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Battling to save the world's river deltas

The fragility of the world's deltas is not solely a consequence of rising ocean waters. Human fresh water use is a predominant force behind receding coastlines.

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The world's coastlines are highly dynamic landforms, tapestries of terrestrial and aquatic life forms and distinctive ecosystems. The area along these coastlines, known as the global coastal zone, arises from physical, chemical, and biological forces that originate on land and later mix with those of the sea. As a result, the coastal fringe is an important repository of dissolved and particulate matter, including carbon, and serves as a huge biogeochemical processor of constituents delivered into it. The coastal zone also contributes to human sustenance, culture, and economics in ways that belie its small spatial footprint, but 5 percent of Earth's landmass.[1] Three-quarters of the global population lives within the coastal zone, and more than half of global gross domestic product is generated within it.[2]

Within the coastal zone, river deltas are among the most consequential of landforms and have played an essential role in human history, serving as a cradle of civilization, the testing grounds for early agriculture, and the birthplace of hydraulic engineering.[3] Today, deltas are home to a half-billion or more people and have uncharacteristically high population densities.[4] More than 200 million people are crowded into the Ganges, Nile, and Mekong deltas alone, and many of Asia's current or emerging megacities are located within deltas.[5] In few other settings are society and coastal landforms so tenuously balanced. Much of the world's marine fish catch is associated with ecosystem services provided by deltas.

As low-lying and low-relief plains, coastal deltas are highly sensitive to even small changes in sea level and thus rightfully claim ground in the debate on greenhouse warming. But the fragility of deltas is not solely a consequence of rising ocean water. With respect to deltas it is fair to say that it's all relative: Any change in the absolute level of local seawater must be evaluated against the change in absolute height of dynamic landscapes. Were it not for a rich set of landforming processes within deltas, modern delta systems would have ceased to exist. Yet under the influence of a range factors, deltas may be hard-pressed to sustain this string of success.

The delta balancing act. The recent history of the world's deltas began with the melting of the large continental ice sheets and the thermal expansion of seawater that commenced after the last period of maximum glacial extent, about 15,000–20,000 years ago.[6] At this time, sea level was more than 100 meters lower than today, dry land extended to the outer portion of the modern continental shelves, and river-borne sediment was often deposited directly onto the continental slope of the ocean. In the subsequent period of rising sea levels between 6,000 and 18,000 years ago, deltas became effectively transient landforms, if they formed at all. About 6,000 years ago, sea level reached more or less its current level, with fluctuations of only a few meters up to the present. A relatively stable dynamic range took hold in the cycles of fresh water and sediment input, as well as in climate variability—temperature, precipitation, winds, waves, and currents—the critical ingredients shaping coastal landscapes. As a consequence, present-day coastal systems formed, and deltas emerged as rivers filled shallow coastal waters with sediment eroded from the continents. Geologically speaking, the current configurations of nearly all riverine deltas are young, having developed close to the dawn of civilization.[7]

Coastal deltas are the by-product of remarkable biogeophysical balancing acts.[8] Natural forces have shaped and reshaped them, but they have persisted during the last 5,000 years, at least those isolated from substantial human influence.[9] Their endurance depends on many site-specific processes but can be understood by examining the interplay between constructive and destructive forces. Constructive forces include the arrival of river-borne sediment worn off the continents and spread onto the delta by floods and, in some cases, coastal processes. Destructive forces include subsidence due to sediment compaction of surface deposits, tectonic processes, the decomposition of organic sediments, and ocean encroachment. (The ocean rises in two ways: eustatic sea-level rise results from melting glaciers, and steric sea-level rise results from the thermal expansion of a warming ocean and the freshening of salt waters.)

In their natural state, deltas are broad areas of near sea-level wetlands interlaced with water bodies through which fresh water and sea water mix in all three dimensions. In a typical year, a river furnishes supplies of fresh water, mineral sediments, inorganic nutrients, and organic materials from the upland drainage basin.

