Biophysical closure criteria without reference sites: Evaluating river diversions around mines

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Abstract The use of 'reference' sites to rehabilitate mined lands often creates unrealistic targets, resulting in environmentally underperforming sites. Previously, we proposed a more achievable approach to mine closure by comparing the bio-physical characteristics of rehabilitated sites to overall ecosystem variability (i.e., the 'system variability' approach), rather than specific target reference sites. We tested this model by evaluating the bio-physical state of river diversions around two mined areas in Australia's Hunter Valley. The model clearly identifies how diversion sites differ from non-diverted sections of river, providing a practical example of model application.

Key words Hunter Valley, multivariate, ordination, aquatic macrophytes, water quality, riparian

Introduction

The use of 'reference sites' is accepted by regulators as rehabilitation targets in areas disturbed by mining activities. A 'reference site' is broadly perceived as having desirable conditions, processes, and/or taxa with which to compare impacted sites. Generally, reference sites co-occur with disturbed sites, yet are unimpacted and retain "naturalness" of the biota (Stoddard et al. 2006). However, this approach is flawed, often creating impossible or unrealistic targets for miners seeking to close rehabilitated lands. For example, many systems are so heavily modified that co-occurring unimpacted sites do not exist (Chessman and Royal 2004). In the instance where reference sites are nominated, a judgement call must be made as to the 'desirable' traits of a reference site (Stoddard et al. 2006). Determination is then required as to how similar impacted sites have to be to reference sites in order to meet rehabilitation objectives. Natural seasonal variability can also confound efforts to define and compare reference sites (sensu Blanchette et al. 2016). Essentially, reference sites are a human construct, resulting in restoration targets where changing ideals and natural variability ensure the goalposts are constantly shifting.

River condition assessment programs that capture the natural variability of the system can provide alternatives to reference sites and clarify rehabilitation goals (see Blanchette et al. 2016 for examples). Our model compares the biophysical criteria in rehabilitated sites to the overall spatial and temporal bio-physical variability of the local environment (hereafter referred to as 'system variability'), rather than specific reference sites. We used riverine environments in the Hunter Valley, New South Wales, Australia to develop and test the model but the system variability approach can also be applied to terrestrial ecosystems.

The system variability approach to closure uses established analytical techniques (multivariate ordination) and current monitoring approaches. It has many advantages over the use of reference sites, in that the criteria are likely to be more ecologically relevant by reflecting natural variability and existing land impacts, as well as having clear endpoints. Essentially, our approach is an extension of commonly used ecological assessment methods that have been applied to facilitate closure. Current ecological assessment techniques focus on using multivariate approaches to highlight *differences* in communities (i.e., demonstrating the impact of mining); we are simply suggesting that where there is *no significant difference* between the rehabilitated area and other parts of the ecosystem, closure has been achieved. Therefore, the purpose of this research is to test the model developed in Blanchette et al. (2016).

Methods

Catchment description and hydrology – The Hunter Catchment (21,500 km^2) is located in New South Wales, south eastern Australia. The Hunter River has been highly modified since European settlement for industry, agriculture, flood mitigation and domestic use. Hunter Catchment waterways are seasonal, tending to flow more during the 'wet season' in response to rainfall (November-April) and less during the 'dry season' (May-October), although flooding can occur at any time. The overall flow regime of the Upper Hunter River consists of long periods of seasonally-responsive low flows punctuated by rare high-magnitude flood events (see Hoyle et al. 2007).

This research focusses on The Goulburn River (Figure 1) and Bowman's Creek (Figure 2), two waterways within the Hunter Catchment. Both rivers have been modified by coal mining activities, resulting in complex hydrological conditions where anthropogenic effects interact with the natural seasonal flows.

The Goulburn River contains a trapezoidal diversion currently undergoing terrestrial rehabilitation. Downstream of the diversion the discharge of operational groundwater transformed the naturally seasonally-flowing river into a continuously flowing system. Artificially increasing base flow stability and reducing flow variability (i.e., drying periods) promotes excessive growth of certain aquatic macrophyte species (Bunn and Arthington 2002), which was observed throughout the Goulburn River study area (see Fig. 3A).

