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Comparison of pollution indices for the assessment of heavy metals in the sediments of seaports of NSW, Australia

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ABSTRACT

Sediments samples from six seaports of NSW, Australia were analysed for the presence of metal contamination. Geoaccumulation index (Igeo), enrichment factor (EF), pollution load index (PLI), potential ecological risk (PER) and sediment pollution index (SPI) along with multivariate statistical analysis were used to identify the pollution pattern and possible sources of metals in the ports. The results demonstrate Cu, Pb and Zn pollution (Igeo > 5) at most sites and enrichment of As, Ni, Mn (EF > 3) and other metals. The PER recommends serious pollution at Port Kembla and Eden. By contrast, PLI and SPI demonstrate high contamination in all ports with exception of Port Botany and Yamba. PCA and cluster analysis detected major groups of elements in which three distinct clusters of pollutants and sites were apparent by dendrogram which portray simple and effective baseline scenarios for port activity-related quality assessment of surface sediments.

1. Introduction

The global economy is significantly influenced by the activities of sea ports contributing 80% of the global trade by volume and over 70% by value (UNCTAD, 2015; Shen et al., 2017). Marine sea ports, which underpin industry and commerce, are also intensively used for tourism and recreation (Niemi et al., 2004; Birch and McCready, 2009; Birch, 2017b). However, intensive economic and recreational activities also cause environmental pressures from metal pollution, oil spills, ballast water, garbage, ship paint, greenhouse gas emissions and other pollutants (UNCTAD, 2015; Shen et al., 2017). Metal pollution in port environments is now a global environmental concern because of toxicity, wide sources, persistence, slow degradation and rapid accumulative behaviours (Klavinš et al., 2000; Yuan et al., 2004; Dural et al., 2007; Hu et al., 2011; Alyazichi, 2015). Metals discharged into the port environments are generally eliminated from the water column by binding with suspended particles and are ultimately deposited as bottom sediments under favourable hydraulic conditions (Zeng and Wu, 2009; Hosono et al., 2010; Zhang et al., 2013; Zhang et al., 2014). Accordingly, sediments are considered to be the most important sinks and play a pivotal role in the accumulation of metals, with significantly higher elemental concentration than in the water column (Li et al., 2001; Ridgway and Shimmield, 2002; Hung and Hsu, 2004; Xia et al., 2011; Wang et al., 2012; Mashiatullah et al., 2015). Metal distribution characteristics in sediment cores can show time-dependent historical variations of metal concentrations and can provide useful information on metal accumulation and alteration from a past period (Jain et al., 2008; Wang and Rly, 2010; Alvarez et al., 2011; Ma et al., 2013; Tang et al., 2016; Wang et al., 2016).

Metals entering the marine environment mostly settle down and absorb into sediments together with organic matter, Fe/Mn oxides, sulfides and clay (Wang and Chen, 2000). Marine sediments act as scavengers for metals and most often bear an excellent evidence of anthropogenic impacts (Guevara et al., 2005). To some extent, metal contents in sediment can represent the quality of the water body. Sediments cannot fix metals permanently although they are some of the endmost sinks for metals input into the aquatic environment. Under variable hydraulic conditions and through various remobilisation processes some sediment bound metals might be released again into the water body. Therefore, sediments play an important role in the transport and storage of potentially hazardous metals (Ruilian et al., 2008).

Considering sediments are pollutant traps they are valid for long term studies (Mostafa and El-Naggar, 2003; Zaghden et al., 2007) and act as indicators for the relationship between natural and anthropogenic variables as they pass pollutants to the food chain (Calman et al., 1996; Hassanshahian et al., 2010). The retention capacity of sediment may be related to its physicochemical properties, such as grain size and organic matter (Abdallah et al., 2016).

However, in the assessment of environmental health, the use of sedimentary indicators are often poorly appreciated, deemphasised and misused. Traditionally, water columns and biological indicators are the preferred media for assessment of the marine and estuarine health

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(Rainbow, 1995; Rainbow, 2006). As water is dynamic with highly variable short- and long-term properties, analysis of large number of samples is required to spatially and temporally characterise water quality with confidence (Birch and Olmos, 2008). Moreover, low chemical concentrations in water and complex and expensive analysis often compromise data quality and interpretation (Bubb et al., 1990; Siaka et al., 1998; Birch and Taylor, 2000). On the other hand, analysis of flora and fauna is often difficult due to significant variations in the chemistry of tissues between individuals, species, gender, organs and age (Birch, 2017a).

In recent years the status of aquatic environments is assessed through sediment analysis rather than other traditional media because of its extensive habitat and large contaminants storage which has a substantial influence on the biological health in the marine environment. However, for a comprehensive assessment of aquatic systems sediments should be used in combination with other screening tools (Belin et al., 2014). Sediments have advantage over other indicators because they record and combine environmental events over time within the aquatic system, commonly referred to as 'the memory of sediments'. Furthermore, sediments not only provide useful spatial and temporal information (Birch, 2007; Birch et al., 2013) but allow prediction of future environmental change and status from the integration of environmental events over time (Birch et al., 2010; Birch et al., 2012; Birch et al., 2013). Additionally, sediments greatly affect the quality of overlying and interstitial water through physical (re-suspension), (Peterson et al., 1997; Simpson et al., 2000), biological (bio-turbation), (Reible et al., 1996) and chemical (desorption and benthic diffusion), (Rivera-Duarte and Flegal, 1994) processes (Birch, 2017a). Finally, compared to other indicators of marine and estuarine health, sediments are less time consuming and inexpensive to measure the environmental conditions (Maher et al., 1999; Birch et al., 2000; Birch, 2003).

