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Detecting the impact of heavy metal contaminated sediment on benthic macroinvertebrate communities in tropical streams

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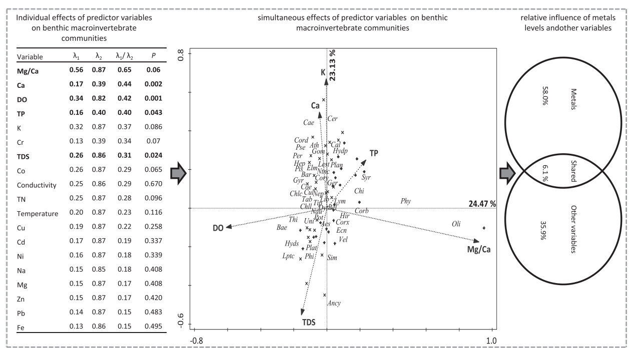
HIGHLIGHTS

- Response of macroinvertebrate communities to sediment metal levels was investigated in tropical streams.
- Mg/Ca ratio > Ca > DO > TP > TDS > Cr > K: in order of importance in determining macroinvertebrate communities
- Relative variation explained: metals levels = 58.0%; other variables = 35.9%
- Assessment of tropical metal-contaminated streams to focus more on macroinvertebrate community structure than on the EPT related metrics

GRAPHICAL ABSTRACT



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ABSTRACT

The effects of heavy metal pollution on benthic macroinvertebrate communities in tropical streams draining ultramafic systems have not been explored, despite a pressing need for ecological risk assessment to protect and manage aquatic ecosystems in these areas. The objective of this study was to examine benthic macroinvertebrate community composition in relation to metal concentrations in stream sediments and other physico-chemical variables in the Manyame River system, which drains part of the Great Dyke of Zimbabwe. Benthic macroinvertebrate sampling and community composition analysis, sediment collection, processing and metal analysis and assessment of other variables in the water column were done once at 55 sampling sites: 12 urban, 30 communal (i.e. sparsely populated rural areas, with livelihoods centred around subsistence agriculture) and 11 Great Dyke sites. Canonical correspondence analysis and partial canonical correspondence analysis (pCCA) were used to determine the importance of sediment heavy metal concentrations in explaining benthic macroinvertebrate community composition in comparison with other factors. Water quality ranged from very poor for urban locations due to sewage pollution, to good in communal locations. Significantly high concentrations of metals (ANOVA, $p < 0.05$) and high magnesium/calcium (Mg/Ca) ratio were recorded in sediments for the Great Dyke site locations. The Mg/Ca ratio, Ca^{2+}, Cr^{3+} and K^{+} were found to be important metals structuring benthic macroinvertebrate communities in the study streams, with metals explaining a larger percentage (58.0%) of the total variation explained compared to other variables (35.9%). However, taxa richness, diversity, evenness, percentage of Ephemeroptera, Plecoptera Trichoptera related metrics were higher at some Great Dyke sites than at communal sites. Thus, measures of taxa richness, diversity and %EPT may provide misleading information when assessing heavy metals in moderately polluted environments as in this study. Assessment of tropical streams draining ultramafic systems that are heavy metal-contaminated should also include benthic invertebrate community structure analysis, as it is possible that common endpoints, such as %EPT, may not identify impacts to aquatic communities.

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1. Introduction

Benthic macroinvertebrates occupy an important position in the aquatic food webs (Vannote et al., 1980; Rosi-Marshall and Wallace, 2002; Runck, 2007). These benthic macroinvertebrates are either attached to or intimately linked with the benthic substrate, and are the primary material exchangers across the sediment-water interface (Hawkins et al., 1982; Hussain and Pandit, 2012; Maharaj and Alkins-Koo, 2007). The assemblages consist of species which are highly sensitivity to contaminants, and are widely used to assess the ecological impacts and detecting long-term heavy metal contamination in aquatic ecosystems (Cairns and Pratt, 1993; Bere and Nyamupingidza, 2014; Akindele and Olutona, 2015). Metals in water column or sediment can be assimilated through direct uptake across the gill surfaces and other external body parts (Dodge and Theis, 1979; Hare et al., 1991). Ingestion of contaminated food materials may also expose benthic macroinvertebrates and other organisms to heavy metal bioaccumulation (Merritt and Cummins, 1984).

Metal pollution is of widespread concern for ecological management of aquatic ecosystems (Iwasaki et al., 2009; Bentum et al., 2011). Both anthropogenic pressures (e.g. industrial activities, mining, and urban runoff) and natural processes (e.g. weathering) account for heavy metals in aquatic ecosystems (Carpenter, 1925; Iwasaki et al., 2009; Bentum et al., 2011). The release of heavy metals into aquatic ecosystems through natural processes of weathering is highly dependent on geology (Gupta and Banerjee, 2012); while mining is regarded as a significant source of mercury (Hg), lead (Pb) and other heavy metals contamination in the environment (Hanson et al., 2007; Obiri, 2007; Singh et al., 2007). Small scale miners and illegal gold panners, due to lack of relevant infrastructure and adequate resources, pollute the environment with heavy metals (Kibena et al., 2014). During mining, olivine, orthopyroxene, and other metallic minerals which are normally buried deep into the earth's crust are exhumed and heaped as waste outside the shaft exposing them to weathering and transportation forces, which releases the toxic chemicals such as lead, cadmium, iron and mercury, into the environment (Bentum et al., 2011). Heavy metals in aquatic ecosystems are considered as serious pollutants due to their environmental persistence, toxicity and ability to be incorporated into food webs (Demirbas, 2008).

