Heavy Minerals Conference 2011

Paper Number: 42

SETTING RESTORATION GOALS FOR RESTORING PIT LAKES AS AQUATIC ECOSYSTEMS: A CASE STUDY FROM SOUTHWEST AUSTRALIA

E. J. B. van Etten[1], C. D. McCullough[2,3] and M. A. Lund[4]

1.
Senior Lecturer, Terrestrial Ecology Research Group (TERG), 270 Joondalup Drive, Perth, WA 6027, Australia. Email: e.van_etten@ecu.edu.au

2.
Principal Environmental Scientist, Golder Associates, West Perth, WA 6005, Australia. Email: cmccullough@golder.com.au. MAusIMM

3.
Senior Research Fellow, Mine Water and Environment Research Centre (MiWER), 270 Joondalup Drive, Perth, WA 6027, Australia. Email: c.mccullough@ecu.edu.au

4.
Associate Professor, Mine Water and Environment Research Centre (MiWER), 270 Joondalup Drive, Perth, WA 6027, Australia. Email: m.lund@ecu.edu.au

ABSTRACT

Pit lakes may form when open cut mining leaves a pit void that then fills with ground and surface waters. This often replaces terrestrial ecosystems that existed prior to mining with an aquatic ecosystem, affording an opportunity to improve regional aquatic biodiversity values through targeted aquatic restoration (McCullough & Van Etten, 2011). Restoration theory provides guidance when restoring disturbed systems towards landscapes that are of regional value and relevance. But how do we identify a restoration target for a novel aquatic habitat that only exists in the new post-mining landscape? This paper presents a process of first identifying and then surveying local representative aquatic systems to provide a direction for pit lake restoration efforts and achievement criteria for pit lake relinquishment using a case study from a sand mining operation amongst wetlands in south-western Australia.

The company mines silica sands following mechanical removal of topsoil and then extraction of the ore from below the watertable by dredging. Assessment of wetland and riparian vegetation was achieved through the establishment and measurement of temporary monitoring transects across five natural

wetlands in the Kemerton area. Several more regional wetlands were also visited and observations made to supplement and validate these data.

Distinct vegetation zonation was found across each wetland, although typically wetland basins were unvegetated or filled with younger woody plants with patchy distributions. Fringing riparian vegetation consisted of few species (commonly the paperbark *Melaleuca rhaphiophylla* and the sedge *Lepidosperma longitudinale*) but community composition and structure were variable between wetlands. The pattern of vegetation seen across natural wetlands was best explained by topography and soil chemistry, with low lying wetland areas more likely to experience regular flooding and accumulate organic matter and nutrients.

In conclusion, where they are available, regional natural waterbodies may constitute the best valid restoration goal. Nevertheless, the goal may need to consist of a range of closure design opportunities, rather than a single target.

INTRODUCTION

Open-cut/cast mining has left a legacy of many thousands of mining pit voids worldwide (Castendyk & Eary, 2009) and across Australia (Kumar *et al.*, 2009). Restoration of mining landform terrestrial habitats has now become a well-researched practice that borrows from the disciplines of ecology and engineering to rehabilitate landscapes left completely altered, often scaling across entire bioregions. However, mining restoration typically ceases at the edge of these pit voids (McCullough *et al.*, 2009b; Van Etten, 2011). Where backfill of pits is not an economic or feasible option and the pit extends into the watertable then pit lakes with aquatic ecosystems may be desirable beneficial end uses (McCullough & Lund, 2006). Planning for such end uses is best made early in the life-of-mine to maximise opportunities and to minimise restoration costs (McCullough, 2011).

A first step in developing a pit lake ecosystem of environmental value is to identify an ‘Identifiable Desired State‘ (c.f., Grant, 2006) as a restoration goal (McCullough *et al.*, 2009a). This can be achieved by having a restoration target of aquatic ecosystems that are considered of ecological value and that are regionally representative. For shallow pit lakes or wetlands, restoration of a representative and functional amphibious vegetation community is often challenging. Natural wetland margins typically experience pronounced zonation in response to a seasonal flooding regime, which is further complicated by high inter-annual and longer-term variability in water levels. Pit lakes often have very stable water levels and margins due to smaller surface area:volume ratios reducing the effects of evaporative drying and rainfall changes to water level. Ecotones of riparian zones are noted for their acute spatial heterogeneity which results in high levels of species change presenting a distinct zonation across their perimeters (Ward *et al.*, 2002; Naiman *et al.*, 2005).

This study sought to determine what regional wetlands might act as restoration targets for a sand mining operation that was causing direct loss to natural wetland habitat. This study also sought to understand what physical and chemical drivers were most important for rehabilitating wetland vegetation community structure around the pit lakes formed by the extractive activities.

Location & Study Area

The study was conducted at a silica sand mine located at Kemerton (33°08'S, 115°47'E), 30 km north of Bunbury and 150 km south of Perth on the Swan Coastal Plain (SCP), Western Australia (FIG 1 - Location of Kemerton wetlands in south-western Australia.). Climate is distinctly Mediterranean with most of the average *ca*.890 mm annual rainfall falling in winter and spring (Commonwealth of Australia Bureau of Meteorology, 25/10/2010). Summers are warm to hot and typically very dry (average February maximum temperature 28^{o}C and rainfall 13 mm) and winters are cool and wet (average July maximum is 17^{o}C and rainfall 186 mm). The sampling period 2001–2008 was one of the driest on record with total rainfall each year below the long-term average, and most below the recent (1995–2008) average.

FIG 1 - Location of Kemerton wetlands in south-western Australia.

Shallow depth to groundwater in the inter-dunal depressions results in numerous wetland areas of palusplain, damplands, sumplands and lakes (as per the definitions of Semeniuk (1987)) within the project area. The climate and shallow nature of wetlands in the Kemerton area ensure that all natural wetlands are seasonal and these wetlands become inundated from rainfall or the rising groundwater table, typically from July to November.