Recently, sediment quality monitoring identified high to moderately polluted areas (Birch, 2017b). Birch (2017b) stated that metal concentrations in sediments of the Sydney estuary are some of the highest reported in New South Wales and Australia. McCready et al. (2000, 2004, 2006a, 2006b, 2006c) revealed significant metals and nutrient contamination in the sediments of Sydney harbour estuary. Spooner et al. (2003) demonstrated significant concentrations of zinc, copper, lead and arsenic in surfacial sediment of Port Botany. Dafforn et al. (2012) investigated high concentrations of metals (Cu, Pb and Cd) in the sediment of Port Kembla. Another study by Birch and Gillis (2006) explained the non-dredged part of the Newcastle port has higher levels of sedimentary metals. Although a number of studies have been conducted in the ports of NSW or elsewhere, they were mainly based on analysis of some selective elemental concentrations of the sediments, using limited sediment quality indices to quantify the environmental state of the sediments. The present study analysed large sets of trace elements and assessed the sediment quality using a wide range of environmental quality indices and compares the indices to determine the most effective method for assessing sediment quality.

The aim of this study was to apply a wide range of environmental quality indices including the geoaccumulation index, pollution load index, enrichment factor, potential ecological risk index, sediment pollution index, factor analysis and multivariate statistical analysis to assess the sediment quality and ecological state of the major ports of NSW, Australia and determine the most accurate and suitable quantitative assessment method for analysis of the sediment quality. This will impart a tool for prime stakeholders, including marine and estuarine managers, government and the public in connection to protecting aquatic biota and environment.

2. Materials and methods

2.1. Study area

The study areas in this work were the six domionant ports in New South Wales, Australia, namely Port Jackson, Botany, Kembla, Newcastle, Yamba and Eden, which are away from one another and are engaged with different shipping activities (Jahan and Strezov, 2017). Port Jackson of Sydney is a premier port of Australia, well known for passenger shipping, recreational boating and water sports (Hatje et al., 2003). The area is floored with a clean, flood delta sand, containing < 10% mud, which extends ~2 km into the embayment from the entrance. Port Botany, located in the mouth of George river is mainly engaged with container, cruide oil and bulk liquid operations (fossil fuel, chemical and bio-fuel) (Harris and O'Brien, 1998). The depositional environment of Port Botany is characterised by bay sediments and tidal deltaic sediments composed of mostly fine to medium grained sand (Roy and Crawford, 1981). Port Kembla is a major export location for coal mined in the southern and western regions of New South Wales with many facilities and berths including the grain terminal, bulk liquids, oil, various products berths (steel berth) and multi-purpose berths (fertiliser, pulp & steel products). The port is important for importing iron ore, dolomite, limestone, sulphur, copper, phosphate rock and petroleum products and exporting iron and steel, coal, coke, tinplate and copper cables (Harris and O'Brien, 1998). The surface sediments of Port Kembla are coarse grained sediments (slightly gravelly sands and gravelly sands) is affected by the presence of large amounts (up to 80%) of calcium carbonate derived mainly from coralline algae (Bosher, 1977). The Port of Newcastle is the world's largest coal export port that also receives raw materials for steelworks, fertiliser and aluminium industries, grain, steel products, mineral sands and woodchips (Harris and O'Brien, 1998) and is known as one of Australia's largest ports by throughput tonnage (Bateman, 1996). The port is the economic and trading centre for the Hunter Valley and much of New South Wales, and is a critical supply chain interface for the movement of cargo (Clarson, 2017). The Hunter River channel sediment is derived from the relict marine and aeolian dune sand deposits. Fine sediments transported by the river system are trapped in Fullerton Cove (mud basin) and deposited on the middle shelf mud belt (Roy, 1977). Port Yamba is located at the mouth of the Clarence River in the Northern New South Wales and is Australia's most eastern sea port. Port Yamba is home port of the New South Wales' second largest fishing fleet and handles a range of imports and exports, such as container liquid berth-livestock and explosive products. The Clarence River is the largest catchment area on NSW Tasman Sea coast comprising mainly of clayey mineral rich sandy sediments (Smith, 1996). Port of Eden is a small seaport, located in the Twofold Bay of South Coast region of New South Wales, Australia. The port is home to one of the largest fishing fleets in New South Wales. Woodchip export is currently the major trade for the port, while the principal imports are break bulk, and machinery and equipment, mainly for the oil and gas industry (Harris and O'Brien, 1998). Based on texture and composition (lithology and calcium carbonate content) surfacial sediments of Twofolds Bay are mainly fine quartz sand in the inner bay area, with a zone of coarse sand along the southern and outer parts of the bay (Hudson, 1991).

The coordinates and details of the sampling location points are listed in Table 1 and shown in Fig. 1.

Sediment samples from the six sea ports were collected for metal analysis during the period of April–May 2017 using a stainless steel Ekman Grab Sampler. From each individual port three composite surface sediment samples were collected at water depths ranging from 1 to 10 m, one of which was a background sample selected from the same hydrogeological area but away from any influences of the port activities. Two replicate samples were collected in order to obtain a composite sample and ensure the sediment profiles were not disturbed by collection procedures or by local human activities. Replicate samples were collected at a distance of 1 m apart. After sampling, the sediment samples were packed and carried to the laboratory in iced-boxes and stored at 4 °C until analysis. The sediment samples were then submitted for analysis of heavy metals, grain size, total organic carbon, nitrite, nitrate, ammonia, sodium, potassium and calcium.