How representative are pit lakes of regional natural water bodies? A case study from silica sand mining

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Abstract In many regions, regulators view pit lakes akin to natural lakes and impose similar guidelines for water quality and biodiversity. At Kemerton (south Western Australia), extraction of silica sands is creating a large deep dredge pond. This is progressively split into smaller lakes, which are then rehabilitated. The water quality and macroinvertebrate communities of a rehabilitated pond, 3 other artificial wetlands, and 13 nearby natural wetlands were investigated. Catchment rehabilitation has successfully returned some terrestrial vegetation, however the pond edge lacked a developed riparian zone. Species diversity and abundance was substantially lower (≈ 50% and 10% respectively) than in natural wetlands. Overall the macroinvertebrate communities and water quality of artificial wetlands were significantly different to the natural wetlands.

Key Words Water quality, biota, ecology, pit lake, end-uses, mine closure

Introduction

In many regions, regulators view pit lakes akin to natural lakes and impose similar guidelines with regards to long-term water quality and biodiversity (see Nixdorf *et al.*, 2005; Williams, 2009). Where the likely closure endpoint is return of the mine lease to the state conservation reserve, then the minimum likely regulator/community expectation is for the pit lake to be representative of regional natural water bodies. To be regionally representative we hypothesize that a pit lake would have similar a) water quality, and b) species richness in extent (numbers) and coverage (species present), to the range found within regional wetlands. Macroinvertebrates are typically the most popular biological community chosen to assess aquatic impacts. Internationally, analysis of macroinvertebrate communities has been the foremost tool for biological assessment of aquatic ecosystems due to the availability of good taxonomy, a speciose community and extensive literature of pollutant effects (Havens *et al.*, 1996; Schofield & Davies, 1996). We have chosen to focus on a pit lake, surrounded by natural wetlands that should have every possibility to form a 'natural' water quality and biota. The main limiting factor to representativeness should be age since rehabilitation.

Methods

Study Site

The Kemerton Silica Sand Pty Ltd (KSS) project area occupies some 1 600 ha of land, 20 km north of Bunbury, south Western Australia (Figure 1). Located on the Swan Coastal Plain (SCP, a series of old sand dune systems), and primarily on old gently undulating Bassendean Sands, with Eucalypt-Banksia woodland on the uplands.

Feldspathic silica sands generally lie beneath <1 m of topsoil and 4 to 7 m of overburden (which generally contains an aquiclude at the inter-phase between high and low groundwater levels). The overburden is removed and the ore resource is then extracted from a superficial aquifer using a surface floating dredge to a maximum permitted depth of 15 m. As the dredge pond is essentially an expression of the groundwater, the results are permanently inundated lakes. Washing fines, overburden and topsoil are available for sculpting and landscaping of the dredge ponds and surrounds.

Shallow depth to groundwater in the interdunal depressions results in numerous wetlands within the project area. These wetlands become inundated from rainfall or the rising groundwater table, typically from July to November. A total of 17 wetlands were sampled, including four artificial wetlands, a rehabilitated dredge pond (NL), a satellite of the main dredge pond (NS), and an old unrehabilitated small test dredge pond (NO), and a rehabilitated shallow wetland (NN). Wetlands associated with larger nearby wetlands have been given the number of the main wetland augmented with A, B etc (Figure 1).

Sampling Methods

The KSS project area was visited in late September and early October 2007 as this time represents peak water levels for wetlands on the SCP. Wetlands were sampled in a stratified design to encompass habitat heterogeneity including shallow and deep open water, and vegetated and bare littoral edge. Each wetland habitat type was sampled in replicate (3–5 concomitant with wetland size). At each site temperature, dissolved oxygen (DO as % and mg^{-1}), specific conductance (EC), pH, Oxidation-Reduction Potential (ORP), and turbidity with