Sediment samples have proved to be useful in studying heavy metal levels accumulation because they act as sinks and usually contain historical evidence of natural and anthropogenic fluxes of heavy metals (Hseu et al., 2002; Aksoy et al., 2005; Nguyen et al., 2005; Boamponsem et al., 2010). Contaminated sediments pose a threat to benthic macroinvertebrates which in turn expose high trophic organisms to hazardous heavy metals (Begum et al., 2009; Bentum et al., 2011). The use of benthic macroinvertebrates in monitoring heavy metal contamination in aquatic ecosystems is rare and incipient in most developing countries (i.e. Smolders et al., 2003; Arimoro, 2009; Beyene et al., 2009), with most studies concentrating on the impact of organic pollution and eutrophication (Chakona et al., 2008, 2009; Bere and Nyamupingidza, 2014).

In Zimbabwe, the Great Dyke represents a layered magma system largely composed of ultramafic rocks which have large deposits of magnesium, olivine, orthopyroxene, copper, chrome, gold, nickel and platinum group of metals (PGM) (Proctor and Cole, 1992; Kibena et al., 2014). The effects of heavy metal pollution on benthic macroinvertebrates communities in streams draining parts of the ultramafic Great Dyke are obscured. There is, however, a pressing need for ecological risk assessments to protect and manage aquatic ecosystems in these areas. Heavy metals (i.e. metal ions) emanating from anthropogenic activities such as mining and natural weathering processes of ultramafic rocks end up accumulating in river sediments. This is likely to affect the benthic macroinvertebrate communities in river systems draining the Great Dyke and hence, biotic integrity of these systems. Monitoring and managing of contaminated lotic systems requires knowledge of possible pollutants and their mode of entering into the system. Therefore, this study seeks to add knowledge on the effects of heavy metal contamination on benthic macroinvertebrate communities. Emphasis will be put on providing information on the contribution of mining and predominant geology to heavy metal pollution through macroinvertebrate community analysis.

The current study examines benthic macroinvertebrate community composition in relation to metal concentrations in stream sediments and other physico-chemical variables in the Manyame River system, which drains part of the Great Dyke of Zimbabwe. The study used partial canonical correspondence analysis (pCCA) to determine: 1) the importance of sediment heavy metal concentrations in explaining benthic macroinvertebrate community composition in comparison with other factors; 2) the relative importance of different heavy metals on macroinvertebrate community compositions; and 3) the macroinvertebrate families that are tolerant of and those that are sensitive to metal loadings.

2. Materials and methods

2.1. Study area

The study area lies in Zimbabwe Manyame catchment area, with a wet-dry tropical climate (Fig. 1). The annual rainfall ranges from ~450 to 880 mm and mean annual temperature is 24.5 ± 5.1 °C, with a mean monthly maximum and minimum of 29.5 ± 6.5 °C and 18.9 ± 5.8 °C, respectively (Meteorological Services Department of Zimbabwe; data from 1965 to 2012). The study area encompasses streams draining part of the Great Dyke, a linear geological feature that extends nearly north-south through the centre of Zimbabwe passing just to the west of the capital, Harare (Wilson, 1996). The Great Dyke consists of a band of short, narrow ridges and hills spanning approximately 550 km and consists of large commercial deposits of nickel, copper, cobalt, gold and platinum group metals (PGM; Proctor and Cole, 1992; Wilson, 1996). The Great Dyke consists of many seasonal and perennial river systems that drain it and form part of the Manyame catchment. Mining is the major socio-economic activity along these streams. Streams in the study area also flow through urban areas. Due to population growth, uncontrolled urbanisation and industrialization, various town councils in the study area do not meet the technical standards for sewage treatment, garbage collection and urban drainage. Streams in the study area, therefore, receive pollutants from various point and diffuse sources and their habitats have been greatly altered resulting in stream health deterioration (Kibena et al., 2014).

Sites were identified and characterised as urban, communal and Great Dyke. Fifty-three sampling sites: 12 urban, 30 communal and 11 Great Dyke, were identified for sampling based on the need to evaluate the influence of natural and anthropogenic processes on macroinvertebrates communities. The control sites were relatively clean streams, draining sparsely populated communal areas which practised small subsistence farming and had no mining impacts or anthropogenic impacts.

2.2. Physico-chemical variables measurement

Water sample collection and physico-chemical measurements were carried along the river transect, on both littoral zones and middle section. Water column dissolved oxygen (DO), conductivity, pH, total dissolved solids (TDS) and temperature were measured on-site using a YSI Pro-Plus multiparameter water quality meter (Xylem Inc., USA). A flow velocity meter (flow watch, JDC Electronics SA, Switzerland) was used to measure flow surface velocity at different points on the site. Embeddedness and velocity/depth combinations were evaluated following the Rapid habitat assessment protocol developed by the United States Environmental Protection Agency (EPA; Barbour et al., 1999). Five hundred millilitres of water, fixed with 3 drops of