Floodwaters rise and spread over deltaic wetlands from main and so-called distributary channels, transporting mass and energy laterally across the delta, in essence nourishing the landscape. The inputs to deltas occur as a series of pulses ranging from daily tides to changes in river channels that occur over hundreds of years and include annual and great river floods, and storms such as frontal passages and tropical storms.[10] This nourishment is unique to each delta, preserving a fingerprint of the hydrology, sediment dynamics, chemistry, and even biology integrated over the contributing upland drainage basin. For the world's largest rivers, this fingerprint extends far upstream. Inputs of freshwater, minerals, and inorganic and organic materials stimulate local plant growth, which both directly and indirectly supports fish and wildlife. Sediments and nutrients fertilize wetland plant communities, leading to increased organic soil formation, an important hedge against sea-level rise. Freshwater inputs also give rise to estuarine water circulation patterns that act like conveyor belts bringing nutrient rich bottom waters to the surface where they fuel high levels of productivity. These changes are punctuated further by storm surges and flooding.

An interplay of factors regularly reconfigures deltas, often abruptly and often catastrophically. This characteristic pattern of change has rarely forced the present-day natural systems over the threshold to collapse. But this might soon change.

The interplay of these factors regularly reconfigures deltas, often abruptly and often catastrophically, on both geologic and historical time frames.[11] This characteristic pattern of change within deltas, however, has rarely forced the present-day natural systems over the threshold to collapse.[12] But this might soon change.

Humans tipping the scales. There is a basic tension between the human desire for stability and the dynamism by which natural deltas maintain themselves. Humans have devised a broad array of stabilizing strategies, enforced by hydraulic engineering, to create what is essentially a custom-made coastal habitat for humans and to thereafter protect life and property.

Local-scale engineering within deltas typically involves straightening and stabilizing freshwater channels and constructing levees (i.e. stopbanks), which restrict the flow of water and sediments during floods. Converting natural channels into conduits and breaking the critical links between channels and their floodplains starves delta systems of necessary sediments and bypasses an important natural filtration system. The direct discharge to the sea of suspended matter, often rich in carbon and carried along with dissolved nutrients, contributes to algal blooms, excessive decomposition, and hypoxia in nearshore receiving waters. For example, today's Mississippi River shunts nearly all of its influent sediment directly into the ocean.[13] This contributes to a multi-year oxygen dead zone in the Gulf of Mexico and the loss of 25 percent of the delta's wetlands.[14] Human use (or more accurately overuse) of groundwater in cities and in agriculture further increases natural levels of subsidence, outstripping natural delta-building processes.[15] Many systems, such as the Mississippi and Niger river deltas, are also the sites of oil and natural gas extraction, which affects land subsidence similarly.[16]

In addition to these local-scale effects, far-field, chronic impacts originating in the ocean involve the many aspects of sea-level rise discussed earlier, as well as storm surges and the rising intensity of hurricanes.[17] While most experts believe that sea level will rise somewhere on the order of a half-meter in the next century, others place bets on a value much greater.[18]

One of the largest global influences on the future of river deltas is the integrity of upland drainage basins, which is defined fundamentally by the abundance of landscape sediment and solute sources, any sinks encountered along the journey downstream, and the ultimate conveyance of this matter to the delta. Human influence on these major sedimentary, solute, and hydrologic cycles, at least in populated parts of the world, is unavoidable. Humans simultaneously accelerate and decelerate transports.[19] Construction and mining activities have increased exponentially throughout human history, with a corresponding rise in the movement of sediment.[20] While much of this sediment is trapped in valley floors and floodplains and never gets to the sea, the imprint of this human activity rivals that of natural sediment processes.[21] In addition, humans use or otherwise control the productivity of as much as one-third of the land on Earth.[22] In regions such as east and south Central Asia and Western Europe, the total is closer to two-thirds, with attendant impacts on the soil resource base. Unintentional, accelerated erosion from agricultural clearing and tillage could be twice to more than three times the total for intentional earth moving.[23]

