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Modeling catchment nutrients and sediment loads to inform regional management of water quality in coastal-marine ecosystems: A comparison of two approaches

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ABSTRACT

Human-induced changes in flows of water, nutrients, and sediments have impacts on marine ecosystems. Quantifying these changes to systematically allocate management actions is a priority for many areas worldwide. Modeling nutrient and sediment loads and contributions from subcatchments can inform prioritization of management interventions to mitigate the impacts of land-based pollution on marine ecosystems. Among the catchment models appropriate for large-scale applications, N-SPECT and SedNet have been used to prioritize areas for management of water quality in coastal-marine ecosystems. However, an assessment of their relative performance, parameterization, and utility for regional-scale planning is needed. We examined how these considerations can influence the choice between the two models and the areas identified as priorities for management actions. We assessed their application in selected catchments of the Gulf of California, where managing land-based threats to marine ecosystems is a priority. We found important differences in performance between models. SedNet consistently estimated spatial variations in runoff with higher accuracy than N-SPECT and modeled suspended sediment (TSS) loads mostly within the range of variation in observed loads. N-SPECT overestimated TSS loads by orders of magnitude when using the spatially-distributed sediment delivery ratio (SDR), but outperformed SedNet when using a calibrated SDR. Differences in subcatchments' contribution to pollutant loads were principally due to explicit representation of sediment sinks and particulate nutrients by SedNet. Improving the floodplain extent model, and constraining erosion estimates by local data including gully erosion in SedNet, would improve results of this model and help identify effective management responses. Differences between models in the patterns of modeled pollutant supply were modest, but significantly influenced the prioritization of subcatchments for management.

1. Introduction

Human-induced changes in flows of nutrients, sediments, and fresh water are major threats to coastal and marine ecosystems worldwide (Doney, 2010; Tilman et al., 2001). Nutrient enrichment of coastal and marine waters associated with agricultural fertilizers creates eutrophic and hypoxic or anoxic conditions that affect the functioning of marine ecosystems and the status of biodiversity and human health (Diaz and Rosenberg, 2008; Gabric and Bell, 1993). Loads of sediments derived from land clearing, urbanization, and agriculture have significantly increased in many regions (Walling, 2006) and are a major threat to vulnerable ecosystems such as coral reefs and seagrass beds (Cabaco et al., 2008; Maina et al., 2011). In contrast, damming of rivers reduces the delivery of

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river-borne sediment and nutrients to the sea (Walling, 2006), but also has potential adverse effects, significantly altering biogeochemical cycles and species composition in estuarine and marine ecosystems (Humborg et al., 2000). Managing such land-based threats is increasingly recognized as a crucial component of maintaining healthy coastal and marine ecosystems globally (Halpern et al., 2009; Maina et al., 2011).

Regional studies to identify and assess land-based threats to coastal-marine ecosystems and to explore options to prevent or mitigate these threats are urgently needed (e.g., Burke and Sugg, 2006; McKergow et al., 2005). Catchment models are powerful tools to explore management options to improve water quality (Walling et al., 2011) because they link sources of pollutants (e.g., sediment, nutrients) to affected areas and ecosystems. Furthermore, they facilitate identification of dominant processes associated with production and delivery of pollutants (Drewry et al., 2006; Walling et al., 2011), and thus help to determine appropriate strategies to minimize downstream impacts. Applications of catchment modeling for water-quality control include identifying erosion hotspots and estimating pollutant loads delivered to the sea, which can then be incorporated into river plume models to assess vulnerability of coastal-marine ecosystems to land-based threats (Álvarez-Romero et al., 2013a; Burke and Sugg, 2006). Mapping major sources of pollutants within catchments is thus needed to guide management to prevent or reduce downstream impacts (Brodie et al., 2009). Management actions include implementation of best practices in agriculture and livestock management, water treatment, restoration of riparian vegetation, protection of erosion-prone areas, and gully stabilization (Thorburn et al., 2013; Wilkinson and Brodie, 2011).

