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Development of a diatom-based multimetric index for acid mine drainage impacted depressional wetlands

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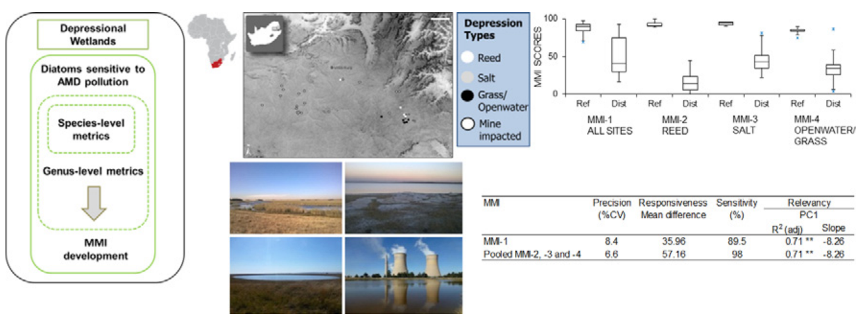
HIGHLIGHTS

- Diatom metrics are responsive to AMD pollution in depressional wetlands.
- Site classification by diatom typologies increases MMI performance.
- Simple metrics can be used beyond traditional species-based diatom assessment tools.
- This study highlights the discriminatory power of diatom-based metrics in wetlands.

GRAPHICAL ABSTRACT



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ABSTRACT

Acid mine drainage (AMD) from coal mining in the Mpumalanga Highveld region of South Africa has caused severe chemical and biological degradation of aquatic habitats, specifically depressional wetlands, as mines use these wetlands for storage of AMD. Diatom-based multimetric indices (MMIs) to assess wetland condition have mostly been developed to assess agricultural and urban land use impacts. No diatom MMI of wetland condition has been developed to assess AMD impacts related to mining activities. Previous approaches to diatom-based MMI development in wetlands have not accounted for natural variability. Natural variability among depressional wetlands may influence the accuracy of MMIs. Epiphytic diatom MMIs sensitive to AMD were developed for a range of depressional wetland types to account for natural variation in biological metrics. For this, we classified wetland types based on diatom typologies. A range of 4–15 final metrics were selected from a pool of ~140 candidate metrics to develop the MMIs based on their: (1) broad range, (2) high separation power and (3) low correlation among metrics. Final metrics were selected from three categories: similarity to reference sites, functional groups, and taxonomic composition, which represent different aspects of diatom assemblage structure and function. MMI performances were evaluated according to their precision in distinguishing reference sites, responsiveness to discriminate reference and disturbed sites, sensitivity to human disturbances and relevancy to AMD-related stressors. Each MMI showed excellent discriminatory power, whether or not it accounted for natural variation. However, accounting for variation by grouping sites based on diatom typologies improved overall performance of MMIs. Our study highlights the usefulness of diatom-based metrics and provides a model for the biological assessment of depressional wetland condition in South Africa and elsewhere.

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1. Introduction

Multimetric indices (MMIs) based on diatom assemblage responses to human disturbance have mostly been developed to assess the biological condition of lotic environments, specifically US streams and rivers (e.g., Cao et al., 2007; Potapova and Carlisle, 2011; Tao et al., 2016; Wang et al., 2005). Diatom-based MMIs developed for lentic systems have recently received increasing research attention, where efforts to develop MMIs for national-scale assessments of lakes (Stevenson et al., 2013) and ecoregional-scale assessments of freshwater wetlands (Miller et al., 2016) have benefited from US Environmental Protection Agency's National Aquatic Resource Surveys initiated programmes. On a relatively smaller scale, MMI development for diatom assemblages has been successful for statewide-scale assessments of depressional wetlands (those surrounded by upland) in the state of Florida (Lane and Brown, 2007) and for riverine and depressional wetlands in the Casco Bay watershed in Maine (Wang et al., 2006).

However, no diatom MMI developed for wetlands has controlled for effects of natural variation on index values, where natural variability of environmental factors among sites (i.e. factors least affected by human disturbances) can reduce accuracy of the index (Cao et al., 2007; Stoddard et al., 2008; Hawkins et al., 2010a). This is particularly vital for wetland habitats which are inherently highly variable, even within wetland types (such as depressional wetlands), which can vary significantly over small spatial scales (Bird et al., 2013). Wetlands differ widely due to intra- and inter- regional differences in naturally varying environmental factors (e.g., climate, geology, soils, topography, hydrology, water chemistry and vegetation) that can contribute to natural differences in their biological assemblages (e.g., USEPA, 2016). Consequently, surveys with high heterogeneity among wetlands will likely result in poorly performing MMIs if indices are not controlled for the effects of natural gradients, as was found by (Miller et al., 2016) when developing a diatom-based MMI for a range of northeastern US wetlands. Ecologically robust biological assessment indices should account for natural variability in biological assemblages so as to provide a more accurate assessment of deviation from reference condition (minimally disturbed conditions) as a result of human disturbances (Hawkins et al., 2000; Hughes et al., 1986).