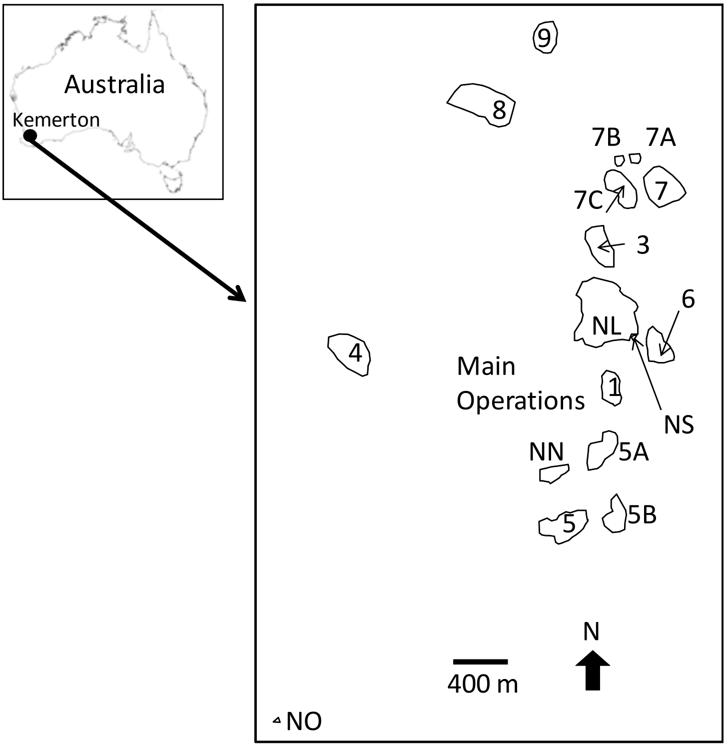

Figure 1. Map showing location of Kemerton Silica Sand Operations and wetlands sampled.

a Hydrolab Datasonde 4a. Single water samples for nutrients and metals were also taking by pooling across all water body habitats and replicates. Water samples were prepared and analysed for ammonium, NO_2^-/NO_3^- (NO_x), and filterable reactive phosphate (FRP), Total P and Total N after APHA (1998), SO_4^{2-} by ion chromatograph (Dionex ICS-1000), non-purgeable organic C (NPOC) by TOC analyser (Schimadzu), gilvin (g440) as per Kirk (1976), and metals/metalloids Al, Ba, Be, Ca, Cd, Cr, Co, Cu, Fe, Mn, Na, Ni, Sb, Sn and V) (ICP-AES Varian).

Aquatic macroinvertebrates were collected with a 250 µm mesh sweep net along a 10 m transect at each site. All samples were preserved in 80% ethanol, then sorted, counted and identified to the lowest taxonomic resolution that was easily achievable. Where necessary, highly abundant taxa were subsampled (as per Wrona *et al.*, 1982).

Data Analysis

Multivariate data analyses was undertaken using PRIMER v6 software (Clarke, 1993) and followed a procedure of data transformation, graphical exploration and then statistical hypothesis testing. The key to these techniques is that they attempt to represent on a graph (usually 2 dimensions) the degree of similarity between sites based on either their macroinvertebrate communities or water quality so that this similarity is equal to relative distances between sites on the plot. Principal Components Analysis (PCA) was used to produce ordinations of log10 transformed water quality data. A nMDS ordination of taxa abundance data was completed using a Ln(x+1) transformation (Faith *et al.*, 1987) and the Bray-Curtis dissimilarity matrix (Faith *et al.*, 1987). Differences between a priori treatment groups were tested using the Analysis Of SIMilarity(ANOSIM) (Clarke, 1993).

Results and Discussion

Temperature varied across and within wetlands from 13.9 to 28.2 °C affected by water depth and shading, the mean temperature across all sites was 19 °C. However, pH was much more variable with wetland 1 (located on a limestone outcrop) and dredge ponds (NL, NO and NS) with a pH of 7—8.5. Most other wetlands tended towards being acidic with a pH of 4.6—7. Wetlands 1, 7, 7C, NS, and NL had the highest EC at >1.1 mS cm^{-1}. Interestingly, NO had low EC <0.4 mS cm^{-1}, probably showing a lack of connection with the groundwater. Dissolved oxygen concentrations ranged up to 120% in NS, NO and NL down to 60% in 9. ORP was very variable but positive across all wetlands (except 5A, with a mean of -6 mV) at around 100 mV. Turbidity was close to 0 NTU across 1, 3, 4—9, ranged from 0.5 to 43.8 NTU the other wetlands.

