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A screening model for assessing water quality in small, dynamic estuaries

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ABSTRACT

Despite mounting evidence of the harm associated with excessive nutrient loading to estuaries, tools to translate this body of knowledge into sound environmental management and planning practices in data-poor environments are lacking. In this paper, a design science approach is adopted to develop a screening (box) model for the water quality assessment of South African estuaries. The key design principles are first distilled from literature on the nutrient dynamics and hydro-morphological functioning of small, dynamic, bar-blocked estuaries. The proportional volume contribution of land-based flows (river inflows, diffuse inflows from the peri-catchment, point source discharges) is determined, a water quality class is allocated to each of the inflows, and the overall water quality class for the land-based inflows to an estuary is determined. Taking the percentage mouth closure and the perched nature of the estuaries into account, a WQ Similarity rating is allocated. This similarity rating reflects the degree of similarity of the water quality in the estuary to the reference (natural) water quality. The entire water quality assessment uses readily available information such as land-cover data, legal limits for disposal and water quality monitoring data where they exist, making it suitable for a data-poor environment. The screening model is calibrated and validated on a selection of South African estuaries for which official health condition assessments exist. Results are promising, and the screening model is deemed appropriate for assessing the water quality of individual estuaries and for comparing the sensitivity of multiple estuaries to changes in the volume and nutrient loading of land-based inflows. As such, the screening model can be employed at a regional or national scale for strategic assessments of water quality in small, dynamic estuaries.

1. Introduction

Coastal environments support more than 75% of the world's population with ever-increasing growth and development pressures (Paerl, 2006). As a result coastal ecosystems, such as estuaries, receive large quantities of land-based nutrients and other pollutants from agriculture, wastewater treatment works and diffuse urban runoff (De Jonge et al., 2002; Bricker et al., 2008; Steward and Lowe, 2010; Lemley et al., 2017). Although nutrient inputs to estuaries and coastal waters occur naturally, through geological weathering and inputs from ocean upwelling for instance, anthropogenic inputs have increased nutrient loading to many times that of nature (Bricker et al., 2008; Cloern et al., 2016). It is estimated that nitrogen (N) loading alone has increased 10-fold over the past century (Howarth et al., 1996; Bricker et al., 2003; Whitall et al., 2007). Such excessive nutrient loading can cause accelerated primary production (or eutrophication), the accumulation of organic matter, increased turbidity, and subsequently excessive oxygen consumption. These symptoms of excessive nutrient loading impair the ecological and socio-economic value of estuaries resulting in aesthetically unpleasing conditions, harmful algal blooms, fish kills and fish consumption warnings (to prevent human health issues) (Bricker et al., 2008). Effective intervention takes the form of sound evidence-based environmental management and planning (Lillebø et al., 2005).

Knowledge of the present condition of a natural resource provides a logical departure point for environmental management and

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planning. Trophic classification systems and water quality indices (WQIs) may be used in establishing the degree to which the current condition of a system has already been modified from the natural or a baseline condition (e.g. Paerl, 2006; Lumb et al., 2011; Lemley et al., 2015; Caeiro et al, 2016). The concept of using water quality to assess the degree of purity (or similarity to natural) of a water resource emerged in the 1848 in Germany (Ott, 1978; Steinhart et al., 1981; Dojlido and Best, 1993; Lumb et al., 2011). Since then various water quality index formulations and models have been suggested, as reviewed by Lumb et al. (2011). Most of the existing WQIs rely on the availability of accurate monitoring data and guidelines or targets for intended water uses. Measured data on selected water quality parameters are mathematically manipulated, and then rated against guidelines to provide a simple expression of suitability for use (e.g. Steward and Lowe, 2010). As technologies advance, the suite of parameters continuously expands, but interestingly also the ability to predict non-measured parameters through correlation modelling (Lumb et al., 2011). The latter is especially important in data-poor environments, where extensive monitoring networks are just not available.

