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Modeling impacts of sea-level rise, oil price, and management strategy on the costs of sustaining Mississippi delta marshes with hydraulic dredging

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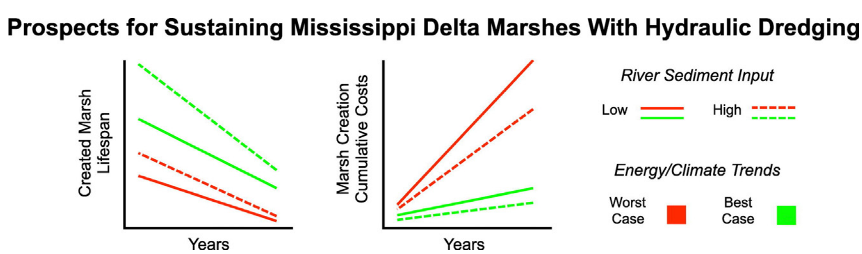
HIGHLIGHTS

- Hydraulic dredging can be used to create new coastal marsh.
- Oil price has a significant effect on the costs of hydraulic dredging.
- We modeled energy and climate impacts on marsh creation costs.
- Costs increase significantly due to increasing dredging price and frequency.
- Marshes receiving sediment from river diversions are cheaper to sustain.

GRAPHICAL ABSTRACT



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ABSTRACT

Over 25% of Mississippi River delta plain (MRDP) wetlands were lost over the past century. There is currently a major effort to restore the MRDP focused on a 50-year time horizon, a period during which the energy system and climate will change dramatically. We used a calibrated MRDP marsh elevation model to assess the costs of hydraulic dredging to sustain wetlands from 2016 to 2066 and 2016 to 2100 under a range of scenarios for sea level rise, energy price, and management regimes. We developed a subroutine to simulate dredging costs based on the price of crude oil and a project efficiency factor. Crude oil prices were projected using forecasts from global energy models. The costs to sustain marsh between 2016 and 2100 changed from $128,000/ha in the no change scenario to ~$1,010,000/ha in the worst-case scenario for sea level rise and energy price, an ~8-fold increase. Increasing suspended sediment concentrations, which is possible using managed river diversions, raised created marsh lifespan and decreased long term dredging costs. Created marsh lifespan changed nonlinearly with dredging fill elevation and suspended sediment level. Cost effectiveness of marsh creation and nourishment can be optimized by adjusting dredging fill elevation to the local sediment regime. Regardless of management scenario, sustaining the MRDP with hydraulic dredging suffered declining returns on investment due to the convergence of energy and climate trends. Marsh creation will likely become unaffordable in the mid to late 21st century, especially if river sediment diversions are not constructed before 2030. We recommend that environmental managers take into consideration coupled energy and climate scenarios for long-term risk assessments and adjust restoration goals accordingly.

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1. Introduction

1.1. 21st century megatrends and Mississippi delta restoration

About 28% of the wetlands of the Mississippi River Deltaic Plain (MRDP) were lost in the 20th century, due to land subsidence, exclusion of river sediment by dams and levees, and other hydrologic modifications along the coast (Couvillion et al., 2011; Day et al., 2005). Major restoration is needed to sustain the MRDP (CPRA, 2017a). The forces expected to impact coastal areas during the 21st century include accelerating sea-level rise (SLR), changes in river discharge, increase in the frequency of extreme weather events (including drought, intense precipitation, and tropical cyclones), and the cost and availability of energy (Balaguru et al., 2016; Day et al., 2016a; IPCC, 2013; Prein et al., 2017; Tao et al., 2014; Tessler et al., 2015; Sobel et al., 2016). CO_2 levels are now tracking the highest IPCC scenarios (Friedlingstein et al., 2014; Strauss et al., 2015) and 1–2 m of SLR is projected during the 21st century (DeConto and Pollard, 2016; Horton et al., 2014; IPCC, 2013). World fossil fuel production is projected to peak by mid-century or possibly sooner (Mohr et al., 2015). The net energy ratio, an indicator of energy quality, is declining for fossil fuel production, with negative implications for societal well-being (Hall et al., 2014; Lambert et al., 2014; Tripathi and Brandt, 2017). In coming decades, the transition from cheap, high net energy yielding fossil fuels to expensive, low net energy yielding fuels will increase the cost of energy, unless there is revolutionary new technology or dramatic reduction in demand (Heun and de Wit, 2012; EIA, 2015). This will affect petroleum prices (McGlade, 2014), upon which maritime activities and delta restoration are heavily reliant (Bray et al., 1997).

The high wetland loss rates in the MRDP are projected to continue with an additional loss of over 5000 km^2 by 2050 (Blum and Roberts, 2009; CPRA, 2017a). The Louisiana Coastal Master Plan (LACMP), developed by the Louisiana Coastal Protection and Restoration Authority (CPRA), is a 50-year, $50 billion effort to restore and protect the MRDP's coastal ecosystems and economy (CPRA, 2012a, 2017a). CPRA projects that 2017 LACMP restoration projects will build and/or sustain ~2000 km^2 of wetlands that would otherwise be lost (CPRA, 2017a). The two main restoration strategies for land building in the LACMP are marsh creation (MC) and nourishment via hydraulically dredged sediments and river sediment diversions (henceforth referred to as "diversions") (CPRA, 2017a). Marsh "creation" refers to filling an open water area with a mean depth of 30 cm or greater. Marsh "nourishment" refers to filling area with patches of deteriorating marsh with a mean depth between 0 and 30 cm. In terms of land building, MC is an energy-intensive approach with immediate impacts, while diversions, once constructed, are a lower energy approach with recurring positive impacts over time (Day et al., 2016a, 2016b). Here, we investigate the influence of energy costs, SLR, river sediment input, and construction specifications on the costs and sustainability of marsh creation and nourishment using hydraulic dredging.