The diversion in Bowman's Creek was operational in 2012 and designed to mimic 'natural' river characteristics (morphology, in-stream aquatic habitats). The hydrology of Bowman's Creek appears to be largely unregulated and similar to the overall flow regime of the Upper Hunter River (station GS 210130; NSW Office of Water; May 1994-April 2017). Similar to the Goulburn River, however, excessive growth of reeds and other aquatic macrophytes occurred within the diversions (Fig. 3B), indicating that even subtle changes in the natural flow regime by artificial diversions, which may undetectable by gauging stations, have an ecological effect.

Data collection – The overall experimental design was 32 sites at two rivers (Bowman's Creek; 12 sites, Goulburn River; 20 sites) repeatedly sampled during a hydro-period (May-December 2016). Sites (50 m fixed longitudinal transects) were selected based on

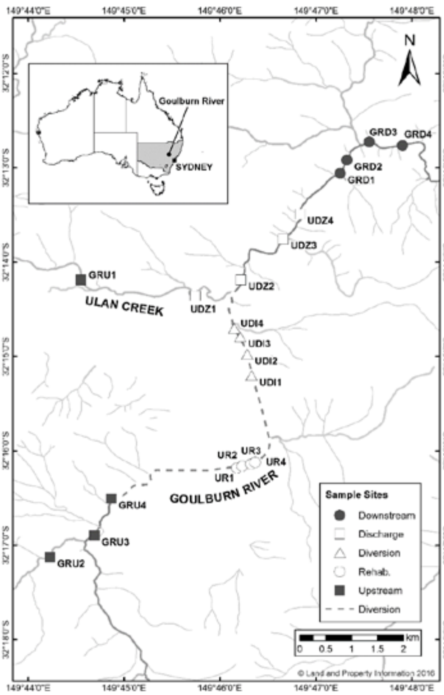

Figure 1 *Goulburn River, New South Wales, Australia. Sites numbered upstream (1) to downstream (4) and grouped according to river section. Dashed lines are constructed river diversions and solid lines are natural water courses.*

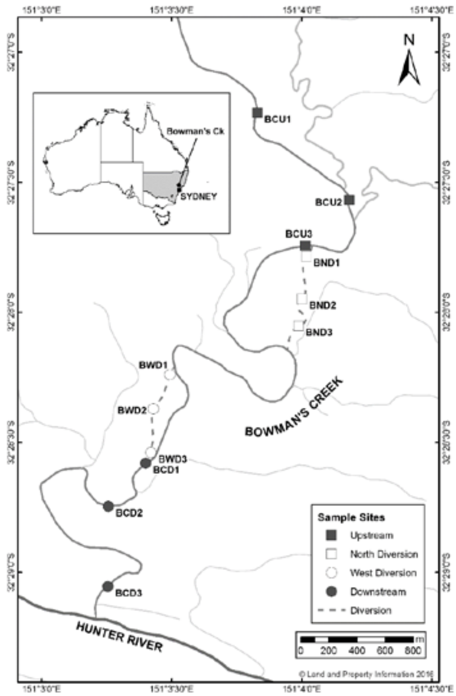

Figure 2 *Bowman's Creek, New South Wales, Australia. Sites and lines arranged as per Figure 1. (n.b., river currently flows through constructed diversions rather than co-occurring natural stretches of Bowman's Creek).*

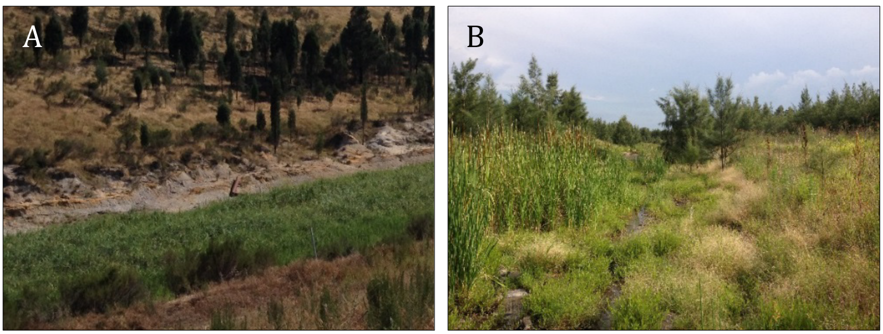

Figure 3 *Study sites on the Goulburn River (Fig. 3A; 'rehab' site UR2, and Bowman's Creek (Fig. 3B; 'diversion' site BND1). See Figures 1 and 2 for map and site references.*

