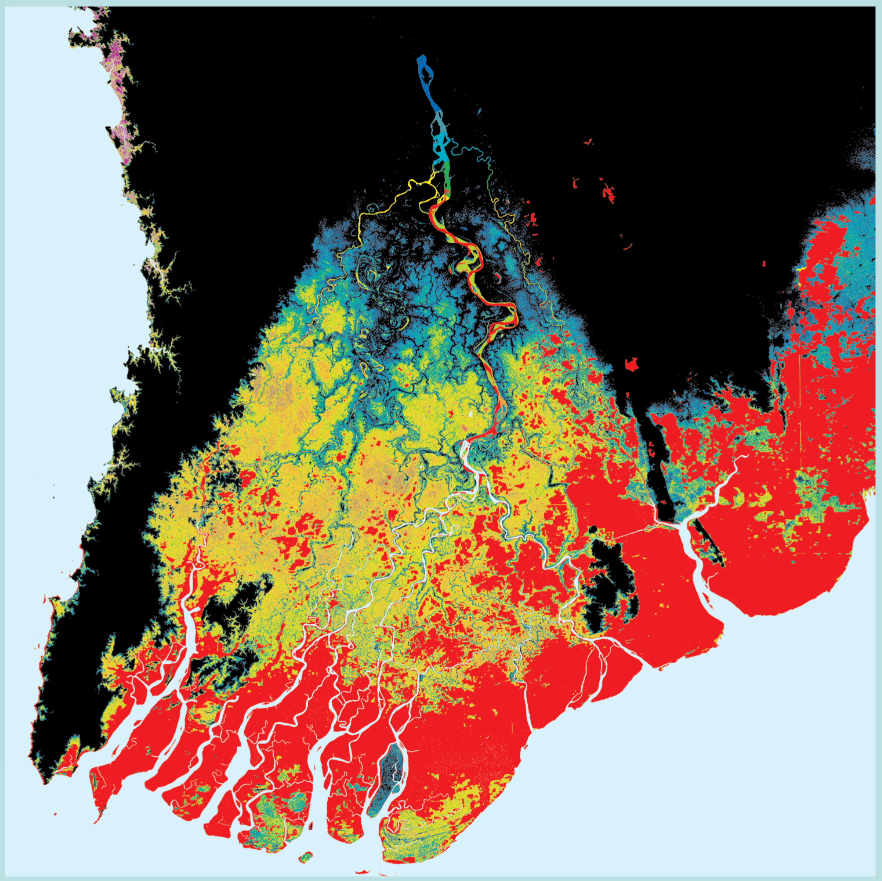
LAND-OCEAN INTERACTIONS IN THE COASTAL ZONE (LOICZ)

Core Project of the International Geosphere-Biosphere Programme (IGBP) and
the International Human Dimensions Programme on Global Environmental Change (IHDP)



Dynamics and Vulnerability of Delta Systems

Irina Overeem and James P. M. Syvitski

CSDMS
COMMUNITY SURFACE DYNAMICS MODELING SYSTEM

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Dynamics and Vulnerability of Delta Systems

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Cover: The cover photograph shows a Shuttle Radar Topography Mission (SRTM) data for the Irrawaddy delta overlain with the flood extend at time of Cyclone Nargis in April 2008 (in red), mapped by the Darthmouth Flood Observatory (courtesy CSDMS).

The LOICZ Reports and Studies Series is published and distributed free of charge to scientists involved in global change research in coastal areas.

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Executive Summary

Deltas form where rivers meet the ocean. They are then naturally shaped by the forces of rivers, waves and tides. Intricate mazes of river channels, wetlands and coastal features, that ever-change host a wide variety of unique ecosystems. Deltas are recognized as critically important habitats for threatened terrestrial and marine species. Deltas act as filters, repositories, and reactors for a suite of continental materials, including carbon, on their way to the coastal ocean.

Due to their low topography, high productivity, rich biodiversity, and easy transport along abundant waterways, deltas are preferred locales of human habitation as well. Deltas may only comprise 5% of the land area, but over 500 million people live on them, including many heavily populated megadeltas in Asia. The Ganges-Brahmaputra, Yangtze and Nile deltas alone are extremely densely populated with 230 million people in 2000. It is expected that there will be a 35% increase of population in the major world deltas by 2015.

Deltas are unfortunately also fragile geomorphic features, and can change dramatically with modest modifications in the controlling environmental conditions. Already, thirty-three major deltas collectively include significant area (~26,000 km^2) below local mean sea level and another ~70,000 km^2 of vulnerable area below 2 m. This vulnerable area may increase by 50% under projected 21st century eustatic sea level rise. Intensive human development, population growth, as well as recent human-induced global changes are degrading deltas and often transforming them into increasingly hazardous coastal regions. Given current trends including shifts in climate, upstream changes in water quantity and quality, and population pressure, many deltas are in danger of collapse within the 21st century.

What would a collapse look like? A collapse may include complete loss of wetlands and concomitant biodiversity, cities and villages and the associated infrastructure flooded, permanent loss of fishing areas, farming lands, and valuable forests, and rapid shoreline retreat. Future preservation of deltas will become increasingly difficult and costly. Restoration or maintenance will require developing integrated management strategies that incorporate extensive monitoring, focused research and complex numerical modeling as well as detailed consultation with people affecting and affected by deltas.

To assess the state-of-the-art understanding of the changes in and vulnerability of delta systems, the following report was commissioned jointly by: 1) LOICZ, the joint IGBP (International Geosphere-Biosphere Programme) and IHDP (International Human Dimensions Programme on Global Environmental Change) Core Project entitled Land-Ocean Interactions in the Coastal Zone, 2) GWSP, an Earth System Science Partnership project of DIVERSITAS, IGBP, IHDP and WCRP (World Climate Research Program), entitled Global Water Systems Project, and 3) CSDMS, the Community Surface Dynamics Modeling System.

The report discusses the changes and vulnerabilities of world deltas resulting from anthropogenic alteration of upstream freshwater and sediment inflows, anthropogenic alteration of sediment and water routing through deltas, hydrocarbon and groundwater extraction from deltas, sea-level change, and the increased frequency of extreme climate events. A conceptual framework highlights the importance of temporal and spatial scaling in deltas, and the complex interlinkages between constructive and destructive forces of pulsed energy coming from the feeding rivers and the attacking ocean, and the role of extreme climate events.

These concepts lead the authors to target their research strategies and questions to enhance understanding of change and vulnerability of world deltas, and include research agendas for a linked technology for socio-economical, ecological, and morphological process modeling. Along with thoughts on implementation strategies, a series of case study vignettes are included to document the uniqueness of world deltas and the challenges before us. A multidisciplinary community effort is sought to bring intellectual resources to address the urgent challenge of stewardship and sustainable management of delta systems.

Acknowledgements

We acknowledge the scoping meeting sponsored by LOICZ, GWSP and CSDMS entitled "Dynamics and Vulnerability of River Delta Systems", details of which can be found at http://csdms.colorado.edu/wiki/index.php/Deltas_2007. The list of authors and workshop participants and their contact information can be found at the end of the report.

Prolog

Deltas all over the world are identified to be among the most important sources of ecosystem goods and services. They are a reflection of past and current global change phenomena along our coasts as well as the societal dimensions associated with these changes. In terms of spatial and temporal scales, deltas are an expression of the complex geomorphic interplay between natural and human forcing, and thus provide a mirror of the multiple feedbacks between man and the environment. The relevant spatial extension of deltas and the processes that govern their geomorphologic dynamics and shape encompass the water continuum from source areas in the river catchments down onto our continental shelves. Along this continuum, anthropogenic pressures exact their toll, involving changes and responses.

Many transboundary rivers meet the sea in large deltas, thus next to natural processes and flow regimes deltas may reflect also the upstream sociopolitical condition. Since historical times, deltas have been society's edge, supporting social, cultural and economic development and welfare. Today they are subject to the impacts of climate change and increasingly prone to natural hazards standing in opposition to accelerating land and coastal use for urbanization, transport business and exploitation of natural resources. Upstream and in the densely urbanized delta regions, hydrological management including groundwater abstraction and other human induced soil compaction have led to the increasingly global phenomena of subsiding deltas and their cities, exacerbating their vulnerability to storms and erosion. Deltas therefore deserve priority attention by a truly holistic scientific community. Three institutions in the wider Earth System science context therefore have joined forces in late 2007 to review our current state of the art understanding of deltas their physical, biological and socio-ecological features and to identify key deltaic research questions.

The CSDMS, *Community Surface Dynamics Modeling System*, Integration Facility based in Boulder, Colorado, is a virtual home for a diverse community of experts, presently from 22 countries and 135 institutions, who foster and promote the modeling of earth surface processes, with emphasis on fluids, sediments and solutes in landscapes, seascapes and sedimentary basins. CSDMS offerings to the public include a library of useful, vetted models, "middleware" to couple models and data systems, and educational products related to its mission of better understanding our planet's surface environment. One of CSDMS's Working Groups is charged with coordinating the development of morphodynamic and biogeochemical models that specifically relate to how deltas respond to both upstream watershed perturbations, and offshore marine climate.

LOICZ, Land Ocean Interactions in the Coastal Zone, is a Core Project of the International Geo-sphere-Biosphere Programme, IGBP, and the International Human Dimensions Programme on Global Environmental Change, IHDP. With a growing network of scientists working on global scale it has been analyzing coastal change and underlying processes and feedbacks since the early 1990s. During the recent past LOICZ evolved, however, from its originally biogeochemical focus global into a truly interdisciplinary Earth System Science experiment, which looks into the multiple features of coastal change in a holistic manner. The key objective is to inform sustainable development and use of coastal zones by applying a socio ecological systems perspective along the whole water cascade. It aims to provide the knowledge, understanding and prediction needed to allow coastal communities to assess, anticipate and respond to the interaction of global and local pressures which precipitate coastal change. For LOICZ, deltas are one of the top priority coastal areas where global change, regional and local drivers and governance response lead to complex feedbacks and changes

The GWSP, *Global Water System Project*, a joint project of the Earth System Science Partnership is committed to analyze global change effects on the planet's water system, i.e. to the freshwater components of the hydrological cycle. GWSP has since its early stages focused not just on modeling these effects and consequences such a water demand and supply now and in future in different climate change scenarios; it has also applied a human dimensions perspective to showcase what the feedbacks are humanity needs to face in future water use and management. Deltas are not only human habitats, they also the link between aquatic and marine ecosystems. Deltas reflect both wise resource use and unsustainable practices in the river basin. Diagnosing deltas reveal much of the upstream problems of mighty river basins.

The collaboration between CSDMS, the GWSP and LOICZ underlines that the joined thinking in terms of scales, processes and tools that is needed to adequately address global change issues and human dimensions in deltas cannot be handled as well by one actor alone as it can be done collectively in a such a strategic partnership.

In conclusion and even after this concerted effort of multidisciplinary experts we have to recognize that deltas still remain a priority to be studied. As this report states, the scope of the challenge is large. All three organizations, CSDMS, LOICZ and the GWSP are collaborating here to highlight the vulnerability of deltas. We are developing plans to marshal our respective scientific communities to work together and better understand the scale and function of deltas. This report offers important strategies for understanding and managing change in deltas. On behalf of our respective communities, we hope this new spotlight will illuminate the constellation of issues, and document what we know and list what we do not know on this important topic. We also hope that this report will be able to communicate the key findings and issues in current and future delta research to multiple audiences and assist to open new avenues for advanced interdisciplinary research to be implemented by the leading environmental and research institutions world wide.

James Syvitski

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1 Introduction

Deltas are the landforms formed where rivers drain into a lake or ocean basin. River processes dynamically interact with ocean processes (mainly waves and tides) to control a delta's form. Every delta is a unique result of the precise balance of these controlling processes over time (Galloway 1975, Postma 1995, Giosan & Bhattacharya 2005). It is difficult to define exactly what area of coastal lowlands is incorporated by a delta (Syvitski 2008). World deltas formed when global sea level stabilized within a few meters of the present level, around 6000 years ago. As the deltas developed, their main stem channel split into a series of distributary channels that swept flow across incredibly flat terrain.

Deltas have been a preferred human habitat due to their high productivity, rich biodiversity, and easy transport along abundant waterways. It has been argued that deltas fostered the development of civilizations (Day et al. 2007). Today, more than 500 million people reside in deltaic regions (Ericson et al. 2006, Syvitski & Saito 2007). Average population density in deltas is estimated to be ~500/km^2, as a comparison the world population density is 45/km^2 and the US population density is 31/km^2 (UN 2005). Many of the Asian megacities are located in deltas.

Deltas are important ecologically and economically – their wetlands offer the potential for water quality improvement and freshwater storage, fish production, agriculture, forestry, salt production, and recreation. Most of the world's coastal wetlands are located in deltas. Most coastal fisheries are associated with deltas (Vörösmarty et al. 2009), and in some countries the majority of agricultural production comes from deltas.

As termini of large drainage basins, deltas act as filters, repositories, and reactors for a suite of continental materials on their way to the coastal ocean, including freshwater, sediment, carbon, nutrients, and pollutants, significantly affecting both the regional environment at the land-ocean boundary and global biogeochemical cycles (Meybeck et al. 2006, Fig. 1.1). High river flows supply materials that stimulate biologic production and control a series of high-diversity deltaic habitats. Wetlands create organic soil that in turn process pollutants contributing to the maintenance of water quality in coastal regions. A large part of the organic carbon reaching or being produced in deltas is buried and stored with their sediments.

Deltaic wetlands and forests act as natural buffers that reduce storm impacts to landward settlements. However, deltas are fragile geomorphic features that can change dramatically with modest modifications in the controlling environmental conditions. Energy expended at the coast through storm surges or wave action, coastal currents and tides, all limit the retention of the delivered fluvial sediment, even under natural conditions.

A common morphological trait of deltas is their low relief, with gradients smaller than decimeters per km. Formation and maintenance of deltaic plains is highly dependent on water, sediment and nutrient delivery from drainage basins that are several orders of magnitude larger than the deltas themselves. The gentle topography of the subaerial delta plain is strongly influenced by peat formation in wetlands, and by isostasy, i.e. the response of the Earths crust to loading by water on deposited sediment, as well as sediment compaction due to loading or oxidation. Delta channels naturally switch locations over the decades, in response to subtle changes in topography. These channel switches may involve gradually abandoning a major channel and favoring a previously small channel, or they may be triggered by catastrophic events.

Controlling processes offer a delicate balance to maintain a delta's morphology, given how a delta's low relief is so easily modified and inherently vulnerable to disturbance. Deltas are susceptible to degradation or damage from adverse factors or influences. A delta self-organizes the position of its channels and river mouth and thus responds dynamically to controlling processes. This self-organizing capacity of a system makes it resilient to adapt to hazards, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure.

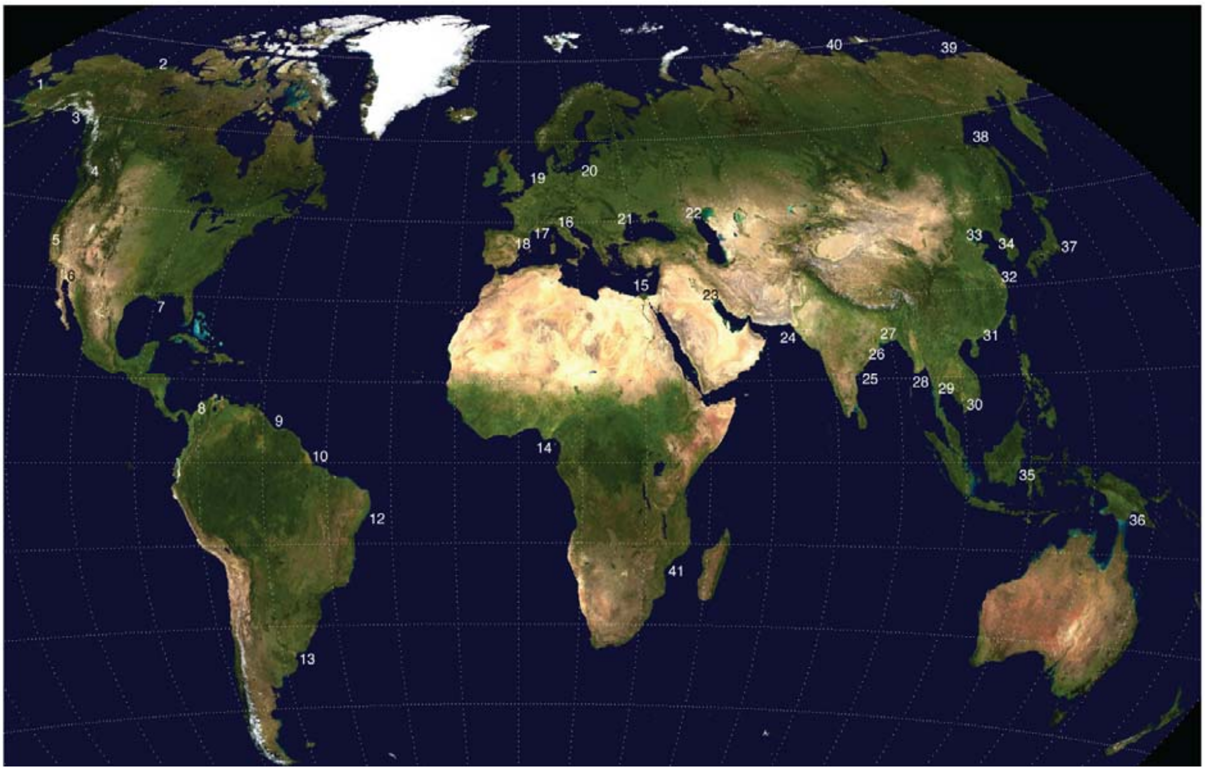


Fig. 1.1: *Location map of the world's better-known or studied deltas. 1) Yukon, 2) Mackenzie, 3) Copper, 4) Fraser, 5) Sacramento, 6) Colorado, 7) Mississippi, 8) Magdalena, 9) Orinoco, 10) Amazon, 11) Sao Francisco, 13) Parana, 14) Niger, 15) Nile, 16) Po, 17) Rhone, 18) Ebro, 19) Rhine/Meuse, 20) Vistula, 21) Danube, 22) Volga, 23) Shatt el Arab (Tigris-Euphrates), 24) Indus, 25) Krishna and Godavari, 26) Mahanadi and Brahmani, 27) Ganges and Brahmaputra, 28) Irrawaddy, 29) Chao Phraya, 30) Mekong, 31) Pearl, 32) Yangtze, 33) Yellow, 34) Han, 35) Mahakam, 36) Fly, 37) Tone, 38) Amur, 39) Kolyma, and 40) Lena.*

Intensive human development, population growth, and recent human-induced global changes are transforming deltas into highly vulnerable coastal regions. Various human impacts have led to deterioration in deltas. Dams, impoundments, dikes, and canal construction have led to decreased sediment supply to the delta and problems such as enhanced subsidence and reduced accretion.

Local water and mineral extraction further aggravates more natural rates of subsidence and increases the chance of salt water intruding into wetlands. Destruction of wetland habitats has diminished water quality, decreased biological production, and reduced biodiversity.

In response to rising sea levels and/or diminishing fluvial sediment discharge, most deltas would naturally reduce their size under wave and current interaction and migrate to shallow parts of the basin by switching and/or inundation. Many deltas are so populated nowadays that landward migration of coastal wetland zones is not possible anymore. The deltaic fringe (i.e., subaerial and subaqueous parts of the deltaic coast interacting with and being modified by waves, tides, and currents) responds by barrier and dune buildup and sediment redistribution. Negative feedbacks or engineering efforts may delay but are unlikely to prevent the destruction of deltas.

In this report, we argue and demonstrate that given current trends (shifts in climate, upstream changes in water quantity and quality, population pressure), many deltas are in danger of collapse within the 21st Century. Future preservation of deltas will become increasingly difficult and costly. Restoration or maintenance will require developing integrated management strategies that incorporate extensive monitoring and complex numerical modeling as well as detailed consultation with people affecting and affected by deltas.

This report provides a preliminary assessment of the impacts to coastal ecosystems of environmental change, associated with climate change and with human activities in coastal watersheds, and the response of coastal and shelf ecosystems to these changes. The report offers an Implementation Plan for a joint assessment and synthesis research project on the vulnerability of deltas, based on input from representatives of earth system scientists, engineers, physical scientists, ecologists, economists, geographers, and demographers.

This assessment was commissioned jointly by: 1) LOICZ, a joint IGBP / IHDP core project entitled Land-Ocean Interactions in the Coastal Zone (http://www.loicz.org), 2) GWSP, a project of the Earth System Science Partnership (DIVERSITAS, IGBP, IHDP and WCRP) entitled Global Water Systems Project (http://www.gwsp.org), and 3) CSDMS, the National Science Foundation effort entitled Community Surface Dynamics Modeling System (http://csdms.colorado.edu).

