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Organic carbon dynamics in a constructed mangrove wastewater wetland populated with benthic fauna: A modelling approach

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ABSTRACT

The use of wetlands for processing nutrient- and organic-rich wastewater has proved effective to prevent coastal pollution in developing countries, mainly due to low running costs (low energy consumption and training requirements) and relatively high system filtration efficiency (difference of is flushed in the system minus what is flushed out, multiplied by 100). In this study we present a management model that simulate the fate of area specific organic carbon loadings in constructed mangrove wetlands (CMW). The model was calibrated and validated by measured data obtained from a newly established CMW system in Tanzania. Sewage from a nearby hotel was pumped to a primary stabilization pond with a residence time of 12 h. Subsequently, sewage was discharged into 9 unvegetated cells and 9 cells planted with mangrove trees (*Avicennia marina*). Each group of 9 cells was split into 3 subgroups of 3 cells receiving seawater mixed with 0, 20 and 60% sewage for six months. Raw sewage was assumed to contain 0.5 (150 mg BOD L^{-1}) person equivalent. The model provided a good simulation of oxygen, carbon and nutrient dynamics in the systems; primary production (by benthic microalgae and phytoplankton); and biomass change of important faunal groups (crabs and gastropods). High sewage loadings and reduced residence time decreased the system filtration efficiency. Thus a discharge of 100 L of 1 PE (300 mg BOD L^{-1}) m^{-2} into the system requires a water residence time of about 60 h within the CMW to achieve the Tanzanian emission standards (30 mg BOD L^{-1}). Higher mangrove fauna biomass and abundance of biogenic structures (i.e. pneumatophores and crab burrows) increased carbon mineralization in the CMW sediment by up to a factor of 2.

1. Introduction

The main goal of wastewater treatment is protection of aquatic environments from eutrophication and public health from transmission of waterborne diseases (Crites et al., 2006). A variety of approaches are applied for this purpose in developed countries, including waste stabilization ponds, septic tanks, activated sludge, trickling filters, anaerobic systems, chemical precipitation and land application systems. However, most developing countries have limited financial resources and require low-tech systems with limited construction and maintenance costs. The most widely used treatment approach in tropical areas, where many developing countries are located, are waste stabilization ponds. Optimal light regimes and high temperatures for biological processes in the tropics assures a high removal rate of organic waste in such ponds (Kivaisi, 2001). However, effluents released from these ponds without further treatment can still lead to contamination of groundwater and eutrophication in adjacent aquatic ecosystems, such as seagrass habitats and coral reefs (Diaz and Rosenberg, 2008). The application of wetland technology coupled to waste stabilization ponds have proved effective for further removal of organic matter, nutrients and pathogens from wastewater. Furthermore, construction costs, energy consumption and training requirements of such systems are low (Kivaisi, 2001).

Mangrove forests have proved their potential as natural wastewater treatment facilities, thus preventing coastal pollution (Wong et al., 1997). Trials in mangrove wetlands surrounding peri-urban areas have shown that sediments of these ecosystems have the capacity to remove significant amounts (40–60%) of nutrients from diluted sewage for long time periods (Tam and Wong, 1995, 1996). In most cases, no significant impacts of diluted sewage discharge are observed on mangrove trees (Wong et al., 1995) or benthic invertebrate communities (Yu et al., 1997; Amaral et al., 2009; Cannicci et al., 2009). However, uncontrolled excessive

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sewage loadings may lead to eutrophic conditions and stress to the biota within wetlands, resulting in lower vegetation diversity, productivity and canopy cover as well as an impoverished faunal abundance and activity (McDonald et al., 2003; Hogarth, 2007; Amaral et al., 2009; Penha-Lopes et al., 2009, 2010a). Deforestation of natural mangrove wetlands (Al-Sayed et al., 2005) have in many areas forced managers to establish constructed wetlands (Kivaisi, 2001). Such constructed systems are now used worldwide in many countries (Kivaisi, 2001; Crites et al., 2006), and have shown great success in e.g. China (Tam and Wong, 1996; Yang et al., 2008) and Thailand (Boonsong et al., 2003).

Constructed wetlands are designed to mimic natural systems, utilizing tolerant plants, sediment, and associated microorganisms to remove contaminants from wastewater effluents (Kivaisi, 2001). Benthic fauna and biogenic structures, such as pneumatophores and faunal burrows, are particularly important for the functioning of mangrove forests (Cannicci et al., 2008; Kristensen, 2008). Nevertheless, both components are usually disregarded when the functioning of constructed wetlands is assessed. Benthic invertebrates incorporate nutrients and organic matter directly into biomass (Yates et al., 2002; Penha-Lopes et al., 2010a, under review), and together with their constructions (such as crab burrows) they enhance carbon mineralization in the sediment and consequently increase sewage filtration efficiency (Canfield et al., 2005; Kristensen, 2008; Penha-Lopes et al., 2010b).