Different modeling approaches have been used to estimate the supply and delivery of sediment and nutrient loads, varying in complexity, data requirements, and intended spatial and temporal scales of application (see Borah and Bera, 2003; Merritt et al., 2003 for reviews on sediment and nutrient export models). For modeling approaches to be relevant for identifying and assessing land-based threats to coastal-marine ecosystems, several considerations are important: intended spatial and temporal scales, data availability *vs*. data requirements of models (climatic, flow, *in situ* water-quality sampling), existing technical expertise, and constraints on time and budget (Walling et al., 2011). Commonly, flow data and water-quality sampling or monitoring are spatially incomplete (covering only some parts of regions) and temporally fragmented (spanning limited and/or different time periods in different places). Data gaps, together with limited technical capacity, have constrained applications of more complex and realistic models applicable to regional scales.

Many modeling approaches have been developed for local, field-scale applications (Jetten et al., 1999), including event-based or daily time-step models that are appropriate for short-term and local management or ongoing water-quality monitoring (e.g., SWAT: Arnold and Fohrer, 2005; AGNPS: Young et al., 1989). These models, however, are generally too data-intensive and detailed to be applicable for large or multiple catchments. There are fewer models appropriate for large-scale applications, although several regional catchment models are pertinent (e.g., N-SPECT: Eslinger et al., 2005; SWIM: Krysanova et al., 2005; SedNet: Wilkinson, 2008). SedNet and N-SPECT have been used in extensive applications to estimate end-of-river loads of sediment and nutrients, and to target catchment management to minimize impacts of terrestrial runoff on coastal ecosystems (e.g., N-SPECT – Mesoamerican Reef: Burke and Sugg, 2006; Madagascar: Maina et al., 2012; SedNet – Great Barrier Reef: McKergow et al., 2005). Both models are appropriate to estimate long-term annual pollutant supply and end-of-river loads and are also considered to be good compromises in terms of model scope, data requirements, and performance.

The aim of this study is to compare two prominent regional catchment models (N-SPECT: NOAA, 2008; SedNet: Wilkinson et al., 2004) in terms of their performance, data requirements, ease of implementation, and utility for regional-scale planning. Data required to parameterize these models (as well as availability of these data) vary between studies, as do their outputs and applications to identify specific areas for catchment management. Our study thus aims to examine how these considerations can influence the choice between these models and the areas identified as priorities for management actions. Here we apply the models to catchments draining to the Gulf of California, Mexico, where there is an urgent need to study and incorporate land-based threats to marine ecosystems into conservation planning (Álvarez-Romero et al., 2013b). Our study area also has highly variable hydrological and climatic conditions and limited data, making it a good test case for many similar regions around the world. Previous studies have examined nutrient enrichment of coastal waters in the Gulf of California, but focused on irrigated agriculture (Ahrens et al., 2008), and local scales (Christensen et al., 2006). Our study investigates the use of catchment models to estimate runoff at a regional (whole-of-catchment) scale. To our knowledge, our study is the first to apply these two models within the same region and assess the differences in their outputs, and implications for management decisions.

2. Methods and data

We compared two models commonly used to prioritize areas for management of water quality in coastal-marine ecosystems: N-SPECT and SedNet/ANNEX (hereafter we refer to “SedNet” when referring to both the base model used for modeling sediment sources and transport and the ANNEX module employed when modeling nutrients). We examined the differences in parameterization of the models, as well as the capabilities, performance, and differences in their outputs in terms of pollutant supply patterns and loads. We explore the differences in the allocation of management actions based on the outputs of each model and discuss the potential consequences of management decisions, thus providing criteria to guide managers when selecting and parameterizing a model.

2.1. Study area

The Gulf of California is a marine ecosystem globally recognized for its rich and unique sea life, and is currently threatened by sea- and land-based activities (Lluch-Cota et al., 2007). Human population density is relatively low in the catchments draining into the Gulf of California, but is rapidly increasing, with associated increases in threats to the marine environment (Lluch-Cota et al., 2007). While the western coast remains comparatively undisturbed, many eastern coastal areas are affected by land-based threats, including agriculture, urbanization, aquaculture, and damming (Lluch-Cota et al., 2007; Páez-Osuna and Ruiz-Fernández, 2005). Existing studies in the region show that the impacts of land-based pollution can extend hundreds of kilometers from the coast (Beman et al., 2005).

This study focuses on selected catchments draining into the Gulf of California, including one of the most important agricultural regions in Mexico, the Yaqui Valley. The region stands out globally for the intensive use of agrochemicals and fertilizer (Ahrens et al., 2008). Effects of terrestrial runoff (e.g., associated with the intensive use of fertilizers) have been observed in offshore marine areas within the Gulf (Beman et al., 2005). This is particularly relevant