2 Change in and Vulnerability of Deltas

Modern deltas developed during the Holocene, during dynamic, but relatively gradual changes in relative sea level, freshwater and sediment input regimes, and other environmental characteristics. Human modification of this dynamic balance begins with far-field upstream measures causing changes in freshwater and sediment fluxes downstream. Fluxes are observed to change in both directions; damming and irrigation strongly reduces sediment delivery, whereas deforestation and other land-use changes can increase upstream erosion and thus sediment delivery to deltas.

The habitat of modern deltas appears as a contradiction, sensitive and dynamic in nature, yet host to hundreds of millions of people. Occupation is made possible by embanking of distributary channels and building coastal flood protection. This is often accompanied by groundwater and petroleum extraction, which promotes accelerated subsidence. As a consequence of direct human occupation and infrastructure development, natural delta dynamics are reduced, as is the area of wetland areas.

The global ocean volume is now rising at ≈1.8 to 3 mm/y (Bindoff et al. 2007), making the protective coastal wetlands vulnerable to storm surge and wave erosion. Predicted climate change is expected to affect the frequency of extreme events such as fluvial floods and coastal storms, including the destructive nature of hurricanes.

2.1 Upstream Changes of Freshwater and Sediments Loads

Humans presently regulate most river systems. Vörösmarty et al. (2003) have estimated that >40% of global river discharge is currently intercepted by large (≥0.5 km^3) reservoirs in a process they have described as 'Neo-Castorization', emphasizing dramatically the manner in which river managers have emulated the behavior of beaver, Castor spp., and built dams to regulate flow. Syvitski et al. (2005a) estimated that on a global scale 26% of the sediment that would flow to the coast and deltas has been intercepted by retention in reservoirs. While there are a number of immediate and beneficial consequences of this activity, some of the implications of this process for downstream systems have been identified only recently. Inevitably, dam construction and regulation has been associated with immediate changes in the flow regime downstream, including the attenuation of high flows, a modified seasonal distribution of flow, and reductions in sediment transfer. These effects have been compounded, in many catchments, by downstream flow withdrawal for irrigation or domestic and industrial water supply.

CS1: Largest irrigation system in the world reduces flow to the Indus Delta

James Syvitski, Liviu Giosan, Mark Hannon, and Albert Kettner

The Indus delta provides a classic example of how through the 19th Century, and earlier (Homes 1968), river distributary channels migrated across the delta surface (Fig. CS1). SRTM topographic data reveal the fan-like sediment deposits from the ancient crevasse splay and paleo-river channels (Fig. CS1a). Distributary channels were numerous, and successive surveys show channels to have been mobile (Fig. CS1b). To better use precious water resources on the Indus floodplain, an elaborate 20th Century irrigation system was put in place (Fig. CS1c) that captured much of the water, sediment and nutrients. Upstream barrages and diversions redirect river water across the floodplain along canals (Syvitski & Saito 2007). Today very little water and sediment makes it to the delta plain through its remaining connection to the ocean (Giosan et al. 2006).

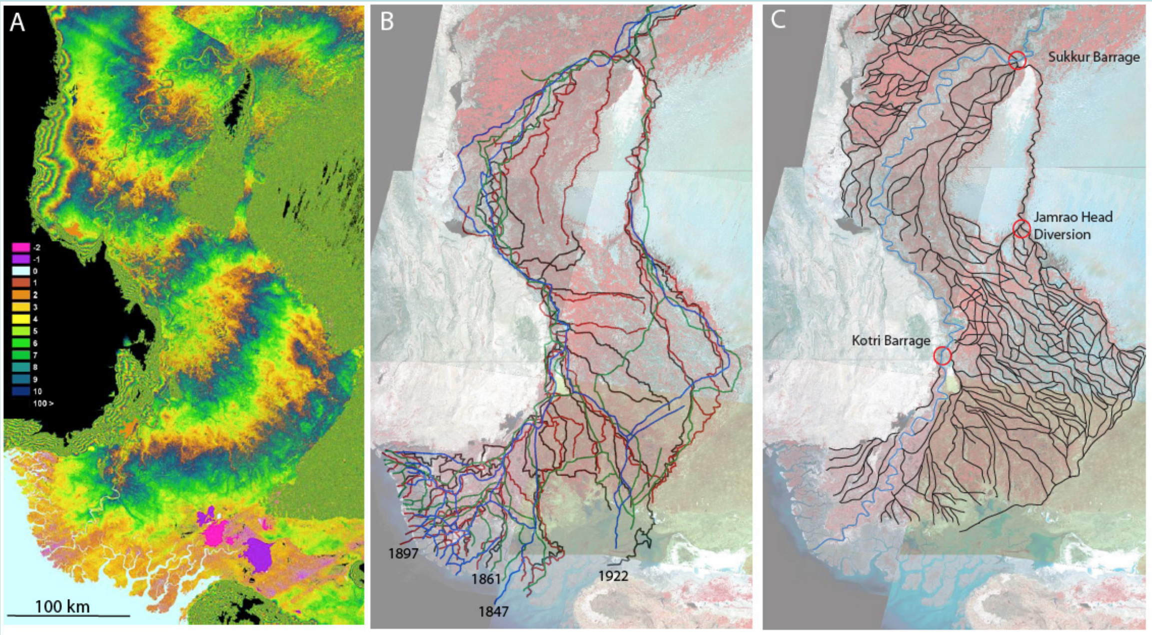


Figure CS1: A) The Indus floodplain and Delta (Pakistan) displayed with SRTM altimetry, binned at 1 m vertical intervals, starting at sea level (light blue), then 1 color per 1 m interval, with colors cycled every 10 m, to a height of 100 m, then black. Topography below mean sea level is in shades of pink. B) 1) Historical location of distributary channels (cartographer, color, year and registration error): Weiland, blue, 1847, ±3.8 km; Johnston, green, 1861, ±3.8 km; Rand McNally, red, 1897, ±3.7 km; and Bartholomew, black, 1922, ±3.1 km. C) Irrigation channel system with main water distribution stations. (Syvitski et al., in review, Holmes 1968).

The Indus River in Pakistan is one of the most dramatic examples of irrigation promoting a loss of water and sediment transported to the coast (Case Study 1). Recent analysis of data from the catchments of 40 globally significant deltas indicates that >75% are threatened by upstream loss of sediment and consequently nearly 10 million delta residents are vulnerable to coastal flooding (Ericson et al. 2006).

Many other variables have a significant effect on downstream water and sediment transfer and it is important not to draw too simplistic an association between dam construction and changes in water and sediment flux. Globally, catchment sediment fluxes have responded continually to changes in land use, deforestation, and land clearance (Walling & Fang 2003, Walling 2006).

Historic anthropogenic activities still have an impact on sediment supply to certain deltas, such as the Yellow River, where almost 90% of the sediment supplied to the delta is derived from the river's middle reaches where it crosses the Loess Plateau (Ren & Walker 1998). Sediment fluxes are also affected by the extent of alluvial / floodplain sediment storage which may buffer downstream sediment supply contributing to temporal variations in the relationship between sediment supply and deposition at any point in the catchment (Phillips & Slattery 2006). The buffering is likely to be more significant in large heterogeneous basins of continental rivers such as the Mississippi, Nile, Yellow and Yangtze. In contrast smaller rivers such as the Ebro are likely to be considerably more responsive to changing material fluxes given a more limited potential for floodplain water and sediment storage.

2.2 Anthropogenic Interference in the Delta

Deltas have been a preferred place to settle for humans, and channel stabilization and water diversion have taken place since the earliest occupation until today (Vörösmarty & Sahagian 2000). The Yellow River in China was first diverted in the 7th Century BC (Case Study 2). Analysis of ancient maps of deltas shows that most deltas presently have fewer active distributary channels than they did in a less engineered condition a few centuries ago. This creates a disequilibrium situation of super-elevated channels that are more prone to levee breaches and flooding. For example, in the Yellow River a number of channel diversions were undertaken after 1855, but sediment builds up rapidly in the constrained channel belts, creating a channel belt superelevated over the adjacent floodplain. This makes flooding in the delta area difficult to manage.

Withdrawals of water, oil, and gas cause sinking of the land surface at rates more rapid than geological subsidence. Natural gas withdrawal led to high subsidence rates in the Po delta and large areas of the delta are now more than two meters below sea level (Case Study 3). Likewise, oil and gas withdrawal in the Mississippi delta in some cases has increased subsidence by a factor of 2-3 (Morton et al. 2003, 2005).

Draining wetlands can cause soil organic matter oxidation and increase subsidence rates far above geologic subsidence rates. There have been enhanced rates of subsidence in the Rhine and Sacramento deltas because of soil oxidation. In the Sacramento delta, for example, over 100,000 ha of reed swamp have been drained and are now under pump and cropped (Weir 1950, Newmarch 1981). Initial subsidence rates were greater than 20 cm/yr and it is predicted that after 100 years the rate will be 3.2 cm/yr. In the Mississippi delta, initial rates of subsidence in drained wetlands were on the order of 10 cm/yr (Okey 1918).

Delta plains contain valuable ecosystems, which are lost at astonishing rates due to human-induced changes (Richards 1990, Coleman et al. 2008). On the North-American continent the rates of land loss in the Mississippi delta area, which contains about 40% of the wetlands in the USA, are the most striking. Louisiana lost 3,460 km^2 of coastal wetlands to open water between 1956-1990, and continues to lose between 65-91 km^2 every year (Bourne 2000). USGS scientists reported that Hurricane Katrina alone caused landloss of 388 km^2 (Barras 2006). Because the major Mississippi channels are constrained between high levees and do not bring in fresh sediments into the deltaic floodplain anymore natural subsidence in the delta is compounded by reduced sediment supply. In addition, navigation channels have increased saltwater intrusion into the marshes causing massive 'brown-outs' of dying freshwater vegetation.

In other deltas worldwide, major infrastructural changes are still underway, like e.g. the construction of a shipping channel in the Ukraine part of the Danube delta, which will likely affect fish and wetland bird habitats (Schiermeier 2004). The two major causes of global deltaic wetland loss are expansion of open water in the delta plain and expansion of agricultural and industrial land-use. Satellite images of 14 major world deltas show all experienced net wetland loss over the last 15-20 years (Coleman et al. 2008). Conversion to agricultural or industrial land was predominant in the developing world, e.g. the Ganges-Brahmaputra and Indus deltas saw the most wetland loss due to human development. Drowning lands and increase in open water was predominant in Arctic deltas as well as some tropical systems, but those estimates are severely hampered by natural inter- and intra-annual variability in standing water in the delta plain.

CS2: Engineering distributary channels in the Yellow River delta

James Syvitski and Yoshiki Saito

Humans have influenced the evolution of the Yellow River delta for over 2,500 years. The Yellow River is known for carrying large amounts of sediment from the Loess Plateau that allow rapid aggradation in floodplain and delta. Frequent devastating flooding, largely due to the elevated riverbed in the delta, has earned the Yellow River the unenviable name "China's Sorrow". The sediment load of the Yellow River has changed dramatically over time. The pristine sediment load of the Yellow River was ~0.1 BT/y prior to 2000 years BP. Due to accelerated soil erosion on the Loess Plateau, the load increased to ~1 BT/y about 1000 years BP, reaching a maximum level of ~1.8 BT/y in the 1950's. Since then the load has steadily decreased back to its pristine level of ~0.1 BT/y, largely related to interception of the sediment load by upstream dams, and reduction in the water discharge to the delta (Wang et al. 2007).

The Yellow River is one of the most dramatic examples of humans directing the river course to mitigate floods and claim land for infrastructure. In 1855, a breach in the Tongwaxiang dike, Henan province, changed the course of the Huanghe artificially, from discharging into the Yellow Sea to discharging into the Bohai Sea. Once rerouted, the main-stem distributary channel avulsed and formed a fan shape from its apex near the town of Ninghai and later Yuwa in the delta area at a rate of ca. 22 km^2/yr. From January 1964 to May 1976, the river discharged through the Diaokou distributary (Fig. CS2a). In May 1976, the Diaokou branch was artificially cut off and the mainstream distributary was moved to the Qinshuigou channel, to reduce the river-bed elevation for flood disaster prevention, and to obtain new land to support drilling for oil production and for a new port (Fig. CS2b). The Gudong oil field was subsequently protected from coastal erosion by dikes, and the river course was shifted southward (Fig. CS2c). In just 10 years, the delta prograded seaward at a rate of 4 km/yr. In May 1996, an artificial bifurcation channel, Chahe distributary was opened for new land formation for new oil production, with concerns of safety and stability of the Qinshuigou distributary, and potential risk of flooding (Fig. CS2d). The operation reduced the length of the river channel by 16 km and steepened the riverbed gradient by 2.9 times, resulting in upstream scouring (Fan & Huang 2008). The Yellow River delta is unique in that the huge sediment loads are directly used to build new land.

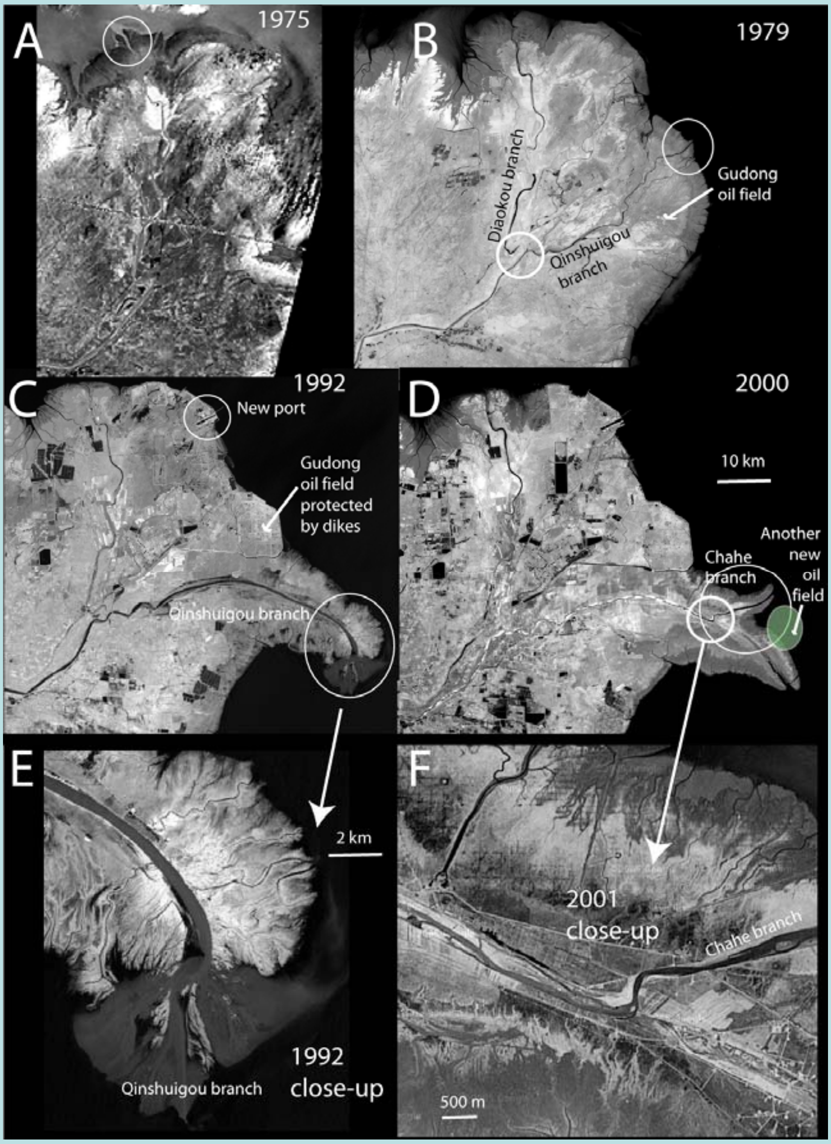
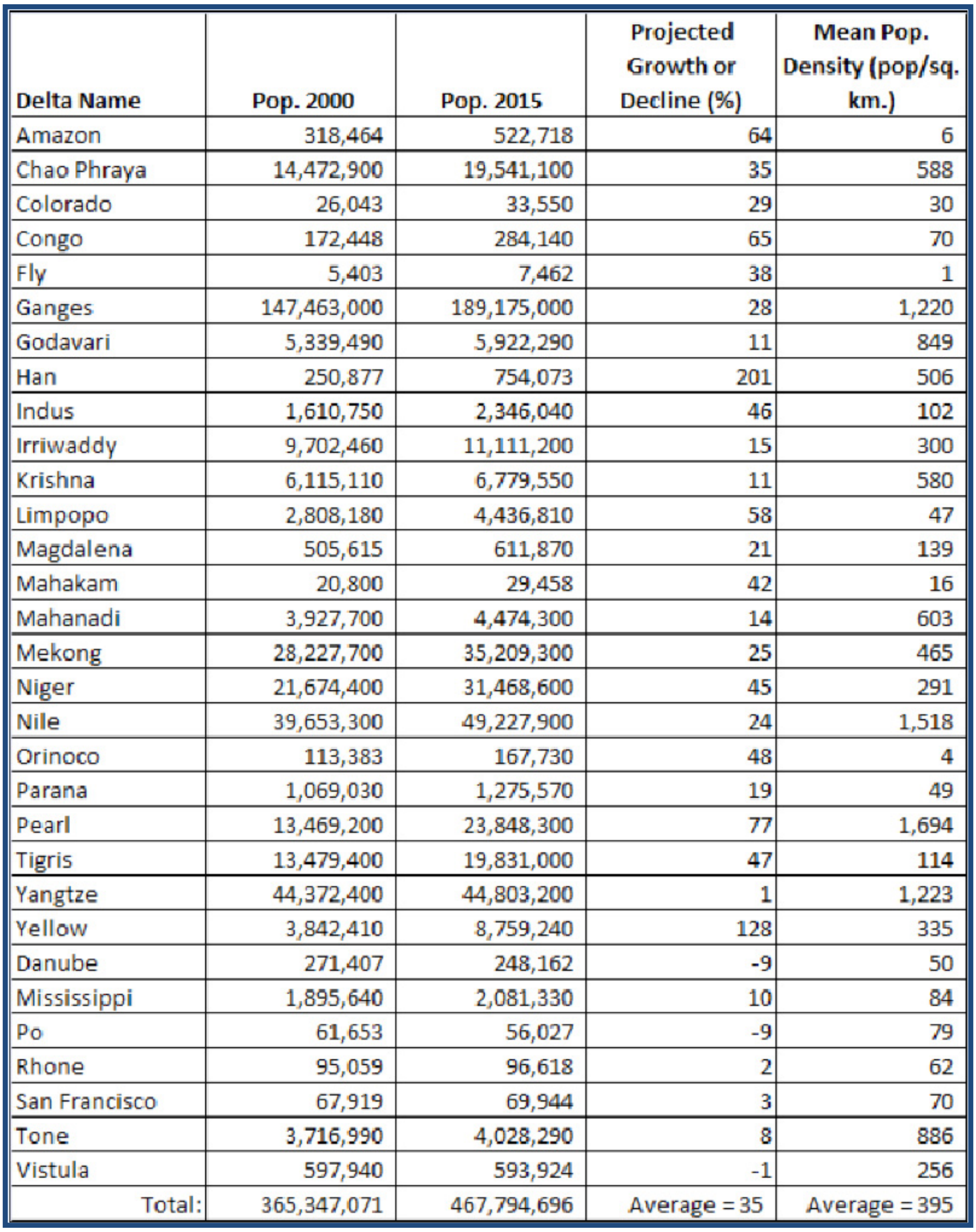


***Fig. CS2**: The evolution of the distributary channels of the Huanghe or Yellow River delta seen by LANDSAT.*

Human population settlements and growth has been one among a number of anthropogenic drivers that has resulted in transformations to delta ecosystems. Table 2.1 below shows population in the year 2000 and projected to 2015, projected growth, and mean population density for 31 major deltas. One delta, the Ganges-Brahmaputra delta, with close to 150 million people, accounts for virtually half the population of all the deltas listed. Another heavily populated and subsiding delta is the Yangtze delta, with 44 million people and a major city, Shanghai (de Sherbinin et al. 2007). Population densities are well over a thousand persons per square kilometer for three Asian deltas (the Ganges, Pearl, and Yangzte deltas) and for the Nile delta. Growth rates are projected to be highest in the Han (where Seoul is located) and the Yellow deltas, where several medium-sized cities are located. Several deltas are projected to see greater than 50% population growth over the 15-year period, including the Amazon, Congo, Limpopo, and Pearl River deltas. While populations affect land cover and land use in delta areas, the low lying nature of deltas and the large urban areas and associated infrastructure in some (e.g., Shanghai, Dhaka, Lagos, New Orleans) makes them particularly vulnerable to storm surges and sea-level rise (see Table 2.1).



