Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in Environmental Sustainability

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

Fabrice G Renaud[1], James PM Syvitski[2,3], Zita Sebesvari[1], Saskia E Werners[4], Hartwig Kremer[5], Claudia Kuenzer[6], Ramachandran Ramesh[7], Ad Jeuken[8] and Jana Friedrich[9]

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.

Addresses
[1] United Nations University Institute for Environment and Human Security, Bonn, Germany
[2] University of Colorado-Boulder, USA
[3] International Geosphere-Biosphere Programme, Royal Swedish Academy of Sciences, Stockholm, Sweden
[4] Wageningen University and Research Centre, Alterra, The Netherlands
[5] Helmholtz-Zentrum Geesthacht Centre for Materials and Coastal Research, LOICZ International Project Office, Geesthacht, Germany
[6] German Aerospace Center, Earth Observation Center, German Remote Sensing Data Center, Land Surface, Wessling, Germany
[7] National Centre for Sustainable Coastal Management, Ministry of Environment and Forests, Chennai, India
[8] Deltares, Utrecht, The Netherlands
[9] Helmholtz-Zentrum Geesthacht Centre for Materials and Coastal Research, Geesthacht, Germany

Corresponding authors: Renaud, Fabrice G (renaud@ehs.unu.edu)

Current Opinion in Environmental Sustainability 2013, **5**:644–654

This review comes from a themed issue on **Aquatic and marine systems**

Edited by **Charles J Vörösmarty**, **Claudia Pahl-Wostl** and **Anik Bhaduri**

For a complete overview see the Issue and the Editorial

Received 13 July 2013; Accepted 05 November 2013

Available online 21st November 2013

http://dx.doi.org/10.1016/j.cosust.2013.11.007

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.

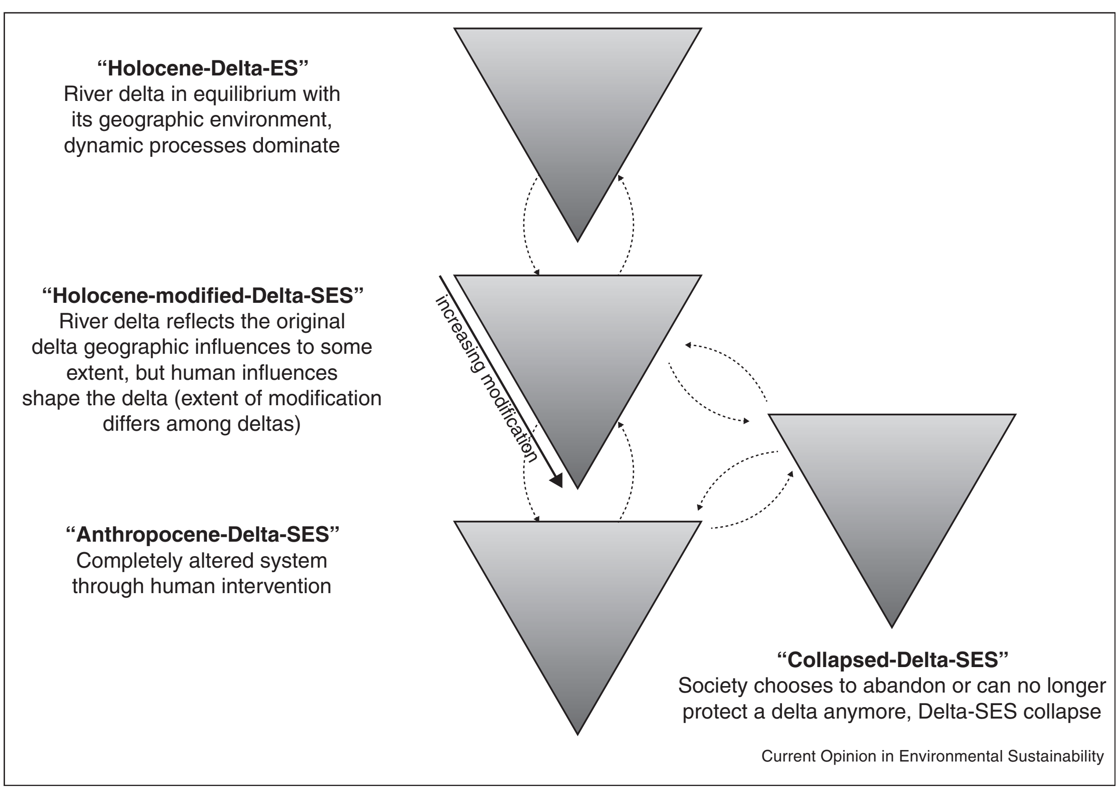
Human activities can increase the risk of reaching tipping points or motivate the design of strategies to avoid them. From an anthropocentric perspective, tipping points to undesirable system configurations can be avoided by anticipating 'adaptation turning points', thanks to proactive policy decisions 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

SES (internal or external) and changing some of the system's controlling variables.

