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Editorial

Assessing Resilience and Sustainability of the Mississippi River Delta as a Coupled Natural-Human System

Y. Jun Xu [1,2,*], Nina S.-N. Lam [3] and Kam-biu Liu [4]

1 School of Renewable Natural Resources, Louisiana State University Agricultural Center, Baton Rouge, LA 70803, USA
2 Coastal Studies Institute, Louisiana State University, Baton Rouge, LA 70803, USA
3 Department of Environmental Sciences, Louisiana State University, Baton Rouge, LA 70803, USA; nlam@lsu.edu
4 Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA 70803, USA; kliu1@lsu.edu
* Correspondence: yjxu@lsu.edu; Tel.: +1-225-667-1698

Received: 27 August 2018; Accepted: 21 September 2018; Published: 24 September 2018

Abstract: This book contains 14 articles selected from a special issue on the assessment of resilience and sustainability of the Mississippi River Delta as a coupled natural-human system. This effort is supported in part by a U. S. National Science Foundation grant. The goal of this book is to present some of the recent advances in research and research methodologies, major discoveries, and new understanding of the Mississippi River Delta, which represents one of the most challenging cases in finding the pathways for coastal resilience and sustainability because of the complexity of environmental and socioeconomic interactions. The articles are contributed by 39 researchers and they studied the deltaic system from five aspects including 1) riverine processes and sediment availability, 2) sediment deposition and land creation, 3) wetland loss, saltwater intrusion, and subsidence, 4) community resilience and planning, and 5) review and synthesis. As editors, by reviewing and putting these papers together, we have realized a major challenge in conducting an interdisciplinary assessment of resilience: ***How to identify a "Common Threshold" from different scientific disciplines for a highly nature-human intertwined river delta system?*** For instance, the threshold for sustaining a river delta in the view of physical sciences is different from that of social sciences. Such a common threshold would be a radical change and/or a collapse of a coupled natural-human delta system if nothing can be or will be done. Identifying the common threshold would help guide assessment and evaluation of the resilience of a CNH system as well as the feasibility and willingness of protecting the system's resilience. We hope this book will be a first step toward inspiring researchers from different disciplines to work closely together to solve real problems in sustaining precious river delta ecosystems across the globe.

Keywords: river deltas; coupled natural-human system (CNH); resilience; sustainability; Mississippi River Delta; Gulf of Mexico

1. Introduction

River deltas are naturally built by continuous flow that carries sediment and nutrients. Across the world, humans have exploited river deltas for many benefits they provide—access to abundant natural resources, fertile lands for farming and grazing, good locations for shipping, and more. Many large river deltas have become vibrant economic regions serving as transportation hubs and industrial, commercial, and population centers. However, today, many of these deltaic areas face a tremendous challenge with land loss due to a number of factors such as reduced riverine sediment supply, coastal land erosion, subsidence, and a sea level rise [1–4]. Humans have not only exploited river deltas, but have also changed them. We have dammed rivers upstream, channelized them downstream, and confined them with levees and dikes on deltaic floodplains—actions that contribute to the reduction of sediment supply and, thus, land growth. Concurrently, we have cut channels through deltaic wetlands for oil, gas, and seafood productions, which causes deltaic land to sink as sea levels keep rising.

The change of the Mississippi River Delta in Southern United States over the past century is a prime example. Across the main channels of the Upper Mississippi, Ohio, Missouri, Tennessee, and Arkansas-White-Red Rivers, which are five tributaries of the Lower Mississippi River, approximately 100 dams and locks were built. Annual sediment load to the Lower Mississippi River has reduced from 400 million tons (MT) a century ago to the current annual load of about 180 million tons combined from the Lower Mississippi River main channel and its Atchafalaya distributary channel [5,6]. Levees were built after the 1927 mega flood along both sides of the river from its mouth at the Gulf of Mexico to Baton Rouge in Louisiana, 367 km upstream, which prohibited the sediment supply to the river delta plain. Since 1932, the Mississippi River Delta has lost nearly 5000 km^2 of land and the lower Mississippi River main channel entering the Gulf of Mexico has become an isolated waterway with land on both sides submerging into water [6].