A variety of models have been applied to simulate mangrove hydrology, biogeochemistry and community dynamics (see Berger et al., 2008; Twilley and Rivera-Monroy, 2009). Thus, the fate of organic carbon has been modelled with success in an East African mangrove forest partly affected by anthropogenic activity (Machiwa and Hallberg, 2002). Similarly, physico-chemical and biological conditions as well as biological community dynamics have been modelled well in waste stabilization ponds and constructed mangrove wetlands (Kayombo et al., 2000, 2002, 2003; Mashauri and Kayombo, 2002). Nevertheless, development of modelling approaches that considers all key components including the role of flora and fauna as well as biogenic structures for assessing carbon and nutrient dynamics in constructed mangrove wetlands (CMW) exposed to sewage are strongly needed. Such modelling tools will not only improve our understanding of the system filtering efficiency, but also provide essential information for management plans that can reduce construction and maintenance costs.

The present work aims at demonstrating the performance and organic carbon mineralization efficiency of a newly established CMW in Tanzania using an integrated ecological modelling approach (Fig. 1). The model is composed of 6 interconnected process sub-models that for clarity will be dealt with separately. The 6 sub-models applied are: (1) carbon degradation; (2) nutrient dynamics; (3) oxygen dynamics; (4) phytoplankton dynamics; (5) benthic microalgal dynamics; and (6) faunal dynamics. The sewage filtration efficiency of the system and its long term sustainability was evaluated by the integrated model where all sub-models were running simultaneously. The modelling approach was based different on scenarios with changing sewage loading and residence time, as well as initial abundance of fauna and biogenic structures (mangrove pneumatophores and crab burrows).

2. Methodology

2.1. Constructed mangrove wetland

To determine the efficiency of constructed mangrove wetlands (CMW), a controlled experimental facility consisting of 18 cells (9 m^2 each), surrounded by concrete walls, was established in

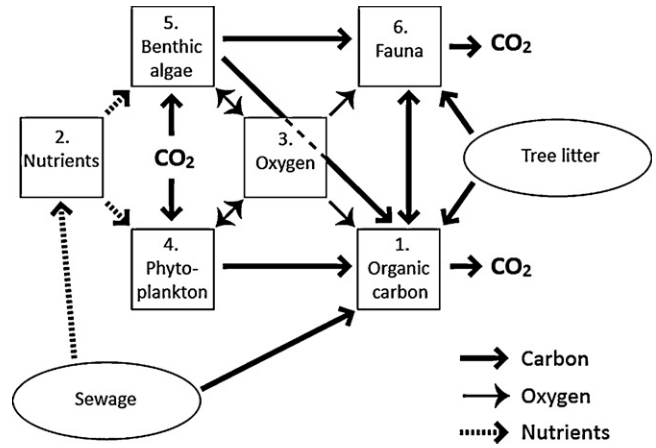

Fig. 1. Integrated model diagram with the 6 sub-models indicated (numbered squares). Major flows between sub-models are shown indicated by arrows. Heavy arrows represent carbon flow; dotted arrows nutrient flow; and thin arrows oxygen flow. Ellipses represent other carbon and nutrient sources (sewage and mangrove litter) (see text for further explanation).

2005 at Jangwani Beach (6°41′S, 39°13′E) Dar es Salaam, Tanzania. Sediment inside cells was laid on top of a clay layer that prevented drainage. Mangrove saplings (*Avicennia marina*) were planted at a density of 2.8 ind. m^{-2} (average natural density in the surrounding area) in 9 of the 18 cells in early February 2006, leaving 9 vegetated cells and 9 unvegetated control cells. A primary stabilization pond dug near the cells received sewage from a nearby hotel at a rate during the experimental period that assured a residence time of 12 h before sewage was discharged into the cells. The dominant processes in this pond were sedimentation and initial degradation of organic matter. Raw secondary treated sewage corresponded to 0.5 PE m^{-2}, assuming that an average 1 person equivalent (PE) is equal to about 300 mg BOD L^{-1} for East African countries (Scheren et al., 2000; Yang et al., 2008). Each group of 9 cells was split into 3 subgroups of 3 cells receiving seawater mixed with 0, 20 and 60% sewage (equivalent to 0, 0.1 and 0.3 PE), respectively, for the six months experimental period (October 2006 to April 2007). The position of the different treatments among cells in the system was randomized except for cells receiving only seawater that were grouped on a sealed side of the system to avoid contamination from the sewage treated cells. A diurnal tidal rhythm was simulated with 12-h immersion to 0.1 m depth starting at 23:00. After the immersion period, the effluent was flushed out to a nearby mangrove creek.

All cells in the CMW were initially inundated exclusively with seawater from a nearby creek for ecological stabilization of the system (for about 8 months). Daily secondary sewage discharge was initiated in early October 2006 (see Fig. 2). From October 2006 to February 2007, monthly sampling (low resolution monitoring) for determination of fauna and flora populations and health parameters as well as the chemical characteristics of sewage–seawater mixtures (see Table 1). These data were used for model calibration (Fig. 2). A high resolution campaign was done in March and April 2007 where data was obtained for model validation. For example, while the low resolution monitoring determined mainly "in and out" values of several water/sewage parameters, the high resolution campaign analyzed samples collected every 3 h during inundation periods. Fauna and flora parameters (from density to ecosystem engineering behaviour) were also obtained with more precise analytical methods and techniques during this high resolution campaign.