During what we consider to be the 'stable' Holocene state, a river delta is assumed to be at equilibrium with its geographic environment, with mobile rivers across their floodplains and distributary channels and their estuaries mobile across the delta plain. A stable state does not imply a lack of dynamic features, but ecosystems and perhaps to a lesser extent human systems are well adapted to these forces. A reduction of this dynamic nature by human activities lies at the heart of many problems facing deltas. Their attractiveness for agricultural production is essentially linked to these dynamics. At the same time, humankind has often tried to tame deltas to reduce natural variability through the development of infrastructure upstream (such as dams), within the delta themselves (dykes, canals) and along the coastline (such as breakwaters). The functioning of the delta over the last 10 000 years largely depends on a balance between dynamics and control. At an extreme, human action could tip deltas from a Holocene state to an Anthropocene state where natural delta dynamics are highly limited (Figure 1). To a large degree, designation of this state is subjective, as demonstrated by the case studies presented below. Processes leading to this new state could include land subsidence, rapid coastal erosion, and reduction in sediment delivery. During this transition phase, a delta could be in a modified Holocene state.

The Anthropocene state is not only influenced by direct or intended human action but also by indirect impacts such as climate change-induced sea-level rise or upstream influences affecting a delta to an extent that threatens the very existence of the delta itself. Another tipping point can be considered at the stage where society would give up protecting a delta or parts of it and the SES could collapse [22]. While the first tipping point from the Holocene to the Anthropocene is mainly characterized by a growing extent of human control on the ecological part of the SES, the second tipping point is rather characterized by forces which cannot be controlled or compensated anymore neither by the social nor by the ecological part of the SES. While societies are rather familiar with the first tipping point, the second is largely unexplored. This is exemplified by the ongoing debate on what and how to protect or not protect in the Mississippi delta: it seems that we lack the knowledge base to decide which parts we should give up and which part to preserve [23,24]. Deltas in this state are highly susceptible to large-scale and potentially irreversible trends of the 21st century.

Figure 1



Possible ecological system (ES) and social-ecological systems (SESs) states and tipping points for deltas.

Tipped or on the way to tipping

Five major deltas were selected to discuss various system states and transitions from one state to another (Table 1). Some of these deltas are currently rapidly being transformed (Mekong, Ganges, and Indus), while others represent deltas that have already been transformed through various engineered means (Rhine-Meuse and Danube). The deltas also represent different climates (temperate and tropical, arid to tropical monsoonal).

The Rhine-Meuse delta

The Rhine river is the third largest river in Europe (1233 km in length). Originating in Switzerland, it connects 6 riparian countries, and the 185 000 km^2 watershed is currently inhabited by about 58 million people. Together with the Meuse river (originating in Northern France, connecting four riparian countries, inhabited by some six million people, 950 km in length, it's watershed covering 36 000 km^2) the Rhine has formed a delta that constitutes roughly two third of the Netherlands.

The Rhine-Meuse delta in the Netherlands is a river delta that has originated from marine and fluvial sediments but over the last 1000 years, it has mainly been shaped by human actions. It has gone through all stages from a Holocene to an Anthropocene state. It has been a highly engineered delta over the course of many centuries. In this transitioning to an Anthropocene state (Table 1), canalisation, the creation of drainage systems, polders, the embankment of rivers, and coastal protection has brought prosperity through a better control of water levels and a reduction of floods. However, the lack of new sedimentation and extensive drainage has caused land subsidence in most parts of the delta, drawing land surface elevations to below sea level [18].

