Evaluating the long-term sustainability of deltas

by Andrew Moodie

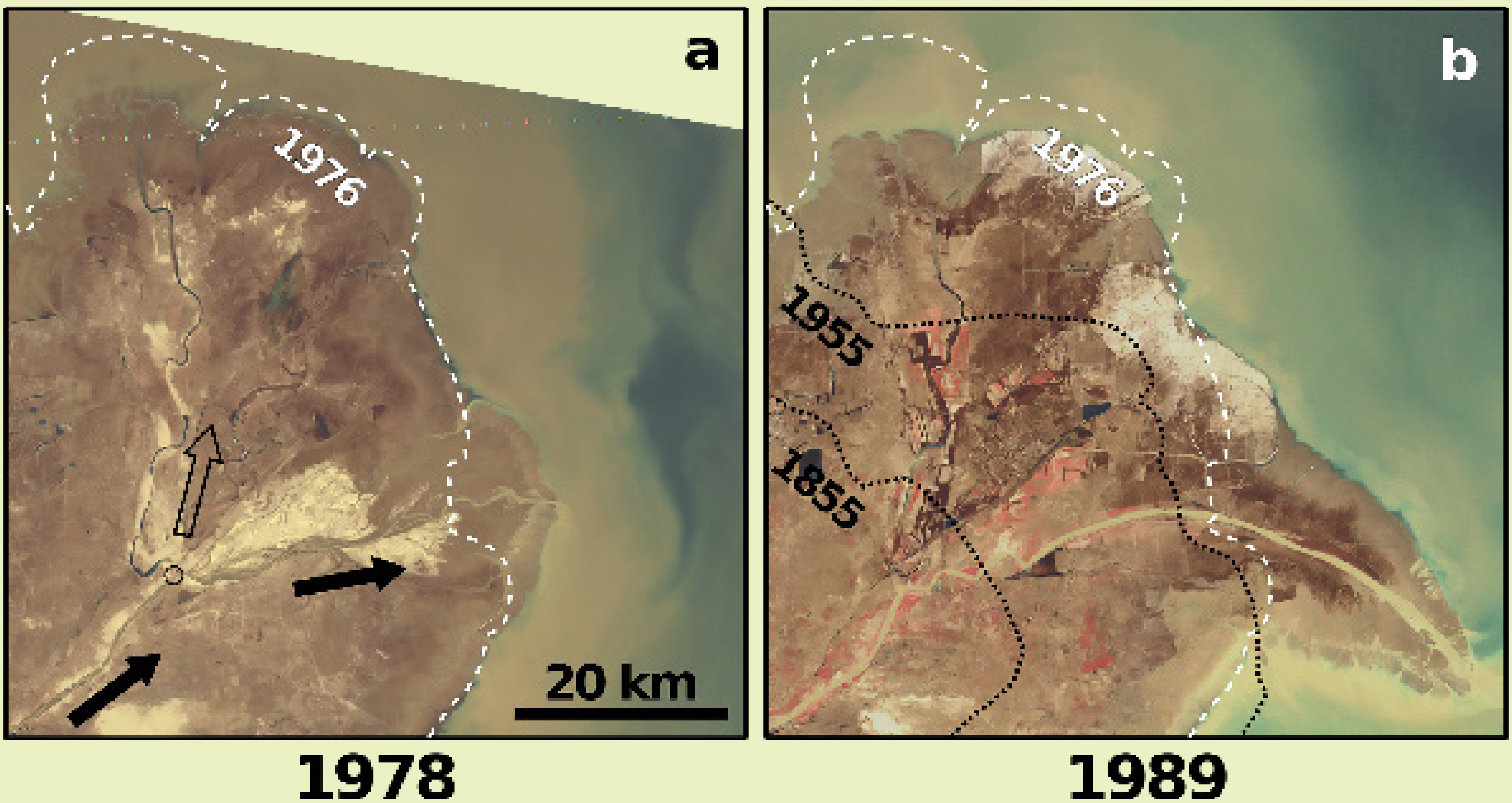

Figure 1: (a) satellite composite of the Yellow River delta, China in 1978, two years after a deltaic avulsion in 1976 occurred ~60 km upstream of the old river mouth (circle) which changed the channel course from the north (open arrow) to the east (solid arrow). The shift in the 1976 coastline demarcates the over 250 km^2 of land built as a new channel lobe in just two years and the significant marine reworking of the old channel lobe. (b) satellite composite from 1989 over the same area overlain with a historical record of mapped coastlines demonstrating the net delta growth over many avulsion cycles (black dotted lines) [van Gelder et al., 1994]. Satelllite data courtesy USGS.

Deltaic environments are critical for societal well-being because these landscapes possess an abundance of natural resources that promote human welfare, such as fertile soil and shipping channels. However, the sustainability of deltas is far from certain, due to a multitude of natural and anthropogenic factors. The management of important domestic deltas for the last several centuries, for example the Mississippi River delta, has led to a retreating delta coastline and channel shoaling, threatening the port of New Orleans with exposure to coastal storms and reduced channel navigability.