Various approaches have been applied to MMIs to partition the effects of natural variability. One common approach is an a priori classification using geographic regionalisations, such as ecoregions, or abiotic factors such as altitude, geology, climate and water chemistry, to classify reference sites into environmentally homogenous types or classes (discrete categories) (Barbour et al., 1999). However, this approach has generally proven to be less effective in accounting for enough natural variation in assemblage composition (e.g., Hawkins et al., 2000; Heino et al., 2002; Herlihy et al., 2006) than using a biological typology approach, in which sites are grouped based on similarity in composition of biological assemblages (Davies and Jackson, 2006; Lavoie et al., 2014; Vander Laan and Hawkins, 2014). Classification by biological typology has accounted for more natural variability among reference sites and improved MMI accuracy than grouping sites by ecoregions (Hawkins, 2006; Tao et al., 2016).

MMIs offer a simple tool that can summarise complex biological systems, where a gradient of anthropogenic disturbance can be successfully evaluated using a collection of individual assemblage metrics combined into a single index of human disturbance (Karr and Chu, 1997). A multimetric approach can be more effective in assessing biological condition than using individual metrics because multiple metrics incorporate a variety of taxonomic and functional groups which have varying responses to different stressors and thus, can indicate the overall biological condition in a more comprehensive manner (Gerritsen, 1995; Karr, 1999).

Diatom-based MMIs to assess wetland condition have mostly been developed to quantify nutrient loading, elevated salinity and changes in pH resulting from agricultural and urban landuse (e.g., Lane and Brown, 2007; Miller et al., 2016; Wang et al., 2006), but no diatom index of wetland condition has been developed to quantify acid mine drainage (AMD) impacts related to mining activities.

AMD is a primary stressor in depressional wetlands of the Mpumalanga Highveld region of South Africa, where coal mines use these wetlands for dirty water storage by pumping AMD directly into the wetland (Ochieng et al., 2010). AMD can also enter the wetland via seepage and surface runoff from contaminated mine tailings dumps and stockpiles. AMD pollution arises when pyrite, a sulphur bearing mineral found in coal deposits, is exposed to oxygenated water and consequently produces sulphuric acid (Johnson and Hallberg, 2005). The acidic water becomes neutralised by dilution, and various chemical reactions with natural alkaline waters often are found in permanent depressional wetlands used to store mine wastewater in the Mpumalanga Highveld. Nevertheless, some elements have high solubilities and in such cases, persist in the water; this is particularly true for sulphate (McCarthy, 2011). Consequently, AMD impacted depressional wetlands in the region are typically sulphate-rich and extremely saline. Such alterations to the physical and chemical environment may render the water toxic to varying degrees and inhospitable to aquatic biota (Hirst et al., 2002; Sabater, 2000).

Numerous studies, focused mostly on streams, have demonstrated that the distribution of diatom communities can be significantly explained by dominant indicators of AMD, such as pH, alkalinity, conductivity, sulphate, and metals (e.g., Ferreira da Silva et al., 2009; Gray and Vis, 2013; Oberholster et al., 2013; Zalack et al., 2010). An effective diatom MMI used to assess the impacts of AMD has already been successfully applied to mine-impacted Appalachian streams (Gray and Vis, 2013; Pool et al., 2013). Thus, the use of diatoms as indicators of wetland condition responsive to mining impacts is a promising alternative to the traditional approach employed in South Africa, using macroinvertebrates and macrophytes, which have shown weak associations with wetland impairment (Bird and Day, 2010; Corry, 2017, in press; Day and Malan, 2010; Ferreira et al., 2012).

Depressional wetlands are one of the most valuable wetland types in the Mpumalanga Highveld region in terms of providing habitat for vulnerable species and socio-economic benefits to local communities. Remarkably, these wetlands (approximately 2600 of them in the region), have received relatively limited attention despite their importance and the ever-increasing threat to these systems from rapid mining development. In this study, our primary goal was to develop an MMI for depressional wetland condition in the Mpumalanga Highveld region based on epiphytic diatom assemblages that would be sensitive to mining impacts. To account for natural variability among reference sites, separate MMIs for classes of depressional wetland types were constructed. Our objectives were (1) to evaluate the performance of MMIs in their ability to discriminate between wetland diatom communities in AMD-impacted sites and non-AMD impacted reference sites; and (2) to determine whether accounting for natural variation in assemblages by diatom typology based classifications will improve MMI performance. Performance of MMIs were compared to test the hypothesis that accounting for natural variation based on site classification by diatom typologies will improve MMI performance.

2. Materials and methods

2.1. Study area and site selection

Diatom assemblages of permanent depressional wetlands in the Mpumalanga Highveld region were studied because depressional wetlands used for AMD storage in this area tend to be permanently inundated. Using information provided by wetland specialists around South Africa, forty-six depressional wetlands that reflect an AMD pollution gradient based on historical water chemistry, vegetation and diatom data were selected. Sites were also selected based on inundation conditions (permanence), which were examined using