Approximately 500,000 t of feldspathic silica sands are extracted annually at this mine from below the watertable using dredging. Once ore extraction is complete, the permanently inundated pit lakes are approximately 10 m deep.

METHODS

Riparian Vegetation Community Structure Assessment

Riparian transects were used to characterise the wetland vegetation patterns and to identify processes driving vegetation structure. We assessed: 1) structural attributes of the vegetation; 2) plant composition using the multivariate technique of ordination; 3) dominance and diversity patterns within plant communities (Grant & Loneragan, 2003); and 4) soil and topographic features.

Riparian vegetation community structure was assessed through transects across several natural wetlands in the KSS Project area and nearby Kemerton Nature Reserve (KNR) in winter 2007. These are numbered as “EPP4”, etc. to indicate Western Australian State Government Environmental Protection Policy Plant wetlands. Plant species were identified using a combination of prior experience, published keys, Florabase (DEC, 2008), herbarium records and other resources (FIG 2). Transects commenced at wetland base (lowest point in profile), traversed the fringing wetland and then finished at the upland vegetation (if present). To capture the variation in vegetation along transects in the most efficient manner, the relevé sampling approach was used, where a study site (or relevé) was established within each distinct vegetation type along the transect.

Soil and Topographic Profiling

A theodolite, GPS and tape measure were used from the wetland gauge board (if present) to determine the changes in slope along the riparian transect. In each of the different vegetation zones identified a sampling trench was dug along transects and different soil horizons were identified to a maximum depth of 0.50 m (FIG 2). A soil sample was then collected from three different sites to form a pooled sample for the vegetation zone. The soil sample was then dried, ground and analysed for: texture, colour, nitrate-N, ammonium, phosphate, potassium, sulfur, iron (all in mg/kg), carbon (%), conductivity, (dS/cm) and paste pH (pH H_2O).

FIG 2 – Sampling of sand mine project area wetland vegetation and wetland soils.

Data analysis

The mean and standard error of relevé cover, density (number of plants per relevé) and richness (number of species per relevé) was calculated for each transect. Differences between transects, depth and position along transect were tested using univariate analyses of soil variables such as one- and two-way ANOVA in SPSS (2007).

Multivariate data analyses were made using PRIMER v6 software (Clarke, 1993) following a process of data transformation, graphical exploration and then statistical hypothesis testing. Environmental – vegetation relationships were explored using Redundancy Analysis (RDA) within CANOCO for WINDOWS version 4 (ter Braak, 1998).

RESULTS

Topographic Profiles

Topographic profiles of the wetlands show that wetland basins are generally flat with slopes of <0.1% which end in relatively abrupt change of slope where dense fringing vegetation develops on slightly higher ground of 0.2 to 1 m above the wetland basin (FIG 3). Wetland EP4 is slightly different as the lake basin was generally smaller in area and had a more concave profile with slopes between 0.2 to 0.4%.

Wetland EP7 was deeper than EP4 which appears to limit the vegetation development on the basin. EP4 was in the process of being colonised by *Melaleuca* spp. EP5 had patchy shrub and trees over the wetland basin, whereas other regional wetlands (e.g., EP8 and EP9) had been almost completely infilled with woody vegetation.

Dense fringing vegetation of paperbark (*Melaleuca* spp.) and sedge/rush develop at elevations of only 0.2–0.5 m above the wetland basin. A further 0.5 m or so increase in elevation corresponded to a change to flooded gum (*Eucalyptus rudis*) and a more diverse shrub and sedge understorey, whereas 1.5 m above the wetland basin the vegetation was generally typical of uplands of the region (i.e., jarrah (*Eucalyptus marginata*)-marri (*Corymbia calophylla*) woodlands).

FIG 3 – Typical wetland (EP5) base level of bare ground around gauge board, colonised by herbaceous vegetation when immersed in winter changing to a paperbark fringe over very slight topographic changes.

Soil Characteristics

The first or A-horizon of wetland riparian soil was generally sand with the highest content of organic matter (6.2±0.9% organic C) and was consequently grey to black in colour. The A-horizon was generally thicker in the wetland basin (0.06–0.30 m) compared to fringing vegetation and uplands (0.05-0.10 m). The second or B-horizon was generally deep sand with low organic matter content (3.0±0.7% organic C) and generally white or yellow in colour (TABLE 1).

EP7 and the adjoining two small wetlands (PD and PS) had thick, dense organic matter accumulation at the surface (i.e., peat) to 0.3 m depth. Organic carbon and soil nutrients, including nitrogen and phosphorus, were substantially higher in these wetland soils compared to others (TABLE 1).

Soil nutrient concentrations (phosphorus, ammonia & nitrate) were normally higher in the A1 horizon than in the other horizons. Soil phosphorus levels were generally higher in soils of wetland basins compared to fringing vegetation, whereas ammonia was generally highest in fringing paperbark vegetation. Nitrogen, especially as nitrates, was particularly low in wetland basin soils, often at or below levels of detection (≤1 mg kg^{-1}). Soil phosphorus levels were very low (A1 horizon: 20.3±8.0; range 2–114 mg kg^{-1}) compared to those recorded for Perth wetlands by Davis *et al.* (1993) at a mean of 1,100±580 mg kg^{-1} (range 20–40,000 mg kg^{-1}) (TABLE 1).

Electrical conductivity was generally higher in the wetland basins and reached 2.46 mS cm^{-1} in EP4, 3.24 mS cm^{-1} in EP7 and 2.54 mS cm^{-1} in PS (TABLE 1). pH ($CaCl_2$) at EP7 was 5.5 in the wetland basin but declined to 3.8 in zone 4, and EP4, PD and PS showed similar trends. EP5 had the highest pH, ranging from 5.9–7.3 in zones 1 and 4 respectively. EP5 had significantly more alkaline topsoils and subsoils than other wetlands ($F=4.1$, $p=0.038$ for A1; $F=23.9$, $p<0.001$ for B). pH was generally higher in horizon B (TABLE 1).