2. Highlights of this Special Issue

2.1. Riverine Processes and Sediment Availability

Riverine sediment is a key resource to deltaic development. While substantial knowledge has been gained about suspended sediment loads from the world's large rivers, relatively less has been investigated about riverine sand load, which is the most critical solid fraction for land growth. The work by Joshi and Xu [7] reports a detailed study of sand transport in the Lower Mississippi River. In the study, they analyzed 41-year (1973–2013) records on discharge and sediments at Tarbert Landing on the Mississippi River, 502 kilometers upstream from the river's mouth at the Gulf of Mexico, to assess sand availability under different river flow regimes, peak sand loads, and their recurrence. They found that half of the total sand load over the 41 years occurred during the 20% peak flow events and that the period when river discharge was greater than 18,000 cubic meter per second produced over 70% of the total annual sand load within approximately 120 days of a year. Based on the long-term sand assessment, they suggest that future river engineering and sediment management in the Lower Mississippi River need to consider practices of a hydrograph-based approach for maximally capturing riverine sediments, which was previously also suggested by Rosen and Xu [8].

Wang and Xu's study [9] took a step further to look at how floods can affect sand transport at the Tarbert Landing in the Lower Mississippi River. They analyzed changes in three nearby downstream channel bars during an unprecedented flood known as the 2011 Mississippi River flood by analyzing satellite images taken before, during, and after the flood. They first utilized a series of satellite images taken to determine changes in surface area and then developed a rating curve of the bar surface area with the river stage. The rating was then applied to estimate the volume change of the three large channel bars. The study found that the 2011 large flood significantly increased the surface area and volume of the bars and the sand volume trapped was an equivalent in mass of 1.0 million metric tons. The study demonstrates that channel bars in the lowermost MR are capable of capturing a substantial amount of sediment during floods and that the surface area-river stage rating curve is a very useful approach in assessing areal and volumetric changes of channel bars. This approach has been successfully applied by the researchers in a recent study on decadal dynamics of 30 large channel bars in the Lower Mississippi River [10].

2.2. Sediment Deposition and Land Creation

Sediments travel with the river flow to the coast as a critical source for building new land. An often asked question is how much these sediments can be retained and how much land can be created by the trapped sediments. In the recent decade, large sediment diversions from the Lower Mississippi River have been proposed for coastal land restoration in the Mississippi River Delta [11]. To elucidate how river diversion would create new land, Day and others [12] used ^{210}Pb excess and ^{137}Cs dating techniques to quantify sediment deposition in a 2-km wide crevasse south of New Orleans that was created during the Great 1927 Mississippi River Flood. The study found a 2 to 42 cm thin clay layer deposited from 1926 to 1929, which is approximately 24 to 55 cm below the surface of the Breton Sound estuary. The findings suggest that future Mississippi River diversion projects should consider the flooding pulse to enhance sediment capture efficiency and deposition.

Moving further downstream of the Mississippi River close to its mouth at the Gulf of Mexico, Xu and others [13] investigated two active diversions and compared the grain size of deposits in their receiving basins. The study found that silt was the largest fraction of retained sediment (55%), which was followed by sand (25%) and clay (20%), and there appeared to be an inverse relationship between retention rate and the distance of the river to its outlet. The findings suggest that delivery of fine-grained materials to more landward and protected receiving basins would likely enhance mud retention in the Southeast Louisiana coast.

Sediment deposition in coastal areas can also be affected by hurricane-induced storm surges, which not only push flow landwards but can cause backwater flow for inland rivers. The physical processes can strongly affect sediment transport and deposition, which would result in spatial and temporal variability of vertical accretion rates in coastal wetlands. The study by Bianchette and others [14] utilized an existing database (CRMS-Coastal Reference Monitoring System) with thousands of wetland accretion measurements at 390 sites across coastal Louisiana to analyze the spatial and temporal variability of their elevation changes. Specifically, the study mapped accretion rates in the region during time periods before, around, and after the landfall of Hurricane Isaac of 2012. The study shows a higher accretion rate (4.04 cm/year) during the hurricane period when compared to those before (2.89 cm/year) and after (2.38 cm/year) Hurricane Isaac. The findings indicate that flooding from river channels is the main mechanism responsible for increased wetland accretion in coastal Louisiana. Additionally, future restoration practices need to effectively manage sediment resources from riverine flooding.

2.3. Wetland Loss, Saltwater Intrusion, and Subsidence

Coastal wetlands are an important component of river deltas. They provide habitat and nesting areas for a variety of fish and wildlife. In addition to these ecological functions, coastal wetlands on the Mississippi River Delta play a critical role in reducing hurricane-induced storm surges and coastal erosion in the low-lying, very flat landscape. However, these wetlands are seriously threatened by subsidence, rising sea levels, and saltwater intrusion. The study by Shaffer and others [15] investigated wetland forest ecosystems in the Maurepas swamp, which is the second largest contiguous coastal forest in Louisiana. The study utilized field survey records on a number of environmental variables, vegetation composition, tree mortality, and forest stand parameters to determine environmental stressors on coastal forest health. They found that saltwater intrusion, altered hydrology, and nutrient limitation are the dominant causes of coastal forested wetland degradation in the Lake Maurepas swamp. Much of the soil surface in the swamp is as low or lower than the surface elevation of the lake, which results in near permanent flooding. Based on their findings, the researchers suggest a large river diversion (>1422 $m^3\ s^{-1}$, and up to 5000 $m^3 \cdot s^{-1}$) for the forested swamp, which would deliver the needed quantity of sediments to achieve high accretion rates and stimulate organic soil formation.

