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Tipping from the Holocene to the Anthropocene: How threatened are major world deltas?

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Coastal deltas are landforms that typically offer a wide variety of benefits to society including highly fertile soils for agricultural development, freshwater resources, and rich biodiversity. For these reasons, many deltas are densely populated, are important economic hubs, and have been transformed by human interventions such as agricultural intensification, modification of water and sediment fluxes, as well as urbanization and industrialization. Additionally, deltas are increasingly affected by the consequences of climate change including sea level rise, and by other natural hazards such as cyclones and storm surges. Five examples of major deltas (Rhine-Meuse, Ganges, Indus, Mekong, and Danube) illustrate the force of human interventions in shaping and transforming deltas and in inducing shifts between four different social-ecological system (SES) states: Holocene, modified Holocene, Anthropocene and 'collapsed'. The three Asian deltas are rapidly changing but whereas SES in the Ganges and Indus deltas are in danger of tipping into a 'collapsed' state, SES in the Mekong delta, which is at the crossroads of various development pathways, could increase in resilience in the future. The Rhine-Meuse and Danube delta examples show that highly managed states may allow, under specific conditions, for interventions leading to increasingly resilient systems. However, little is known about the long-term effects of rapid human interventions in deltas. It is therefore critical to increase the knowledge-base related to SES dynamics and to better characterize social tipping points or turning points in order to avoid unacceptable changes.

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Introduction

River deltas are landforms created by the force of rivers, waves and tides and formed over thousands of years when global sea levels stabilized some 6000–8000 years ago. River deltas are located where a river drains into another body of water and sometimes inland over swampy flat terrain such as the Okavango and inner Niger deltas in Africa. In this paper, we focus on coastal deltas. Coastal zones in general and deltas in particular are often densely inhabited, with mean population density in deltas an order of magnitude higher than the land mass as a whole [1]. In deltas located in tropical and temperate regions, this preference in terms of human occupancy is due to the presence of highly productive arable land, the presence of marine and freshwater resources and many other attributes [2•].

Human and natural factors operating over deltas also constitute challenges in terms of maintaining their integrity: first, urbanization, second, groundwater and hydrocarbon extraction, third, agricultural intensification, fourth, anthropogenic alteration of flow path and floodplains, fifth, upstream water consumption, diversion and sediment trapping, sixth, climate change, and seventh, extreme natural hazards in terms of river flooding and coastal storm surges. Urbanization and regulation of flow in many delta regions worldwide have allowed for rapid economic growth but these development pathways have also generated new challenges. Urbanization in river deltas is often accompanied by water channel regulation, surface sealing, land subsidence, water, soil, and air pollution, pressure on natural resources, and an overall alteration of the natural delta regime. Agricultural intensification is observed in many deltas (e.g. Mekong, Nile, northern Mediterranean deltas) which increases water and soil pollution and contributes to a loss of biodiversity due to altered nutrient and trace element fluxes [3••] as well as land subsidence through, for example, groundwater over-abstraction. Large upstream interventions (urban development, water extraction for industry or irrigation, and hydropower dams) can also have extreme impacts on deltas located downstream [4]. When this is combined with infrastructure development within deltas themselves (e.g. control of flow paths of distributary channels and extensive dyke systems for the control of seasonal floods, irrigation, and salinity) which by themselves contribute to an interception of 40% of global river discharge and a trapping of perhaps one-third of continental flux of sediment to the coastal zone [3••,5,6], it is clear that human engineering controls the growth and evolution of many deltas [7]. Climate change in most deltas is typically manifest through rising sea levels [8•], increasing occurrence of environmental hazards (typhoons/hurricanes, storm surges, or extreme tides) but also through local changes in rainfall distribution and intensities as well as increases in temperature. Sea level rise leads to increased coastal erosion and flooding, and increased saline water intrusion into the rivers, canals, aquifers, and soils. In addition, 'technical' hazards induced by human activities in these regions (e.g. oil spills or chemical accidents, dyke breaks, and levee breaches) put social-ecological systems (SESs) in deltas under even more pressure.

Through selected examples, this paper will illustrate the impact of human interventions in shaping and transforming deltas. Human pressures in most delta environments are ubiquitous and we infer that some of these deltas have reached tipping points whereby they have shifted from a Holocene state to an Anthropocene state (the term 'Anthropocene' describing the predominant control by humans of the global environment, recognizing a new geological epoch [9]), and could reach other, less favorable SES states if environmental and development policies are not changed.

Tipping points in the context of deltas

The notion of tipping points (also referred to as thresholds) has been used to characterize relatively rapid and often irreversible changes in systems ranging from local or regional importance such as fish stocks [10,11] to major environmental subsystems of the planet [12]. There are various definitions of what a tipping point represents for SESs [12–15]. Tipping points are closely linked to the concept of resilience which in the context of environmental hazards can be defined as 'the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions' [16]. As system structure and function is central to resilience theory, a tipping point can be defined as 'a breakpoint between two regimes or states which is reached when major and controlling variables of a SES no longer support the prevailing system and the entire system shifts in a different state which is distinct from the previous state and recognizable with specific characteristics. The change can be sudden (e.g. external shocks) or gradual modifications (changes in underlying drivers) and can be induced by changes in both the social and the ecological part of the system' (adapted from Walker and Meyers [15]).

Several factors contribute to reaching a tipping point in deltas including changes in sediment delivery, subsidence, coastal erosion, extreme events such as cyclones or tsunamis, inundation, salinity intrusion, pollution, increased resource scarcity, but also changes in social systems, policies, social perception and development prioritization. For densely inhabited deltas, anthropogenic processes are the main drivers of change, such as land conversion, infrastructure development on river systems and rapid urbanization [17]. Ecological systems can adapt when changes are progressive, but the system might be less resilient during this adaptation phase and could reach a tipping point when affected by even low intensity external stressors. For an SES, we reason that a tipping point will be reached when specific ecosystem services cannot be relied upon anymore, leading to shifts in the ecological state and/or in human activities (changes in agroecosystems, changes in livelihoods, and migration). A tipping point can also be reached when the current management approach simply cannot be maintained because of growing resource constraints.

Human activities can increase the risk of reaching tipping points or motivate the design of strategies to avoid them. From an anthropocentric perspective, tipping points to undesirable system configurations can be avoided by anticipating 'adaptation turning points', thanks to proactive policy decisions which recognize future threats [18] or unacceptable changes [19••]. Transformation can also be linked to anticipatory adaptation to increase system resilience with respect of known hazards [20]. Transformation is defined by Folke *et al.* [21] as 'the fundamental alteration of the nature of a system once the current ecological, social, or economic conditions become untenable or are undesirable'. A key principle here is transformative learning which is 'learning that reconceptualises the system through processes of reflection and engagement' [21]. Turning point adaptation or transformation can therefore eventually lead, through a tipping point, to a desirable but distinct system configuration. Tipping points can therefore be reached through both the loss of resilience due to lack of anticipation of system degradation or external shocks as well as through transformation, by recognizing future threats to an