The flooding disaster of 1953 can be seen as an important tipping point in societal awareness that created a political imperative to act. As a consequence, the first delta plan was launched that implemented major improvements throughout the whole flood protection system in the Netherlands. Arguably the resulting infrastructure, laws and standards resulted in the best protected delta in the world. At this stage, the Rhine-Meuse delta can reasonably be considered to have entered the Anthropocene. The human induced system shifts in the delta included

Table 1

State of five deltas and their potential trajectories

Delta	State	Potential directions of change	Characteristics
Rhine-Meuse	Anthropocene to modified Holocene	Anthropocene → Modified Holocene (e.g. giving more room to nature)	• Highly modified over the last 1000 years • Highly engineered before changes in policies have tried to give a more central role to the environment • Dependent on cheap energy to remain in current state which reduces its resilience
Ganges	Anthropocene	Anthropocene → Collapsed (if e.g. remaining environmental features not maintained)	• Highly regulated basin • Principally agricultural delta • Despite regulation, drought and floods are common • Rapid demographic and development changes • Environmental degradation
Indus	Anthropocene	Anthropocene → Collapsed (high demographic pressure and drastic changes in water and sediment discharge)	• Rapid increases in water-abstraction over the last 150 years drastically reducing water and sediment discharges • Changes in environment directly affecting the livelihoods of millions
Mekong	Anthropocene	Anthropocene → Collapsed (if e.g. construction of dams significantly further alters water and sediment fluxes and over-reliance on engineered structures favored) Anthropocene → Modified Holocene (if limited development of dams in the lower Mekong basin and shifts in agricultural systems favored in place of reliance on engineered structures)	• Large-scale human interventions over the last 400 years, but accelerating in the 20th century • Some natural delta dynamics remain • Increased reliance on engineered structures (flood or salinity intrusion control)
Danube	Holocene-modified to Anthropocene	Holocene-modified → Anthropocene (induced by human interventions and allowing for development of the region)	• Deforestation in the catchment led to rapid delta growth historically • River can still spread over the delta but there is a reduction in sediment discharge due to upstream dams leading to erosion

the full or partial closure of two estuaries, subsequently turning them into freshwater lakes. The freshwater availability stimulated the local agricultural economy. At the same time water quality and the morphodynamics of the new lakes deteriorated. To reduce water quality problems and recover the ecological status of the estuary, it has been suggested to re-establish fresh-saline gradients. For the Rhine-Meuse delta, adaptation tipping points in the hydrological system have been assessed [18] along with changes in governance [25]. However, the impact of exhausting cheap energy has not been fully explored.

The current delta program, which started in 2008, aims at a sustainable flood risk protection and fresh water supply under future scenarios by 2100 [26]. Having learnt from past disasters, a proactive approach is followed using the concept of tipping points in the SES and accounting for the 'adaptation tipping points' in the sense of Kwadijk *et al.* [18]: current policy and management practices are confronted with external changes, either climate or human induced, and by using scenarios, projections are being made to identify when these practices will perform unacceptably (measured against current standards). In this forward looking approach both gradual as well as sudden shifts matter.

The Rhine-Meuse delta case underscores how social and physical system should be regarded separately but also coupled (c.f. Renaud *et al.* [20]). The delta shows several compensating reaction and preparatory actions, which themselves have introduced new tipping points (examples: water bodies turning from saline to fresh, accelerated urbanization). With the recognition of past system shifts, some actions are considered that aim at moving the delta to characteristics of the modified Holocene state by reversing trends in risk accumulation (multi-level safety approach), subsidence (wetland creation), and increasing flood levels (room for river program). Potential future energy scarcity could make the success of these approaches increasingly difficult, however factors such as risk accumulation pose a more immediate threat.

Ganges delta

The Ganges-Brahmaputra-Meghna (GBM) river system is ranked as the third largest freshwater outlet to the sea (after the Amazon and Congo River systems) covering an area of about 1.75 million km^2 stretching across Bangladesh (7.4%), India (62.9%), Nepal (8.0%), Bhutan (2.6%) and China (19.1%). The Ganges is the world's largest delta covering an area of 105 000 km^2 in Bangladesh and India. The long term mean annual discharge for the Ganges is estimated at 1.14×10^4 $m^3 s^{-1}$ compared to 2.01×10^4 $m^3 s^{-1}$ for the Brahmaputra [27] with wide variation in flow between the wet and dry seasons [27,28]. The channels of both rivers are extremely unstable and bank lines can migrate as much as 400 m in a single season.

Most of the river channels seen today in the Gangetic Plain have migrated from their historically recorded positions. The reasons are, first, subsurface geotectonic movement leading to change in slope of the deltaic plain and subsidence of the Bengal basin; second, changing patterns of water discharge with time; and third, variation in sediment load [29]. The Ganges is one of the most regulated river systems with dams and barrages on practically every tributary and extensive embankments throughout the river resulting in diminished flow in the dry season. Systems to bypass dams could perhaps maintain sediment flow to the delta helping to offset subsidence and erosion. The area is of high importance for agriculture with about 250 million people directly dependent on this sector for their livelihood. In addition to river water, groundwater is extensively used for agriculture as well as for industry and municipal use. Decline of the groundwater table has been observed in many parts in the Ganges basin [30]. Changing climatic conditions have resulted in droughts and floods becoming more common in the region, severely affecting the agriculture sector. Many stretches of the river are dry or polluted because, among other factors, the Ganges and its tributaries have become a receptacle for municipal and industrial wastes [31]. The Ganges delta is clearly in an Anthropocene state.