Delta Name	Pop. 2000	Pop. 2015	Projected Growth or Decline (%)	Mean Pop. Density (pop/sq. km.)
Amazon	318,464	522,718	64	6
Chao Phraya	14,472,900	19,541,100	35	588
Colorado	26,043	33,550	29	30
Congo	172,448	284,140	65	70
Fly	5,403	7,462	38	1
Ganges	147,463,000	189,175,000	28	1,220
Godavari	5,339,490	5,922,290	11	849
Han	250,877	754,073	201	506
Indus	1,610,750	2,346,040	46	102
Irriwaddy	9,702,460	11,111,200	15	300
Krishna	6,115,110	6,779,550	11	580
Limpopo	2,808,180	4,436,810	58	47
Magdalena	505,615	611,870	21	139
Mahakam	20,800	29,458	42	16
Mahanadi	3,927,700	4,474,300	14	603
Mekong	28,227,700	35,209,300	25	465
Niger	21,674,400	31,468,600	45	291
Nile	39,653,300	49,227,900	24	1,518
Orinoco	113,383	167,730	48	4
Parana	1,069,030	1,275,570	19	49
Pearl	13,469,200	23,848,300	77	1,694
Tigris	13,479,400	19,831,000	47	114
Yangtze	44,372,400	44,803,200	1	1,223
Yellow	3,842,410	8,759,240	128	335
Danube	271,407	248,162	-9	50
Mississippi	1,895,640	2,081,330	10	84
Po	61,653	56,027	-9	79
Rhone	95,059	96,618	2	62
San Francisco	67,919	69,944	3	70
Tone	3,716,990	4,028,290	8	886
Vistula	597,940	593,924	-1	256
Total:	365,347,071	467,794,696	Average = 35	Average = 395

***Table 2.1**: Population in 2000, and projected population growth to 2015 for thirty-one major deltas, both in developing and developed countries. (A. de Sherbinin calculations based on the following data sources: CIESIN et al. 2005a, 2005b, 2005c, and Kettner (unpublished delta delineations from SRTM DEM data).*

CS3: Subsidence of the Po River Delta

Albert Kettner

Deltas are almost always prone to subsidence and the Po delta is no exception. Tectonics, sediment loading and sediment compaction are the main components driving natural subsidence rates for the Po Delta, which is only partly compensated by post-glacial rebound (Carminati & Martinelli 2002). The net natural subsidence rate for the Po Delta is estimated to be ~ 2-4mm/y (Simeoni et al. 2007). However, observed subsidence rates have been significantly higher since the 1950s. Anthropogenic factors like groundwater extraction accelerated as the area became more populated, but natural gas mining was central to increasing subsidence rates to 40-60 mm/y on average in the late 1950s, early 1960s (Fig. CS3.1a). Gas extraction in the Po Delta stopped at the end of the 1970s, which almost instantly decreased the subsidence rate to 10-20mm/yr (Fig. CS3.1b). It took till the 1990s to slow subsidence to its natural rate (Bondesan et al. 1995).

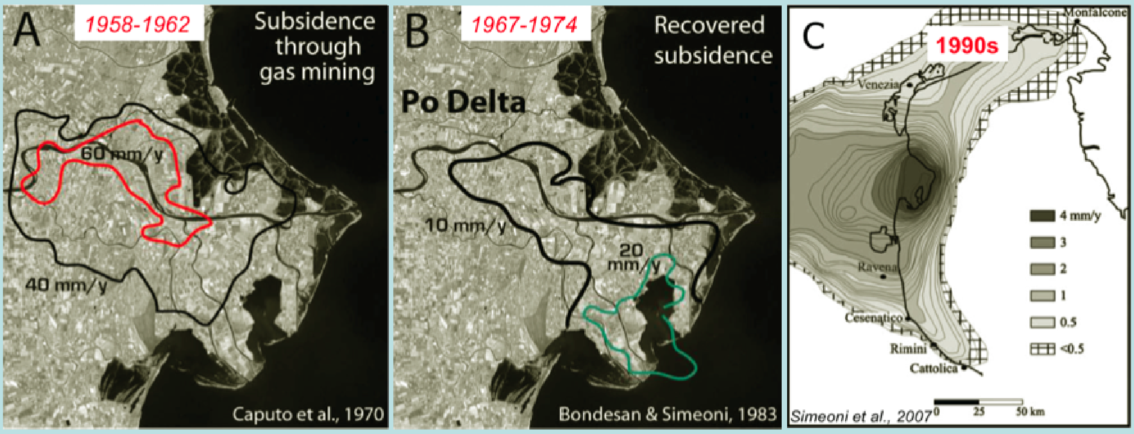


***Fig. CS3.1**: Decreasing subsidence rates (A-C) of the Po Delta. A) Subsidence rates during active mining of methane rich water (after Caputo et al. 1970), B) Recovered subsidence rates when most mining activity stopped (after Bondesan & Simeoni 1983), and C) Simulated natural subsidence rates (after Simeoni et al. 2007).*

Over the same time, the demand for sediment for building material increased with the rapidly growing population. Between 1958 and 1981, 90-95 x 10^6 m^3 of sediment was mined in the lower course of the river (Simeoni et al. 2007). In addition there was significant sediment trapping in the upper drainage basin by dams and reservoirs. Elevated subsidence rates, decreasing sediment supply due to dam and reservoir interception, and sediment mining (Fig. CS3.2) caused major delta erosion after the 1950s.

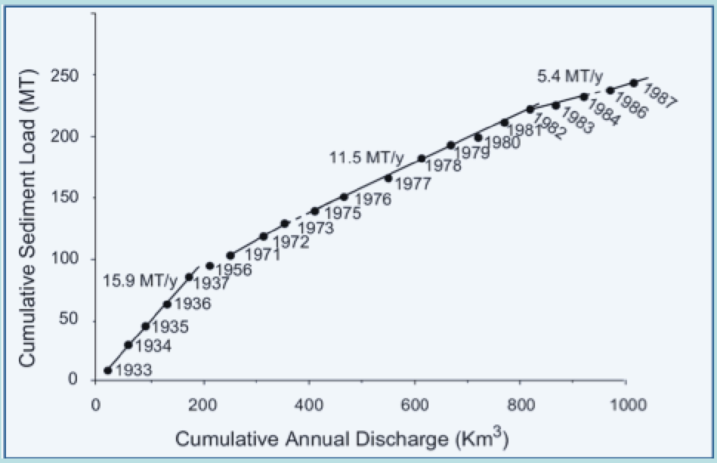
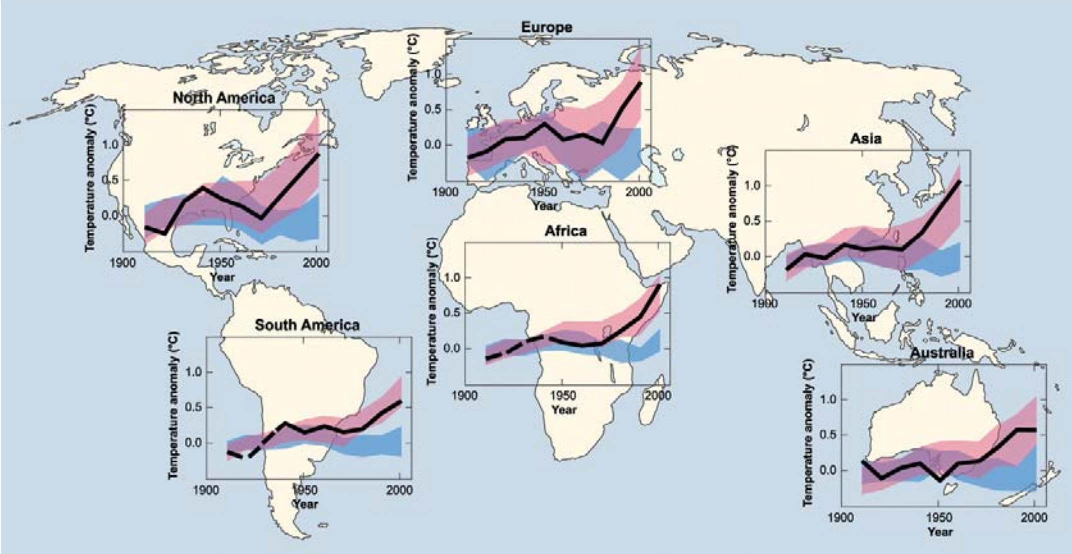


***Fig. CS3.2**: Sediment load decreased by a factor 2.9 in less than 60 years (after Syvitski & Kettner 2007).*

2.3 Sea-Level Change

For a given deltaic coast, changes in its elevation relative to sea level depends on three factors (Syvitski et al., in review): (1) Changes to the volume of the global ocean (Eustasy), as influenced by fluctuations in the storage of terrestrial water (e.g. glaciers, ice sheets, groundwater, lakes, and reservoirs), and fluctuations in temperature of the ocean's surface waters (Warrick & Oerlemans 1990, Bindoff et al. 2007). Sea level is presently increasing at a rate of 1.8 to 3 mm/y under the anthropogenic influence of global warming. (2) Vertical movements of the land surface, as influenced by hydro-isostasy related to sea level fluctuation, loading due to the weight of delta deposits, glacio-isostasy related to the growth or shrinkage of nearby ice masses, tectonics, and deep-seated thermal subsidence (Syvitski 2008). Isostatic changes can cause deltas to subside at rates of 1-5 mm/y. (3) Changes to the sedimentary volume of the delta, through natural compaction (≤3 mm/y), accelerated compaction (≤150 mm/y), and aggradation or sediment deposition onto the delta's surface (≤50 mm/y). Aggradation depends on both the rate sediment is delivered to a delta, and the amount of sediment retained on the delta during its transport across the delta surface.



Climate Scenarios	Temperature Change in °C	Sea Level Rise in m
B1	1.8	0.18 - 0.38
A1T	2.4	0.20 - 0.45
B2	2.4	0.20 - 0.43
A1B	2.8	0.21 - 0.48
A2	3.4	0.23 - 0.51
A1F1	4.0	0.26 - 0.59

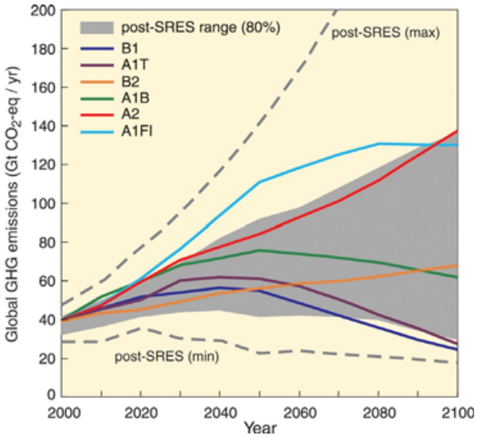


***Fig. 2.1**: IPCC comparison of observed continental changes in temperature over the last century; blue envelop is model predictions using only natural forces, pink envelop are model predictions including anthropogenic forces. Lower panel shows the projected emissions and tabelizes the projected associated temperature changes and sea level rise for 2090-2099 as compared to 1980-1999 (Bindoff et al. 2007).*

CS4: Rapid Caspian sea level change and the Volga Delta

Irina Overeem

The Volga delta is a prime example of a delta that has been subjected to rapid sea-level change. IPCC reports alarming rates of worldwide sea-level rise over the last four decades, 1,8 mm/yr over 1961-2003. Model projections of sea-level rise for the next century may amount to 6mm/yr. However, the Caspian Sea changes much more rapidly than the global oceans (100 mm/yr). Over the last century the Caspian Sea went through an entire 3 m sea level cycle.

70% of the fresh water influx to the Caspian Sea is derived from the Volga River. As a result Caspian sea-level changes show a statistically significant correlation with changes in the discharge of the Volga River. These in turn have been shown to record variations in precipitation over the Volga drainage basin, related to variations in the amount of Atlantic depressions that reach the Russian mainland. Arpe et al. (2000) showed the correlation of Caspian Sea level change with ENSO. This implies that at times of sea-level fall, water and sediment flux towards the coast is low, whereas at times of sea-level rise fluxes towards the coast are relatively high.

Consequently, the Volga delta experiences extremely rapid progradation of the coastline during sea-level fall, i.e. the system shoots out into its shallow basin. This was observed in the delta between 1935 and 1951. However, during sea-level rise the delta only drowns relatively slowly because sediment input helps to keep up with the rising water levels, as can be seen from the period 1981-1989. The coastline is stable then and levees were found to aggrade despite 1,5m sea level rise (Overeem et al. 2003a, 2003b). The Volga serves as an example of a delta system in which water and sediment inputs are correlated with sea-level change, making the response to change highly asymmetric.

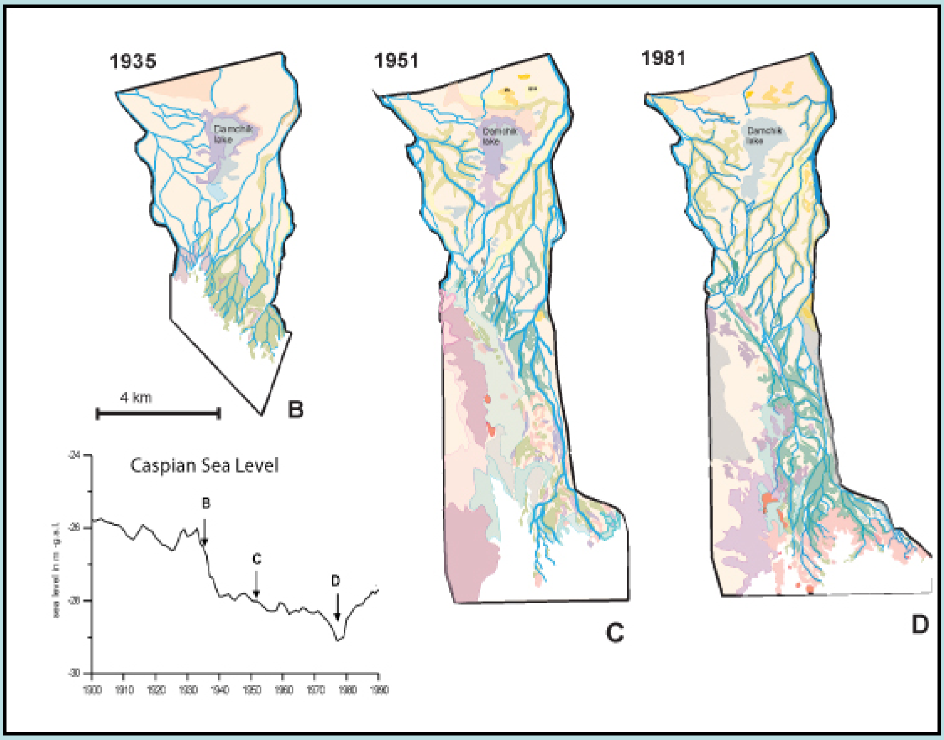


__Fig. CS4.1__: Vegetation mapping in the Astrakhan Nature Reserve area of the Volga delta records the rapid shoreline changes during sea level fall and more moderate infill during sea level rise over the last century (Overeem et al. 2003a, 2003b).

Sea-level change related to global warming increases delta instability. The Volga delta forms a dramatic example of a delta wandering across its delta plain under influence of the rapid sea level changes of the Caspian Sea (Case Study 4). Other deltas will be influenced in the coming century; the IPCC projected sea level will likely rise by 18-71 cm by the year 2070 with a best estimate of

44 cm (Bindoff et al. 2007). There is ongoing discussion on the dynamic response of the major ice sheets that could potentially contribute even more water over this period (Vaughan & Spouge 2002, Rahmstorf 2007). Most of this rise will be due to an intensification of factors causing present sea level rise; thermal expansion of ocean water and melting of land-based ice masses. Thirty-three deltas have a combined area of 33,036 km^2 below sea level at present already, whereas a suite of analyzed major deltas show a combined vulnerable area of 96,000 km^2 near local sea level. This area would increase to ~143,000 km^2 over the 21st Century if global sea level continues to rise rapidly and we consider vulnerable delta lowlands to be <3 m a.s.l (Syvitski et al., in review). In spite of the significance of global warming induced sea-level rise, human engineering impacts such as groundwater and hydrocarbon extraction can have much greater effects on relative sea level and delta stability.

2.4 Increased Frequency of Extreme Climate Events?

Human-induced climate change is expected to critically affect the frequency of extreme climate events such as fluvial floods or droughts, as well as coastal storms or hurricanes. While providing separation from quotidian delta dynamics, human stabilization of naturally dynamic deltaic systems is likely to result in less frequent, but catastrophic failures of delta system components following extreme events. Compounding chronic problems of deltas, extreme events may contribute to the collapse of entire deltaic systems. River floods that are increasingly devastating the populous Ganges-Brahmaputra delta and hurricanes that wreaked havoc on the Mississippi and Irrawaddy deltas recently provided dramatic examples. Over the 1980-2000 180,000 deaths in Bangladesh were associated with tropical cyclones. Over 1800 people lost their lives and ~300,000 homes were destroyed during Hurricane Katrina in the Southeastern US in 2005 (Nicholls et al. 2007).

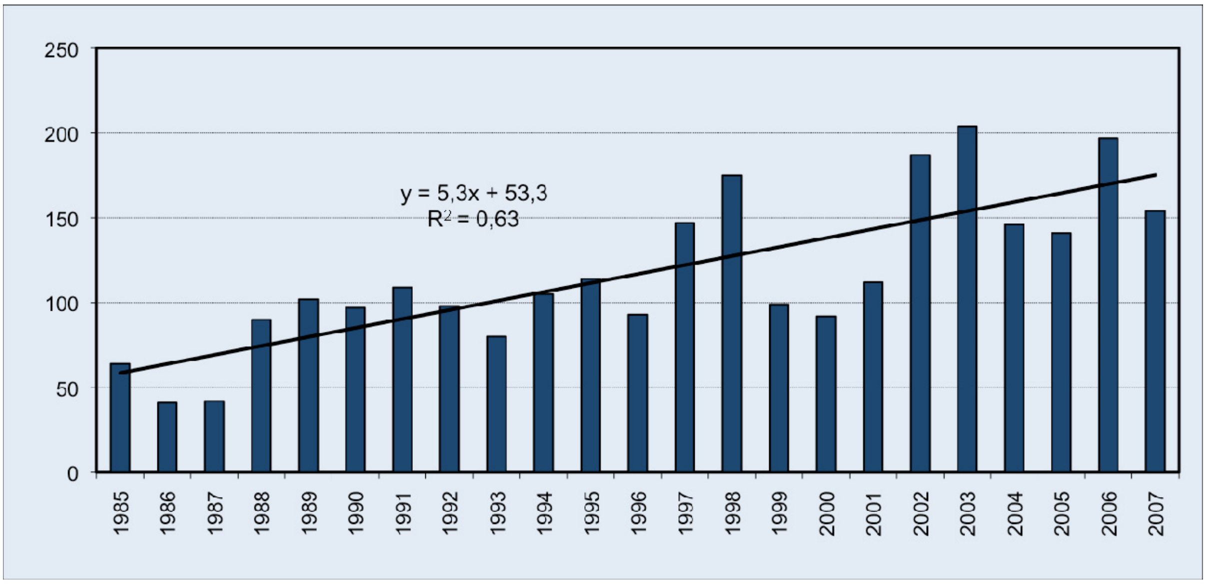
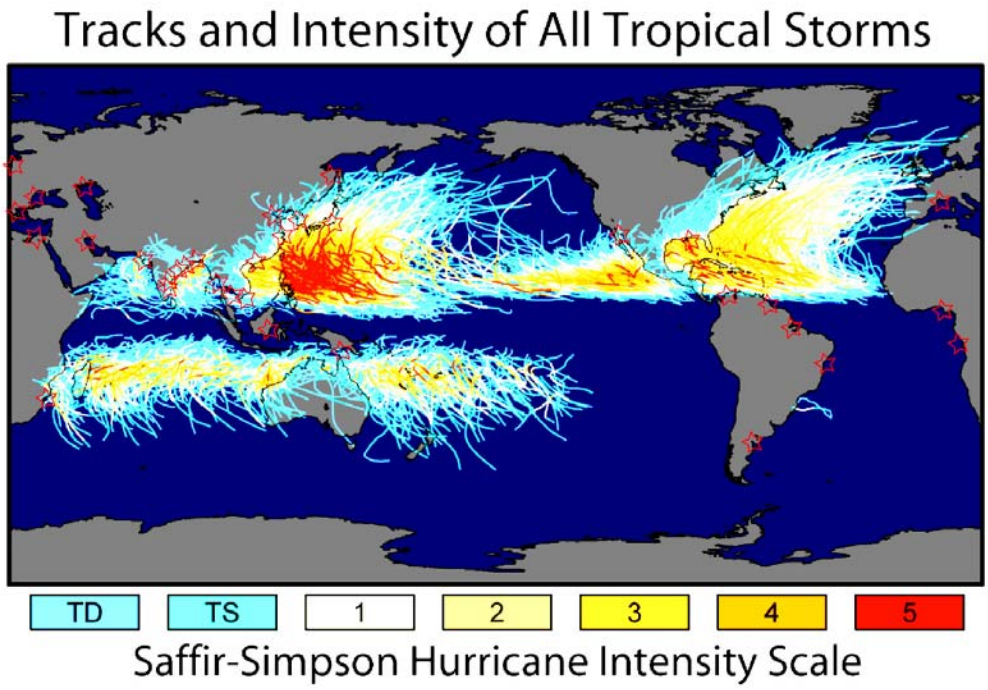


***Fig. 2.2**: Plot of the number of severe river floods, globally (1985-2007); from the Dartmouth Flood Observatory*

Deltas are probably as susceptible to coastal storms as to the previously discussed river floods. Hurricanes can produce storm surges over 10m, and that does not include the waves carried by the surges. It is the storm surge that allows breaking waves to move inland and which is responsible for most deaths in deltaic regions. Figure 2.3 provides an example of the storm tracks of historical hurricanes.



