of the Mandora springs and wetlands is similarly classified, with the non-insect mound spring fauna having the highest conservation value. In terms of aquatic fauna biodiversity, each wetland at Mandora is not particularly species rich, but as a heterogeneous wetland suite it does support a relatively diverse fauna. However, the highest conservation value arises when the overall ecological values of the Marsh are considered in the context of the mix of waterbird (Halse *et al*. 2005), aquatic invertebrate (this study) and plant values (Graham 1999). The assemblage values for the mound springs and Salt Creek, and the species values for Mandora Lake (Walyarta) where waterbird values are very high after flooding (Halse *et al.* 2005) make this system worthy of protection. Currently the Mandora Marsh system is part of the Eighty-mile Beach Ramsar site, with the beach and the episodically-flooded country between the beach and the Marsh regularly supporting substantial waterbird values. As such, the values of Mandora Marsh should not be viewed in isolation from those west of the Great Northern Highway (Fig. 1).

In conclusion, this study has extended our knowledge of the ecological values of Mandora Marsh, but the values are yet to be fully described and, given possible threats from future adjacent development, it is important that values are documented so that any planning process is properly informed. Subsequent to this survey, and in recognition of the conservation value of the marsh system, it is planned to revise the pastoral lease boundary of Anna Plains Station in 2015 to encompass Mandora Marsh in a nature reserve (Hale & Butcher 2009). In recognition of the threat feral camels pose to arid zone ecosystems across northern and central Australia, the Federal Government in 2009 committed $17M to the control of camels. The 2010 groundwater allocation and management plan for the La Grange subareas (Department of Water 2010) also acknowledges the need for further investigation of the water requirements of groundwater dependent ecosystems including those of Mandora Marsh. All initiatives will help protect the mound springs of Mandora Marsh.

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Appendix

Systematic listing of taxa recorded from 12 sites. Codes: BS = Bretts Spring; CC = Coolabah Claypan; EE = Eil Eil Spring; FS = Fern Spring; FW = Friday Well; LEE = Little Eil Eil Spring; LS = Linear Spring; LW = Lyngett Well; MS = Melaleuca Spring; SCS = Salt Creek Claypan Spring; SS = Saunders Spring; TS = Top Spring; core = microinvertebrates taken from pore water in a peat core; † microinvertebrates not sampled.

Taxon	BS	CC	EE	EE core	FS	FS core	FW	LEE	LEE core	LS †	LW	MS	SCS	SS	SS core	TS †	No. of occurrences
PROTISTA																	
Ciliophora			*														1
Foraminifera						*			*						*		3
RHIZOPODA																	
Arcellidae																	
Arcella cf. *discoides* Ehrenberg, 1843													*				1
Arcella sp. A			*		*				*						*		4
Arcella sp. B															*		1
Arcella sp. C		*															1
Arcella sp. D			*														1
Centropyxidae																	
Centropyxis aculeata (Ehrenberg, 1830)	*	*	*	*				*	*								6
Centropyxis constricta (Ehrenberg, 1841)								*									1
Centropyxis cf. *discoides* Penard, 1890					*												1
Centropyxis cf. *platystoma* Penard, 1890								*									1
Centropyxis sp.		*															1
Difflugiidae																	
Difflugia cf. *ventricosa* Deflandre, 1926															*		1
Difflugia sp.		*							*								2
Gromiidae																	
Pseudodifflugia sp.								*									1
Hyalospheniidae																	
Cyclopyxis cf. *kahli* (Deflandre, 1929)								*									1
ROTIFERA																	
Bdelloidea																	
Bdelloidea sp. indet. contracted [L]	*	*	*					*							*		5
Bdelloidea sp. indet. contracted [S]			*														1
Monogononta																	
Asplanchnidae																	
Asplanchna brightwelli Gosse, 1850		*															1
Brachionidae																	
Brachionus angularis Gosse, 1851		*															1
Brachionus cf. *budapestinensis* Daday, 1885		*															1
Brachionus quadridentatus Hermann, 1783		*															1
Plationus patulus (Müller, 1786)	*	*															2
Conochilidae																	
Conochilus dossuarius (Hudson, 1885)		*															1