Total sulfur concentrations were highest in the wetland basins (240, 115 and 202 mg kg^{-1} respectively) but generally declined in the outer zones. Sulfur concentrations were generally lower in horizon B although PS, PD (zone 1) and EP5 (zone 1) were no exceptions. EP5 had low sulfur concentrations across the zones (<32 mg kg^{-1}) in horizon A1. Iron concentrations were also lowest in EP5 ranging from 0.13–0.66 g kg^{-1} and generally the highest in zone 2 followed by zone 1, where it ranged from 0.36–1.88 g kg^{-1}. These concentrations are very low compared to those recorded by Davis *et al.* (1993) who recorded values of 19.2±5.9 g kg^{-1} (range: 1–324 g kg^{-1}).

TABLE 1

Chemical parameters of soils collected at multiple horizons and zones across wetlands of the Kemerton Silica Sands Project area and Kemerton Nature Reserve (the full dataset is available in Appendix 2).

Wetland		**EP4**		**EP5**				**EP7**				**PD**		**PD-PS**	**PS**
Zone		**1**	**2**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**1**	**1**
Soil Horizons (cm)	A1	0-6	0-5	0-8	0-8	0-8	0-5	0-20	0-5	0-5	0-5	0-30	0-3	0-3	0-10
	A2	6-19	-	8-25	8-15	-	5-27	-	-	-	-	-	-	-	-
	B	19-50	5-50	25-50	15-50	8-50	27-50	20-50	5-50	5-50	5-50	30-50	3-50	3-50	10-50
Nitrate-N (mg/kg)	A1	1	1	1	1	3	3	4	2	1	1	1	7	1	5
	A2	1	-	1	1	-	3	-	-	-	-	-	-	-	-
	B	1	1	1	1	1	2	4	1	1	1	1	1	1	2
Ammonium-N (mg/kg)	A1	1	2	1	3	19	5	1	15	7	6	2	33	5	18
	A2	1	-	1	3	-	2	-	-	-	-	-	-	-	-
	B	1	1	1	1	2	1	3	3	2	1	2	1	1	9
Phosphorus (mg/kg)	A1	10	2	2	2	24	6	114	41	39	6	3	18	6	11
	A2	2	-	2	2	-	4	-	-	-	-	-	-	-	-
	B	2	2	2	5	5	21	17	5	2	2	5	4	4	4
Potassium (mg/kg)	A1	364	325	121	295	790	402	436	495	374	113	57	303	110	439
	A2	73	-	66	25	-	134	-	-	-	-	-	-	-	-
	B	109	58	91	160	417	136	382	33	25	28	138	40	107	151

Wetland		EP4		EP5				EP7				PD		PD-PS	PS
Zone		**1**	**2**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**1**	**1**
Sulfur (mg/kg)	A1	240	185	22	5	32	15	202	24	17	3	52	65	7	115
	A2	112	-	66	2	-	12	-	-	-	-	-	-	-	-
	B	151	84	74	9	12	21	92	40	9	4	108	4	3	269
Organic Carbon (%)	A1	2.1	6.6	1.2	3.0	10.0	6.1	10.0	4.7	10.0	4.2	3.9	10.0	6.0	9.3
	A2	0.2	-	0.4	0.2	-	3.4	-	-	-	-	-	-	-	-
	B	0.2	0.4	0.5	0.6	3.4	1.4	4.2	3.5	2.3	2.6	6.8	3.5	2.9	9.8
Iron (g/kg)	A1	0.98	0.80	0.13	0.66	0.30	0.48	1.49	1.88	0.39	0.17	0.36	1.06	0.33	1.06
	A2	0.19	-	0.16	0.11	-	0.36	-	-	-	-	-	-	-	-
	B	0.12	0.14	0.32	0.20	0.62	0.29	0.93	0.44	0.23	0.15	0.93	0.39	0.34	0.34
Conductivity (mS/cm)	A1	1.42	2.46	0.49	0.07	0.28	0.33	2.24	3.24	0.18	0.09	0.61	0.65	0.10	2.54
	A2	1.35	-	0.88	0.05	-	0.30	-	-	-	-	-	-	-	-
	B	2.62	1.25	1.02	0.19	0.36	0.33	2.14	0.84	0.21	0.07	1.24	0.12	0.06	4.63
pH ($CaCl_2$)	A1	5.2	4.7	5.9	5.3	5.1	7.3	5.5	4.9	4.4	3.8	4.9	3.9	4.0	4.8
	A2	6.6	-	6.5	6.7	-	7.5	-	-	-	-	-	-	-	-
	B	6.6	6.4	6.8	7.7	7	7.3	5.1	5.1	4.1	3.1	5.3	4.1	3.9	5.0
pH (H_2O)	A1	5.7	5.1	6.8	6.9	5.7	8	6.1	5.4	5.4	5.5	6.3	4.9	5.2	5.4
	A2	7	-	6.9	7	-	8.2	-	-	-	-	-	-	-	-
	B	6.9	6.8	7.3	8.8	7.6	8.2	5.6	6	5.3	5.1	6.2	5.5	5.6	5.4

Riparian and Wetland Vegetation Community Structure

Within the KSS project area and KNR, the basins of larger wetland systems which experience regular winter-spring inundation were largely devoid of perennial vegetation. Instead these basins mostly comprised annual herbland which grew following subsidence of the water in late spring/early summer. Smaller wetlands which do not flood to the same depth or extent had some tree cover in the wetland basin but this vegetation was patchy. Very dense vegetation with total cover sometimes exceeding 100% fringed the wetlands (TABLE 3), was most dense at the edge with little to no understorey. Further out from the wetland basin and at slightly higher elevations, the *Melaleuca* woodland was more open with an understorey of sedges and/or rushes. At slightly higher elevations, woodland dominated by eucalypts with a relatively diverse understorey of shrubs, bracken, sedges and/or rushes occurs. Clear zonation of vegetation types was evident in most areas of wetlands, particularly within the fringing vegetation (TABLE 2). Areas which are seasonally waterlogged typically had more open woodland structure with dense, diverse understorey dominated by shrubs and sedges.