1.2. Environmental controls on coastal marsh sustainability

Coastal marsh elevation is a function of relative SLR (RSLR), tidal range, total suspended sediment concentration (TSS), and marsh productivity (Fagherazzi et al., 2012; Morris et al., 2002; Mudd et al., 2009). RSLR is the sum of eustatic SLR and isostatic movement of the earth's crust. Deltas subside naturally due to consolidation of Holocene sediment (Meckel et al., 2006). Compared to most coastal regions, the MRDP has high RSLR and low tidal range, therefore high sediment input and productivity are needed to sustain marsh elevation (Fig. 1). Much early focus on MRDP restoration has been on deposition of coarse grain sediment (sand) for delta building. At least 75% of the sediment carried by the Mississippi river are fine sediments (Allison et al., 2012; Allison and Meselhe, 2010), but the majority of silt and clay is not deposited immediately within a newly forming delta (Roberts et al., 2015). Rather, fine sediments are deposited in nearby bays and wetlands, or are exported to the coastal ocean. Riverine sediments deposited in bays are re-suspended during storms and some of these sediments are advected onto coastal marshes (Perez et al., 2000). This process has been identified as a key driver sustaining MRDP coastal wetlands, where there is a steady supply of river sediment (Day et al., 2011; Roberts et al., 2015; Twilley et al., 2016). In this paper, we model the influence of increased TSS from river throughput on sustaining coastal marshes (Fig. 1). The analysis is based on data from natural analogs in the MRDP, including new delta lobe development (DeLaune et al., 2016; Roberts et al., 2015; Twilley et al., 2016) and crevasses (Day et al., 2012, 2016a, 2016c).

1.3. The costs and energy intensity of sustaining coastal areas

Coastal restoration is costly and energy intensive (Table 1, Clark et al., 2015; Moerschbaecher and Day, 2014; Tessler et al., 2015). $17.8 billion dollars is allocated for MC projects in the LACMP, while $5.1 billion dollars is allocated for diversion projects (Table 1). To deliver sediment, MC requires large machinery such as "cutter-suction" dredges, bulldozers, booster pumps, generator barges and more (Clark et al., 2015; CPRA, 2017a; Day et al., 2005 Murphy, 2012). Diversions vary in their complexity, but in most cases building a diversion is a major construction project, where concrete, steel, and heavy machinery, are required (Kenney et al., 2013).

The price of energy, oil in particular, influences the costs of restoration (and other) activities directly through changes in fuel prices (which closely follow the price of crude oil) and indirectly by influencing other input commodity prices, such as steel and concrete (Ji and Fan, 2012; World Bank, 2015). Dredges, like most heavy construction equipment, are almost exclusively powered by diesel fuel and costs of operation are sensitive to diesel price (Hollinberger, 2010; Murphy, 2012). Proposed dredging for the 2012 LACMP is estimated to require between 0.71 and 5.2 L of diesel fuel per cubic meter of sediment, depending on pumping distance (Clark et al., 2015). The mean real price of dredging in the U.S. increased 72% between 2000 and 2010 (Cohen et al., 2011), coinciding with a 150% increase in the real price of crude oil (EIA, 2015). Fluctuations in oil prices are linked to economic expansions and recessions, which affect material prices as well (Hamilton, 2012; Murphy and Hall, 2011).

Highly developed deltaic coasts that rely on energy-intensive management are at high risk for non-sustainable outcomes with climate change in a high energy price future (Day et al., 2016a; Tessler et al., 2015). But even without consideration of energy there are significant financial constraints on coastal management in Louisiana. Only about $26 billion dollars have been secured for the LACMP, roughly half of the total cost (CPRA, 2016a). The actual cost to restore and protect Louisiana's coastline, after including omissions from the LACMP, such as maintenance of existing flood control structures, is estimated to exceed $91 billion (Barnes et al., 2015). This amount could rise significantly with increasing energy costs. Our focus on quantifying the influence of energy costs on hydraulic dredging (for marsh creation) makes this study important for the MRDP, and developed coastal areas worldwide.

1.4. Objectives & hypotheses

The objective of this study is to simulate the cost of hydraulic dredging to sustain coastal marshes of the MRDP with and without elevated TSS from a river diversion for a range of trajectories in future SLR and oil prices. We pursued the following sub-objectives: (1) Analyze the statistical relationship between oil prices and the cost of dredging using data from projects completed in the MRDP. (2) Model the costs of coastal restoration into the future as a function of oil prices and sea-level rise (SLR). (3) Investigate the sensitivity of the cost effectiveness of MC efforts to changes in TSS concentration, and the fill elevation of MC projects (E_{fill}).

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