Lecanidae												
Lecane (*Monostyla*) *bulla* Gosse, 1851	*					*						2
Lecane (*M.*) cf. *closterocerca* (Schmarda, 1859)						*						1
Lecane (*s.str.*) *flexilis* (Gosse, 1886)						*						1
Lecane (*M.*) *hamata* Stokes, 1896						*						1
Lecane (s.str.) *hastata* (Murray, 1913)						*						1
Lecane (*s.str.*) *luna* (Müller, 1776)	*			*								2
Notommatidae												
Cephalodella n. sp. (aff. *C. boettgeri* Koste, 1988)						*						1
Testudinellidae												
Testudinella patina (Hermann, 1783)		*										1
MOLLUSCA												
GASTROPODA												
Assimineidae												
Assiminea sp. nov.				*				*				2
Planorbidae												
Gyraulus sp.		*	*	*		*	*	*		*		7
ANNELIDA												
OLIGOCHAETA												
Allonais ranauana (Bolt, 1932)			*					*				2
Pristina longiseta Ehrenberg, 1828			*					*			*	3
Dero furcata Müller, 1774			*								*	2
Naididae												
Naididae sp. (indet.)						*						1
CRUSTACEA												
BRANCHIOPODA: Anomopoda/Ctenopoda												
Chydoridae												
Alona rectangula novaezealandiae Sars, 1904	*											1
Daphnidae												
Ceriodaphnia cornuta (s.l.) Sars, 1885	*	*	*									3
Macrotrichidae												
Macrothrix cf. *breviseta* Smirnov, 1976		*										1
Macrothrix sp. B (cf. *Neothrix*)		*										1
Moinidae												
Moina cf. *micrura* Kurz		*										1
COPEPODA												
Cyclopoidae												
Halicyclops spinifer Kiefer, 1935						*						1
Mesocyclops brooksi Pesce *et al.*, 1996		*	*	*		*						4
Metacyclops mortoni Pesce *et al.*, 1996	*											1
Cyclopoidae					*							1
Canthocamptidae												
Cletocamptus deitersi (Richard, 1897)			*	*		*	*		*			5

Taxon	BS	CC	EE	EE core	FS	FS core	FW	LEE	LEE core	LS †	LW	MS	SCS	SS	SS core	TS †	No. of occurrences
Ameiridae																	
Ameira sp.													*				1
Parastenocarididae																	
Parastenocaris sp.					*												1
OSTRACODA																	
Candonidae																	
?*Candona* sp.			*												*		2
Darwinulidae																	
Vestalenula marmonieri Rosetti & Martens, 1999			*					*									2
Cypridiae																	
Cyprinotus kimberleyensis McKenzie, 1966	*	*															2
Cypretta baylyi McKenzie, 1966			*	*				*			*						4
Cypretta sp. B		*															1
Diacypris spinosa De Deckker, 1981 (dead)													*				1
Limnocytheridae																	
Limnocythere ?dorsosicula De Deckker, 1981											*						1
SYNCARIDA																	
Parabathynellidae																	
Kimberleybathynella mandorana Cho *et al.* 2005						*											1
ARTHROPODA																	
ARACHNIDA																	
Arrenuridae																	
Arrenurus sp.	*	*	*							*							4
Arrenurus balladoniensis Halik, 1940		*															1
Arrenurus tricornutus Viets, 1984		*															1
Eylaidae																	
Eylais sp.			*		*												2
Hydrachnidae																	
Hydrachna sp.												*					1
Unionicolididae											*						1
INSECTA																	
EPHEMEROPTERA																	
Baetidae																	
Cloeon sp.	*	*								*							3
ODONATA																	
ANISOPTERA																	
Libellulidae																	
Orthetrum caledonicum (Brauer, 1865)	*																1