Type	Category	Winds (knts)	Surge (m)
Depression	TD	< 34	-
Tropical Storm	TS	34-39	-
Hurricane	1	64-82	1.2-1.5
Hurricane	2	83-95	1.8-2.4
Hurricane	3	96-113	2.7-3.7
Hurricane	4	114-135	4.0-5.5
Hurricane	5	>135	> 5.5

***Fig. 2.3**: The Saffir-Simpson Scale of hurricane intensity and expected surge height (from Unisys Weather Service http://weather.unisys.com/hurricane/index.html), and better- known deltas (red stars) superimposed on storm track map.*

There is little question that the number of North Atlantic hurricanes increased significantly since the 1850's and even more markedly since 1980 (Webster et al. 2005, Holland & Webster 2007) along with observed increasing sea surface temperature. Importantly, the destructive potential of these storms has increased as well. Data of the other main oceans is more ambiguous.

Modeling hurricanes is notoriously difficult, and model predictions for the coming century remain intensely debated. Some models project increasing frequency of storms (Vecchi & Soden 2007). Recent models reproduce trends observed over the last century and have thus gained in confidence, but these models predict a decrease in the Atlantic hurricane and tropical storm frequency for the late twenty-first century under global warming scenarios (Knutson et al. 2008). This cautions us not to over-interpret the correlation between hurricane frequency and sea surface temperature. However it has to be noted that while weaker storms appear to be reduced, all model simulations do predict a larger number of severe storm events and associated high rainfall intensity.

3 Conceptual framework of scale and function of deltas

In order to understand how humans have affected deltas and to design sustainable management approaches, there is a need for a conceptual framework both of deltaic functioning and for integrated delta management. Most rivers and deltas of the world have been purposefully altered to replace a dynamic natural infrastructure with a static human infrastructure to meet human socioeconomic needs and increase human safety. Loss of natural delta disturbance regimes has resulted in stabilization and reduction in delta landscape complexity, with many consequences to ecosystem functions, goods and services.

Within an integrated framework, a central idea is that system functioning should form the basis for sustainable management. The framework should revolve around the understanding of the delicate balance that every delta forms is of critical importance, and even more so that the balance is dynamic over time and heterogeneous in space.

Elements of an integrated delta framework include the ideas of dynamical systems over time and space; the flood pulse concept of the feeding rivers, the changes in ocean energy delivered to the coast, the changes in human use and management of deltaic regions and the self-organization or scaling of deltas and delta wetlands in response to these changing boundary conditions.

3.1 Concepts of Time and Scale in Delta Systems

Present day deltas, and other coastal systems, are geologically relatively young. At the height of the last glaciation (LGM), circa 22,000 years ago, sea level was ≈ 115 m lower than it is today (Milne & Mitrovica 2008). Deltas, in their current form, did not exist because the LGM shoreline was near the edge of the continental shelf. Figure 3.1 provides results from a numerical model that demonstrates the separation of the LGM delta from its the modern delta (Kubo et al. 2006). In their lower courses, rivers generally flowed to the sea in incised valleys. With the melting of the glaciers, sea level rose reaching near its present level about 6000 years ago. Since that time global sea level has fluctuated within a few meters of its present level. Consequently, deltas developed within a relatively stable dynamic range of sea level change, with relatively stable dynamic range of freshwater and sediment input regimes and relatively stable dynamic range of climatic characteristics resulting in dynamic, open systems, which never or rarely cross a collapse threshold.

The evolution of deltas over the last few thousand years implies that each individual delta has a memory, i.e. its stratal record and morphology. Future development of the delta is thus a function of both past and present forcing. Understanding the deltaic response in terms of changing morphology, response time and lag time to these forcing functions is imperative, especially since they are likely to have a profound impact at the decadal scale and therefore interact to human timescales.

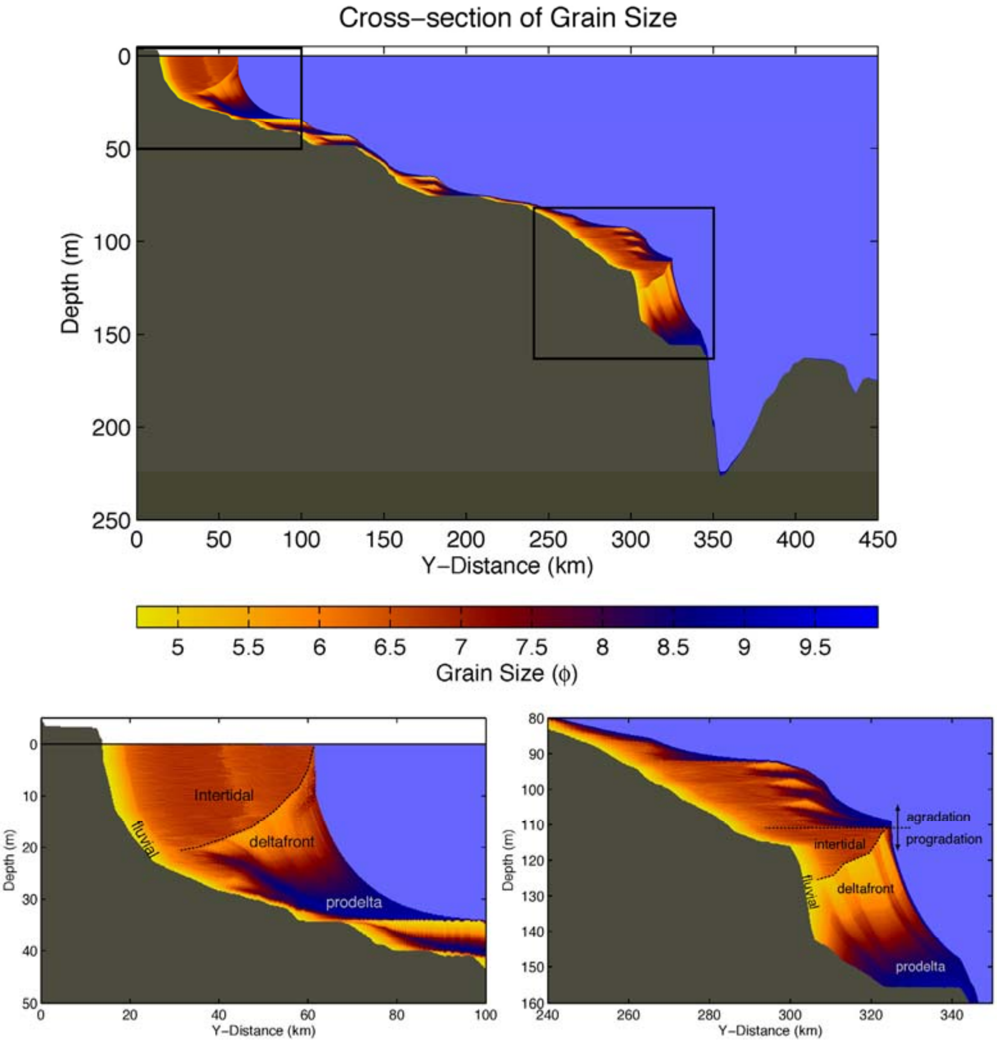


Fig. 3.1: Numerical simulation of the early Po Delta formed during the Late Glacial Maximum when sea level was much lower (bottom right), and when sea level was stabilized during the late Holocene when sea level was at modern levels (bottom left).

Global-scale analyses currently treat individual deltas as if they are homogeneous systems even though some deltas are enormous and we know that even relatively small deltas can be heterogeneous with some areas in an individual delta being river-dominated, while other areas are wave or tide-dominated. Furthermore, various types of risks and vulnerabilities are also likely to be spatially heterogeneous, particularly in large deltas. It is essential that the resolution increase for future analysis to be able to distinguish delta-scale heterogeneity – at least for the enormous deltas. If data resolution is adequate to include relatively small deltas in a global-scale analysis, surely deltas that are orders of magnitude larger could be broken into large sub-units.

Delta heterogeneity is extremely important to ecological function. The life histories of many species are keyed to active movement among different habitats in the delta (Sostoa & Sostoa 1985, Ibañez et al. 2000). Examples of these species are estuarine fishes like the fartet (Aphanius iberus), which is endemic to the western Mediterranean coast (Elvira 1995), or coastal birds like Audouin's Gull (Larus audouinii) (Oro et al. 1997). Sustainable management must be based on this complex ecosystem functioning.

Viewed from space, deltas exhibit marvelous spatial complexity, and it is immediately evident that the patterns are repetitive over different scales. Many aspects of landforms and landform-dependent processes and patterns scale, and this scaling may be a useful interpolation tool to address deltas that might otherwise be omitted from consideration due to data constraints or other constraints.

Scaling patterns might also be used to categorize groups of deltas, which may differ in functionality, i.e., different scaling relationships might exist for different categories of bio-geo-political systems. Possibly scaling relationships extend beyond the geological and ecological realm to the social realm. For example, it seems likely that large deltas will include a larger number of governments (national, regional, local) and stakeholders than small deltas. A species-area scaling relationship, which is well known in ecology, may be applicable to a similar "species richness" of governments and stakeholders. The difficulty of reaching consensus or making rational management decisions will likely be related to government and stakeholder species richness. Planned infrastructural works in the Danube delta form an example of these cross-boundary disputes (Case Study 5). Likewise, the physical, ecological, and socioeconomic heterogeneity of deltas may scale with delta size. This would likely include spatial heterogeneity of various types of risk and the diversity of risks and vulnerabilities.

CS5: Infrastructural development in the Danube Delta

Liviu Giosan

The Danube delta, located in the Black Sea and shared between Romania and Ukraine, is the largest delta in Eastern Europe. It is a sparsely populated rural territory and the main economic activities are tourism and fishing. The Danube's importance as a shipping route to central and Western Europe was recognized early, and after the Crimean War in the 1850s, the European Danube Commission (EDC) was charged with maintaining navigation routes open at the river mouths and through the delta. Since the second half of the 19th Century, the EDC has built and continuously extended protective jetties at the Sulina mouth, and shortened the Sulina arm to maintain it as a shipping channel (Fig. CS5). Before 1940, several canals were dug in the delta to aid fishing in its lakes and to bring freshwater to the brackish lagoons south of the delta. After World War II, Communist authorities dramatically increased the number of canals primarily for industrial scale fishing, fish-farming and reed harvesting, and started to transform large tracts of the delta into agricultural land (Schmidt 2001, Fig. CS5). Fortunately, the Danube delta escaped this "development" fate and remains one of the best-preserved temperate deltaic ecosystems and landscapes. Incorporating the largest reedbed in the world, numerous lakes and extensive lagoons, the Danube delta is home to over 300 species of birds and 45 species of freshwater fish, some globally threatened. The Danube delta was internationally recognized as a UNESCO Biosphere Reserve in 1992.

A 70% decrease in the Danube's sediment discharge following construction of Iron Gate dams in the 1970s and 1980s, coupled with eustatic sea level rise and engineering projects that redistribute sediments, is affecting the delta especially at its coastal fringe. Rates of vertical change in the near-shore zone radically changed from natural accumulation at active river mouths to a dominantly erosional pattern along most of the coast. Intensive canalization in the latter half of 20th Century lead to dramatically increased sediment deposition on the delta plain and within lakes that compensates decreasing sediment discharge linked to damming. However, shoaling and increased turbidity in lakes could have a negative impact in the long run, even if the high connectivity between the lakes provided by canalization may be currently favorable for the aquatic ecosystem (Coops et al. 2008).

Planned new development related to shipping and tourism is one of the key threats for the delta. A much contested deep-water shipping canal along the Chilia arm of the Danube to the Bastroe mouth in the Black Sea was planned and partially executed by the Ukraine, despite concerns regarding its potential for ecosystem damage and pollution (Schiermeier 2004, Wong et al. 2007). Access by boat only, which traditionally provided a certain degree of inaccessibility and helped preserve the delta, is currently threatened by construction of access roads and an increase in tourism-related boating and residences in the Romanian part of the delta. While pollution in the delta decreased considerably after the collapse of Communist economies, the Danube River collects waters from 19 European countries and continues to be the largest polluter of the Black Sea basin (Kideys 2002).

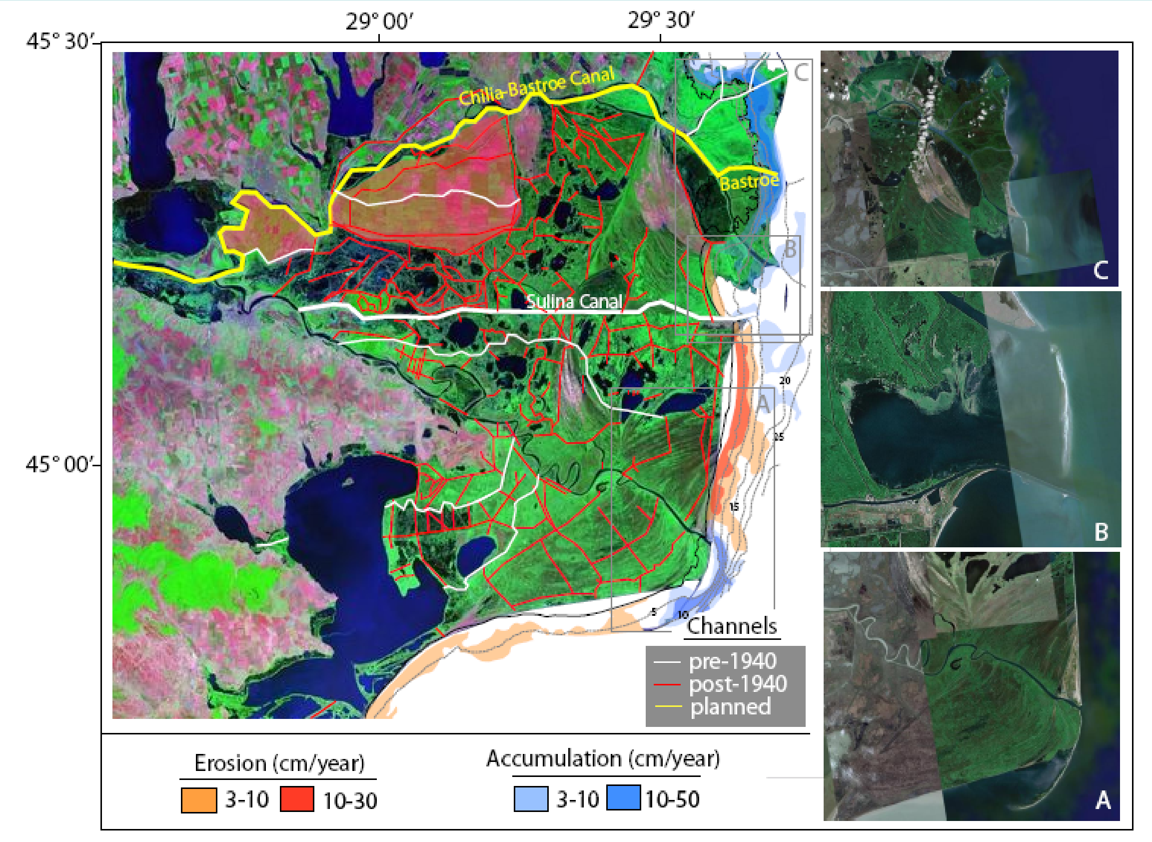


***Fig. CS5**: A synthetic look at large-scale human intervention in the Danube delta (Giosan et al., unpublished data). Canals dug within the delta are shown for two different phases of canalization. The course for the planned Chilia-Bastroe Canal is shown. Principal areas reclaimed for agriculture at the end of 20th Century are indicated by a red mask. On the coastal fringe of the delta the shoreline retreated for most of the region relative to the 1856 coast (in black), except for the active Chilia lobe. Based on analysis of historic surveys, rates of vertical change in the nearshore zone radically changed from a natural pattern of accumulation at active river mouths and erosion in between (from 1856 to 1898 as shown in the figure) to a dominantly erosional pattern at present (not shown). Note the wave-influence indicative of erosional regime suggested by the straightening of the Chilia coast (A) and development of barrier islands and spits in areas A, B, and C.*

3.2 Feeding River Basins: Pulse-Subsidized Sustainability

Deltas are inherently coupled to their feeding river basins and must be considered as part of the overall drainage basin. Within the basin, changes in freshwater, sediment and nutrient input are critical to delta sustainability. Human activities have changed all of these inputs.

Management of river basins and deltas should reflect interactions between different parts of the basin-delta system. There are several conceptual scientific frameworks concerning river basin and delta functioning. These include the concepts of the river continuum (Vannote et al. 1980), the flood pulse hypothesis of lower rivers (Junk et al. 1989), and the pulsing hypothesis of deltas (Day et al. 1995, 1997, 2000). These concepts describe how upstream-downstream interactions in rivers, interactions between rivers and their flood plains, and the diverse interactions among river, delta and sea serve to structure and regulate functioning, including productivity and biodiversity, of river basin ecosystems.

Overall deltaic form and functioning is related to pulsed energetic inputs of matter and energy. Each year, the river flood supplies a pulse of fresh water, mineral sediments, inorganic nutrients, and organic materials. This input varies from year to year from drought conditions to major river floods. These inputs stimulate primary and secondary productivity in the delta plain and wetlands. Increased plant production leads to higher rates of food production for consumers. Sediments and nutrients fertilize wetland plants and leads to increased organic soil formation. Freshwater input also maintains a salinity gradient from fresh to saline that creates estuarine conditions and supports a high diversity of wetland and aquatic habitats that are optimal for estuarine species. The increased area and productivity of wetlands resulting from river input leads to higher secondary production of fisheries and wildlife. Wetlands and shallow water bodies take up and process nutrients and other materials. This leads to higher wetland productivity and lessens water quality problems. The relationship between river input and the productivity of estuaries has been demonstrated by a number of authors (Boynton et al. 1982, Nixon 1982).

There is a component in the variation of pulses of water discharge over the year that is predictable. Seasonal river discharge to deltas varies by latitude and is affected by physiographic, climatic, and human influences. The intertropical convergence zone (ITCZ) controls river discharge in the tropics (Osborne 2000). During the year, the ITCZ moves from the Tropic of Cancer to the Tropic of Capricorn carrying with it a band of heavy rain. This rain band crosses the inner tropics twice but the outer tropics only once. Because of the dynamics of the ITCZ, river discharge is often bimodal near the equator with high discharge most of the year, while being highly seasonal in the outer tropics. The seasonality of discharge in higher latitudes is a function of temperate weather forcing with the highest discharge generally occurring in the spring.

The spring discharge peak has a large snowmelt contribution and generally occurs later with increasing latitude, but the location of the drainage basin is a complicating factor. The location of the drainage basin relative to the delta determines seasonality and quantity of rainfall. For example, the Mississippi, Nile, and Yangtze all discharge near 30°N into the Gulf of Mexico, Mediterranean, and South China Sea, respectively. However patterns of river discharge are different for the three rivers. The Mississippi drainage basin is north of the delta and over 90% of discharge is generated in the upper basin, which is affected by temperate weather. Water input to the Nile is generated far south of the delta in the equatorial zone of central Africa and the river flows through a large desert zone before discharging to the Mediterranean. The Yangtze's drainage basin is west of the delta and water input is generated mainly from the monsoons.