TABLE 2

Summary of vegetation at sample sites in natural wetlands areas showing cover of natives, weeds and trees, and the number of native species per relevé. Closest community based on vegetation mapping of the study area by Mattiske Consulting is also indicated.

Wetland	Site	Description	Cover Native (%)	Cover Weeds (%)	Tree Cover (%)	Native Species Richness
7	1	Wetland basin with annuals	40	0	1	2
	2	Fringing *M. rhaphiophylla*	60	2	60	3
	3	Fringing *M. rhaphiophylla* with sedge	100	10	45	5
	4	Fringing Eucalypt woodland	100	1	45	13
PD	1	Wetland basin	60	0	30	4
	2	Fringing *M. rhaphiophylla* with sedge	60	0	40	4
PD-PS	1	Fringing Eucalypt woodland	40	0	25	6
PS	1	Fringing *M. rhaphiophylla*	80	0	80	2
5	1	Wetland basin	40	0	10	5
	2	*Melaleuca* thicket with sedge and rush	70	0	40	8
	3	Fringing *M. rhaphiophylla* with sedge	100+	0	60	10

	4	Fringing *Melaleuca* – Eucalypt Transition	100+	0	60	8
	5	Fringing mixed *Melaleuca*	80	0	60	10
	6	Fringing Eucalypt woodland	100+	0	30	13
4	1	Wetland basin with *Melaleuca viminea*	45	0	45	3
	2	Fringing mixed *Melaleuca*	55	0	55	4
	3	Dampland Community – *Melaleuca* over heath	65	0	13	13

Environment – Vegetation Relationships

The first two axes of the Redundancy Analysis (RDA, where the ordination was constrained by environmental variables) using all variables explained 50.6% of the variance in species composition. A bi-plot of these two axes showed the relationship between main floristic gradients (the axes), sites and environmental variables (**Error! Reference source not found.**). This suggested two different complexes of environmental variables primarily differentiated sites in terms of their community structure and composition. The first of these environmental complexes was generally correlated with the first (horizontal) axis and revealed changes in species composition along the toposequence from wetland lowest point (left side) to upland (right side). This complex included soil fertility (N, P, etc), conductivity, gravel content and organic carbon which all increased with height above wetland basin. Only depth of horizon A generally declined with distance along this toposequence. The second complex of environmental variables was related to pH, iron concentration and texture and separated the wetland basin sites (with EP5 the most alkaline and EP7 the most acidic) (FIG 4).