Saltwater intrusion is increasingly widespread in the Mississippi River Deltaic region. The study by Hunter and others [16] investigated a 12,000-ha wetland east of New Orleans that was boarded completely by levees. The area was a healthy forested swamp and fresh/low salinity marsh before construction of the levees prevented Mississippi River floodwaters. Later, construction of the Mississippi River Gulf Outlet (MRGO) funneled saltwater inland from the Gulf of Mexico, which caused mortality of almost all the trees and the fresh/low salinity marsh. The authors postulated that the area would continue to degrade, which would increase the vulnerability of nearby populations if timely and large-scale restoration measures are not taken.

Navigation channels in coastal areas have been recognized as conduits for saltwater intrusion. The study by Snedden [17] used salt flux decomposition and time series measurements of velocity and salinity in an estuarine navigation channel to examine salt flux components and drivers of baroclinic and barotropic exchange. The study was conducted in the Houma Navigation Channel located in the Mississippi River Delta plain that receives freshwater inputs from the Mississippi-Atchafalaya River system. The study found two modes of vertical current structure: 1) a mode that accounted for 90% of the total flow variability, resembled a barotropic current structure, and was coherent with a long shelf wind stress over the coastal Gulf of Mexico, and 2) another mode that was indicative of gravitational circulation and was linked to variability in tidal stirring and the horizontal salinity gradient along the channel's length. From all tidal cycles sampled, the researcher found that the advective flux driven by a combination of freshwater discharge and wind-driven changes in storage was the dominant transport term and a net flux of salt was always out of the estuary. The findings indicate that, although human-made channels can effectively facilitate inland intrusion of saline water, this intrusion can be minimized or reversed when they are subjected to significant freshwater inputs.

Subsidence has been a serious issue for the Mississippi River Delta. How would this continue in the future as sea levels continue to rise? The study by Zou and others [18] utilized historical benchmark survey data from 1922 to 1995 to construct a subsidence rate surface for the MRD. The authors found a subsidence rate in the region varying largely from 1.7 to 29 mm/year with an increasing trend from the north to the south. They found four areas with high subsidence rates all located in the southeast parishes including Orleans, Jefferson, Terrebonne, and Plaquemines. They projected that areas below zero elevation in the MRD would increase from 3.86% in 2004 to 19.79% by 2013 and to 30.88% by 2050. Under this projection, Lafourche, Plaquemines, and Terrebonne parishes would experience serious loss of wetlands while Orleans and Jefferson parishes would lose significant developed land and Lafourche parish would endure severe loss of agriculture land.

2.4. Community Resilience and Planning

Communities living on Louisiana's coast have been facing a range of threats such as land subsidence, sea level rise, a hurricane-induced storm surge and wind damages, and floods. The National Flood Insurance Program (NFIP) has a Community Rating System (CRS) that offers an incentive for community planning to reduce exposure to flood risks. The study by Paille and others [19] examined the context under which coastal parishes (i.e., counties) in South Louisiana may be more likely to take steps to make themselves safer through floodplain management and other measures encouraged by the CRS. Their findings show that higher CRS scores are associated most closely with higher median housing values as well as in parishes with more local municipalities that participate in the CRS program. It is interesting that the number of floods in the last five years and the revenue base of the parish did not appear to influence CRS scores. The study provides insights for program administrators, researchers, and community stakeholders.

The study by Cai and others [20] assessed community resilience to coastal hazards in the Mississippi River Delta using the Resilience Inference Measurement (RIM) model. The assessment was conducted at the census block group scale intending to provide a quantitative method for assessing community resilience to coastal hazards and for identifying relationships of resilience with a set of socio-environmental indicators. The resilience index derived from the approach was empirically validated through two statistical procedures. The results show that block groups with higher resilience were concentrated generally in the northern part of South Louisiana including those located north of Lake Pontchartrain and in East Baton Rouge, West Baton Rouge, and Lafayette parishes.

The lower-resilience communities were located mostly along the coastline and the lower elevation area including block groups in Southern Plaquemines Parish and Terrebonne Parish. The information gained will help develop adaptation strategies to reduce vulnerability, increase resilience, and improve long-term sustainability for the coastal region.