***Fig. 3.2**: Villagers are building a drainage channel and dykes to regulate yearly recurring monsoonal floods in the lower parts of the Ganges delta, West-Bengal (Photo: Irina Overeem).*

Other aspects of variability are less predictable. For many catchments, the 'natural', or 'pre-disturbance' water and sediment regime has still to be determined, although analysis of sedimentary data from deltas has the potential to identify historic rates of sediment transfer from catchment to coast (Walling 2006) and associated delta evolution. The natural regime of most rivers is characterized by stream flow variability reflecting precipitation dynamics across the catchment, the extent of seasonal snow and ice-melt, and the various pathways taken by water in passing through the drainage basin. Understanding and quantifying this natural flow regime helps us determine whether there are critical flow criteria that are fundamental to the functioning of a delta downstream. These flow statistics may relate to the regular occurrence of high flows of a given magnitude and duration, perhaps because such flows account for most of the sediment transfer, or affect the functioning of the deltaic ecosystem in some other way (ensuring, for example, continued avulsion in the delta). Conversely, statistics relating to low flows may be important in determining aspects of local ecosystem functioning, and affect local vegetation distribution. To quantify natural regimes and their variability we need to take advantage of the revolution in paleoclimate studies that are concerned with millennial to centennial abrupt climate changes. These high resolution studies hold great potential for understanding and managing deltas and underline the need to collect and reconstruct high-resolution delta evolution data that can take advantage of advances in climate studies, and at the same time, be more relevant for immediate societal concerns.

Floods control the occurrence of crevasses, which transport river water out of channel into the deltaic floodplain. Crevasses function at high water via temporary channels through low points in the natural levee. These discharges form crevasse splays with areas on the order of tens of km^2 compared to hundreds to thousands of km^2 for full deltaic lobes. In the Mississippi delta, hundreds of crevasses have been identified along distributary channels (Wells & Coleman 1987). These overlap to form a continuous band of crevasses that were essential both to formation and maintaining the natural levee and to river input into interdistributary basins. During the historical period, more than 200 crevasses were documented to occur in a single year (Davis 2000). During the 1927 flood, an artificial crevasse was formed, by dynamiting the levee downstream of New Orleans. A blanket of river sediments up to 60 cm thick was deposited over an area of 150 km^2.

Regularity of flooding results in an annual and predictable reduction in salinity, and input of nutrients throughout the delta. Biota within the deltaic systems have adapted to this seasonality, and are therefore dependent upon their regular occurrence (Day & Templet 1989). Recent work in river ecology now recognizes that 'natural' or 'normative' flows are desirable to support river function and geomorphology (e.g. Poff et al. 2006a, 2006b), and that effective river management depends upon representing the different component elements of hydrologic variability. To a certain extent these are scale dependent, and large rivers are affected by the spatial averaging of spatially distributed flows, but globally 'natural' flow variability is a reflection of climate, coupled with geology and vegetation cover. Local quantification of the significance of key flow characteristics, i.e. in relation to an individual delta, would enable relationships to be established between geomorphological processes and the hydrological regime, and identify critical timescales beyond which the clear and discernible impacts on the delta will be apparent. In effect this would enable the definition of 'environmentally acceptable flows' for coastal deltas, although a number of problems would need to be considered, not least how to balance the allocation of flow resources to these environments with the need to sustain downstream ecosystems ensuring appropriate hydrological connectivity through the catchment.

Although further work is needed in this area, it highlights an important shortcoming in current catchment management practices. In most cases catchment, river and floodplain management historically has focused almost exclusively on the resolution of pressing local problems, or on changing the local situation in order to support views of a wider regional or national interest (e.g. supporting the development of a port which becomes a country's leading shipping locale) such as flooding, navigation, ensuring water availability, and has failed to consider sufficiently the implications for coastal ecosystems downstream. It follows that to a certain extent, the current 'health' of downstream coastal environments provides a measure of the sustainability of recent catchment and river management, highlighting the importance of adopting an holistic, or whole catchment, approach to managing river deltas.

There are a number of difficulties in following this approach. First, many large catchments transcend political boundaries and water resources may disregard downstream impacts entirely, or be allocated on the basis of an out-dated or incomplete understanding of the environmental implications of management activities. Secondly, holistic catchment management requires the effective integration of a number of scientific disciplines across the physical, biological and social sciences, and the geographical interests (headwater, floodplain, river, delta, coastal) of individual bodies.

However, in many respects this is an opportune time to explore the possibilities of integrated catchment management: the engineering facilities constructed to regulate river flows have a finite working life and in the United States it is estimated that by the year 2020 >85% of the dams will be approaching the end of their operational life, with the result that removal of selected individual dams may be feasible (Doyle et al. 2003a, 2003b). There also appears to be increasing recognition that fluvial ecosystems are legitimate users of water which can be conserved if certain basic principles are followed, although there are considerable problems in forecasting the ecological consequences of changing water regimes, and in quantifying the cumulative effects of environmental change (Naiman et al. 2002).

CS 6: The Magdalena River Delta: deforestation and coastal erosion

Juan D. Restrepo

Throughout the Magdalena basin in Colombia, deforestation has led to severe soil erosion. The only remaining rainforest area is located in the lower Magdalena valley, whereas most of the land on the lower and middle slopes is under cultivation. Forest cover in the basin declined from 46% in 1970 to 27% in 1990, with an annual deforestation rate of 1.9% (Restrepo & Syvitski 2006). A recent estimate presented by IDEAM, the National Environmental Institute of Colombia, indicates that between 1990 and 1996, total forest cover declined by 15%, an annual average loss of 2.4%. This deforestation rate in the Magdalena River is considered to be among the highest in the world (Sayer & Whitmore 1991, Cairns et al. 1995). Analysis of the percentage change in area under each land cover category shows that agricultural lands doubled during the 20-year period (1970-1990), meaning that most deforested land area between 1970 and 1990 was transformed for agricultural practices (Restrepo & Syvitski 2006). The area of forest cover in the upper basin was estimated to have declined by ~ 4,000 km^2, representing an area of 23% of the upper Magdalena catchment (Restrepo 2008). The Magdalena River discharges into the southwestern Caribbean and forms a 1690 km^2 triangular delta. The delta plain consists of alluvial plains, a marginal lagoon systems, and beach ridges (Fig. CS6). The construction of the Barranquilla port has seriously affected the erosion/accretion equilibrium along the delta front. Due to engineering structures such as jetties and dikes, which were constructed during early 1900's to facilitate navigation and create an open channel into the Caribbean (Alvarado 2005) (Fig. CS6b), the present delta mouth empties into an offshore canyon with a steep slope (40^{o}). So even when soil erosion in the Magdalena basin increased, sediments are lost to the deep sea. In addition, strong littoral currents flowing predominantly toward the west, create beach accretion and erosion on the eastern and western sides of the navigation channel, respectively. The net estimate of beach erosion on the western part of the delta for the 1936-2002 year period is ~ 3.5 km (Alvarado 2005) (Figs. CS6b/c). Further analysis of satellite images indicates coastal retreat rates up to 600 m in the western part of the delta for 1989-2000.

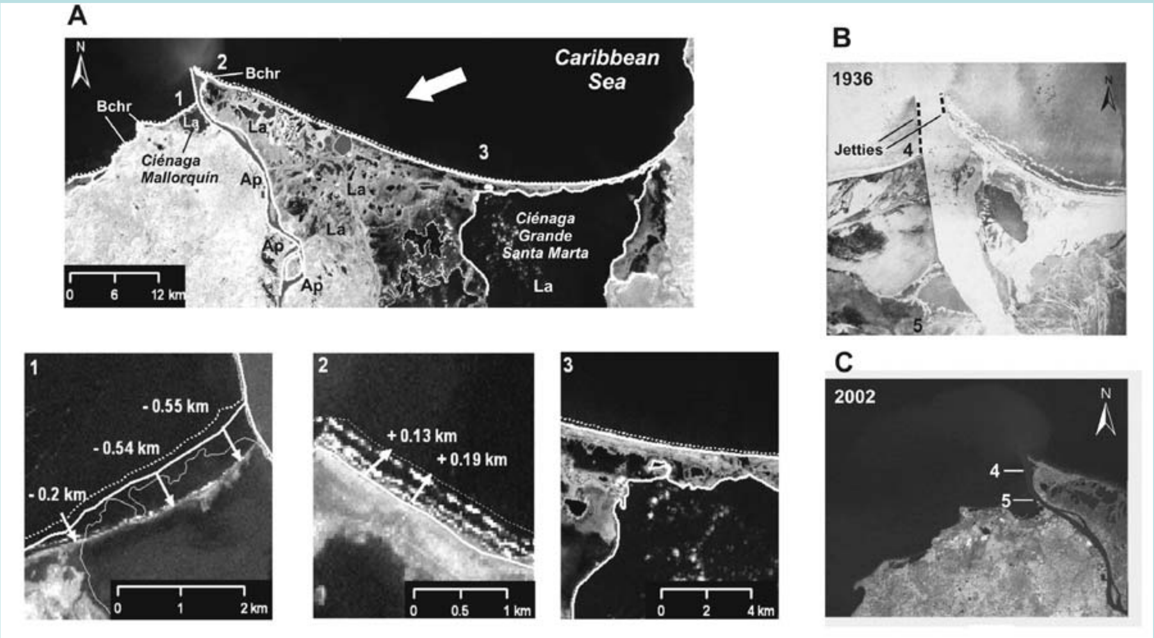


***Fig. CS6**: (A) LANDSAT Satellite image of the Magdalena delta, showing the locations of alluvial plains (Ap), lagoon systems (La) and beach ridges (Bchr), and shoreline changes between 1989 (dashed) and 2000 (bold). (B) Aerial photograph of the Magdalena River mouth from 1936, showing the location of coastal engineering structures and common points (4,5) also shown in C; and (C) 2002 satellite image of the Magdalena River delta, showing the coastal retreat between 1936 and 2002 (after Restrepo et al. 2002, Restrepo 2008).*

3.3 Pulsed Energy from the Ocean and its Trends over Time

Coastal deltas are systems that are transitional between the catchment and marine environments. In the lower river basin, bi-directional flows of energy, organisms and material, between the river and flood plain, become important in the ecological functioning of the river (Junk et al. 1989). In deltas, strong interactions among river, wetlands and shallow water bodies and the sea that occur over a range of temporal and spatial scales are essential to maintenance of hydrology, biogeochemical cycling, productivity, and biodiversity (Day et al. 1995, 1997, 2000).

Functioning of deltas is the result of external and internal inputs of energy and materials. These inputs are not constant over time, but occur as pulses, which occur over different spatial and temporal scales (Day et al. 1995, Day et al. 2007). Pulsing events are hierarchical and produce benefits over different temporal and spatial scales. These energetic events range from daily tides to frontal passages and infrequent strong storm events, and are important in maintaining salinity gradients, delivering nutrients and regulating biological processes.

At a daily timescale tides are an important pulse of the deltaic system. The daily rise and fall of tides leads to higher biological production and enhanced interaction between wetlands and adjacent water bodies (Case Study 6). The rise and fall of the tide allows drainage of wetland sediments and permits fish to use the surface of the marsh for feeding during periods of high tide.

Similar to seasonal patterns in the river discharge, frontal passages and storms operate variably over different seasons. Annual storm seasons have been shown to be important in causing sedimentation in deltaic areas of low tidal range (Baumann et al. 1984, Cahoon et al. 1995, Day et al. 1995, Roberts 1997). Currents generated by frontal passages are also important in transporting organisms and organic matter into and out of estuaries.

Large storms such as hurricanes and typhoons, occurring every 10 to 20 years, are another pulsing mechanism that supplies deltaic wetlands with sediments. Baumann et al. (1984) reported that two tropical storms were responsible for 40% of total accretion over a five-year period in salt marshes in the Mississippi delta. Cahoon et al. (1995) reported that during the passage of Hurricane Andrew in 1992, short-term sedimentation rates in Mississippi delta marshes were between 3-8 $g/m^2/day$ as compared to rates generally less than 0.5 $g/m^2/day$ during non-storm periods. Strong storms breach barrier islands but they also mobilize large volumes of sand from offshore and move it in front of beaches where transported to barrier islands by normal waves and winds.

Because of their very low gradient deltas are particularly sensitive to sea level rise. Subsidence in deltaic regions often leads to a Relative Sea Level Rise (RSLR) rate, which is much greater than eustatic rise. For example, while the 20th Century rate of eustatic rise was between 1-2 mm/yr (Gornitz et al. 1982), RSLR in the Mississippi delta was in excess of 10 mm/yr, thus eustatic sea level increase accounted for only 10-15% of total RSLR in these deltas. RSLR in the Nile is as high as 5 mm/yr, and RSLR is between 2 and 6 mm/yr for the Rhone and Ebro deltas (L'Homer et al. 1981, Baumann et al. 1984, Ibañez et al. 1996). Subsidence in deltas results naturally from compaction, consolidation and dewatering of sediments.

If wetlands in deltas do not accrete vertically at a rate equal to the rate of RSLR, they will become stressed due to water logging and salt stress, and ultimately disappear. Current evidence indicates that sea level rise (due both to eustatic rise and subsidence) is leading to wetland loss, coastal erosion, and salt water intrusion in a number of coastal areas (Clark 1986, Hackney & Cleary 1987, Kana et al. 1986, Stevenson et al. 1985, Salinas et al. 1986, Sestini 1992, Stanley 1988, Ibanez et al. 1996, Day et al. 2007). The relative elevation of the land with respect to sea level is a function of the balance between RSLR and accretion leading to vertical growth (Cahoon et al. 2005). The rate of accretion is a function of the combination of the inputs of both inorganic and organic material to the soil. Inorganic sediments can come from either the sea or from terrestrial sources. Organic material is usually from in situ plant production. The higher the inputs of both organic and inorganic material to the soil, the higher is the rate of RSLR that can be tolerated without loss of wetland surface elevation. Therefore, management should attempt to increase both organic soil formation and the input of inorganic sediments. Using river water to bring in sediments also brings nutrients, which enhances organic soil formation. Thus, management to increase the ability of deltas to survive rising water levels will also enhance deltaic functioning in terms of higher productivity.

***Fig. 3.3**: Women in the Ganges-Brahmaputra delta harvest fish trapped at low tide in small ponds on the outer tidal flats (Photo: Irina Overeem).*

Sea level rise also affects the delta fringe, i.e. the coastal sector of a delta, both subaerial and subaqueous, that is affected in a significant degree by marine processes. The fringe usually acts as a defense line for the delta plain via negative feedback loops such as barrier-dune buildup or shoaling of the near shore leading to lower wave activity at shoreline. If the marine processes become more important, for example due to increase of wave-dominance, the delta fringe expands relative to delta plain. Tide-dominated deltas are even more vulnerable to sea level rise, due to their inability to sustain protective barriers. Deep penetration of saline waters in the delta plain leads to rapid delta fringe expansion in those cases.

CS7: Puget Sound Deltas: habitat loss for Chinook salmon

W. Gregory Hood

Throughout the world, loss of native ecosystems through agricultural and industrial development has impacted fisheries, migratory waterfowl, shorebirds, and other wildlife associated with river deltas. Many impacts have occurred over the past 2000 years, with accelerated conversions of fish and wildlife habitat in the last three hundred years. In Puget Sound, agricultural and industrial development occurred only in the past 150 years, so habitat losses are relatively well documented by historical surveys (1850-1870), maps (1870-1890), and aerial photographs (since 1931). Large river deltas historically accounted for 90% of tidal wetland area in Puget Sound, with the greater Skagit Delta alone accounting for 53% of the total (Collins & Sheikh 2005). Agricultural and industrial development destroyed 80% of the historical tidal wetlands, with greater losses in river deltas and for certain habitats. For example, estuarine emergent wetlands declined by 63%, but tidal shrub-shrub and tidal forested wetlands declined by 98% and 92%, respectively (Collins & Sheikh 2005). Consequently, the ecology of tidal shrub-shrub and forested wetlands is poorly known, as is the ecological consequence of their disproportionate loss. We can speculate that because the dominant shrub-shrub species was a nitrogen-fixing plant it likely contributed to high secondary production through herbivore and detritivore food chains. Current research also suggests that the tidal shrub-shrub ecosystem may have high value as rearing and refuge habitat by juvenile Chinook salmon, a threatened species.

In addition to direct ecosystem and fish and wildlife habitat impacts there have also been less obvious indirect impacts. When tidelands are enclosed and drained, tidal prism is removed from channels outside the dikes. Decreased tidal flushing causes increased sediment accretion in the remaining channels (Fig. CS7). Because dikes cause seaward reduction in channels as well as landward channel loss, there has likely been disproportionately higher loss of tidal channels than marshes (Hood 2004). In spite of the relatively recent history of ecosystem changes in Puget Sound river deltas, ecological amnesia afflicts almost all Puget Sound residents, even scientists researching delta ecology and geomorphology. We have generally forgotten how intact Puget Sound ecosystems appeared, and we have never known how they functioned. How much more complete is our amnesia in systems with longer histories of human manipulation? How do we sustainably restore ecosystems and the associated habitats upon which fisheries and wildlife depend if we cannot remember them?

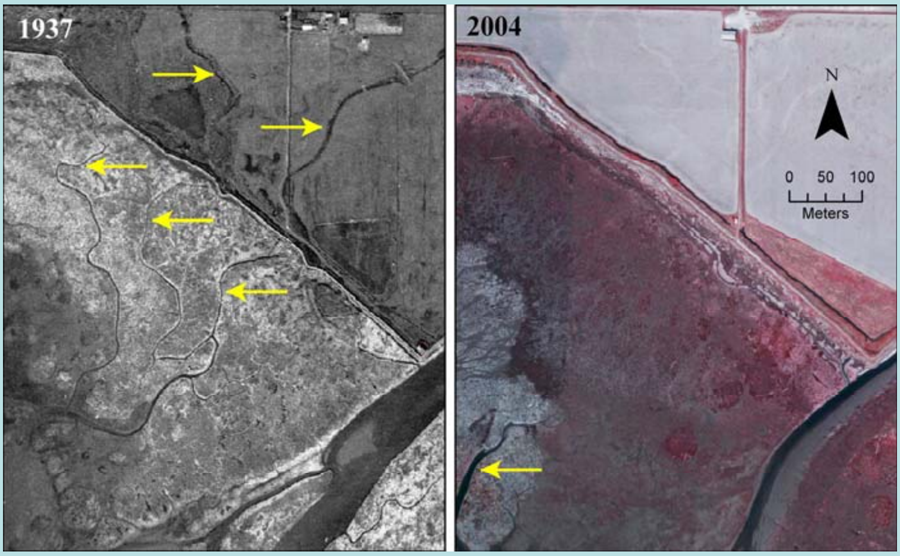


Fig. CS7: Remnant blind tidal channels in Skagit Delta marshes seaward (left-pointing arrows) and farmland landward (right-pointing arrows) of dikes constructed between 1870 and 1889. Blind tidal channels disappeared landward of dikes due to fill placement and rerouting drainage to ditches along property boundaries. Seaward of dikes they filled with resuspended bay sediments due to lost tidal prism. Only one shallow channel remains seaward of the dikes. The lower right corner of each photo shows a distributary, disconnected from the river by dikes in the 1950s. Much lower volumes of tide gate-mediated farm drainage, causing the remnant distributary to fill and narrow with resuspended bay sediments, replaced river discharge. The 1937 photo is courtesy of the Puget Sound River History Project. Both photos are at the same scale.

3.4 The Importance of Extreme Events

The primary importance of the infrequent events such as channel switching, great river floods and very strong storms such as hurricanes is in sediment delivery to the delta and in major spatial changes in geomorphology. These infrequent events difficult to manage and are generally not tolerated by people.

Major growth cycles of deltas take place through the formation of new delta lobes. Overlapping deltaic lobes are an efficient way to self organize, distribute sediments, and continually build land over the entire coastal plain. Evidence of major changes in the route to the sea, which occur approximately every 500 to 1000 years and affect 1000's of square kilometers, has been documented for many deltaic systems (Coleman & Wright 1975, Wells & Coleman 1987, Ibañez et al. 1996, 2000, Törnqvist et al. 1996, Stanley & Warne 1993, Day et al. 2007). Channel switching occurs as the existing channel lengthens so that its slope decreases and the channel becomes less efficient. Eventually, the height of the riverbed is raised and the upstream levee is breached permanently in favor of a more hydraulically efficient, shorter route to the sea. This process is pulse dependent as the breaching of the levee most often takes place during large flood events. River flow is never confined to one channel, but generally the primary channel receives more than 50% of total discharge with the remainder divided among older distributaries, thus insuring efficient sediment dispersal over the entire deltaic plain. Delta development forms a skeletal framework of distributary ridges and barrier islands (Kesel 1989) that protect interior freshwater wetlands from marine forces and saltwater intrusion.