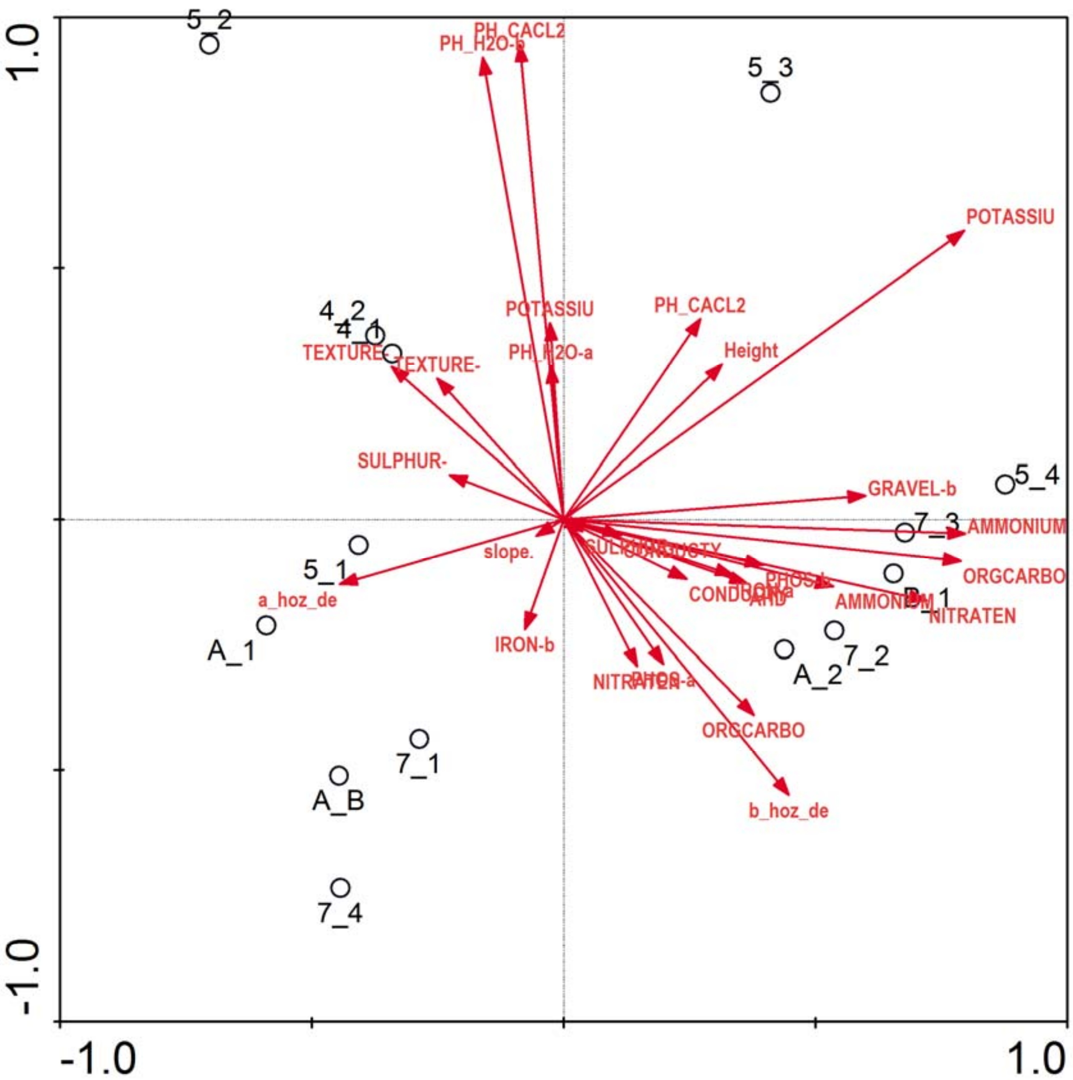

FIG 4 – Environmental RDA biplot of all species, all environmental variables and sites where soil was collected (14 sites). Length of arrow is proportional to strength of correlation between environmental variables and axes (major floristic gradients). Note: Site A_1 is PD_1, Site A_2 is PD_2 and Site A_B is PD-PS transition.

Many of the variables in the RDA biplot were poorly correlated to floristic gradients (shown by short arrows, FIG 4) and were highly correlated to other environmental variables. The forward selection procedure showed that only three variables could explain a significant and unique proportion of the variance in species composition: potassium (horizon A), pH (horizon B) and gravel content (horizon B) (TABLE 3). These three variables could explain 46% of the variance in the species-environment relationship.

TABLE 3

Results of forward selection (in order of selection) of environmental variables in redundancy analysis (RDA) with significance determined following Monte-Carlo testing against a random model. *Variance explained is proportion of variance in species-environment relationship.

Order	Variable	Variance Explained*	P-value
1	Topsoil Potassium-a	18%	0.008
2	Subsoil pH (H_2O)	14%	0.022
3	Subsoil Gravel	14%	0.024
4	Subsoil Phosphorus	9%	0.108
5	Subsoil Iron	7%	0.238
6	Slope	6%	0.304

The species richness of wetlands of the KSS project area and KNR was not high relative to adjacent uplands. In fact, wetland basin and fringing vegetation were often depauperate in species with as few as 1–3 species in dense fringing vegetation (TABLE 3). Fringing eucalypt woodland and winter-wet depressions were found to have the highest number of species (each had 13). As survey work occurred in early winter, these figures do not include most of the annual and geophytic species.

Vegetation Dynamics

The measurements of the three EPP wetlands and observations made at other wetlands in the KSS project area and KNR enabled a clear picture of wetland dynamics at the KSS Project Area to emerge. Such vegetation change was most clearly demonstrated at EP4 where basin vegetation of EP4 had two zones of distinct tree age (or cohorts). The inner basin consists of *ca.* 5 years old saplings (as judged by growth rings counted on cut stems) of more-or-less the same height (1.5 m) and stem diameter (25–40 mm). This was surrounded by a ring of fringing vegetation which was 7–10 m tall and likely to be much older (FIG 5)**Error! Reference source not found.**. The hypothesis is that a reduced incidence of flooding (through combination of groundwater and/or rainfall decline) has allowed colonisation of *M. viminea* and some *M. rhaphiophylla* in the basin of this wetland. These saplings were very likely to be the large numbers of seedlings reported emerging between July 2001 and January 2002. Previously the wetland basin was devoid of vegetation. It is anticipated that seedlings may successfully establish during drier times, but maybe eliminated if and when prolonged inundation returns. These plants are now 5 years old, reflecting a prolonged dry period and it is likely that tolerance to inundation will increase with age and size of tree. The plants are in reasonable health but have developed a distinct yellowing of the leaves suggesting nitrogen deficiency. This is perhaps not surprising given that nitrogen levels (both ammonium and nitrate) were below 1 mg kg^{-1} at surface and at depth (TABLE 1).