NPOC and gilvin were highly correlated (r=0.94) indicating that most of the NPOC in the water was as coloured humic and fulvic acids and unlikely to very available for bacterial use. Strongly coloured waters are typical of wetlands on Bassendean sands (Wrigley *et al.*, 1988). Wetlands 1 and 4 and the dredge ponds (NL and NO) had the lowest gilvin concentrations. Higher calcium carbonate causes precipitation of gilvin (Lund & Ryder, 1998), which probably accounts for the gilvin concentrations in NL and 1, while 4 and NO probably have little gilvin as their waters as they are largely rainwater derived.

All undisturbed natural KSS project area wetlands showed Cl:SO_4 molar ratios >5, with only NL and NN below this indicating the presence of acid sulphate soils (ASS) (Department of Local Government and Planning, 2002). NN was just acidic at pH 5.6. Buffering with high Ca concentrations prevented acidification in NL, while comparatively low Ca concentrations in NN, suggest that this wetland needs to be monitored to determine if acidification is going to become a problem. KSS will remove the ASS in NN to reduce this problem. Around pit lakes careful choice of substrates used in rehabilitation is essential to prevent undesirable outcomes such as acid production. Fe levels are generally low across all waterbodies.

Wetlands which seasonally dry have much higher levels of NH_3 than permanent wetlands indicating breakdown of organic matter in the sediment while the wetland is dry. This NH_3 is converted to NOx by nitrification. Wetland 6 had particularly high NOx concentrations at 339 μgL^{-1}; this was also accompanied by high FRP at 36 μgL^{-1} which suggests that the wetland might be receiving fertiliser runoff from nearby paddocks. Otherwise all other wetlands had low nutrient concentrations, with the exception of 7A which had elevated FRP concentrations of 297 μgL^{-1}.

A PCA of all the physico-chemical variables is shown in Figure 2. KSS wetlands were significantly different (Global R = 0.991, p = 0.01) to the artificial wetlands and possessed a distinct chemical signature, with greatest within chemical variability in NS. Relative to the natural wetlands, NL had higher water temperatures, turbidity, DO, pH and SO_4 concentrations (Figure 2). NL also had lower NPOC, ammonia and total N. NL water chemistry was very similar to that of 1, but different from the other wetlands. Across the wetlands, EC was generally positively correlated with solute concentrations of Na, K, Fe, Cl and Mg. Surprisingly, concentrations of Fe were not correlated with concentrations of SO_4. There appeared to be similarities in water quality of nearby wetlands, with adjacent wetland pairs such as 5 and 6, NN and 5B, and 7A and 3 very similar to each other. Wetland 7 was unusual in having much higher solute concentrations of Na, Cl, K, Fe, TN and NPOC, with the closest wetland being 7C indicating either a similar source of water or recent connection. Wetland 4 appeared to have distinct water chemistry from other natural wetlands in having low EC, nutrients