accessibility and representativeness of the biophysical variables of each river. Bowman's Creek was sampled twice: once during the nominal 'late wet/early dry' season (May 2016) and once during the nominal 'late dry/early wet' season (December 2016). The Goulburn was sampled three times (May, September, December 2016).

In situ water quality measurements of turbidity (NTU), pH, conductivity (mS/cm), temperature (°C) and oxidation-reduction potential (ORP; mV) were collected with a Hydrolab Quanta at a 10-cm depth once at each site. *In situ* soil measurements of pH and ORP (mV) at a 1 cm depth were collected at five points along the 50 m transect encompassing all in-stream habitats, where present (i.e., hydrological features, aquatic macrophytes, sediment variability). Flow (m/s) was measured 5-7 cm below the water surface using a digital flow meter at five points along transects, accounting for all in-stream hydraulic habitats. Water was collected and analysed for metals and nutrients (Appendix 1) at the Edith Cowan University Analytical Chemical Laboratory.

Percent cover of the wetted transect by periphyton/filamentous algae, aquatic plants, terrestrial leaf litter, bare sediments, iron flocculent, blanketing supra-benthic silt, or bacterial-algal mat was quantified using an index as per Blanchette and Pearson (2012), and sediment composition was determined using a modified Phi scale index as per Blanchette and Pearson (2012). Riparian condition was quantified on both left and right banks with a modified 'tropical rapid appraisal of riparian condition' method (sensu Blanchette and Pearson 2012; Dixon et al. 2006) developed specifically for intermittently-flowing rivers disturbed by mining.

Data analysis – Data were analysed as described in Blanchette et al. (2016), and rivers were analysed separately. Briefly, principal components analysis (PCA) in PRIMER (Clarke and Gorley 2006) was used to visually portray similarity among sites based on multiple variables as a physical distance, allowing variability tracking over time and determination of influential variables (Ramette 2007). Permutational MANOVA (PERMANOVA; also in PRIMER) with a Euclidean distance (9999 permutations) was used as a hypothesis test to ascertain whether biophysical variables between and among sites were significantly different ($p < 0.05$; H_o = no significant difference) (Clarke and Gorley 2006). Data were analysed in three separate components: *in situ* continuous data, *in situ* indices, and water quality analyses (Appendix A). Variables were individually transformed where appropriate and all data was normalised prior to analysis.

Results & Discussion – Rivers

Goulburn River – Across all sites, time was a significant ($F_2 = 6.31$, $p < 0.001$) factor structuring *in situ* continuous data (see Appendix 1). Within individual times (May, September and December 2016), *in situ* continuous data from 'rehab.' and 'diversion' sites were consistently significantly different ($p < 0.05$) from the rest of the catchment. PCA for *in situ* continuous data indicated that the rehab and diversion sites tracked together through time yet remained distinct from the rest of the study sites due to a higher percent cover of rushes, turbidity, and benthic shade, as well as lower soil ORP and pH levels, slower (but more persistent) velocities, lower water ORP readings and less canopy cover and fringing bank vegetation (Figure 4). Rush-covered sites were associated with lower soil ORP due to organic matter turnover in a thick benthic root mat. Low levels of ORP are associated with anoxic (and even methanogenic) conditions (Boulton et al. 2014), indicating that the microbial activity of these sites – fundamental to ecosystem processes – likely differs from the rest of the catchment. Excessive aquatic plant growth was likely due to changes in the natural flow regime and increased light levels due to a loss of canopy.