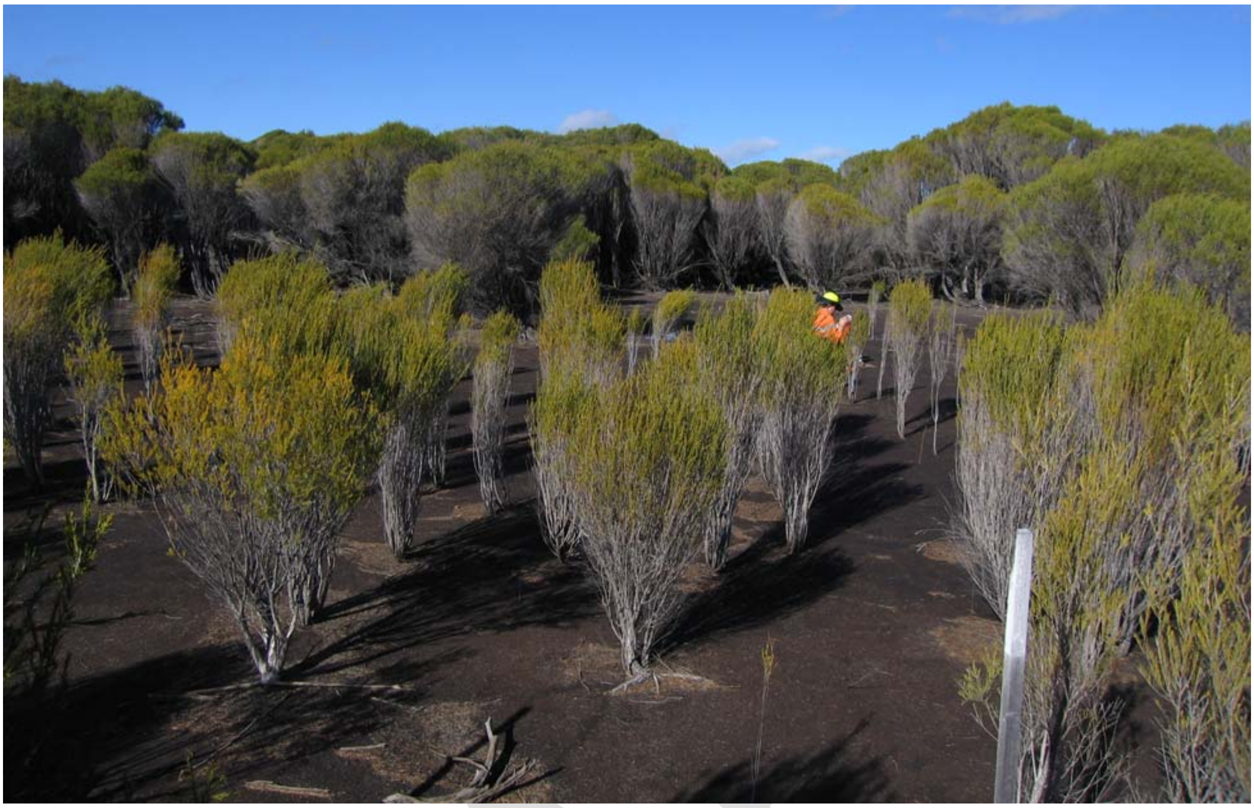

FIG 5 – Wetland EP4 showing a centre of *ca.* 5 years old saplings (as judged by growth rings counted on cut stems) of more-or-less the same height (1.5 m) and stem diameter (25–40 mm) surrounded by a ring of fringing vegetation of 7–10 m tall and likely to be much older.

DISCUSSION & CONCLUSIONS

Spatial Patterns of Wetland Vegetation

Wetlands of the Swan Coastal Plain (SCP) are renowned for their complexity with geomorphic, edaphic and hydrological characteristics influencing vegetation composition and structure (Balla, 1994a). Wetlands of the SCP have been classified in numerous ways, based on attributes such as geomorphology, hydrology, vegetation, aquatic biota, as well as combinations of these. Wetland vegetation of the SCP has been commonly categorised at two levels: the uppermost level or 'complex' refers to vegetation units linked by dominant plant species and structural attributes, and the secondary level for classification, the 'community', based on common or typical species within the overall complex (Cresswell & Bridgewater, 1985; Semeniuk *et al.*, 1990; Gibson *et al.*, 1995; Pen, 1997).

Substantial differences were found in vegetation structure and species composition within wetlands with distinct zonation of vegetation often present across the wetland profile. Wetland basins were generally flat and varied from bare in terms of perennial plants through to having a variable but patchy cover of paperbark trees and shrubs. These areas were seasonally inundated for some months each year. On raised ground around the edge of the basin, where some minor flooding would be expected, dense paperbark thickets were typical. At higher elevations, flooded gum woodland and then, higher still, jarrah-marri-banksia uplands were found. This substantial change in vegetation characteristics *across* wetlands masks any differences in species composition *between* wetlands. Although the major paperbark trees (*M. rhaphiophylla* and *M. preissiana*) and the understorey sedges and rush species were common to all fringing vegetation wetlands, other species of tree and shrubs did vary.

In addition to seasonally flooded wetland complexes, the KSS Project Area and KNR had large expanses of seasonally waterlogged vegetation consisting of sparse paperbark such as *Melaleuca preissiana* and banksia such as *Banksia littoralis* tree canopy over a diverse shrub and sedge/rush understorey.

Whereas the majority of wetlands on the SCP are expressions of underlying aquifers (i.e., they are discharge areas; Balla, 1994b), there is evidence that many wetlands of the Kemerton area are perched wetlands which are separated from aquifers by thick clay and other impermeable layers (e.g., ‘coffee rock’). Consequently inundation in these perched wetlands is a function of rainfall directly onto the wetland basins plus run-off from surrounding slopes. EP4 appears to be a perched wetland, primarily receiving water inflows from the surrounding Conservation Category wetland which effectively acts as a catchment to this wetland. It is therefore important that this catchment area is actively managed to avoid adverse impacts on inflow water quantity and quality.

Environmental Drivers of Vegetation Patterns

The environmental variables driving vegetation patterns remain unclear. This study found few clear correlates and associations between plant species composition and environmental variables. In particular, we found that elevation (AHD) was not a good predictor of vegetation composition, although relative height above the wetland basins and slope were reasonable predictors of the main floristic differences found across wetlands. Soil variables such as thickness of horizon A (humus layer), organic carbon, nutrient levels and potassium were also linked to this main floristic gradient. This general topographic-soil-vegetation relationship is also likely to be linked to the hydrological regime. The higher an area is elevated above the wetland basins, the lower the duration and depth of flooding it will experience and, consequently, the lower the accumulation of organic matter (peat and so on). Both the direct impacts of inundation and soil changes which flooding promotes are likely to influence vegetation composition and structure. A clearer picture of environmental causes of vegetation patterns should emerge through more detailed studies of the hydrology of these wetland systems, with variables such as distance to groundwater and their fluctuations (for groundwater-dependent wetlands) and area of catchment (for perched wetlands), suspected to be strongly correlated to vegetation patterns.

A second floristic gradient was found to be linked to soil pH and appeared to separate EP5 from the others. This is likely to be due to its proximity to limestone formations (and/or seepage from the rehabilitated dredge pond) and may explain floristic differences in wetland basins and fringing vegetation for wetland systems in the south-east side of Kemerton compared to those of the north and west.