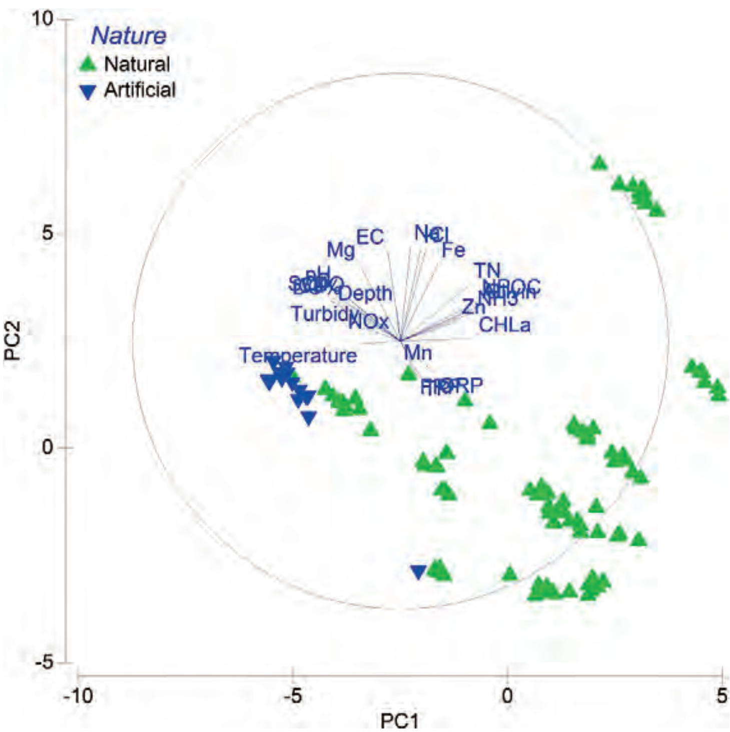

Figure 2. PCA of natural vs artificial lakes for physico-chemical parameters PC1 = 33.9%, PC2 = 25.5%.

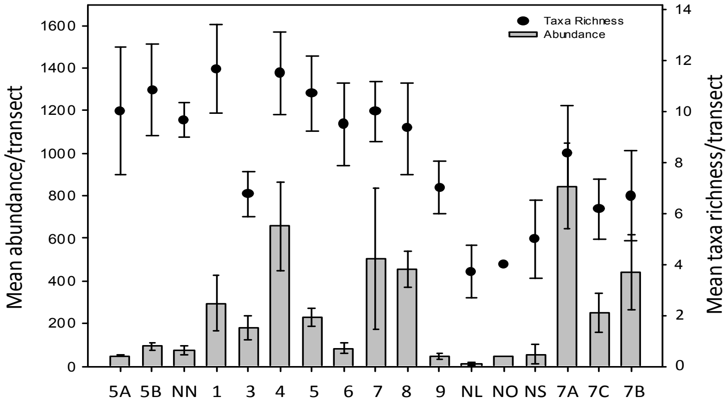

***Figure 3**. Mean aquatic macroinvertebrate abundance and taxa richness per transect in KSS project area wetlands.*

and solute concentrations of Na, Cl, Fe, Mg and K. Intriguingly, the closest wetland was NO, supporting the suggestion that that the predominate source of water in these sites was rainwater. There was no significant difference between water quality between the different habitat types of deep and shallow open water, and vegetated and bare littoral edges (Global R = -0.007, p = 0.578).

There was a diverse range of 147 taxa collected in the KSS project area survey. Aquatic macroinvertebrate communities were generally dominated by zooplankton, then chironomid larvae (an order of magnitude less abundant) and beetle, mosquito and hemipteran larvae. Aquatic macroinvertebrates of natural wetlands were abundant in most samples with an overall mean of 309±49 (standard error of the mean) macroinvertebrates per sample and a mean of 850 macroinvertebrates per sample recorded from 7A. Natural wetland macroinvertebrate samples were also moderately diverse, with an overall mean of 9±0.0 taxa per sample to a maximum of 19 taxa per sample encountered in 1 and 4. Macroinvertebrate community abundance and diversity was lower in artificial waterbodies, with NO, NL and NS showing only a mean of 24±10 macroinvertebrates per sample and a mean of 4±1 taxa per sample (Figure 3). Wetlands 1 and 5 were the most diverse (with a total of 58 and 55 taxa respectively). Wetlands 7, 4, 6 and 5B had similar diversity ranging from 47 to 40 taxa. Wetlands 9 and 8 have 30 and 28 taxa respectively which could be due to their close proximity. Wetlands 3, 7A, 5A, NL, 7C, and NN all had taxa richness between 23 and 19. Of particular note is the richness of NN which was high considering the wetland had only just been created. The results show that when compared to the other permanent wetland 1, NL still had a long way to go to develop its full biodiversity. The low richness of 7B is surprising at 13 while NO had a richness of only 5 which can be partially attributed to only a single sample being collected. Only one taxon (*Necterosoma* larvae) was common across all wetlands and only 10% of taxa were found in over half of the wetlands. Forty percent of taxa only occurred in one wetland with all wetlands except 7B and NO having unique species. This result suggests that either more sampling was required at each wetland to get a complete taxa list or that as wetlands may have filled at different times that there is temporal species variation. An nMDS ordination of KSS macroinvertebrate communities showed a high stress of 0.23 as a result of the large number of data points collected (Figure 4).