Evidence-based environmental management and planning also requires information on the proportional contribution of various anthropogenic sources or pressures (e.g. Whitall et al., 2007; Swaney et al., 2008), as well as knowledge on the key ecological processes influencing estuarine nutrient dynamics (e.g. Lillebø et al., 2005; Saraiva et al., 2007; Steward and Lowe, 2010). Numerous processes have an influence on the ambient nutrient characteristics of an estuary (Moss, 1998; Galbraith and Burns, 2007). However, the primary water sources, namely catchment (or land-based) runoff and intruding seawater, as well as their nutrient properties, are key influencing factors. The proportional contribution to the nutrient characteristics of the estuary by these water sources is mainly determined by dynamic flushing and mixing processes. However, *in situ* processes (e.g. primary production and biochemical remineralisation) can also exert a major influence (e.g. Church, 1986; Lillebø et al., 2005). Such *in situ* processes typically exert greater influence on nutrient processes in estuaries where the residence time or retention efficiency is high, while dynamic exchange processes such as flushing and mixing, tend to dominate nutrient characteristics where the retention efficiency is low (Eyre, 2000; Taljaard et al., 2009a). Earlier studies on lake systems affirm that the effects of nutrient loading are strongly influenced by water residence time (Lerman, 1974; Dillon, 1975; Schindler and Nighswander, 1970 as referenced in Steward and Lowe, 2010). Building on this earlier limnological work, Swaney et al. (2008) showed that water residence time together with nutrient loading rates were the most critical factors controlling nutrient concentrations in an estuary.

Despite mounting evidence and deeper scientific understanding regarding the critical factors controlling nutrient concentrations in estuaries, tools to translate this knowledge into sound environmental management and planning practices in data-poor environments are lacking. Of particular interest is the development of a method for assessing the water quality of the estuaries on the South African coast. South Africa has about 300 microtidal, relatively small estuaries (Van Niekerk et al., 2013), located along a narrow coastal plain extending for some 3000 km. Although several biogeochemical studies have been conducted on South African estuaries (as reviewed for example, in Allanson and Winter (1999) and Taljaard et al. (2009a)), in most instances the studies did not address water quality *per se.* Instead, they investigated specific characteristics or processes influencing the biogeochemistry of the estuaries. The biogeochemical understanding derived from such studies has been applied in environmental impact assessments and designing estuary management plans (Slinger et al., 2005), and in determining ecological water requirements of the estuaries. Indeed, in accordance with the National Water Act (1998), South Africa's national government has commissioned studies to develop methods for the preliminary determination of ecological water requirements for the country's water resources, which include estuaries (DWAF, 1999; DWAF, 2008).

The official methods for determining ecological water requirements include an estuarine health index (EHI) for assessing the present ecological condition of an estuary; a component of which is estuarine water quality (Turpie et al., 2012). Six health categories are distinguished in the Estuarine Health Index (Turpie et al., 2012), namely A to F. Category A reflects near pristine conditions, while Category F represents a highly modified estuarine health condition. Each of these categories is associated with a predefined range of similarity to a natural or reference condition, within the spectrum from zero to 100% similarity (Table 1).

In the water quality component of the EHI, the percentage similarity to the natural or reference condition of (i) the salinity distributions in the estuary (primarily influenced by changes in freshwater inflows) and, (ii) four other biogeochemical parameters, namely dissolved inorganic nutrients, dissolved oxygen, transparency and toxic substances (primarily influenced by anthropogenic sources, such as polluted wastewater and contaminated runoff), are assessed and aggregated. In each case, for a given estuary water volume, the percentage similarity is determined using an adaptation of the Czekanowski's similarity index (Turpie et al., 2012):

$$2[\min(Conc_{natural}; Conc_{present}]/[Conc_{natural} + Conc_{present}]) \quad (1)$$

where $Conc_{natural}$= Natural concentration

$Conc_{present}$ = Present concentration

The EHI was developed primarily for application to individual estuaries, requiring site-specific data and information on selected water quality parameters either based on detailed measurements

Table 1
Percentage similarity ranges for the six categories in the EHI (Turpie et al., 2012).

CATEGORY	PERCENTAGE SIMILARITY	DESCRIPTION
A	91-100	Unmodified, natural
B	76-90	Largely natural with few modifications
C	61-75	Moderately modified
D	41-60	Largely modified
E	21-40	Highly modified
F	0-20	Extremely degraded