Implications for restoration and use of reference sites

The high variability between floral communities of EPP wetlands on the KSS project area show that no single reference wetland type should be defined as the goal for rehabilitating dredge pit lakes. Instead, a broad range of seasonally wetted habitats all seem to have value as ecosystems contributing to the region's wider ecology, and play an important role in ecosystem function. The relationships between fringing flora, soil characteristics, topography and hydrology should help improve revegetation practices and overall rehabilitation success. Specifically this information indicates that rehabilitation slopes should be subtle, with varying depth to groundwater and that organic matter levels in new topsoils should be enhanced in rehabilitation attempts.

Flat or gently sloping wetland basins would be difficult to recreate in any post-mining setting where extraction follows ore bodies and typically results in steep sided void shells with low surface area:depth ratios. Post-mining, pit lakes created at Kemerton are essentially expressions of underlying groundwater with previous impervious layers such as coffee-rock removed. However there is scope for more subtle slopes to be created near the wetland and more dramatic slope changes to be located higher in the profile (opposite to current practice in some areas where the steepest slopes are closest to the water) (FIG 6). Also such gradual slopes would result in a greater area of fringing vegetation around mine lakes and areas which are heavily waterlogged or partly inundated by groundwater. Our studies suggest that dense paperbark-sedge fringing vegetation is only likely to establish in the seasonally flooded zone between high and low lake water levels (van Etten *et al.*, 2008). Areas up to 1.5 m above this lake level appear to be influenced by groundwater (i.e., capillary uptake leading to waterlogged soil) and appear to favour dampland or seasonally-waterlogged areas such as site 4-3. As aforementioned, above 1.5–2.5 m, normal woodland re-occurs. Thus the total zonation takes place over only around 1.5m of height from the wetland base. For a sustainable and functional width of fringing and flooded zone to be established around the margin lake margin contouring would therefore require gentle contouring immediately out from the lake edge in order to maximise the width of these significant zones.

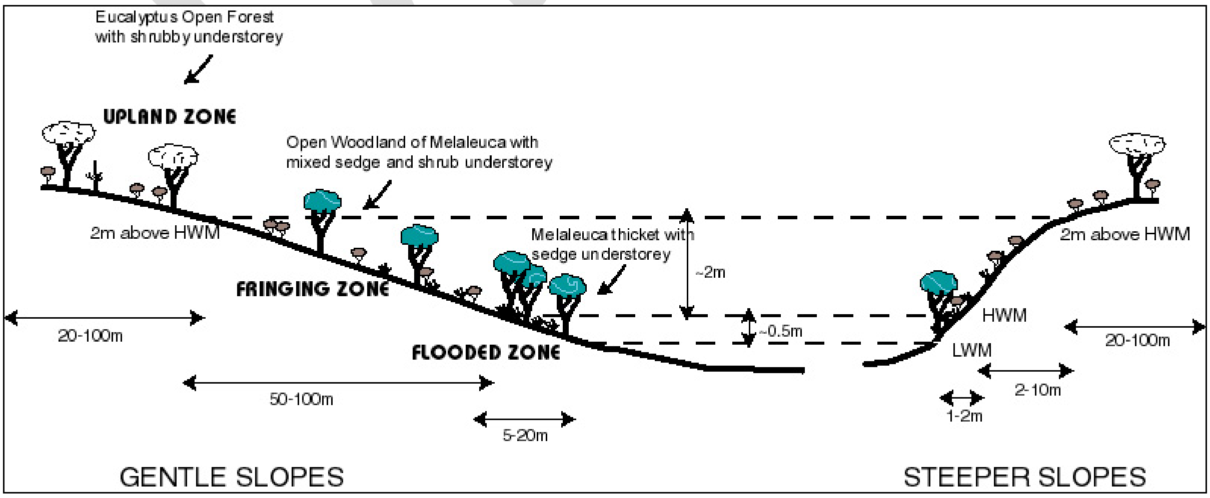

FIG 6 – Generalised topographic profiles showing position of three specific restoration zones relative to wetland water levels (HWM refers to high water mark as reached in typical spring; LWM refers to low water mark as seen in typical autumn). Two profiles are shown: typical gentle slope (left) and steeper slopes (right). Approximate horizontal distances and brief vegetation descriptions for each zone are also given. Note: vertical and horizontal axes on different scales.

Fringing wetland vegetation of natural wetlands was found to be floristically simple but structurally complex. They therefore represent a mixed challenge for rehabilitation; only relatively few species need to be restored, however they need to be encouraged to develop into relatively dense vegetation formations, with distinct bands of zonation. Vegetation of fringing zones are relatively species rich (some 10–30 species per 10 m^2), but are probably not as diverse as many upland areas of Kemerton dominated by jarrah, marri and banksia trees. The focus on these areas should be on quick return of topsoil matched to site condition so that high diversity will be encouraged.

There is as a strong a need to establish field trials and demonstration sites within rehabilitation areas as there is to experimentally test novel wetland rehabilitation techniques that are developing from these studies to date. These trials/demonstration sites should aim to result in wetlands which more closely resemble the range of natural wetlands in the area. It is also vital to continue monitoring pit lakes as they are restored and broaden the survey to better establish the processes and underlying cause(s) of wetland dynamics in the study area (Gammons, 2011).

In conclusion, where available, the use of regional wetlands provides for clear direction and restoration goals for restoring pit lakes into aquatic ecosystems of regional value.

ACKNOWLEDGEMENTS

We thank Kemerton Silica Sands Pty Ltd for funding the research and, in particular, Mark Gell, Resident Manager, for his vision in initiating and supporting this project. Thanks also to an anonymous reviewer who improved the manuscript.

REFERENCES

Balla, S. (1994a). *Their Nature and Management.* Water Authority of Western Australia and the Western Australian Department of Environmental Protection, Perth. 176pp.