Fig. 3.4*: Dams on the Oosterschelde protect the southern part of the Rhine-Meuse and Scheldt Deltas in the Netherlands against flooding. These dams were built in response to a major storm and flood event in 1953 in which over 2300 people were killed across the North Sea region. The dams have sluices through which tidal water freely move in and out to preserve the marine-estuarine ecosystem, but during major storms sluices are lowered. (Photo: James Syvitski).*

Major river floods occur once or twice a century. When conditions are right for channel switching, the major shift in flow between channels normally occurs during great river floods. In addition, these floods are important in delivering major sediment pulses to the delta plain. Both of these processes are exemplified for the Atchafalaya delta in the great flood of 1973 on the Mississippi River. For several decades prior to the 1973 flood, Atchafalaya Bay filled with fine sediment. In 1973, large amounts of coarse sediments were mobilized and the Atchafalaya delta became sub-aerial for the first time (van Heerden & Roberts 1980). It is mainly during floods such as 1973 that current velocities are large enough for coarse-grained material to reach to the new delta lobe and provide a foundation upon which to build land (Roberts 1997, 1998). The flood almost undermined the control structure at Old River that prevents the Atchafalaya from capturing the Mississippi. If the control structure were not in place, the major portion of the Mississippi would probably have been captured by the Atchafalaya. While every major river flood does not result in delta switching, levees are breached and large amounts of sediments contribute to the delta plain via overbank flooding at crevasses (Kesel 1989). In the Ebro delta in Spain, the last major switch in the position of the river mouth occurred during the large flood in 1937 (Ibañez et al. 1996). The effect of such events is clearly evident in areas affected by floodwaters. In 1993-94, there were two "100-year" floods on the Rhone River. Massive flooding of the upper delta occurred as the levee along the Petit Rhône broke in separate locations during each flood. In sites affected by the floods, there was accretion up to 24 mm (Hensel et al. 1999). Accretion in impounded habitats not impacted by the river was very low showing that these habitats were largely uncoupled from riverine processes.

4 Strategies for understanding and managing change and vulnerability of deltas

The fact that delta systems are dynamical by nature and are controlled by a complex of ever-changing factors makes it difficult to develop a comprehensive framework for research and management. Deltas may be intricate in their natural state, but human influences on delta systems add on to the complexity, and go beyond population numbers to a whole range of issues such as infrastructure development, institutional arrangements, and equity concerns. Any effort to understand and manage these systems will need to take into account these complexities, and also the interlinkage with upstream regions.

Many deltas are now out of equilibrium as a result of human-induced changes in the controlling factors; historical increases in sediment discharge following deforestation and agriculture. Large dams, however, continue to reduce the delivery of sediment and water to deltas, often reaching levels that once again shift deltas out their natural equilibrium, but in the opposite direction. Relative sea level will continue to rise in the foreseeable future, more rapidly in subsiding deltas. Climate change and sea level rise will have significant ramifications for these low-lying areas, creating even greater human vulnerability. Present deterioration of river deltas could put 100's of millions of people at imminent risk (Vörösmarty et al. 2009). Management strategies should have realistic expectations on how much of the area of a delta can be morphologically, ecologically and economically sustained based on an understanding of the delta dynamics, and changes in controls.

A 21st Century framework for integrated, multidisciplinary delta management must be developed to tackle the pandemic nature of these problems. Organizations such as the Earth System Science Partnership and its Global Water System Project (GWSP), the Land-Ocean Interactions in the Coastal Zone (LOICZ) component of the IGBP, the Community Surface Dynamics Modeling System CSDMS, and the National Center for Earth-surface Dynamics (NCED) advocate here for a truly multidisciplinary research project to assess dynamics and vulnerability of deltas, based on input from different experts, scientists, and decision-makers.

We envision development of a management strategy towards understanding of human vulnerability on a global scale consisting of two main components:

1. A prototype global database of river-delta systems featuring status, scenarios of change and options for adaptation.
2. A coupled modeling system of morphological-ecological process models linked to GIS tools, which can be applied to scenario modeling.

Key aspects of the multidisciplinary approach, research questions for the assessment of delta dynamics and vulnerability, and challenges for sustainable development, to which the integrated database and subsequent analysis and modeling could be applied by geoscientists, environmental engineers, ecologists, social scientists and policymakers alike, are presented in the following discussion.

4.1 Multidisciplinary Research linked to Practice

For monitoring and understanding change and vulnerability in deltas, we suggest a scientific approach involving both problem-driven research and action research. Problem-driven research means that rather than choosing a disciplinary-based method or a disciplinary perspective for research, a practical problem is identified and research is used for tackling that problem, irrespective of the academic origins of the approaches selected. Action research means that the research helps to catalyze action rather than being for science only, and as such have relevance for the people living on deltas (Chambers 2002).

For example, warning systems for extreme events such as tsunamis or storm surges are often seen as a telecommunications engineering concern. Research and practice illustrate that they are more effective for appropriate and timely decision-making when they are viewed as a social process which is part of day-to-day living, using telecommunications as one possible approach amongst many (Glantz 2003, 2004, Gruntfest et al. 1978, Kelman 2006).

Problem-driven action research ensures that the research approach and the scientific results are directly linked to policy and practice. Another aspect of the method is that for a focused study on deltas, specific, rather than comprehensive, questions will be addressed across disciplines. Rather than trying to monitor all data for a specific delta or trying to monitor one parameter for all deltas, specific questions to address might be for example: “How have different protected area statuses supported and inhibited delta ecosystems?” Such a specific question would assist in formulating a baseline method for more comprehensive monitoring and understanding change in deltas.

Engagement of policy-relevant bodies, such as the Intergovernmental Panel Climate Change (IPCC), and the Millennium Development Goals and the Millennium Ecosystem Assessment, to elevate the understanding of this additional element of the global environmental change question is urgently needed. IPCC so far focused fundamentally on eustatic and steric sea-level rise and a broader discussion of deltas at risk is just beginning. We envision a policy structure designed to help establish a legal framework and monitor research, modeling, and management practices. The structure should be used to strengthen cooperation among jurisdictions and cultures to tackle problems affecting deltas irrespective of human-imposed borders and boundaries.

4.2 Assessing Natural Delta Dynamics

More and more deltas are moving away from their pre-Anthropocene morphology (Syvitski & Saito 2007), and few systems can be studied under their natural settings (Ericson et al. 2006). Arctic delta systems are among the rare examples of systems relatively undisturbed by humans and they may provide an opportunity to study how rapid changes in climate per se affect the deltaic system (Overeem & Syvitski 2008, Figure 4.1). Reconstructions of paleo-deltas will help to recover historical changes so as to understand how deltas function without human interference, and thus establish the pre-human state of a delta. It remains imperative to understand natural dynamics of deltas prior to human intervention, just as it was imperative to understand Holocene climate before the recent Anthropocene.

This fundamental understanding should lead us in the further enhancement of process-based numerical delta models (Paola 2000, Overeem et al. 2005). We envision that there will be a merged approach between existing detailed 'fluid dynamics models' and more geological 'stratigraphic' or 'morphodynamic' models.

- How are deltas formed where natural forcing processes are dominant? How are these processes best modeled? How dynamic are deltas in a natural environment? Does the dominance of forcing processes change over time?
- What are the basic mass balances of water, nutrients and sediment in specific delta systems?
- Can we resolve sources and pathways of delta food webs at various scales?
- How do upstream processes impact delta form and function? When and where do delta river channels switch or bifurcate?
- Deltas developed within a relatively stable range of sea level change. What is the dynamic range of sea-level rates for stability of deltas, based on freshwater and sediment input regimes and climatic characteristics?
- How are geomorphology and ecology linked? What are ecological consequences of natural changes in landforms? How do we numerically model this interaction?
- What is the role of delta fringe processes as protective buffers to the inland deltas?
- What is the role of extreme events, e.g. river floods and hurricanes, in creating and shaping deltas? What is the coherence (or incoherence) between river flood events and ocean storms and is this systematic and forced by regional climate patterns?

- Beyond scale, do small deltas function differently from large deltas, particularly in their hydrological-biogeochemical-ecological dynamics? How best to combine sediment transport system functions across different timescales? Can the models mimic delta self-organization?
- Can we quantify the role of deltas as carbon sinks? What role will Arctic deltas play in buffering old carbon from permafrost to be transported to the ocean?
- How can baseline conditions for deltas serve as a reference for measuring human impact?

***Fig. 4.1**: High Arctic Colville River close to the apex of the Colville delta, water and sediment load of this river is changing under influence of Arctic warming. (Photo: Irina Overeem).*

4.3 Assessment of Human Influence on Delta Dynamics

Human impacts are now overwhelming natural processes, and assessment of modern delta dynamics can not be done without quantifying where humans live, how they behave and how they change delta controls and delta state. Humans desire stability for management and have devised strategies to tame the dynamical behavior of deltas by hydraulic and coastal engineering. However, humans now simultaneously accelerate and decelerate fluxes of water and particles on a scale that exceeds natural fluxes (Syvitski et al. 2005b). Unintentionally, human actions are deteriorating delta systems. Quantitative mapping the human influences on deltas and enhancing our understanding of human dimensions is a critical piece of an integrated delta research and management framework.

- Where on deltas do people live, how do they live there, and why do they live in those locations in those ways? What are the different livelihood systems in the poorest deltas? How do humans and societies shape, and how are they shaped by, their delta environment?
- How do different cultures, value systems, and interests govern decisions to live in delta regions and how do they govern behavior within those regions?

- How can different knowledge bases, such as traditional and scientific knowledge bases, be combined complementarily?

Have humans brought on fundamental trends that cause changes from background conditions in delta morphology and ecology due to:

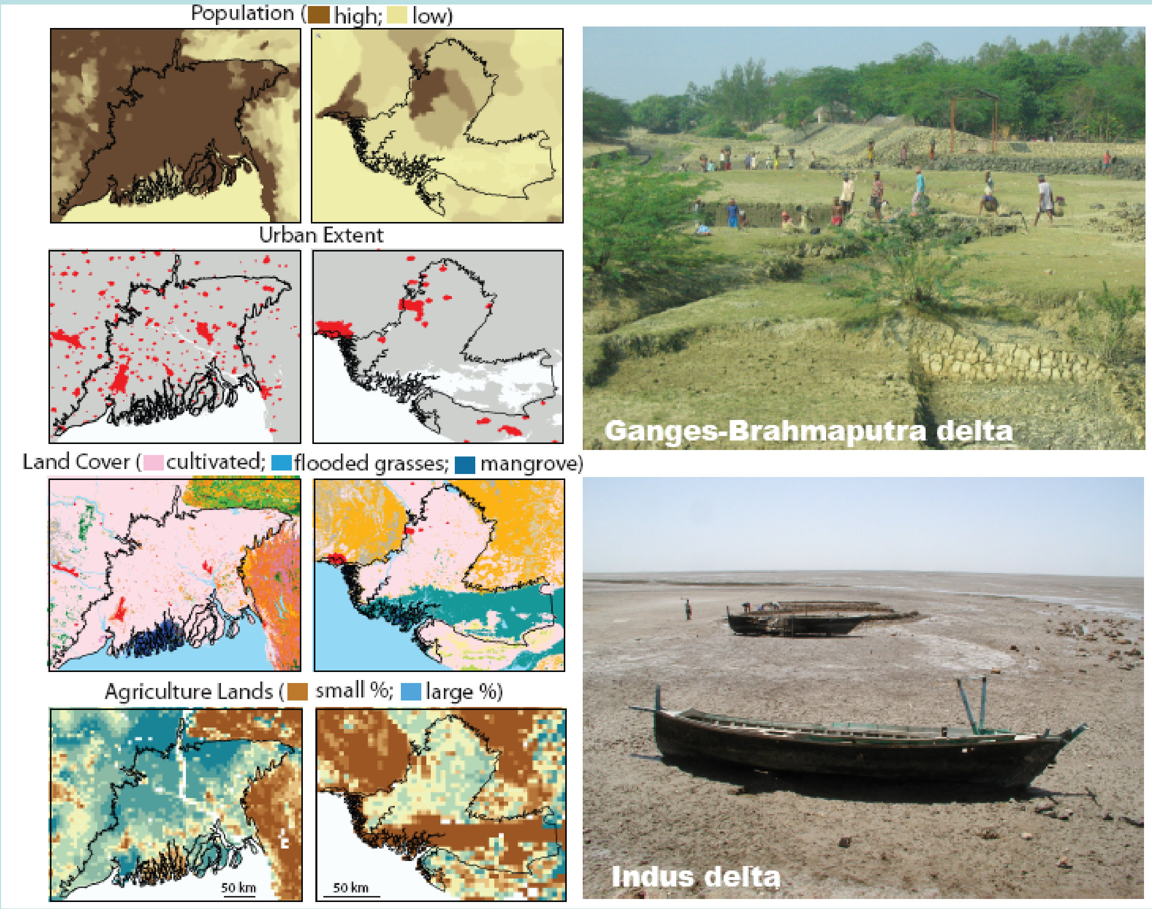
- Changes in the amounts and timing of the pulses of river water and sediment discharge and associated organic and organic solutes?
- Changes in land use within the drainage basins, and on the delta and its ecosystems itself, due to deforestation, conversion to agriculture, urbanization and aquaculture industry.
- Changes in channelization: humans are reducing the number of distributary channels and stabilizing their position; irrigation channels are replacing distributary channels. How does this affect areas in the delta sinking under sea level?
- Changes in relative sea level: eustatic, sea-level rise is a minor component of most of the factors affecting a deltas drowning, isostasy, natural and accelerated compaction, and the elimination of floodplain aggradation further enhances the sinking of deltas. Is a delta subject to accelerated compaction due to gas, petroleum or groundwater extractions?
- Changes in hurricanes: storm surges are a hurricane’s most destructive force. Hurricane intensity and rainfall are increasing with global warming so the question remains of the significance of this increase on the vulnerability of a delta.

CS8 Different population patterns in tropical Asian deltas

Alex de Sherbinin

The human factor in two contrasting deltas: the Ganges-Brahmaputra (left column) and the Indus (right column). While similarly controlled by tropical monsoonal discharge and affected by strong tides and cyclones, the Indus delta in Pakistan is far more arid compared to the Ganges-Brahma–putra delta in Bangladesh and India.

The population is significantly higher and more uniformly distributed in the Ganges-Brahmaputra delta compared to the Indus, where urban agglomerations are located at the periphery of the delta. Both deltas are cultivated to great extent, but extensive deterioration is noticeable in the land cover type of the lower Indus delta plain. Water reaching the delta is reduced to a trickle and extreme salinization prevails while irrigation agriculture is pursued in the upper delta plain. In contrast, a large sector of mangroves is still preserved in the Ganges-Brahmaputra delta. This area forms the Sunderbans National Park, a UNESCO World Heritage Site, and is home to ~250 threatened Bengal Tigers. Management solutions are likely to be very different for these two deltas (Gopal & Chauhan 2006, de Sherbinin et al. 2007).



***CS 10**: Figure based on unpublished data of A. de Sherbinin & A.J. Kettner. Data sources: CIESIN et al. 2004, 2005a, Bartholomé & Belward 2005, and Ramankutty et al. 2008.*

4.4 Coupling Morphodynamic Models with Geographic Information Systems

Prototype datasets of delta systems must involve a variety of locations to ensure that a balance of similarities and differences exist for comparability. One approach to better understanding the types of issues confronting deltas is to use Geographic Information Systems (GIS) to overlay delta "masks" with socioeconomic and infrastructure data sets to identify a typology of "densely populated deltas", "agricultural deltas", "deltas with extensive flood control and water management infrastructure", or "pristine deltas" (for example see Case Study 8).

Datasets to be used in such classifications would encompass physical parameters, like topography, climate, local sea-level changes, occurrence of extreme events as well as population density, Gross Domestic Product (GDP), but also land-use type, infrastructure, and urbanization. Many of these parameters would be generated from analysis of remotely-sensed data, like the detailed SRTM (Shuttle Radar Topography Mission) data.

Socioeconomic data like GDP, infant mortality rates, could potentially be used as quantitative correlates of human behavior, since wealthy socioeconomic systems presumably behave differently from poor ones. Wealthy socioeconomic systems may be more likely to have expensive and extensive engineering structures affecting delta morphodynamics, or more likely to have significant economic vulnerabilities. They may have predictably different decision-making systems or conflict resolution systems, or different attitudes to ecosystem dynamics. The relationship between GDP or other correlates with behavior are probably not linear. An important task under this approach would be to determine the form of the relationships between various quantitative indices of various types of human behavior. Hopefully, socioeconomic systems can be classified into relatively few categories so that relatively few models would be required. If all socioeconomic systems are unique, this approach will be challenging because it will require customized models for each delta system. That might nonetheless be the most scientifically accurate way of approaching the problem.

It will also be important to start gathering baseline data for deltas with limited understanding currently, to develop and test new methods for data collection, and ensure the transferability of techniques and approaches from well studied case studies to less studied locations.

To predict or evaluate the effects of local and regional socioeconomic measures on deltas it is of prime importance to simulate the physical and ecological formation and functioning of deltas. However, we also need GIS tools to forecast temporally and spatially varying effects of socioeconomic and restoration measures on deltas. This can be achieved by linking process-based models to a GIS-based modeling tool to evaluate scenarios of management measures (c.f. a "SimCity" for deltas) to calculate the morphodynamic and ecological effects of such scenarios. The coupling of these model systems would highlight the 'human poking' of the natural system. It is known that human poking affects changes in deposition and flow patterns. Applying the coupled model approach will shed light on the sustainability of the nearshore parts of the delta. This will also provide a framework to evaluate potential changes in ecosystem sustainability and potential changes in pollution pathways.

- Which global deltas are prograding, in equilibrium, receding or disintegrating?
- Can we engineer deltas to achieve higher elevation, as an alternative mitigation strategy to solve land surface loss?
- Is there a place for simple models to be distributed to decision makers? Can we provide scenario simulations to inform behavioral change?
- Is there a model requirement for standardizing the data collection, either for model initializations or boundary conditions, or for model validation?
- How best to employ scenario simulations to deal with uncertainty questions? How do we deal with and communicate and differentiate aliatory (not knowable) and epistemic (not known) uncertainty?

4.5 Vulnerability and Risk Mapping

As a first step, combined process modeling and GIS database analysis should help to construct of global-scale risk or vulnerability maps for deltas, such as those based on the well-established flood plain mapping or volcanic hazard mapping (Hayes et al. 2007). The US FEMA, the Federal Emergency Management Agency, provides river flood maps that show the spatial extent and depth of flooding for 10yr, 20yr, 50yr, 100yr, and 500yr flood events. FEMA maps are available for all deltas in the USA and similar maps exist for many other industrialized countries.

Other types of risk that might be mapped analogously could include subsidence risk, erosion risk, distributary channel avulsion risk, tsunami risk (Case Study 9), and sensitive ecosystems or species. The choice of risks to be mapped would focus our attention on what necessary data is available and what data requires development, and what types of models may be needed to develop a mapping methodology analogous to that used for floodplain mapping. The various maps of different types of risk/vulnerability could then be overlain to see if there are hotspots of risk/vulnerability, either on a global scale or a local scale.

CS9 Tsunami risk on the Fraser River Delta

Philip R. Hill

The Fraser River Delta, located on the Pacific coast of Canada, is the site of several suburban centers of Metro Vancouver and of major transportation infrastructure. The international airport and residential areas of the delta lie below high tide level and are protected against flooding by earthwork dykes. Recent research indicates that the delta plain is subsiding by an average of 1 to 2 mm yr-1 (Lambert et al. 2008). In this seismically active area, the risk of a tsunami causing sudden and extensive flooding is significant. There are three possible mechanisms for generating tsunamis in the area: 1) displacement on active faults in the Strait of Georgia, 2) movement related to subduction zone mega-thrust earthquakes in the offshore, and 3) submarine landslides.

Faults showing Holocene displacement of the seabed have been mapped in the Strait of Georgia (Barrie & Hill 2004), and Puget Sound (Atwater & Moore 1992). The return period of movement on these faults is long (>1000 years), but the potential displacement and resulting tsunami would be large. A tsunami generated by a mega-thrust earthquake on the offshore Cascadia subduction zone has a higher return period (500 -700 yrs) and would propagate into the Strait of Georgia. However, model simulations suggest that the tsunami waves would be dissipated by passage into the strait and would be unlikely to exceed 1 m in height on the Fraser Delta (Cherniawsky et al. 2007).

Deltas are well known as the sites of submarine landslides. Main Channel of the Fraser River has been fixed in place by training jetties since the 1930s (Luternauer & Finn 1983), which has resulted in local progradation and over-steepening of the delta slope. Sedimentation rates at the river mouth exceed 1 m yr-1 and small slope failures have occurred several times over the last 30 years (Hill, in press). There is also geological evidence on the delta slope for older slope failures of possibly larger scale (Mosher & Hamilton 1998). Numerical simulation of tsunami waves generated by delta slope landslides indicate that for the extreme case of a major collapse of the delta slope, waves up to 18 m high would propagate away from the delta front (Rabinovich et al. 2003). On the delta itself, wave heights would be attenuated by the extensive tidal flats, but would potentially be high enough to over-top the dikes.