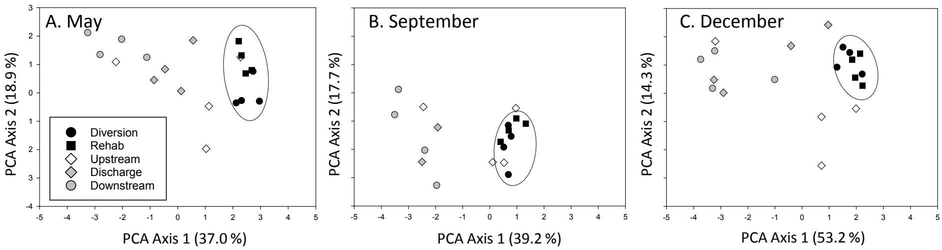

Figure 4 *Principal components analysis (PCA) plots of in situ continuous data (see Appendix 1) from the Goulburn River. Plots depict temporal shifts in the data at the river scale. Diversion and rehab sites were significantly different to the rest of the river, despite tracking similarly over time.*

Similar to the *in situ* continuous data, time was significant (F_2 = 1.88, p = 0.04) on *in situ* indices (Appendix 1) across all sites. However, unlike the continuous data, the *in situ* indices were only different across all sites in May and September (p < 0.01). At the river scale there was a significant spatial effect (F_4 = 6.76, p < 0.001), with pairwise analyses indicating that, with the exception of the discharge and upstream sites (p = 0.06), *in situ* indices between all sites were significantly different (p < 0.05). PCA for *in situ* indices indicated little temporal variability across all sites, with rehab and diversion sites clustering together across all times (not shown). The rehab and diversion sites separated from the rest of the catchment due to the presence of blanketing iron flocculent. Downstream sites (located in a national park) had higher levels of leaf litter, filamentous algae, canopy cover and canopy health, more understory, and bare benthic sediments.

Across all sites in the Goulburn River, there was a significant effect of time (F_2 = 13.10, p < 0.001) on water quality (Appendix 1), and pairwise analysis indicated that water qualities at all times were significantly different from each other (p < 0.001). Within individual times, water quality data from downstream and discharge sites were significantly different (p < 0.05) from the rest of the river, particularly in May and December. PCA for water quality data in the Goulburn demonstrated that the discharge and downstream sites tracked together through time, remaining distinct from the rest of the study sites (data not shown), and were associated with SO_4, K, S, Ca, and Mg (commonly associated with groundwater discharge). Upstream sites were associated with phosphorous (total P, PO_4), likely due to surface run off from agriculture and clearing (Schoumans et al. 2014), and the diversion/rehab sites were rich in iron (due to groundwater incursion), nitrogen, and carbon (likely due to decomposition of reeds). The strongest relationships between sites and water quality variables occurred in May, when sites were shallower and less hydrologically connected. This is a classic phenomenon in Australian rivers, where sites evolve into unique 'mesocosms' along a drying river (Blanchette and Pearson 2013; Sheldon 2005).

Bowman's Creek – Across all sites, time was significant (F_1 = 3.58, p < 0.01) in structuring *in situ* continuous data (Appendix 1). Within times (May and December), pairwise analysis indicated that sites were not significantly different (p > 0.05). However, across both times, site was a significant factor (F_3 = 3.91, p < 0.001), and PCA showed separation between diversion and non-diversion sites (data not shown). This seemingly incongruous result highlights the issue of scale, a concept underpinning ecological monitoring and rehabilitation (Lindenmayer and Likens 2010). Diversion sites had a higher cover of rushes, and non-diversion had more trailing bank vegetation, greater canopy cover, and were deeper. Rushes were outcompeting trailing bank vegetation in the diversion. Trailing bank vegetation is an important structural component of river ecosystems, with invertebrate communities changing in response to vegetation growth and concurrent effects on localised flow regime (Armitage et al. 2001). Rushes were also altering benthic characteristics by forming layers of silt over gravel and cobble. Aquatic macroinvertebrates are particularly reliant on benthic composition as it forms a significant aspect of their 'habitat templet' (Townsend and Hildrew 1994). Increased growth of rushes has also resulted in sites becoming shallower; pools that serve as dry-season refugia for aquatic taxa (Dudgeon et al. 2006) are at risk of disappearing.

