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Modeling linkages between sediment resuspension and water quality in a shallow, eutrophic, wind-exposed lake

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ABSTRACT

The interactions between bed sediments and the water column in shallow, eutrophic lakes have tremendous implications for the fate and transport of nutrients in those water bodies. This has resulted in the development of water quality models for lakes incorporating the processes of sediment resuspension. Reliable resuspension models are thus needed to accurately represent this phenomenon. In this paper, three different sediment-resuspension models are combined with a hydrodynamic and water quality model, dynamic lake model-water quality (DLM-WQ), and the resulting models are used to simulate nutrient distributions in the highly eutrophic Salton Sea, California, USA. One of the resuspension formulas is based upon sediment characteristics as well as the bed shear stress exerted by wind-induced waves and currents, while the other two are standard, power-law-type formulas for cohesive sediments with two different exponents. The outputs for water quality variables, such as temperature, chlorophyll *a*, dissolved oxygen and nutrients, obtained from the three resulting models and from an earlier DLM-WQ run with a simple empirical sediment-resuspension model are compared with measured data. The level of agreement between the simulations and the measured data is assessed by using both statistical and graphical model evaluation methods, including measures of residual errors, sample autocorrelations, *t*-tests, and box plots. Based on these assessments, DLM-WQ with an extended version of the García and Parker [García, M.H., Parker, G., 1993. Experiments on the entrainment of sediment into suspension by a dense bottom current. J. Geophys. Res.-Oceans 98, 4793–4807] relationship gave the best results for water quality in the Salton Sea, confirming that the use of formulas with more information on the sediment characteristics yields more accurate results. To the best of our knowledge, this is the first effort to combine water quality models for lakes and reservoirs with a sediment-resuspension model which was originally intended for open-channel flows. The simulations confirm that sediment resuspension is the most dominant process in the Salton Sea's nutrient cycling. The effect of proposed physical changes to the Salton Sea on water quality characteristics is also addressed.

1. Introduction

Sediment–water interactions in shallow lakes and reservoirs may become enormously important with time, since bed sediments constitute the ultimate repository for nutrients and contaminants, and fine particles and nutrients in the bed may repeatedly be recycled (Luettich et al., 1990). Nutrient-rich sediment layers in eutrophic lakes and reservoirs participate in chemical and biological processes and exchange mass with the water column. Therefore, these sediment layers influence the nutrient cycles via the diffusive fluxes of nutrients from sediments (the process by which dissolved nutrients are diffused from the sediments into the water column after being mineralized in the sediment) (DiToro, 2001), as well as via sediment resuspension (the process by which nutrients and particles are released from the bottom to the water column) (Horne and Goldman, 1994). Furthermore, resuspension of toxic bottom sediments is an ecological concern, since toxins and other hydrophobic organic contaminants can accumulate in the biota and food-web of a lake (Gbah et al., 2001).

The relevance of sediment resuspension to water quality in shallow, eutrophic, wind-exposed lakes has led to the development of water quality models describing sediment resuspension as a main source of nutrients (Søndergaard et al., 1992; Dortch et al., 1996; Mian and Yanful, 2004; Chung et al., 2008). Among these sediment-resuspension models, some are formulated through a simple relationship between just wind speed and the sediment entrainment rates (Aalderink et al., 1985; Somlyòdy, 1986), while some others include a measure of the bed shear stress and an indirect reference to the sediment size (Hakanson and Jansson, 1983; Sanford and Maa, 2001; Mian and Yanful, 2004). More sophisticated

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expressions for sediment resuspension include the characteristics of the sediment in the formulation, expressed through the settling velocity (García and Parker, 1991, 1993). Based on this wide set of formulas, there is a clear question as to which formula provides the most accurate description of the resuspension rates. Moreover, it becomes very important to choose an appropriate sediment-resuspension model which can competently predict the dynamic linkages between sediment resuspension and water quality in shallow lakes and reservoirs.

The Salton Sea, California, USA, is a shallow, highly eutrophic, wind-dominated, and terminal lake in which the nutrient cycles are strongly related to sediment-resuspension events (Chung et al., 2008, in press). Furthermore, the Salton Sea provides a rare example where the physical size will be significantly reduced in response to major inflow diversions that are planned under the Colorado River Quantification Settlement Agreement (QSA). The change of the morphology of the Sea will alter the fetch of the Sea which in turn will likely affect the sediment-resuspension process in the lake (fetch in a particular direction is typically not variable for most water bodies). The impact of sediment-resuspension events on the nutrient cycles of the Sea has recently been modeled using a hydrodynamic and water quality model, the dynamic lake model-water quality (DLM-WQ) (Hamilton and Schladow, 1997; Schladow and Hamilton, 1997; Losada, 2001; Chung et al., 2008). This model had been combined with the empirical sediment-resuspension model of Somlyòdy (1986) which makes no provision for variable sediment characteristics (Chung et al., 2008). Even though some water quality model outputs of DLM-WQ combined with the Somlyòdy (1986) model captured some of the seasonal trends and short-term variations, variables related to sediment concentrations (particulate phosphorus and nitrogen in particular) did not show short-term variation and needed further refinement. This suggested the need to link DLM-WQ to more sophisticated sediment-resuspension models, which are based on sediment characteristics and the wind-induced bed shear stresses and, thus, are able to describe linkages between variable sediment characteristics and water quality in the Salton Sea more accurately.

