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Effect of rainfall spatial variability and sampling on salinity prediction in an estuarine system

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Summary Reliable and accurate forecasts of salinity changes are essential for the success of current and future management scenarios aimed at restoring and sustaining natural resources of coastal and estuarine ecosystems. Because of the physical complexity of such ecosystems, information on uncertainty associated with salinity forecasts should be assessed and incorporated into management and restoration decisions. This study focuses on the impact of spatial variability and limited sampling of rainfall on salinity prediction in an estuarine system. The analysis is conducted on the Barataria basin, which is a wetland-dominated estuarine system located directly west of the Mississippi Delta complex on the United States coast of south Louisiana. The basin has been experiencing significant losses of wetland at a rate of nearly 23 km^2/year. Radar-rainfall data with high spatial resolution are used to simulate various scenarios of hypothetical rain gauge sampling densities over the basin. A mass-balance hydrologic salinity model is used to assess the effect of reduced rainfall sampling on salinity prediction in the basin. The results indicated that, due to the critical role played by rainfall in determining the overall balance of the basin freshwater budget, a high degree of uncertainty exists in salinity predictions when using typical average rain gauge densities (e.g., 1.3 gauges/1000 km^2 in the US). These uncertainties decline sharply as the number of available gauges is increased beyond the typically available density. Uncertainties in salinity predictions in the Barataria basin are larger in inland locations and smaller near the mouth of the basin, where salinity conditions in the coastal

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waters of the Gulf of Mexico exert a large influence. Rainfall uncertainties also affected parameter estimation during model calibration, where the estimation of some parameters exhibited significant levels of bias and random scatter. The study highlights the necessity of improving rainfall monitoring especially in estuarine systems that are controlled by rainfall as a main source of freshwater and where the management of freshwater supply is a viable option.

Introduction

Salinity forecasting models are expected to play a central role in managing, restoring, and sustaining natural resources in estuarine and coastal ecosystems. Many of the world's ecosystems (e.g., Florida Everglades, Childers, 2006; coastal wetlands along the northern Gulf of Mexico, Day et al., 2005; California estuaries and wetlands, Van Dyke and Wasson, 2005; coastal wetlands in China, Zhang et al., 2006; estuaries and river ecosystems in the Netherlands, de Jonge and de Jong, 2002) have been and continue to be endangered due to the adverse effects of human activities such as conversion to agricultural lands, hydrologic alterations, water quality degradation, erosion, and industrial activities. For example, coastal Louisiana as a part of the Mississippi River Deltaic Plain is experiencing the most critical coastal wetland loss and degradation problems in North America. Long-term reductions in freshwater and sediment inputs are known to be a primary cause for this decline (Boesch et al., 1994). In response to such accelerated wetland loss rates, coastal restoration scenarios have been proposed in the Mississippi River Delta area and along the northern coast of the Gulf of Mexico. The need for such restoration efforts has been further exemplified following the devastating impacts of hurricanes Katrina and Rita that affected coastal areas in the northern Gulf of Mexico in the fall of 2005.

In coastal Louisiana, salinity of surface waters is recognized as a primary factor in the productivity of coastal fisheries, and in controlling the extent and spatial distribution of freshwater, mesohaline and euhaline wetland communities (Visser et al., 2000; Turner, 2006). Therefore, coastal resource managers must be able to predict changes in estuarine salinity that may occur as a result of activities proposed for protecting and restoring coastal resources. In this context, salinity models can provide critical forecast information to assess risks and benefits (i.e., changes in wetland communities, estuarine water quality, and coastal fisheries) under current management activities and for various future alternative management scenarios. However, due to the models inherent approximation of complex ecosystem physical processes, model salinity predictions are inevitably prone to uncertainties. In general, these uncertainties can be attributed to various factors such as limited understanding of the processes involved, inaccuracies in model formulation, and inadequate or inaccurate information needed to apply the models (i.e., input and calibration data, and the lack of direct information on model parameters) (NRC, 2002; Lall et al., 2002; Habib et al., 2007). In the current study, we focus on sources of uncertainties related to inaccurate estimation of rainfall as one of the driving variables of salinity forecasting models.

Summer and Belaineh (2005) highlighted the importance of accounting for temporal rainfall variability in explaining salinity changes especially in flow-restricted estuarine systems. In addition to its pronounced temporal variability, rainfall can be highly variable in space (Crane, 1990; Seed and Austin, 1990), especially with the occurrence of localized convective storms. High spatial variability can translate into large uncertainty in estimating rainfall quantities especially over large areas. Most modeling efforts in estuarine systems are based on operational rainfall monitoring stations, which are usually characterized with low sampling densities. For example, a typical rain gauge average density in the US is about 1.3 rain gauges per 1000 km^2 (Linsley et al., 1992). These sparse measurements provide a poor representation of areal-average rainfall quantities (Bras and Rodriguez-Iturbe, 1993; Morrissey et al., 1995). Therefore, there is a need to analyze the effects of uncertainty imposed by limitations in rainfall measurements on salinity predictions. Rainfall-related uncertainties with respect to salinity forecasting were recently investigated by Habib et al. (2007); however, their analysis was based on synthetically generated rainfall data and therefore was limited to a single case of rainfall sampling density (one gauge in the basin). In the present study, an approach based on actual rainfall data is followed to thoroughly investigate the effect of various rainfall sampling scenarios on the uncertainty of a salinity forecasting mass-balance model when applied to an estuarine system in coastal Louisiana (Barataria basin). We used radar-rainfall data with high spatial resolution to establish a reference state of the Barataria basin in terms of model rainfall input and salinity output. The fully-distributed radar data were sub-sampled to generate rainfall datasets that represent measurements of ''hypothetical rain gauges'' with various degrees of reduced sampling density. A mass-balance model is used with each of these reduced rainfall sampling scenarios to investigate the effect on model calibration (i.e., estimation of model parameters) and subsequent salinity predictions. The paper is organized as follows. First, we present a description of the study basin (Barataria estuarine system) and its representation through a mass-balance model. An exploratory analysis is then introduced on the magnitude of rainfall spatial variability in the basin, followed by a brief description of radar-rainfall data and methodology applied to simulate various scenarios of hypothetical rain gauge densities. We then assess the impact of limited rainfall sampling on model calibration and salinity predictions. Finally we summarize the main conclusions and discuss their practical implications.