The prospect of tsunamigenic slope failures is one of the motivations for incorporating sediment transport and slope stability instrumentation into the VENUS Submarine Observatory (http://www.venus.uvic.ca). A benthic lander instrumented with ADCP current meters, pencil lasers and scanning sonar has been deployed near the river mouth and will be on-line in March 2008. Acoustic piezometers capable of measuring in situ pore pressures and seismic wave loading will be deployed in September 2008.

One could also compare vulnerability maps for different scenarios of climate change, economic growth, or management (including management options to reduce risk). The advantage of pursuing the risk mapping approach is that the FEMA floodplain map example is well understood by governmental agencies and insurance companies so that analogs are likely to be quickly accepted and adopted (Wisner et al. 2004). While the practicality of this task will appeal to governments and business, development of the methodology for creating these maps will require development and synthesis of basic science.

- What delta areas in the world are vulnerable in the near future (50 - 200 years)? By running different scenarios (e.g. climate, sea-level change, subsidence, extreme events), can we unravel what makes deltas vulnerable and communicate that to development planners, managers, and politicians?
- Can a collapse threshold be established for each delta? How do multiple stresses combine to influence a collapse?
- What are the management strategies for deltas that cannot be returned to a "natural" state (such as the deltas hosting megacities) and those that can be protected from over-development?

4.6 Towards Sustainable Management of Deltas

Sustainable development has been defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Chambers & Conway 1992, WCED 1987, UNDP 1998). But in practice, what does this mean for a delta system? Day et al. (1997) define sustainability for deltas from three different points of view, geomorphic, ecological, and economic.

A deltaic landscape is geomorphically sustainable in the vertical dimension if the long-term net change in wetland surface elevation balances sea level change. From a horizontal perspective, a delta is sustainable if the total area does not decrease significantly. Deltas can be managed to withstand a moderate acceleration of sea level rise by increasing accretion. Accretion can be measured using marker horizons or Cs^{137} or Pb^{210} and elevation change can be measured with a sediment elevation table (Cahoon et al. 1995). Repeated detailed topographic surveying, such as LIDAR surveys, is another critical tool for assessment of accretion. The accretion rates are then compared to RSLR to determine if the area is sustainable.

A delta is ecologically sustainable if change in total net primary productivity over the decadal time scale is stable. Under natural conditions, deltaic productivity is maintained within an equilibrium range based on the total area of the delta and the relative proportions and productivities of different habitat types. Conversion of deltaic wetlands to open water or uplands will generally result in lower production because of the high productivity of wetlands. Many deltas have probably experienced decreasing NPP over time due to human activities. Estimates of total deltaic productivity can be determined from mapping temporal changes in the area and productivity of different habitat types. In the Mississippi delta, about 25% of the wetlands were lost in the 20th Century, mainly due to conversion to open water (Day et al. 2007). Clearly, much of the Mississippi delta is not ecologically sustainable at present. Deltas are one of the most complex ecosystem mosaics that are structured and maintained by discrete hydrogeomorphical processes. As a result, restoration of lost and degraded delta ecosystems demands a much more comprehensive, strategic approach than the "opportunistic" approaches that are typically applied to other ecosystems. Given the important role of naturally dynamic processes in structuring delta ecosystems, restoration planning needs to be organized around the spatially explicit nature of ecosystem processes. Selection and positioning restoration actions should consider physicochemical gradients and other non-linear distributions that influence how particular restoration actions will contribute to the overall delta system integrity and function. Delta restoration will not be effective if approached from a less systematic deployment of ecosystem creation, remediation or other attempts to 'engineer' delta processes and ecosystems.

A delta system is economically sustainable if the output of goods and services is greater than the economic inputs or subsidies required for production. Analysis of economic sustainability is complicated because economic activities supported by deltas, like shipping and fisheries, are often counted elsewhere and human populations dependent on deltas often do not live in deltas. Humans have lived in and around delta for millennia because of the benefits provided by deltas. In fact, it seems likely that most early civilizations arose in deltas and lower river valleys because of the rich food resources (Day et al. 2007). Major rivers brought transport and trade and thus economic wealth to populations living in and around deltas. Deltas and lower river valleys also provide rich resources of food and fiber and were places of productive agriculture. The costs of development in deltas were more than offset by the economic gains. Thus deltas were economically sustainable because of the subsidy provided by the physical and ecological energies of deltas. Many deltas, however, have degraded due to human impacts such as levees and impoundments and their net economic yield has decreased or is projected to decrease (e.g. Milliman et al. 1989). This has resulted in the substitution of human capital for natural capital with the benefits resulting from the use of human capital being more easily directed to certain groups or individuals. For example, bounding rivers by levees improved navigation and flood control thus subsidizing and benefiting those involved in these activities. However, a severe cost was incurred in that natural capital, i.e. the sediments in the river were no longer used to maintain the delta leading to loss of wetlands and the services they provide. Thus, the costs were externalized to those benefiting from the wetlands, i.e. fishermen, and the public commons. Templet (1998) showed that increasing human subsidies, which result from externalities, leads to poorer environmental and socioeconomic conditions and less sustainability. If, instead of substituting industrial energies for natural capital energy, we were to use the natural capital and industrial energies in reaching economic goals, then we would expend less to achieve more and be more sustainable. Practically, this means using man-made energies to engineer the system to allow the river's water and sediment and other energy pulses to sustain and build wetlands that then produce goods and services at lower cost.

Increasingly, more economists are incorporating goods and services with the environmental conditions and costs incurred with uses (Costanza et al. 2002, Daly 1994). Central to this thesis is the idea that economic estimates that incorporate environmental degradation reveal true costs of operating in those environments. This could ultimately result in better environmental management as a result of long-term economic incentives. In the case of deltas, determining economic stability is intimately tied to the existence of the delta itself, thus depending on geomorphic and ecological sustainability which are, in turn, often dependent on economic decisions.

- What are the human vulnerabilities in delta systems? How could the concepts from the best and most comprehensive vulnerability literature outlining theory and practice (Hewitt 1983, Lewis 1999, Oliver-Smith 1986, Wisner et al. 2004) be applied for deltas in general and for specific delta case studies?
- How could delta health be defined, described, and improved? How do ecosystem and human health interact in delta regions and how could that be influenced for mutual benefit?

- Where and when do social stresses overpower physical stresses, magnify physical stresses, and alleviate physical stresses on deltas?
- How are decision-making processes selected and enacted? How could all scales be addressed and connected for decisions, such as transboundary differences and upstream/downstream linkages?
- Can we assess delta restoration measures and ecological sustainability by evaluating delta food webs?
- Can we do cost analyses to determine the economical impact of potential vulnerability in delta areas?
- Can we develop 'sustainable development practices' to reduce human impacts to a minimum such that we are still able to live on deltas and are able to use the various resources that are available in deltas?

5 Conclusions

Deltas connect river drainage basins and the world oceans, and are inherently influenced by both physical domains. Both the river and the ocean nourish the delta system with fluxes of water, sediment and nutrients. Consequently, deltas are highly productive, ecologically rich systems and have been attractive areas for settlement of humans from the earliest civilizations. Deltas are immensely important for food production and aquaculture.

Today, an estimated 500 million people live in deltas. Many of the most densely populated areas are located in deltas; the Nile delta in Egypt, the Ganges-Brahmaputra delta in Bangladesh, the Yangtze and Pearl deltas in China, all have population densities exceeding 1000 people/km^2, as compared to a global average of 45 people/km^2.

Deltas are coastal lowlands and incorporate in their natural state extensive wetlands and large areas of low-relief river floodplain. This makes them highly susceptible to changes of sea level and prominent examples of areas at risk due to greenhouse warming. The International Panel of Climate Change first recognized this vulnerability in the latest 2007 report. Already, thirty-three major deltas collectively include ~26,000 km^2 of area below local mean sea level and ~96,000 km^2 of vulnerable area below 2 m. This vulnerable area may increase 50% under the mean projected 21st Century eustatic sea level rise of 0.44 m. Thus, accelerated sea-level rise poses an immediate and serious threat to delta natural habitats and to the people living in these low-lying areas.

But deltas are not solely threatened by eustatic or steric sea-level rise. Deltas are extremely dynamic and variable, based on the constructive feeding river and destructive ocean forces. If the balance of the constructive and destructive processes only modestly changes, irreversible collapse may occur.

Human influences on the feeding river system are complex and unique to different regions. Even the directionality of the impact may be different from region to region. In dry drainage basins, large irrigation projects take away water that traditionally nourished the delta region, like the

Indus delta or the Nile delta. Global scale reservoir construction induces tremendous sediment storage and deprives deltas from a feeding pulse of sediment. Recent modeling studies suggest that nearly one-third of all sediment that would have reached the coast under pristine conditions, is now being trapped on land. However, humans increase sediment supply by rivers as well, by intense agricultural practices, deforestation and mining. A dramatic example of such increase is the farming on the erodible loess plateau in the Yellow River drainage basin, which increased sediment loads to the river tenfold. Globally, reductions of water and sediment load appear prevalent; a study of observed time-series of 150 systems indicates that 68 basins show reduction of water and sediment loads, whereas only 4 showed increase over time.

In the delta area itself, humans have stabilized channels with levees, and tried to harness the dynamical delta system itself with adverse effects. Similarly, coastal protection engineering has stabilized the coastline locally and often inhibits natural dynamics of the delta fringe. Such measures often cause a loss of natural habitat for fish and wildlife. The Mississippi river delta experiences large wetland losses due to subsidence and reduced flooding and sediment aggradation as a result of hydraulic engineering. Changes to the natural delta channel dimensions may have been a critical factor in the amount of flooding that New Orleans suffered as a result of Hurricane Katrina in 2005 (Day & Boesch 2007).

The topography of low-lying areas of deltas is influenced by natural compaction and tectonics. In addition, groundwater or hydrocarbon extraction can cause accelerated subsidence and thus increase the relative sea-level rise. The Po Delta has subsided 3.7 m in the 20th Century, of which 81% is attributed to methane mining. After the cessation of methane extraction, the rate slowed to <25 mm/y by 1970, and by the 1990's the subsidence rate was ≤4 mm/y. When assessing the relative sea-level rise for a specific delta one needs to take into account the entire budget of incoming river sediment causing surface aggradation, natural and human-induced subsidence, as well as eustatic sea-level rise.

Vulnerability and sustainability of deltas can be measured in terms of geomorphic, ecological, and economic sustainability.

1. A deltaic landscape is geomorphically sustainable if the long-term net change in wetland surface elevation balances sea-level change.
2. A delta is ecologically sustainable if change in total productivity over the decadal time scale is stable, and the relative proportions and productivities of different habitat types remain constant.
3. A delta system is economically sustainable if the output of goods and services is greater than the economic inputs or subsidies required for production.

To monitor and study these different aspect this report calls for a multi-disciplinary, problem-driven approach with experts from the fields of engineering, ecology, geography and human dimensions. The technology envisioned for an integrated framework for delta research and management incorporates morphological models that predict natural delta dynamics as a function of changing processes, combined with GIS tools that help exploring socioeconomic scenarios. Risk mapping would then include a variety of parameters like risk of flooding due to river floods, risk associated with tsunamis and hurricanes, risk of accelerated subsidence, risk of habitat loss for threatened species. 'Human Poking' of the delta system should be explored with this tool and help make management decisions that invoke all different aspects of sustainability of delta regions.

A large, integrated community effort is sought to bring intellectual resources to address the urgent issues raised in this document. Organizations such as the Global Water Systems Project, the Community Surface Dynamic Modeling System, and the Land-Ocean Interactions in the Coastal Zone Project have begun to gather these intellectual resources. Other partners are being sought to address the urgent needs of our world deltas and their vulnerabilities, resilience and risks.

6 References

Alvarado, M. (2005): Cartagena y el plan de restauración ambiental del Canal del Dique, y Barranquiilla y las obras de profundización del canal navegable de acceso a la zona portuaria: Visión general. In: Restrepo, J.D. (eds.): Los Sedimentos del Río Magdalena: Reflejo de la Crisis Ambiental. EAFIT University Press, Medellín, pp. 217-254.

Arpe, K.; Bengtsson, L.; Golitsyn, G.S.; Mokhov, I.I.; Semenov, V.A. & Sporyshev, P.V. (2000): Connection between Caspian sea level variability and ENSO. *Geophysical Research Letters* 27 (17): 2693-2696.

Atwater, B.F. & Moore, A.L. (1992): A Tsunami about 1000 years ago in Puget Sound, Washington. *Science* 258 (5088): 1614-1617.

Barras, J.A. (2006): Land area change in coastal Louisiana after the 2005 hurricanes: a series of three maps. USGS Open file Report 2006-1274.

Barrie, J.V. & Hill, P.R. (2004): Holocene faulting on a tectonic margin: Georgia Basin, British Columbia, Canada. *Geo-Marine Letters* 24 (2): 86-96.

Bartholomé, E. & Belward, A.S. (2005): GLC2000: a new approach to global land cover mapping from earth observation data. *International Journal of Remote Sensing* (26): 1959-1977.

Baumann, R.H.; Day, J.W. Jr. & Miller, C.A. (1984): Mississippi deltaic wetland survival: sedimentation versus coastal submergence. *Science* 224 (4653): 1093-1095.

Bindoff, N.L.; Willebrand, J.; Artale, V.; Cazenave, A.; Gregory, J.; Gulev, S.; Hanawa, K.; Le Quéré, C.; Levitus, S.; Nojiri, Y.; Shum, C.K.; Talley, L.D. & Unnikrishnan, A. (2007): Observations: oceanic climate change and sea level. In: Solomon, S.; Qin, D.; Manning, M.; Chen, Z.; Marquis, M.; Averyt, K.B.; Tignor, M. & Miller, H.L. (eds.): Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 385-432.

Bondesan, M.; Favero, V. & Vinals, M.J. (1995): New evidence on the evolution of the Po-delta coastal plain during the Holocene. *Quaternary International* (29-30): 105-110.

Bondesan, M. & Simeoni, U. (1983): Dinamica e analisi morfologica statistica dei litorali del delta del Po e alle foci dell'Adige e del Brenta. Memorie di Scienze Geologiche, Padova (36): 1-48.

Bourne, J. (2000): Louisiana's vanishing wetlands: going, going ... *Science* 289 (5486): 1860-1863.

Boynton, W.R.; Kemp, W.M. & Keefe, C.W. (1982): A comparative analysis of nutrients and other factors influencing estuarine phytoplankton production. In: Kennedy, V.S. (ed.): Estuarine comparisons. Academic Press, New York, pp. 69-90.

Cahoon, D.; Reed, D. & Day, J. (1995): Estimating shallow subsidence in microtidal salt marshes of the southeastern United States: Kaye and Barghoorn revisited. *Marine Geology* (128): 1-9.

Cairns, M.A.; Dirzo, R. & Zadroga, F. (1995): Forests of Mexico: a diminishing resource? *Journal of Forestry* (93): 21-24.

Caputo, M.; Pieri, L. & Unguendoli, M. (1970): Geometric investigation of the subsidence in the Po Delta. *Bollettino di Geofisica Teorica ed Applicata* 13 (47): 187-207.

Carminati, E. & Martinelli, G. (2002): Subsidence rates in the Po Plain, northern Italy: the relative impact of natural and anthropogenic causation. *Engineering Geology* (66): 241-255.

Center for International Earth Science Information Network (CIESIN), Columbia University; International Food Policy Research Institute (IFPRI); The World Bank; and Centro Internacional de Agricultura Tropical (CIAT) (2004): Global Rural-Urban Mapping Project (GRUMP), Alpha Version: Urban Extents. Palisades, NY: Socioeconomic Data and Applications Center (SEDAC), Columbia University. Available at http://sedac.ciesin.columbia.edu/gpw. (downloaded 07-07).

Center for International Earth Science Information Network (CIESIN), Columbia University; and Centro Internacional de Agricultura Tropical (CIAT) (2005a): Gridded Population of the World Version 3 (GPWv3): Population Grids. Palisades, NY: Socioeconomic Data and Applications Center (SEDAC), Columbia University. Available at http://sedac.ciesin.columbia.edu/gpw. (downloaded 07-07).

Center for International Earth Science Information Network (CIESIN), Columbia University; and Centro Internacional de Agricultura Tropical (CIAT) (2005b): Gridded Population of the World Version 3 (GPWv3): Population Density Grids. Palisades, NY: Socioeconomic Data and Applications Center (SEDAC), Columbia University. Available at http://sedac.ciesin.columbia.edu/gpw. (downloaded 07-07).

Center for International Earth Science Information Network (CIESIN), Columbia University; United Nations Food and Agriculture Programme (FAO); and Centro Internacional de Agricultura Tropical (CIAT) (2005c): Gridded Population of the World: Future Estimates, 2015 (GPW2015): Population Grids. Palisades, NY: Socioeconomic Data and Applications Center (SEDAC), Columbia University. Available at http://sedac.ciesin.columbia.edu/gpw. (downloaded 07-07).

Chambers, R. (2002): Participatory workshops: a sourcebook of 21 sets of ideas and activities. Institute of Development Studies, University of Sussex, Brighton, UK.

Chambers, R. & Conway, G.R. (1992): Sustainable rural livelihoods: practical concepts for the 21st Century. Discussion Paper 296, Institute of Development Studies, University of Sussex, Brighton, UK.

Cherniawsky, J.Y.; Titov, V.V.; Wang, K. & Li., J.-Y. (2007): Numerical simulations of tsunami waves and currents for southern Vancouver Island from a Cascadia megathrust earthquake. *Pure and Applied Geophysics* 164 (2-3): 465-492.

Clark, J.S. (1986): Coastal forest tree populations in a changing environment, southeastern Long Island, New York. *Ecological Monographs* (56): 259-277.

Coleman, J.M. & Wright, L.D. (1975): Modern river deltas: variability of processes and sand bodies. In: Broussard, M. (ed.): Deltas: models for exploration. Houston Geological Society, pp. 99-149.

Coleman, J.M.; Huh, O.K. & Braud, D. (2008): Wetland loss in world deltas. *Journal of Coastal Research* 24 (1a): 1-14.

Collins B.D. & Sheikh, A.J. (2005): Historical reconstruction, classification and change analysis of Puget Sound tidal marshes. Final project report to Washington Department of Natural Resources Aquatic Resources Division, Olympia, WA.

Coops, H.; Buijse, L.L.; Buijse, A.D.; Constantinescu, A.; Covallov, S.; Hanganu, J.; Ibelings, B.W.; Menting, G.; Navodaru, I.; Oosterberg, W.; Staras, M. & Török, L. (2008): Trophic gradients in a large-river delta: ecological structure determined by connectivity gradients in the Danube Delta (Romania). *River Research and Applications* 24 (5): 698-709.

Costanza, R.; Farley, J. & Templet, P. (2002): Quality of life and the distribution of wealth and resources, In: Costanza, R. & Jorgensen, S.E. (eds.): Understanding and solving environmental problems in the 21st Century. Elsevier, Amsterdam, pp. 221-258.

Daly, H.E. (1994): Fostering environmentally sustainable development: four parting suggestions for the World Bank. *Ecological Economics* 10 (3): 183-187.

Davis, D.W. (2000): Historical perspective on crevasses, levees, and the Mississippi River. In: Colten, C.E. (ed.): Transforming New Orleans and its environs: centuries of changes. University of Pittsburgh Press, Pittsburgh, pp. 84-106.

Day, J.W. & Templet, P. (1989): Consequences of sea level rise: implications from the Mississippi delta. *Coastal Management* (17): 241-257.

Day, J.W. & Boesch, D.F. (2007): Restoration of the Mississippi delta: lessons from hurricanes Katrina and Rita. *Science* 315 (5819): 1679-1684.

Day, J.W.; Pont, D.; Hensel, P. & Ibanez, C. (1995): Impacts of sea level rise on deltas in the Gulf of Mexico and the Mediterranean: the importance of pulsing events to sustainability. *Estuaries* (18): 636-647.

Day, J.W.; Martin, J.F.; Cardoch, L. & Templet, P.H. (1997): System functioning as a basis for sustainable management of deltaic ecosystems. *Coastal Management* (25): 115-153.

Day, J.W.; Britsch, L.D.; Hawes, S.R.; Shaffer, G.P.; Reed, D.J. & Cahoon, D. (2000): Pattern and process of land loss in the Mississippi Delta: A Spatial and temporal analysis of wetland habitat change. *Estuaries and Coasts* (23): 425-438.

Day, J.W.; Gunn, J.D.; Folan, W.J.; Yanez-Arancibia, A. & Horton, B.P. (2007): Emergence of complex societies after sea level stabilized. *EOS-AGU Transactions* 88 (15): 169-170.

de Sherbinin, A.; Schiller, A. & Pulsipher, A. (2007): The vulnerability of global cities to climate hazards. *Environment and Urbanization* 19 (1): 39-64.