Time was not a significant factor structuring *in situ* indices (Appendix 1) in Bowman's Creek at the river scale (F_1 = 1.90, p = 0.06), although site was significant (F_3 = 4.46, p < 0.01). Pairwise analysis for site groups indicated that the diversion sites were significantly different (p < 0.01) to the rest of the river. The North and West diversion sites were not significantly different to each other (p = 0.184). PCA showed separation between diversion and non-diversion sites (Figure 5), and diversion sites had a higher cover of true aquatic plants (submerged, floating, and emergent), whereas non-diversion sites had greater canopy health and higher covers of in-stream and bankside leaf litter.

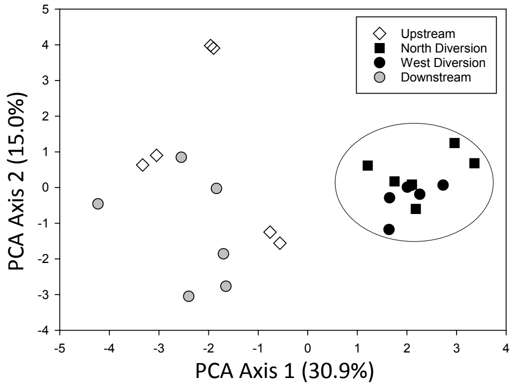

***Figure 5** Principal components analysis of* in situ *indices (see Appendix 1) in Bowman's Creek during May and December 2016. North and West diversion sites were significantly different from upstream and downstream sites (p < 0.05), but not significantly different from each other.*

Water quality parameters (Appendix 1) in Bowman's creek varied over time (F_1 = 9.28, p < 0.001), but not space (*a priori* site groups; F_3 = 1.24, p = 0.21). PCA showed separation between water quality parameters in May and December (data not shown), with May data driven by higher levels of Mn, Zn and Ca, and December sites characterised by nutrients (total N, total P, and DOC).

Discussion – Applying the 'system variability' model to mine closure

Developing the system variability model first involves measuring a suite of meaningful variables that account for seasonality and spatial scale. Next, determination of influential environmental variables and deciding which are influenced by mining (as opposed to other land uses). Finally, weighing up the cost/benefit of altering the variables to achieve rehabilitation. This method is in opposition to the reference site approach, which can force practitioners to choose generic key indicators *before* they begin collecting data. For example, in the Goulburn, reed growth and iron appear to be separating diversion sites from the rest of the river. With that knowledge, the company can decide whether they want to rehabilitate flow regimes and increase canopy cover, and/or correct groundwater inflows. The system variability model can assist this process by tracking progress over time; even if a site isn't fully rehabilitated, tracking towards the rest of the river could be viewed as progress and fulfilment of closure requirements.

Although regulators are used to the 'reference idea' for rehabilitation, ordination is routinely used in government and consulting to 'prove' that a site was impacted by mining. We are using this method in the opposite way: to determine if a site matches the rest of the system, and what variables need to be manipulated for rehabilitation.

This research has demonstrated that rehabilitation programs have to consider within- and among-site variability, not just absolute similarity. Two sites will never share identical ideal characteristics; a more reasonable goal would be to achieve rehabilitated sites that share characteristics of the area in which they exist, and behave in a similar fashion over time. Ignoring variability does not serve to rehabilitate mined landscapes, and productive outcomes are likely to be achieved in collaborations between scientists and industry managers (sensu Blanchette and Lund 2016).

APPENDIX A – Grouped variables for data analysis (units as per methods section).

- *In situ* continuous: turbidity, pH, conductivity, temperature, water ORP, velocity, sample depth, percent of site covered by rushes, percent canopy cover, percent of bank with trailing vegetation, soil pH, soil ORP.
- *In situ* indices: periphyton/filamentous algae, aquatic plants, leaf litter, bare sediments, iron flocculent, sediment composition, canopy cover, canopy health, understory cover, organic litter on bankside, exposed soil on bankside, grass cover on banks, dominant bankside sediment, undercutting, gullying, damage from animals.
- Water quality variables: B, Al, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Cd, Hg, Pb, U, Ca, K, Na, Mg, S, NH_4, NOx, Total N, PO_4, Total P, Cl^-, SO_4, Total C, DOC.

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