The Louisiana coast is a national energy center with a critical infrastructure across industrial sectors including crude oil, natural gas, electric power, and petrochemicals. Communities living there form a highly complicated relation between the human and natural environment. The study by Dismukes and Narra [21] developed a Coastal Infrastructure Vulnerability Index (CIVI) that combines physical, socio-economic, and infrastructure characteristics of the local communities to identify and prioritize coastal vulnerability. Based on the CIVI, the Mississippi River corridor between Baton Rouge and New Orleans is exceptionally vulnerable because of its (a) high concentrations of very large energy infrastructure and (b) very high physical vulnerabilities. Their study demonstrated that a multi-dimensional index system could lead to results that are significantly different than traditional methods and the CIVI could potentially become a more useful tool for coastal planning and policy especially in those areas characterized by very high infrastructure concentrations.

2.5. Review and Synthesis

Kemp and others [22] conducted a review on the development of the two largest river deltas along the Gulf of Mexico coast, the Mississippi River Delta in the United States, and the Usumacinta/Grijalva River (UGR) Delta in Mexico. By comparing these two systems, the authors analyzed geomorphic and oceanographic effects on ecosystem resilience as climate change influences river discharge. Based on the review, the authors concluded that the MRD is vulnerable to anthropogenic interventions reducing fluvial sediment supply to sinking deltaic wetlands, which caused the regional land loss. The MRD also has the highest relative sea level rise rates in North America. On the other hand, the relative sea level rise is low in the UGR Delta and the delta is most threatened by impoundment due to road construction to support logging, oil and gas activities, and other development, which disrupts natural hydrology. Therefore, efforts to save the MRD should focus on reconnecting the areas with wetland basins by constructing artificial, controllable river diversions. While citizen engagement in the restoration of the MRD has been going on since the 1980s, it is beginning to come together in the UGR Delta.

Using the Mississippi River Delta as an example, the article led by Lam [23] gives an overview on the approach of assessing resilience and sustainability of a highly populated and industrialized river delta in the context of a coupled natural-human system (CNH). They illustrated an integrated coastal modeling framework that incorporates both the natural and human components as well as their feedbacks and interactions. The framework was demonstrated by three studies on how community resilience of the MRD system is measured, how land loss is modeled using an artificial neural network-cellular automated approach, and how a system dynamic modeling approach is used to simulate the population change in the region. Based on lessons learned from these studies, the authors suggest that uncertain analysis of the CNH modeling results is necessary to help identify error sources and that future modeling should also consider identifying extremes and/or system-changing thresholds in natural and human environments. Furthermore, the authors call for efforts to cultivate bi-directional communication between researchers and stakeholders to help utilize the findings.

3. Future Perspectives

This book collects 14 articles that present the latest assessments of the Mississippi River Delta under different aspects from riverine sediment availability to sediment trapping, coastal land loss, energy infrastructure, and human population dynamics. The primary goal of this collection is to take a holistic look at the current situation of the delta and evaluate the roles of human and natural processes in order to more realistically predict what will happen to this important delta in the years ahead. Based on the findings from these studies, we identify three main issues that need to be addressed by the research communities.

First, we are still not very clear about how much sediment is available in the last 200-km reach of the Mississippi River where several river diversions have been proposed. We are also not certain about how a sea level rise at the Gulf of Mexico will influence sediment transport and siltation in the tide-affected river reach. These are critical questions that need to be addressed in order to develop engineering practices and management plans to effectively utilize sediment resources.

Second, the subsidence rate and wetland loss on the Mississippi River Delta are spatially and temporally highly heterogeneous. A number of factors could be at play and future studies need to develop models conducive to predicting longer-term coastal land changes using combined information of geology, pedology, wetlands, sea level rise, human factors, and spatial techniques.

Third, in terms of assessing resilience of a delta system that is highly coupled by natural and human domains, it is critical to identify a "Common Threshold." Such a common threshold would be a radical change to and/or a collapse of a coupled natural-human delta system if we humans cannot or will not want to maintain the system. Identifying the common threshold would help guide assessment and evaluation of the resilience of a CNH system as well as the feasibility and willingness of protecting the resilience.

Acknowledgments: This work was supported through a grant from the U.S. National Science Foundation (award#: 1212112). The study also benefited from a United States Department of Agriculture Hatch Fund grant (Project #: LAB94230). The authors of the Editorial would like to thank all authors for their notable contributions to this book and the many reviewers for devoting their time and efforts in evaluating the manuscript drafts. We also thank the Water Editorial team for their support and assistance in publishing this book.

Conflicts of Interest: The authors declare no conflicts of interest.

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