Rivers are the predominant conveyance system for sediments destined for the world's coastal deltas. Four out of five people on Earth are served by the renewable water supply provided by rivers, a resource that is substantially controlled by water works that capture, stabilize, and redirect the often unpredictable discharges.[24] Global-scale assessments have found that water diversion and water engineering measurably affect the world's drainage basins and that the impacts are pandemic.[25] Humans modify 80 percent of continental runoff to some degree, and 30 percent of that runoff is highly impacted.[26] Some rivers no longer flow to their natural endpoints. The Colorado River, for instance, should empty into the Gulf of California but no longer does so because of human consumption and a huge interbasin transfer to California. The Nile River delta discharges to the Mediterranean Sea less than 1 percent of its pre-Aswan Dam flow, and China's Yellow River completely ceased to flow to the ocean at times during the 1990s, in part due to drought but also irrigation losses.[27] Global irretrievable losses from irrigation total one-third of all water use.[28]

Hydraulic engineering is now a predominant force reshaping the character of the contemporary drainage basin. Modern reservoir construction has increased by 600 to 700 percent the volume of water held by rivers globally and has tripled the time necessary for a water molecule to move off land and into the sea.

The scale of human influence on water systems has increased from what once was a local-scale phenomenon into the global arena. Hydraulic engineering is now a predominant force reshaping the character of the contemporary drainage basin. Modern reservoir construction has increased by 600–700 percent the volume of water held by rivers globally and has tripled the time necessary for a water molecule to move off land and into the sea. This storage is significant by any measure of global change, given that it has occurred in only 50 years.[29] Reservoirs act as enormous storage tanks on the world's river networks and trap huge amounts of sediment. After only 3 days, river water sitting inside a reservoir loses to settling 50 percent of the sediment brought in.[30] Because many large drainage basins are home to reservoir systems that hold more than a full year of river inflow, the artificial impoundments retain nearly all of their inflowing sediment.[31]

Recent observations further suggest a pandemic trend. Of nearly 150 time-series studies of changes in the suspended sediment fluxes in major river basins, only four showed increases while 68 showed significant downward trends.[32] About half of the basins with declining sediment flux also had declining water flow. Recent global studies have suggested that nearly one-third of all sediment that otherwise would have found its way into the coastal zone is trapped upstream behind the more than 40,000 registered large dams and other systems that divert the flow of water.[33] The countless smaller dams, farm ponds, and water harvesting systems have a yet-unquantified, additional impact.[34] Given the general design lifetime of hydraulic engineering systems (from 50 to 200 years), existing systems will be a fundamental feature of the Earth system well into the future. Added to a general decrease of river volume in heavily water-stressed drainage basins, these trends lead researchers to expect further declines in the amount of sediment delivered to the world's river mouths. The irony is that this is occurring even as humans increase the amount of sediment carried off the landscape.

The impact on deltas. What does a general increase in local-scale erosion across the uplands of a drainage basin and the simultaneous decrease in the flow of river-borne sediment to the ocean mean for deltas? While the scientific community hasn't yet gathered a complete set of hydrologic and socioeconomic data, it is beginning to assemble a coherent picture, indicating that sea-level rise across the world's deltas is pandemic, rapid, and punctuated by spectacular examples of, quite literally, sinking deltas often in heavily populated parts of the world. Initial assessments show that the number of deltas endangered by both local and far-field effects is large, with many showing rates of relative sea-level rise far in excess of those associated with global sea-level rise alone.[35]

Human activity nearly always tips the scale in favor of forces that have a destructive effect on deltas. Local observations support this assertion and highlight the many interconnected and costly impacts on a delta losing its sediment source. For example, Spain's Ebro River delta has retreated more than 10 meters per year during the last 40 years.[36] To stave off the growing erosion problem, the government transports thousands of truckloads of sediment into the coastal zone each year. Also, scientists have measured a net elevation loss of several centimeters per year along the Chao Phraya delta on which Bangkok rests, a decrease more than 10 times greater than rates of global sea-level rise.[37] Finally, from the 1960s to 1990s, the net subsidence of Italy's Po River delta ranged from 4 to possibly 60 millimeters per year due to the combined effects of levee construction, the removal of groundwater, and riverbed mining.[38] These changes are linked strongly to the state of ecosystems within the delta.