Fortunately, emerging research indicates the feasibility of reversing land-loss through controlled diversion of river water and sediment[1]. This research seeks to build on this work and evaluate the Yellow River fluvial-deltaic system, China, to identify best practices for promoting long-term deltaic sustainability in the face of anthropogenic influence that threatens the sustainability of the delta. Due to an extremely high sediment load, variable water discharge, and confinement within man-made levees, the Yellow River channel is prone to rapid sediment deposition to the bed and aggradation that render this system highly unstable over seasonal to decadal timescales[2, 3]. Interestingly, the rapid system dynamics provide unparalleled opportunities to research delta development mechanisms that normally occur over millennia, and so the Yellow River and its delta are ideal locations to pursue process-based studies linking physical properties of fluid flow and sediment transport to understand the long-term development of deltas.

Deltas represent the dynamic interplay between fluvial sedimentation, subsidence, and sea level change. Where sediment supply is high the delta will locally grow and move the coastline forward as a delta lobe; conversely, where sedimentation is low, the coastline lacks nourishing sediment and experiences local retreat (Fig. 1). Similarly, land subsidence and sea-level rise force coastline retreat across the entire low-relief delta simultaneously. Through overbank flooding and avulsion, the process by which the channel catastrophically floods overbank and carves a new course to the sea via an alternative, gravitationally advantageous path, natural deltas distribute necessary sediment to the entire coastline so as to maintain a state of morphodynamic balance[4]. However, the unanticipated civil disruption associated with flooding and channel relocation is naturally at odds with the societal desire for landscape stability for continued economic use. Therefore, on highly developed deltas sediment delivery to the coast is frequently reduced and is outpaced by land subsidence and sea-level rise, beginning a pattern of deltaic land loss. A commonly cited example of this is the Mississippi River delta, where high channel levees and channel-course engineering have cut off sediment supply to the low-relief bayous of the Louisiana coast, causing a land loss rate of about 44 km^2 per year[5].

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For millennia, Chinese governments have implemented significant engineering efforts to prevent channel avulsions and catastrophic flooding along the lower Yellow River, in accordance with promoting rapid anthropogenic development of the delta for aquaculture and hydrocarbon extraction[6]. Most recently, the Water and Sediment Discharge Regulation project (WSDR) was established to release artificial, sediment-depleted flood waves from a network of reservoirs and dams ending ~800 km upstream of the delta. The intention of the project is to use the higher transport capacity of the flooding river to reverse in-channel sediment aggradation and stave off damaging avulsion and flooding that threaten the society developed on the delta. Additionally, avulsions are engineered to shorten the distance to the sea, and raise the overall channel bed slope and sediment transport capacity of the lowermost ~100 km of the channel. This measure has the added value of distributing sediment to different locations along the river-deltaic coastline, promoting land growth and minimizing effects of sea level rise. These engineering practices are, in essence, large-scale fluvial experiments that have no modern system-scale analogy. Evaluating the efficiency of these practices is therefore critical, because the practices that promote the long-term sustainability and societal development of the Yellow River deltaic landscape are exportable to other fluvial-deltaic systems that are undergoing rapid land-loss due to natural and anthropogenic factors, for example the Mississippi River.

Figure 2: Collecting samples in the Yellow River with Brandee Carlson. Photo by Andrew Moodie.

A fully synthesized 1D-fluid, quasi-2D delta evolution model that simulates individual delta lobe development (e.g., new lobe in Fig. 1a) and the overall planform or “bird’s eye view” development of the delta enables the evaluation of management schemes for a fluvial-deltaic system over a range of important timescales (decades to millenia). The 1D numerical framework explicitly models channel bed aggradation and channel lobe progradation that determine the location and timing of avulsions. Following an avulsion in the model, sediment on the floodplain and beyond the radially-averaged planform shoreline (i.e., sediment in the delta lobe) is redistributed across the delta topset and along the shoreline, respectively, simultaneously prograding and aggrading the 2D delta system. The model is validated by a robust dataset of satellite-derived and historically measured delta development metrics for the Yellow River fluvial-deltaic system. Changing model parameters allows simulation of the effects of different delta management strategies (for example, the WSDR) on the short- and long-term evolution of the delta system, at both the lobe and delta scale. For example, it is possible to produce numerical experiments that test the effects of various sea-level rise rates, ground-fluid extraction rates, flood engineering, or sediment supply changes on the development of a delta.

Results of this analysis confirm that explicit accounting of avulsion processes in a quasi-2D model framework is capable of capturing delta development patterns that otherwise are not resolvable based on previously published delta building models. Instead of allowing an avulsion to occur naturally, we built a numerical experiment that periodically triggered engineered avulsions at strategic locations chosen to maximize the land building potential of the delta system and occurring during engineered flood events, simulating the WSDR project on the Yellow River. Our experiments demonstrated the ability to deliver the necessary sediment to the entire coastline, while controlling the threat of catastrophic flooding interfering with a society developed on the delta. By this result, the implications of this research are in agreement with recent research that supports the feasibility of utilizing river diversions to promote land building in the deltaic environment.

Societal development and natural deltaic processes will continue to be at odds to one another, but recent research out of the process-based sedimentology community supports the notion that coastline stability and a prosperous society are not mutually exclusive, despite a historic record of land use and policy development that have led to land loss across many deltaic landscapes. The Yellow River delta offers a study location for scientists to observe the development patterns of an anthropogenically influenced delta over a short period of time (years to decades). With consideration to the longer timescales of delta dynamics of other fluvial-deltaic systems (e.g., channel lobe switching), the best practices for promoting the long-term deltaic sustainability identified in this Yellow River system research can be applied to the management of deltas around the world. Informed engineering of fluvial-deltaic systems shines as a promising path toward a stable condition able prevent coastal land loss but still accommodate an ever-growing global population and demand for resources.

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