Balla, S. (1994b). *Wetlands of the Swan Coastal Plain*. Water Corporation of Western Australia and Western Australia Department of Environmental Protection, Perth.

Castendyk, D. & Eary, T. (2009). The nature and global distribution of pit lakes. In, *Mine Pit Lakes: Characteristics, Predictive Modeling, and Sustainability* Castendyk, D.; Eary, T. & Park, B. (eds.) Society for Mining Engineering (SME), Colorado, USA, 1-11pp.

Clarke, K. R. (1993). Non-parametric multivariate analyses of changes in community structure. *Australian Journal of Ecology* 18:117–143.

Commonwealth of Australia Bureau of Meteorology (25/10/2010). *Bunbury and Wokalup climate averages*, http://www.bom.gov.au/climate/averages/tables/cw_009628.shtml, Accessed: 25/10/2010.

Cresswell, I. D. & Bridgewater, P. B. (1985). Dune vegetation of the Swan Coastal Plain. *Journal of the Royal Society of Western Australia* 67:137-148.

Davis, J. A.; Rosich, R. S.; Bradley, J. S.; Growns, J. E.; Schmidt, L. G. & Cheal, F. (1993). *Wetland classification on the basis of water quality and invertebrate community data.* Water Authority of Western Australia and the Western Australian Department of Environmental Protection, Perth. 242pp.

DEC (2008). *Florabase: The Western Australia Flora*, http://florabase.calm.wa.gov.au/, Accessed: June 2008.

Gammons, C. H. (2011). Pit lake monitoring. In, *Mine Pit Lakes: Closure and Management,* McCullough, C. D. (ed.) Australian Centre for Geomechanics, Perth, Australia,

Gibson, N.; Keighery, B. J.; Keighery, G. J.; Burbidge, A. H. & Lyons, M. N. (1995). A floristic survey of the south Swan Coastal Plain. Western Australia: Department of Conservation and Land Management.

Grant, C. (2006). State-and-transition successional model for bauxite mining rehabilitation in the jarrah forest of Western Australia. *Restoration Ecology* 14:28-37.

Grant, C. & Loneragan, W. A. (2003). Utilising dominance-diversity curves to assess completion criteria following bauxite mining rehabilitation in Western Australia. *Restoration Ecology* 11:1-7.

Kumar, R. N.; McCullough, C. D. & Lund, M. A. (2009). Water resources in Australian mine pit lakes. *Mining Technology* 118:205-211.

McCullough, C. D. (2011). Pit lakes and mine closure: liability or opportunity? *AusIMM Bulletin* April:20-21.

McCullough, C. D.; Hunt, D. & Evans, L. H. (2009a). Sustainable development of open pit mines: creating beneficial end uses for pit lakes. In, *Mine Pit Lakes: Characteristics, Predictive Modeling, and Sustainability* Castendyk, D.; Eary, T. & Park, B. (eds.) Society for Mining Engineering (SME), Colorado, USA, 249-268pp. 978-0-87335-305-2.

McCullough, C. D. & Lund, M. A. (2006). Opportunities for sustainable mining pit lakes in Australia. *Mine Water and the Environment* 25:220-226.

McCullough, C. D.; Steenbergen, J.; te Beest, C. & Lund, M. A. (2009b). *More than water quality: environmental limitations to a fishery in acid pit lakes of Collie, south-west Australia*. Proceedings of the International Mine Water Conference. Pretoria, South Africa. 19-23 October, International Mine Water Association, 507-511pp.

McCullough, C. D. & Van Etten, E. J. B. (2011). Ecological restoration of novel lake districts: new approaches for new landscapes *Mine Water and the Environment*

Naiman, R. J.; Bechtold, J. S.; Drake, D. S.; Latterell, J. L.; O'Keefe, T. C. & Balian, E. V. (2005). Origins, patterns, and importance of heterogeneity in riparian systems. In, *Ecosystem function in heterogeneous landscapes,* Lovett, G. M.; Turner, M. G.; Jones, C. G. & Weathers, K. C. (eds.) Springer, New York, 279-309pp.

Pen, L. (1997). *A systematic overview of environmental values of the wetlands, rivers and estuaries of the Busselton-Walpole region*. Water and Rivers Commission, Perth.

Semeniuk, C. A. (1987). Wetlands of the Darling system - a geomorphic approach to habitat classification. *Journal of the Royal Society of Western Australia* 69:95-112.

Semeniuk, C. A.; Semeniuk, V.; Cresswell, I. D. & Marchant, N. G. (1990). Wetlands of the Darling System, Southwestern Australia: a descriptive classification using vegetation pattern and form. *Journal of the Royal Society of Western Australia* 72:109-121.

SPSS Inc. (2007). SPSS. 17.0, SPSS Inc., Chicago, USA.

ter Braak, C. J. F. (1998). *CANOCO reference manual and user's guide to Canoco for Windows: software for canonical ordination (version 4).* Microcomputer Power, Ithaca, New York, USA.

van Etten, E.; McCullough, C. D. & Lund, M. A. (2008). *Evaluation of rehabilitation efforts at the Kemerton Silica Sand Pty Ltd project area, June 2007*. Unpublished Commercial in Confidence report to Kemerton Silica Sand Pty Ltd. 2008-10. Mine Water Environment Research/Centre for Ecosystem Management, Edith Cowan University, Perth. 88pp.

Van Etten, E. J. B. (2011). Riparian vegetation considerations for pit lakes. In, *Mine Pit Lakes: Closure and Management,* McCullough, C. D. (ed.) Australian Centre for Geomechanics, Perth, Australia, Ward, J. V.; Malard, F. & Tockner, K. (2002). Landscape ecology: a framework for integrating pattern and process in river corridors. *Landscape Ecology* 17:35-45.