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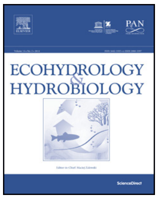

Original Research Article

The application of nutrient budget models to determine the ecosystem health of the Wami Estuary, Tanzania

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1. Introduction

Estuaries receive dissolved and particulate nutrients from different sources in the catchment (e.g. land run-off, sediments, atmospheric deposition and underlying bedrock) and coastal waters (Langston et al., 2003). These nutrients are processed through various hydrodynamic, biogeochemical and sediment transport processes (Day et al., 2006; Wolanski and Elliott, 2015). Increasing populations and socioeconomic activities as well as changing land use practice in many catchments and coastal areas have to a large extent contributed to a global increase in nutrient loading to estuaries and coastal zones worldwide. This can lead to enhanced biological productivity, which may be good, and eutrophication, which is generally bad for the ecosystem and can also negatively affect human health and the provision of ecosystem services. However, eutrophication may be inhibited by increased turbidity, resulting from increased soil erosion from poor land use (Valiela et al., 1997; Smith et al., 2003; Cardoso et al., 2004; Wolanski et al., 2004; Kennison et al., 2004; Painting et al., 2007; van den Belt and Costanza, 2012; Wolanski and Elliott, 2015). Thus, to avoid or temper such problems, the management of estuaries and associated coastal zones requires a proper understanding of sources and sinks of nutrients in the estuary (Nixon et al., 1995; Humborg et al., 2000).

There are various models that can be used to estimate the net budget of C, N and P in estuaries. The basic question posed for such models to answer is "where do the nutrients go?" The simplest models are based on simple mass–balance calculations that ignore the processing of nutrients within the estuarine food web (Chen and Wang, 1999; Eyre and McKee, 2002; Maher and Eyre, 2012). A more realistic model that has been used in more than 250 estuaries worldwide is the LOICZ estuarine biogeochemical model, which considers only dissolved nutrients, ignores the particulate nutrients and the detritus, but includes the net ecosystem metabolism (Gordon et al., 1996; Swaney et al., 2011). This model has been recently improved to consider also the particulate nutrients (i.e. the sorption/desorption of nutrients on the suspended fine sediment; Xu et al., 2013, 2015), though it still ignores the role of detritus as well as the processing of nutrients in the trophic food web above the phytoplankton.

To overcome these shortcomings, the UNESCO estuarine ecohydrology (UEE) model was developed (Wolanski et al., 2004, 2006; Ben-Hamadou et al., 2011; Wolanski and Elliott, 2015; Bonthu et al., 2016). Our study aims to compare the findings of these two models in the Wami Estuary, Tanzania and to use these results, as well as those from field studies, to estimate its ecosystem health.

The whole Wami Estuary is protected in the Saadani National Park. Both models suggest that the ecosystem is healthy, with no sign of eutrophication, and that the system depends on additional nutrients than just riverine dissolved nutrients, and these include detritus, mangrove litter fall, and hippo excreta. The major threat to the ecosystem is the lack of governance, as there is no enforcement of minimum environmental flows of the river; excessive water withdrawal occurs in the catchment and results in the freshwater part of the estuary disappearing in the dry season, with major impacts on the wildlife of Saadani National Park.

We suggest the need for remedial measures at both the watershed and the local scale in managing water resources. This study complements previous studies which have addressed the socioeconomic importance, ecosystem services and environmental flow assessments for the Wami river and its estuary, but not its ecosystem health (Anderson et al., 2007; WRBWO, 2008; McNally et al.,

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2011; Mosha and Gallardo, 2013; Kiwango et al., 2015; FIU-GLOWS, 2016). As such this study provides scientific information to serve as the basis for proper management options and decision making processes for the Wami River at the catchment scale.

2. Materials and methods

2.1. Study area

Our study site was the Wami Estuary in Tanzania (Fig. 1), one of the most productive areas of Tanzania in terms of prawn fisheries (Tobey, 2008; Mosha and Gallardo, 2013). It is strictly protected as it is included in the Saadani National Park (SANAPA). It experiences semi-diurnal tides with strong diurnal inequality. The tidal range reaches up to 4 m during spring tides and the influence may extend up to 8 km upstream. The first five kilometers of the estuary are occupied by mangroves, followed by Acacia trees and palms. The mangroves serve as breeding and nursery grounds for fish, prawns and birds (Anderson et al., 2007). The estuary also supports terrestrial wildlife by providing drinking water in its freshwater region near the tidal limit during the dry season when other water sources in SANAPA are dry, and it also provides a habitat for mammals, crustaceans, reptiles and birds (Kiwango et al., 2015).