In the Ebro, Po, and Nile deltas, humans have converted nearly all wetland habitats to agriculture and more than half of the wetlands in the Rhone River delta in the south of France have been reclaimed.[39] The Mississippi River delta lost about 25 percent of its wetlands in the 20th century, mainly through conversion to open water.[40] The construction of the Aswan High Dam along the Nile River in the late 1960s nearly instantaneously stopped the annual flooding of the Nile delta, which formerly delivered nutrient-rich sediments to the delta and sustained Egyptian civilization over the millennia. This shift resulted in chronic coastal erosion, the collapse of coastal fisheries, and the introduction of industrial fertilizers for crop production.[41] Unexpectedly, the leaching of industrial fertilizers and the construction of a new sewer system in Cairo reversed the initial decimation of the coastal fisheries by reintroducing the necessary nutrients and organic matter to fuel the coastal food web. While it is unclear how environmentally sound or sustainable this unintended consequence will prove to be, it is a testament to the capacity of humans to influence the mechanics of the Earth system. Similarly, the development of the largest irrigation system in the world in Pakistan has reduced the flow of the Indus River to a trickle leading to the build up of salt in the previously agriculturally fertile delta, the destruction of highly productive mangroves, and other rapid coastal changes.[42]

Recent research suggests that human impacts are more universal than previously thought, especially in deltas draining well-populated river basins. An initial global sampling of 40 deltas and their associated drainage basins found nearly 70 percent with relative sea-level rise defined predominantly by the net loss of river-borne sediment and another 20 percent by local groundwater, oil, and gas extraction, with a correspondingly minor impact from eustatic and steric sea-level rise.[43] Thus, it would be fair to conclude that the recent transformation of the world's populated river basins into highly regulated, human-dominated systems has dramatically altered land-to-ocean connections and that these trends now play an increasing role in determining the state of modern deltas.

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A call to research. The increase in the number of individual case studies and global-scale statistics that look at the health of river deltas is a testament to the growing role that deltas will play in understanding human vulnerability on a global scale. That there are already so many deteriorating deltas suggests that humans are indeed ill-prepared to meet the challenges that are just now being understood. Policy makers have traditionally underestimated the importance of factors other than encroaching oceans that put many of the world's deltas at risk. The view of the Intergovernmental Panel on Climate Change, for example, focuses fundamentally on eustatic and steric sea-level rise, though the panel is beginning a broader discussion of at-risk deltas.[44] The present-day deterioration of river deltas could put hundreds of millions of people at imminent risk well before the large-scale impacts of climate change are felt.[45]

Three major organizing concepts appear well-suited to change the traditional ad hoc approaches to managing and protecting our coastal deltas. One way to do this is by bringing a bona fide interdisciplinary perspective to our research. Early knowledge of deltas came from petroleum industry research aimed at understanding shallow water sedimentary systems. A more encompassing view is evolving, reflected by the exponential increase in the number of studies and the accompanied shift from pure geoscience research to research focused on environmental, ecological, and social issues. This more diverse approach must be expanded, and the wealth of subsurface data put to the service of understanding natural deltaic processes operating today.