Trapezostigma stenoloba Watson, 1962	*					*					2
Libellulidae sp. (juvenile)		*			*	*					3
ZYGOPTERA											
Coenagriidae											
Xanthagrion erythroneurum (Selys, 1876)		*									1
HEMIPTERA											
Corixidae											
Agraptocorixa parvipunctata (Hale, 1922)							*				1
Micronecta lansburyi Wroblewski, 1972		*									1
Micronecta virgata Hale, 1922	*	*	*		*	*	*				6
Micronecta sp.		*									1
Naucoridae											
Diplonychus eques (Dufour, 1863)		*	*		*	*					4
Notonectidae											
Anisops canaliculatus Brooks, 1951									*		1
Anisops nasuta Fieber, 1851				*		*	*				3
Anisops nodulata Brooks, 1951										*	1
Anisops semita Brooks, 1951		*					*		*		3
Anisops stali Kirkaldy, 1904		*							*		2
Anisops sp. E									*		1
Anisops sp.		*	*		*				*	*	5
Pleidae											
Paraplea sp.						*					1
COLEOPTERA											
Dytiscidae											
Allodessus bistrigatus (Clark, 1862)									*		1
Allodessus sp. (larva)	*										1
Copelatus nigrolineatus Sharp, 1882							*				1
Cybister tripunctatus (Olivier, 1795)				*							1
Eretes australis (Erichson, 1842)				*					*		2
Hydaticus consanguineus Aubé, 1838				*			*		*		3
Hydaticus vittatus (Fabricius, 1775)				*					*		2
Hydaticus sp. (larva)	*										1
Hydroglyphus leai Guignot, 1939	*	*	*	*			*	*	*		7
Hydroglyphus trifasciatus Watts, 1978	*	*	*	*	*		*	*	*	*	9
Hydroglyphus trilineatus Watts, 1978					*						1
Hyphydrus elegans (Montrouzier, 1860)				*							1
Hyphydrus lyratus Swartz, 1808		*		*							2
Laccophilus sharpi Régimbart, 1889	*	*	*	*		*	*		*		7
Laccophilus sp. (larva)	*										1
Rhantaticus congestus (Klug, 1833)				*							1
Rhantus suturalis (Macleay, 1825)			*	*							2
Hydraenidae											
Octhebius sp.	*			*			*	*	*		5

Taxon	BS	CC	EE	EE core	FS	FS core	FW	LEE	LEE core	LS †	LW	MS	SCS	SS	SS core	TS †	No. of occurrences
Hydrophilidae																	
Amphiops sp. (larva)	*																1
Berosus australiae Mulsant & Rey, 1858					*							*		*			3
Berosus pulchellus Macleay, 1825					*							*	*	*			4
Berosus sp. (larva)										*							1
Coelostoma fabricii (Montrouzier, 1860)					*									*			2
Enochrus (Methydrus) malabarensis (Régimbart, 1903)	*		*		*			*		*		*	*	*			8
Enochrus (Methydrus) deserticola (Blackburn, 1896)	*											*					2
Enochrus (Methydrus) elongatus (Macleay, 1871)												*					1
Enochrus sp. (larva)			*														1
Helochares sp.	*												*				2
Helochares sp. (larva)													*				1
Paracymus sp.			*														1
Regimbartia attenuatus (Fabricius, 1801)	*		*		*			*		*		*		*		*	8
Sternolophus (*Neosternolophus*) *marginicollis* (Hope, 1841)							*										1
Hydrochidae																	
Hydrochus sp.					*												1
DIPTERA																	
Chironomidae																	
Ablabesmyia ?notabilis (Skuse, 1889)		*															1
Chironomus aff. *alternans* Walker, 1856	*		*							*							3
Dicrotendipes sp.		*															1
Paramoima sp.	*																1
Polypedilum (*Pentapedilum*) *leei* Freeman, 1961	*	*												*			3
Polypedilum nubifer (Skuse, 1889)		*															1
Procladius paludicola Skuse, 1889	*	*								*							3
Tanytarsus barbitarsis Freeman, 1961													*				1
Tanytarsus spp.	*	*			*	*		*		*		*				*	8
Ceratopogonidae		*	*		*			*					*				5
Empididae													*				1
Tabanidae			*														1
Culicidae																	
Anopheles (*Cellia*) sp.	*																1
Anopheles sp.													*				1
Culex annulirostris Skuse, 1889	*		*							*						*	4
Culex bitaeniorhynchus Giles, 1901			*														1
Culex sp.	*							*									2
Ephydridae			*														1
Stratiomyidae	*		*		*			*		*		*	*	*		*	9

TRICHOPTERA																	
Ecnomidae																	
Ecnomus sp.		*															1
Leptoceridae																	
Triplectides ciuskus seductus Morse & Neboiss, 1982	*	*															2
Oecetis sp. (larva)		*															1
Oecetis sp. (pupa)		*															1
Total number of taxa	*36*	*48*	*36*	*2*	*31*	*2*	*2*	*32*	*6*	*21*	*3*	*20*	*15*	*21*	*6*	*9*	*138*