2.2. Physical properties

Data on river discharge, rainfall, nutrients (Dissolved Inorganic Nitrogen – DIN and Dissolved Inorganic Phosphorus – DIP), salinity and Suspended Particulate Matter (SPM) were obtained from Kiwango et al. (2015). A summary of all data used in the model is shown in Table 1. The estuary has a surface area of $\sim 1.098 \times 10^6\,m^2$ and a mean volume of $\sim 3 \times 10^6\,m^3$. The estuary is shallow: the average depth is ~2.5 m and the depth may be as small as 0.5 m at some points along the river. Recently, water is increasingly being extracted from the river upstream from the estuary, as a result of which the river discharge (Q_f) during the dry season is much reduced nowadays and flows of $0.2\,m^3\,s^{-1}$ now commonly occur during the dry season (Kiwango et al., 2015).

It is a turbid estuary, with turbidity reaching up to more than 400 NTU and suspended sediment concentration $< 100\,mg\,L^{-1}$ during the dry season and $> 800\,mg\,L^{-1}$ during the wet season (Anderson et al., 2007; Kiwango et al., 2015). As a result the secchi depth is ~0.025–0.04 m during the wet season and ~0.2–0.7 m during the dry season. Throughout the year, the estuarine water is warm, with water temperature ranging between 27.5 °C and 31.9 °C. At high tide during the wet season vertical salinity stratification occurs in the lower 1–2 km of the estuary, with surface salinity <7 psu and ~35 psu at the bottom, the remaining part of the estuary is freshwater; at low tide, freshwater occurs throughout the estuary and a 1 m thick river plume extends up to 2 km offshore into the Indian Ocean. By contrast, during the dry season the system is vertically well mixed, with salinity of ~30 psu at the mouth and ~7 psu at the tidal limit (Kiwango et al., 2015). Because of the absence of human settlement along the estuary and the presence of clay soils, groundwater and sewage flow to the estuary are believed to be negligible, though there are no actual data.

2.3. The muddy LOICZ model

The estuary was divided into three boxes – river, estuary and ocean – following the classical LOICZ model (Gordon et al., 1996). Since the estuary is turbid, we used the one-layer muddy LOICZ model of Xu et al. (2013) for the dry season and the two-layers model of Xu et al. (2015) for the wet season, when the estuary is highly vertically stratified.

A list of parameters used in the model is shown in Table 1. Local data are lacking for the partition coefficient (K_d), which is the fraction of the total nutrients that are in particulate form for the Wami Estuary; we assumed it to be the same as in the Chilika lagoon (Bonthu et al., 2016),

$$K_d = \frac{\mathrm{SPM}}{\mathrm{SPM}} + 72 \tag{1}$$

where SPM is the suspended matter concentration. The desorption/sorption of nutrients between boxes are calculated as a function of changes in K_d between the boxes.

2.3.1. Water and salt budgets Q6

Water and salt budgets were calculated based on the assumption that the system is at steady state. Salt behaves conservatively in the system. Thus the residual flow (VR) is:

$$V_R = -(V_Q + V_P + V_E + V_G + V_O) \tag{2}$$

where V_Q, V_P, V_E, V_G and V_O are the mean river inflow, precipitation, evaporation, groundwater inflow to the estuary and advective inflow from the estuary.

Freshwater has zero salinity and thus the salinity budget is:

$$S_R V_R = (S_{oon} - S_{sys}) V_X \tag{3}$$

where S_R = salinity of residual flow at the ocean–system boundary or the mean calculated as $(S_{oon} - S_{sys})/2$ and $(S_{ocn} - S_{sys})$ are mean salinity of the estuarine system and ocean. V_X is the mixing flow from the seawater intrusion, representing the tidal flushing process that occurs even in the absence of a river inflow and that can be enhanced by estuarine baroclinic flows.

Rearranging the equation to solve for V_X:

$$V_X = S_R V_R (S_{ocn} - S_{sys}) \tag{4}$$

The total water exchange time or the residence time (τ) in days is calculated as:

$$\tau = \frac{V_{sys}}{(V_X + |V_R|)} \tag{5}$$

where V_{sys} is the volume of the estuary.

During wet season, the Wami Estuary is highly stratified and therefore the equation for water balance is modified from the one-box model to account for different

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