The human impacts on delta systems go well beyond population trends, to include issues such as infrastructure development, resource use, and cultural perceptions. Adding to the complexity, official decisions about how to manage river-delta systems often affect groups across national boundaries, governance systems, and cultures that may not be technologically ready to deal with the repercussions. This makes it difficult to develop well-designed and broadly agreed-upon management solutions and will likely lead to response options that are unique to each delta system. Future interdisciplinary studies should focus on understanding the legacies of past human interventions in hydrologic systems, as the capacity to reverse decades of neglect will depend on the condition of deltas and their connected rivers as we observe them today. On a positive note, researchers have found that when humans allow deltas to return to a fundamentally dynamic state, resilient systems re-emerge.[46]

A second possible approach recognizes an explicit role for ecosystem infrastructure and ecosystem services in delta management. Economists are increasingly attempting to assign value to the goods and services produced by the environment and to the true costs incurred with their use, previously considered to be externalities.[47] In so doing, they hope to provide incentives for environmental protection.

Among the many services that natural ecosystems provide, disaster mitigation may be among the most underappreciated and undervalued. Storms, floods, and tidal waves are natural events and have always caused damage. But the degree to which they lead to disastrous outcomes today is more strongly influenced by human actions than ever before. By necessity or choice, more people are living along floodplains and on fragile coastal ecosystems—precisely those settings that place them in harm's way. China, for example, has an explicit policy of moving population to the coasts, based on the premise that such settlement will motivate increased levels of economic activity.[48] Meanwhile, the continual clearing of forests, draining/filling of wetlands, and engineering of rivers around the globe have frayed the natural safety nets that healthy ecosystems provide. When a natural disaster occurs, the risks of substantial loss of life and property are higher because of the loss of beneficial ecosystem infrastructure and ecosystem services. Was the catastrophic loss of life and property from Hurricane Katrina born only of the fury of wind and sea, or was it a failure of long-term environmental stewardship in the larger Mississippi watershed and local decision-making over the delta?

The third approach takes into account the notion of sustainability.[49] A delta is geomorphically sustainable if the net change in wetland surface elevation is equal to or exceeds relative sea-level rise and if the delta's total area remains stable in the long-term. There is a synergy between a delta's ability to withstand sea-level rise and the ecosystem's primary productivity, and thus the delta's ability to support fisheries and material processing. A delta is ecologically sustainable if plant productivity remains steady or increases during the course of decades. When humans convert delta wetlands into open water or agricultural land, productivity is generally lowered, robbing the delta of an important source of organic sediment and the physical integrity to withstand weather extremes.

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A delta system is economically sustainable if its output of goods and services is greater than the amount of money and government subsidies necessary to maintain production and deal with the potential externalities associated with its management. Analysis of economic sustainability is complicated because wealth-generating activities supported by deltas such as shipping and fish farming are often formally credited to the economy elsewhere and to beneficiary populations that live far from deltas. Thus, impairment of many deltas due to control systems such as levees has diminished their net economic yield and has required industrial capital and energy to flow into these systems. Recouping these lost services, on practical grounds, means engineering and operating the system to allow natural processes to sustain and build wetlands, which then produce goods and services at lower cost.

In sum, the status of today's deltas represents the legacy of natural history, with an overlay of human decisions and ongoing sea-level rise. These factors all shape the vulnerability of delta systems. Scientists sometimes view Earth's passage into the Anthropocene, a time when the planet is increasingly being shaped by the purposeful or inadvertent consequences of human action, as being on par with major geological epochs.[50] Through their studies of the Anthropocene, scientists are learning that today's system is laden with previously unrecognized linkages, thresholds, and unintended consequences. The state and trajectory of change in modern deltas provide a textbook example of this concept.

The collective significance of transformations in the basic building blocks of the Earth system, such as water and sediment, should give us pause as we assess our prospects for sustainability moving forward into the 21st century. With Earth's population reaching perhaps 10 billion people by mid-century, humans will have to continue juggling the increasingly complex and tightly linked strategic imperatives of food and energy security, economic development, and carbon mitigation. Our stewardship of the world's deltas, an arguably less complicated challenge, offers a very useful lesson. ■

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