In this paper, we examine three sediment-resuspension models variously formulated based on sediment characteristics as well as the bed shear stress exerted by wind-induced waves and currents. Both the first and second models have been designed for cohesive sediments using either non-linear (Mian and Yanful, 2004) or linear relationships (Sanford and Maa, 2001) between sediment entrainment and shear stress, respectively. The third model has been originally formulated for non-cohesive sediments and for open-channel flows (García and Parker, 1991, 1993), and was recently extended by Chung et al. (2008) for application to lakes. These three sediment models combined with DLM-WQ are applied to the Salton Sea. The output from these resulting models and from an earlier model (i.e., DLM-WQ with the simple Somlyody model) are compared with measured water quality data from the Salton Sea.

There has been considerable debate on the subject of evaluation and validation of numerical models of natural systems, with disagreement on whether model validation is essential or impossible (Mayer and Butler, 1993; Oreskes et al., 1994; Rykiel, 1996; Arhonditsis and Brett, 2005). Here both statistical and graphical evaluation/validation techniques are used for model comparison, including measures of residual errors, sample autocorrelations, *t*-tests, and box plots (Reckhow, 1980; Abraham and Ledolter, 1983; Jørgensen et al., 1986; Reckhow et al., 1990; Loague and Green, 1991; Power, 1993). Based on these comparisons, we determine the particular sediment-resuspension model combined with DLM-WQ that most closely matches the measured data. We also investigate the effect of the physical changes on water quality characteristics in the Salton Sea under two possible future configurations using the selected model.

The scientific and technological goals of our work are as follows: (a) assess whether formulas possessing more information on the sediment characteristics are more representative than standard formulas; (b) determine the most reliable sediment-resuspension model through statistical comparison of model predictions with water quality data in a shallow, eutrophic, wind-exposed lake where sediments play an important role in the dynamics of dissolved and particle nutrients; (c) develop a tool for prediction of future scenarios in shallow lakes. In fact, we show that the model can be used to predict the magnitude of the change of water quality variables due to the physical alteration of the water body.

2. Study area

The Salton Sea is a terminal water body located in the southeastern desert of California, USA (see Fig. 1). It constitutes the areally largest body of water in the state, encompassing 963 km^2, with a maximum depth of 15.5 m, a maximum length and width of 56 km and 24 km respectively, a maximum water elevation of −69 m mean sea level (MSL) and a salinity of approximately 48,000 mg L^{-1}. Its total volume is about 9.25×10^9 m^3 (Cook et al., 2002; Schroeder et al., 2002; Vogl and Henry, 2002).

The Sea is a highly saline and eutrophic water body, characterized by high nutrient concentrations, high algal biomass as demonstrated by high chlorophyll *a* concentrations, high fish productivity, low clarity, frequent very low dissolved oxygen concentrations, massive fish kills, and noxious odors (Watts et al., 2001; Holdren and Montaño, 2002a; Robertson et al., 2008). However, the Salton Sea provides important habitat for large numbers of migratory bird species, some of which are threatened and endangered. The Sea's function as bird habitat has become increasingly important as many other habitat regions have been completely lost to development over the last 100 years (Carpelan, 1958; Cohen et al., 1999; Holdren and Montaño, 2002a).

The bed sediment characteristics of the Salton Sea were analyzed by different authors (Anderson and Amrhein, 2002; Vogl and Henry, 2002; Anderson, 2003). Anderson and Amrhein (2002) estimated a sediment-size distribution of 24.1% sand, 45.4% silt, and 30.5% clay for the Sea. Therefore, the median sediment size, d_{50}, for the Sea would fall within the category of silt, which is usually taken to contain sediment sizes ranging from 2 to 63 μm. Chung et al. (in press) employed a value of 25 μm as a representative sediment size for the southeastern portion of the Sea, to compute sediment resuspension in the lake. In what follows, we use the value of 25 μm as representative of the sediment size of the Sea.

3. Model description and model evaluation methods

3.1. Dynamic lake model-water quality

DLM-WQ is a one-dimensional, process-based, deterministic lake/reservoir simulation model, based on an earlier series of reservoir models called DYRESM (Imberger et al., 1978; Imberger and Patterson, 1981) and DYRESM-WQ (Hamilton and Schladow, 1997; Schladow and Hamilton, 1997). It is based upon a Lagrangian layer scheme (i.e., the layers are regulated within user-defined limits compared with layers in an Eulerian scheme) in which the lake is modeled by a series of horizontal layers of uniform property but variable thickness. The water quality version of the model, DLM-WQ, couples the transport and mixing processes to a set of biological and chemical processes that describe the growth of phytoplankton, the cycling of nutrients and the fate of particulate material (Hamilton and Schladow, 1997; Schladow and Hamilton,