Doyle, M.W.; Harbor, J.M. & Stanley E.H. (2003a): Toward policies and decision-making for dam removal. *Environmental Management* 31 (4): 453-465.

Doyle, M.W.; Stanley, E.H. & Harbor, J.M. (2003b): Channel adjustments following two dam removals in Wisconsin. *Water Resources Research* 39 (1): 1011.

Elvira, B. (1995): Conservation status of endemic freshwater fish in Spain. *Biological Conservation* 72 (2): 129-136.

Ericson, J.P.; Vörösmarty, C.J.; Dingman, S.L.; Ward, L.G. & Meybeck, M. (2006): Effective sea-level rise and deltas: causes of change and human dimension implications. *Global and Planetary Change* (50): 63-82.

Fan, H. & Huang, H. (2008): Response of coastal marine eco-environment to river fluxes into the sea: A case study of the Huanghe (Yellow) River mouth and adjacent waters. *Marine Environmental Research* 65 (5): 378-387.

Galloway, W.E. (1975): Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems. In: Broussard, M.L. (ed.): Deltas, Models of exploration. Houston Geological Society, Houston, pp. 87-98.

Giosan, L. & Bhattacharya, J.P. (eds.), (2005): River deltas: concepts, models, and examples, SEPM (Society for Sedimentary Geology) Special Publication 83, 502 p.

Giosan, L.; Constantinescu, S.; Clift, P.D.; Tabrez, A.R.; Danish, M. & Inam, A. (2006): Recent morphodynamics of the Indus delta shore and shelf. *Continental Shelf Research* (26): 1668-1684.

Glantz, M.H. (2003): Usable science 8: early warning systems: do's and don'ts. Report of workshop, 20-23 October 2003, Shanghai, China. Boulder, CO: National Center for Atmospheric Research. (http://www.ccb.ucar.edu/warning/report.html)

Glantz, M.H. (2004): Usable Science 9: El Niño early warning for sustainable development in Pacific rim countries and islands, report of workshop, 13-16 September 2004, the Galapagos Islands, Ecuador. Boulder, CO: National Center for Atmospheric Research. (http://www.ccb.ucar.edu/galapagos/report)

Gopal, B. & Chauhan. M. (2006): Biodiversity and its conservation in the Sundarban mangrove ecosystem. *Aquatic Sciences* (68) 338-354.

Gornitz, V.; Lebedeff, S. & Hansen, J. (1982): Global sea level trend in the past century. *Science* 215 (4540): 1611.

Gruntfest, E.C.; Downing, T.E. & White, G.F. (1978): Big Thompson flood exposes need for better flood reaction system to save lives. *Civil Engineering* (48): 72-73.

Hackney, C.T. & Cleary W.J. (1987): Saltmarsh loss in southeastern North Carolina lagoons: importance of sea level rise and inlet dredging. *Journal of Coastal Research* (3): 93-97.

Haynes, K.; Barclay, J. & Pidgeon, N. (2007): Volcanic hazard communication using maps: an evaluation of their effectiveness. *Bulletin of Volcanology* 70 (2): 123-138.

Hensel P.F.; Day J.W. & Pont D. (1999): Wetland vertical accretion and soil elevation change in the Rhône River delta, France: the importance of riverine flooding. *Journal of Coastal Research* 15 (3): 668-681.

Hewitt K. (1983): Interpretations of calamity from the viewpoint of human ecology. Allen and Unwin, London.

Hill, P.R. (in press): Changes in submarine channel morphology and strata development from repeat multibeam surveys in the Fraser River delta, western Canada. In: Li, M.; Hill, P.R. & Sherwood, C. (eds.): International Association of Sedimentologists, Special Publication.

Holland, G.J. & Webster, P.J. (2007): Heightened tropical cyclone activity in the North Atlantic: natural variability or climate trend. Philosophical *Transactions of the Royal Society of London - A: Mathematical, Physical, and Engineering Sciences* 365 (1860): 2695-2716.

Holmes, D.A. (1968): The recent history of the Indus. *Geographical Journal* (134): 367-382.

Hood W.G. (2004): Indirect environmental effects of dikes on estuarine tidal channels: thinking outside of the dike for habitat restoration and monitoring. *Estuaries* (27): 273-282.

Ibáñez, C.; Prat, N. & Canicio, N. (1996): Changes in the hydrology and sediment transport produced by large dams on the lower Ebro River and its estuary. *Regular Rivers: Research & Management* 12 (1): 51-62.

Ibáñez, C.; Curcó, A.; Day, J.W. & Prat, N. (2000): Structure and productivity of microtidal Mediterranean coastal marshes. In: Weinstein, M.P. & Kreeger, D.A. (eds.): Concepts and controversies in tidal marsh ecology. Dordrecht, Kluwer.

Junk, W.J.; Bayley, P.B. & Sparks, R.E. (1989): The flood pulse concept in river-floodplain systems. In: Dodge, D.P. (ed.): Proceedings of the International Large River Symposium. Canadian Special Publications of Fisheries and Aquatic Sciences (106): 110-127.

Kana, T.W.; Baca, B.J. & Williams, M.L. (1986): Potential impacts of sea level rise on wetlands around Charleston, South Carolina. U. S. Environmental Protection Agency, EPA 230-10-85-014. 65 pp.

Kelman, I. (2006): Warning for the 26 December 2004 Tsunamis. *Disaster Prevention and Management* (15): 178-189.

Kesel, R.H. (1989): The role of the Mississippi River in wetland loss in Southeastern Louisiana, USA. *Environmental Geology and Water Sciences* (133): 183-193.

Kideys, A.E. (2002): Fall and rise of the Black Sea ecosystem. *Science* 297 (5586): 1482-1484.

Knutson, T.R.; Sirutis, J.J.; Garner, S.T.; Vecchi, G.A. & Held, I.M. (2008): Simulated reduction in Atlantic hurricane frequency under twenty-first-century warming conditions. *Nature Geoscience* (1): 359-364.

Kubo, Y.; Syvitski, J.P.M.; Hutton, E.W.H. & Kettner, A.J. (2006): Inverse modeling of post last glacial maximum transgressive sedimentation using 2D-SedFlux: application to the northern Adriatic Sea. *Marine Geology* (234): 233-243.

L'Homer, A.; Bazile, F.; Thommeret, J. & Thommeret, Y. (1981): Principales étapes de l'édification du delta du Rhône de 7000 BP à nos jours; variations du niveau marin. *Oceanis* 7 (4): 389-408.

Lambert, A.; Mazzotti, S.; van der Kooij, M. & Mainville, A. (2008): Subsidence and relative sea level rise in the Fraser River Delta, Greater Vancouver, British Columbia, from combined geodetic data, Geological Survey of Canada, Open File 5698, 44p.

Lewis, J. (1999): Development in disaster-prone places: studies of vulnerability. Intermediate Technology Publications, London.

Luternauer, J.L. & Finn, W.D.L. (1983): Stability of the Fraser River delta front. *Canadian Geotechnical Journal* (20): 603-616.

Meybeck, M.; Dürr, H.H. & Vörösmarty, C.J. (2006): Global coastal segregation and its river catchment contributors: a new look at land-ocean linkage. *Global Biogeochemical Cycles* (20): GB1S90, doi:10.1029/2005GB002540.

Milliman, J.D.; Broadus, J.M. & Gable, F. (1989): Environmental and economic implications of rising sea level and subsidence deltas: The Nile and Bengal examples. *AMBIO* (18): 340-345.

Milne, G.A. & Mitrovica, J.X. (2008): Searching for eustasy in deglacial sea-level histories. *Quaternary Science Reviews* 27 (25-26): 2292-2302.

Morton, R.A.; Tiling, G. & Ferina, N.F. (2003): Causes of hotspot wetland loss in the Mississippi delta plain. *Environmental Geosciences* 10 (2): 71-80.

Morton, R.A.; Bernier, J.C.; Barras, J.A. & Ferina, N.F. (2005): Rapid subsidence and historical wetland loss in the Mississippi Delta Plain: likely causes and future implications. USGS Open-File Report, 2005-1216.

Mosher, D.C. & Hamilton, T.S. (1998): Morphology, structure, and stratigraphy of the offshore Fraser delta and adjacent Strait of Georgia. In: Clague, J.J.; Luternauer, J.L. & Moosher, D.C. (eds.): Geology and natural hazards of the Fraser River delta, B.C. Geological Survey of Canada, Bulletin 525: 147-160.

Naiman, R.J.; Bunn, S.E.; Nilsson, C.; Petts, G.E.; Pinay, G. & Thompson, L.C. (2002): Legitimizing fluvial ecosystems as users of water: an overview. *Environmental Management* 30 (4): 455-467.

Newmarch, G. (1981): Subsidence of organic soils. *California Geology* 34 (7): 135-138.

Nicholls, R.J.; Wong, P.P.; Burkett, V.R.; Codignotto, J.O.; Hay, J.E.; McLean, R.F.; Ragoonaden, S. & Woodroffe, C.D. (2007): Coastal systems and low-lying areas, Climate Change 2007: impacts, adaptation and vulnerability. In: Parry, M.L.; Canziani, O.F.; Palulutikof, J.P.; van der Linden, P.J. & Hanson, C.E. (eds.): Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp.315-356.

Nixon, S.W. (1982): Nutrient dynamics, primary production and fisheries yields of lagoons. *Oceanologica Acta* (4): 357-371.

Okey, C. (1918): The subsidence of muck and peat soils in southern Louisiana and Florida. *Transactions of the American Society of Civil Engineers* (82): 396-422.

Oliver-Smith, A. (1986): The martyred city: death and rebirth in the Andes. University of New Mexico Press, Albuquerque.

Oro, D.; Ruiz, X.; Jover, L.; Pedrocchi, V. & González-Solís, J. (1997): Diet and adult time budgets of audouin's gull Larus audouinii in response to changes in commercial fisheries. *Ibis* 139 (4): 631-637.

Osborne, P.L. (2000): Tropical ecosystems and ecological concepts. Cambridge University Press, Cambridge.

Overeem, I. & Syvitski, J.P.M. (2008): Changing sediment supply in Arctic rivers. In: Schmidt, J.; Cochrane, T.; Phillips, C.; Elliott, S.; Davies, T. & Basher, L. (eds.): Sediment dynamics in changing environments. IAHS Publication 325: 391-397.

Overeem, I., Kroonenberg, S.B., Veldkamp, A., Groenesteijn, K., Rusakov, G.V.† & Svitoch, A.A. (2003a). Small-scale stratigraphy in a large ramp delta:recent and Holocene sedimentation in the Volga delta, Caspian Sea. Sedimentary Geology, 159, 133-157.

Overeem, I.; Veldkamp, A.; Tebbens, L. & Kroonenberg, S.B. (2003b): Modelling Holocene stratigraphy and depocentre migration of the Volga delta due to Caspian Sea-level change. *Sedimentary Geology* (159): 159-175.

Overeem, I.; Syvitski, J.P.M. & Hutton, E.W.H. (2005): Three-dimensional numerical modeling of deltas. In: Giosan, L. & Bhattacharya, J.P. (eds.): River deltas: concepts, models, and examples. SEPM Special Publication (83): 13-30.

Paola, C. (2000): Quantitative models of sedimentary basin filling. *Sedimentology* (47): 121-178.

Phillips, J.D. & Slattery, M.C. (2006): Sediment storage, sea level, and sediment delivery to the ocean by coastal plain rivers. *Progress in Physical Geography* 30 (4): 513-530.

Poff, N.L.; Bledsoe, B.P. & Cuhaclyan, C.O. (2006a): Hydrologic variation with land use across the contiguous United States: geomorphic and ecological consequences for stream ecosystems. *Geomorphology* (79): 264-285.

Poff, N.L.; Olden J.D.; Pepin, D.M. & Bledsoe, B.P. (2006b): Placing global stream flow variability in geographic and geomorphic contexts. *River Research and Applications* (22): 149-166.

Postma, G. (1995): Causes of architectural variations in deltas. In: Oti, M.N. & Postma, G. (eds.): Geology of deltas. Balkema, Rotterdam, pp. 3-16.

Rabinovich, A.B.; Thomson, R.E.; Bornhold, B.D.; Fine, I.V. & Kulikov, E.A. (2003): Numerical modelling of Tsunamis generated by hypothetical landslides in the Strait of Georgia, British Columbia. *Pure applied Geophysics* 160 (7): 1273-1313.

Rahmstorf, S. (2007): A semi-empirical approach to projecting future sea-level rise. *Science* 315 (5846): 368-370.

Ramankutty, N.; Evan, A.T.; Monfreda, C. & Foley, J.A. (2008): Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Global Biogeochemical Cycles* (22), GB1003, doi:10.1029/2007GB002952

Ren, M. & Walker, H.J. (1998): Environmental consequences of human activity on the Yellow River and its delta, China. *Physical Geography* 19 (5): 421-478.

Restrepo, J.D. (2008): Applicability of LOICZ catchment-coast continuum in a major Caribbean basin: the Magdalena River, Colombia. *Estuarine, Coastal and Shelf Science* (77): 214-229.

Restrepo, J.D.; Kjerfve, B.; Correa, I.D. & González, J.L. (2002): Morphodynamics of a high discharge tropical delta, San Juan River, Pacific coast of Colombia. *Marine Geology* (192): 355-381.

Restrepo, J.D. & Syvitski, J.P.M. (2006): Assessing the effect of natural controls and land use change on sediment yield in a major Andean river: the Magdalena drainage basin, Colombia. *Ambio* (35): 44-53.

Richards, J.F. (1990): Agricultural impacts in tropical wetlands: rice paddies for mangroves in South and Southeast Asia. In: Williams, M. (ed.): Wetlands: a threatened landscape. IBG Special Publication 26, pp. 217-233.

Roberts, H.H. (1997): Dynamic changes of the Holocene Mississippi river delta plain: the delta cycle. *Journal of Coastal Research* (13): 605-627.

Roberts, H.H. (1998): Delta switching: early responses to the Atchafalaya river diversion. *Journal of Coastal Research* (14): 882-899.

Salinas, L.M.; DeLaune, R.D. & Patrick W.H. Jr. (1986): Changes occurring along a rapidly subsiding coastal area: Louisiana, USA. *Journal of Coastal Research* (2): 269-284.

Sayer, J.A. & Whitmore, T.C. (1991): Tropical moist forests destruction and species extinction. *Biological Conservation* (55): 199-213.

Schiermeier, Q. (2004): Ukraine deluged by protests over plans for the Danube delta. *Nature* (431): doi:10.1038/431727a.

Schmidt, K.F. (2001): A true-blue vision for the Danube. *Science* (294): 1444-1447.

Sestini, G. (1992): Implications of climatic changes for the Nile delta. In: Jeftic, L.; Milliman, J.D. & Sestini, G. (eds.): Climatic change and the Mediterranean. Edward Arnold, London, pp. 535-601.

Simeoni, U.; Fontolan, G.; Tessari, U. & Corbau, C. (2007): Domains of spit evolution in the Goro area, Po Delta, Italy. *Geomorphology* (86): 332-348.

Sostoa, A. & Sostoa, F.J. (1985): The fish communities of the Ebro Delta (Northeast Spain): a model of Mediterranean estuarine ecosystem. In: Yáñez-Arancibia, A. (ed.): Fish community ecology in estuaries and coastal lagoons: towards an ecosystem integration. UNAM Press, México, pp 79-126.

Stanley, D.J. (1988): Subsidence in the northeastern Nile delta: rapid rates, possible causes, and consequences. *Science* (240): 497-500.

Stanley, D.J. & Warne, A. (1993): Nile delta: recent geological evolution and human impacts. *Science* (260): 628-634.

Stevenson, J.C.; Kearney, M.S. & Pendleton, E.C. (1985): Sedimentation and erosion in a Chesapeake bay brackish marsh system. *Marine Geology* (67): 213-235.

Syvitski, J.P.M. (2008): Deltas at Risk. *Sustainability Science* (3): 23-32.

Syvitski, J.P.M. & Kettner, A.J. (2007): On the flux of water and sediment into the Northern Adriatic. *Continental Shelf Research* (27): 296-308.

Syvitski, J.P.M. & Saito, Y. (2007): Morphodynamics of deltas under the influence of humans. *Global and Planetary Changes* (57): 261-282.

Syvitski, J.P.M.; Kettner, A.J.; Hannon, M. T.; Hutton, E.W.H.; Overeem, I.; Brakenridge, G.R.; Day, J.; Vörösmarty, C.; Saito, Y.; Giosan, L. & Nicholls, R.J. (submitted): Sinking deltas. *Nature Geoscience.*

Syvitski, J.P.M.; Vörösmarty, C.J.; Kettner, A.J. & Green, P. (2005a): Impacts of humans on the flux of terrestrial sediment to the global coastal ocean. Science (308): 376-380.

Syvitski, J.P.M.; Harvey, N.; Wolanski, E.; Burnett, W.C.; Perillo, G.M.E. & Gornitz, V. (2005b): Dynamics of the coastal zone. In: Crossland, C. J.; Kremer, H.H.; Lindeboom, H.J.; Marshall, J.I. & Le Tissier, M.D.A. (eds.): Global fluxes in the Anthropocene. Springer, Berlin, pp. 39-94.

Templet, P.H. (1998): The neglected benefits of protecting ecological services: a commentary provided to the ecological economics forum. *Ecological Economics* 25 (1): 53-55.

Törnqvist, T.E.; Kidder, T.R.; Autin, W.H.; van der Borg, K.; de Jong, A.F.M.; Klerks, C.J.W.; Snijders, M.A.; Storms, J.E.A.; van Dam, R. & Wiemann, M.C. (1996): A revised chronology for Mississippi River subdeltas. *Science* (273): 1693-1696.

UN (2005): Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, World Population Prospects: The 2006 Revision and World Urbanization Prospects: The 2005 Revision.

UNDP (1998): Integrating human rights with sustainable human development: A UNDP policy document. United Nations Development Programme, New York.

van Heerden, I. Ll. & Roberts, H.H. (1980): The Atchafalaya delta: rapid progradation along a traditionally retreating coast (south central Louisiana). *Zeitschrift für Geomorphologie* (34): 188-201.

Vannote, R.L.; Minshall, G.W.; Cummins, K.W.; Sedell, J.R. & Cushing, C.E. (1980): The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences* (37): 130-137.

Vaughan, D.G. & Spouge, J.R. (2002): Risk estimation of collapse of the West Antarctic ice sheet. *Climatic Change* (52): 65-91.

Vecchi G.A. & Soden, B.J. (2007): Increased tropical Atlantic wind shear in model projections of global warming. *Geophysical Research Letters* (34): L08702, doi:10.1029/2006GL028905.

Vörösmarty, C.J. & Sahagian, D. (2000): Anthropogenic disturbance of the terrestrial water cycle. *Bioscience* 50 (9): 753-765.

Vörösmarty, C.J.; Meybeck, M.; Fekete, B.; Sharma, K.; Green, P. & Syvitski, J.P.M. (2003): Anthropogenic sediment retention: major global-scale impact from the population of registered impoundments. *Global and Planetary Change* 39 (1-2): 169-190.

Vörösmarty, C.J.; Syvitski, J.P.M.; Day, J., de Sherbinin, A.; Giosan, L. & Paola, C. (2009): Battling to save the world's river deltas. *Bulletin of the Atomic Scientists* (65): 31-43.

Walling, D.E. & Fang, D. (2003): Recent trends in the suspended sediment loads of the world's rivers.

Global Planetary Change (39): 111-126.

Walling, D.E. (2006): Human impact on land-ocean sediment transfer by the world's rivers. *Geomorphology* (79): 192-216.

Wang, H.; Yang, Z.; Saito, Y.; Liu, J.P. & Sun X. (2007): Stepwise decreases of the Huanghe (Yellow River) sediment load (1950–2004): impacts from climate changes and human activities. *Global Planetary Change* (57): 331-354.

Warrick, R.A. & Oerlemans, J. (1990): Sea level rise. Cambridge University Press, Cambridge.

WCED (1987): Our common future. Oxford University Press, Oxford.

Webster, P.J.; Holland, G.J.; Curry, J.A. & Chang, H.-R. (2005): Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* 309 (5742): 1844-1846.

Weir, W.W. (1950): Subsidence of peat lands of the Sacramento-San Joaquin Delta, California. *Hilgardia* (20): 37-56.

Wells, J.T. & Coleman, J.M. (1987): Wetland loss and the subdelta life cycle. *Estuarine, Coastal and Shelf Science* (25): 111-125.

Wisner, B.; Blaikie, P.; Cannon, T. & Davis, I. (2004): At risk: natural hazards, people's vulnerability and disasters. 2nd ed., Routledge, London.

Wong, C.M.; Williams, C.E.; Pittock, J.; Collier, U. & Schelle, P. (2007): World's top 10 rivers at risk. WWF International. Gland, Switzerland.

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