Many wetland macroinvertebrate communities were highly spatially variable and showed great overlap between each other. For example, 1 and 5 showed a range of community overlap with most other waterbodies. Macroinvertebrate communities of KSS wetlands were often quite variable between replicates. Macroinvertebrate community structure of the artificial wetlands were highly significantly different to those of natural water bodies (Global R = 0.536, P<0.01,). These differences were primarily due to dominance by zooplankton in natural wetlands and dominance by chironomid larvae in the artificial wetlands (Figure 3). Although macroinvertebrate community structure of the habitats of deep and shallow open water and vegetated and bare edge initially appeared to be similar, the large sample size permitted some differences to be detected. Macroinvertebrate community structures of some different wetland habitats were significantly different to each other (Global R = 0.129, P = 0.02). Macroinvertebrate community structure of bare littoral habitat was significantly different to all other habitat types (P<0.05). Macroinvertebrate community structure of vegetated littoral habitat was also significantly different to that of open water (P<0.01). All KSS project area water bodies considered, turbidity and NOx explained most macroinvertebrate community structure variation. Sulphate, Mn and DO (%) only slightly increased the correlation between

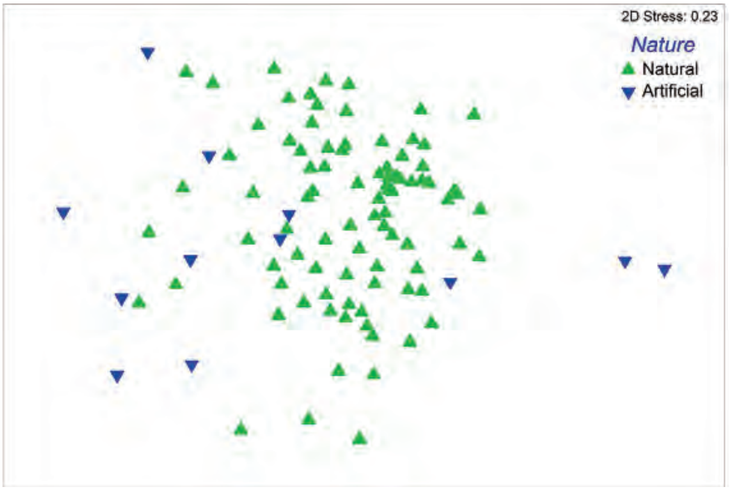

Figure 4*. nMDS of natural vs artificial lakes for macroinvertebrate communities*

macroinvertebrate communities and water quality. Considering only natural wetlands of the KSS project area, turbidity and NOx again explained most macroinvertebrate community structure variation.

The natural wetlands represent some of the best conserved wetlands on the SCP, with generally good water quality and high biodiversity (Davis *et al.*, 1993). The small test pond (NO) proved not to be very similar to NL primarily as it appeared to be filled with rainwater rather than groundwater. The satellite waterbodies (NS) around NL which were generally more physically similar natural wetlands had slightly improved macroinvertebrate richness compared to NL. This suggests that greater shallow areas and/or more riparian vegetation would improve biodiversity. The newly created seasonal wetland NN had similar taxa richness to natural wetlands.

Conclusions

In terms of water quality and macroinvertebrate community structure, the rehabilitated dredge pond and the other artificial wetlands were all significantly different to the natural wetlands. The dredge pond accessed the deeper more calcium carbonate rich groundwater, which was not available to other wetlands, except wetland 1. Its permanence and depth are distinctive features that will ensure that its water quality is different to the natural wetlands at other times (ie. summer) of the year. The dredge pond is only a few years old and its riparian vegetation is very limited and banks relatively unstable. This habitat is therefore not very suitable for macroinvertebrates which limits their diversity.

In this highly favourable environment, the pit lake studied appeared to be on a trajectory to regional representativeness. The pit lake is relatively new and it is anticipated that as the riparian vegetation develops that the lake's biota will continue to increase in diversity and abundance. The pit lake due to its permanence and depth will never be the same as a natural wetland in the region but can make an important contribution to the ongoing maintenance of aquatic ecosystems that are currently severely threatened on the SCP.

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