The Ganges delta is also listed among the deltas in peril due to the reduction in aggradation plus accelerated compaction which is higher than rates of global sea-level rise [4]. The delta is highly influenced by the monsoon which defines the riverine flow. Climate change is expected to have an impact on the reliability and intensity of the monsoon as well as on the intensity of cyclones affecting the region [32] and its river flow. With higher temperatures, there is an expected increase in glacial meltwater contributions to river flow; in the case of the Ganges and Brahmaputra, meltwater contributions are expected to be relatively lower (cf. to the Indus), although increase in rainfall may lead to higher flows but with increased variability and thus potential for devastation [32]. Should the status quo prevail in terms of development, the SES could very well tip into an unfavorable configuration.

The Sundarbans is the largest contiguous mangrove forest in the world located in the GBM delta. It is extremely important for the various ecosystem services provided ranging from erosion control and protection from cyclones to high biodiversity [33,34]. About 200 years ago, the Sunderbans reportedly covered an area of 16 700 km^2, now reduced to about 10 000 km^2. Further rapid reduction in area could serve as a tipping point, changing the structure of the delta when linked to threats due to both anthropogenic and natural stressors with the added component of climate change. Anthropogenic stressors include growing human population and cross-border migration, growing livestock population, encroachment, land ownership conflicts, shrimp farming and poaching, and reduced sediment loads due to upstream dams, especially across the Ganges. Natural stressors include storm surges due to cyclones [35]. Loucks *et al.* [36] estimate a 28 cm rise in sea level above 2000 levels in the Sunderbans over the next 50–90 years. Others have documented the presence of mangroves and other halophytic species upstream near Kolkata city located about 60 km from the shore of the Bay of Bengal, indicating saline intrusion [37,38]. Dams across the Ganges have resulted in reduced sediment and water flows especially during the dry season and are considered to be part of the cause of reduction in the mangrove extent. New dams across the Brahmaputra especially in China could further reduce water and sediment loads reaching the mangroves and result in further changes in the structure of the delta. Increased efforts aimed at mangrove conservation as well as watershed management are therefore needed to avoid this tipping point.

Indus delta

The Indus delta receives water, sediment and nutrients from the 1 million km^2 Indus drainage basin. Before human intervention the average discharge was 3000 m^3 s^{-1} carrying an average sediment load of 250 Mt year^{-1} [39]. Peak discharges exceeded 30 000 m^3 s^{-1}, driven by heavy south-west monsoon rains. The delta's climate is arid sub-tropical, and is subject to a tidal range of 2.7 m and powerful offshore waves [40]. The Indus delta globally ranks seventh in size, at 30 000 km^2, and once offered the largest arid area of mangroves in the world [41]. Warm coastal waters (22°C on average) and summer tidal inundation often result in evaporate-salt deposits [42]. Historically the Indus discharged into the Arabian Sea via 14 river mouths — today most discharge is through just one mouth. Excluding Karachi which resides on the western limit of the delta, the Indus delta has a population of about 1.5 million people [43].

The systematic extraction of fresh water from the Indus river over the last 150 years to feed the world's largest irrigation system has led to a situation where in contrast to pre-human times when there was water discharge year round, today the number of days of zero water discharge to the Indus delta averages 138 days and increasingly may exceed 250 days per year [44]. The annual water and sediment discharges between 1931 and 1954 averaged 107 km^3 and 193 Gt, respectively. These discharge rates during the period 1993 to 2003 dropped by an order of magnitude to 10 km^3 and 13 Gt, respectively [41]. The delta has shifted to an Anthropocene state.

The drying of the Indus downstream from Kotri Barrage has permanently damaged the ecosystem. The sea has intruded in surface water bodies up to 225 km inland and salinity intrusion has also affected groundwater resources [42,43]. Shrimp production has decreased to one-tenth and has affected the livelihood of a vast majority of the nearly 0.5 million fishermen in the region [43]. The mangrove forest which covered 0.24 million ha has been reduced to 0.1 million ha [43]. The active Indus delta is now about one tenth of its original size. The Indus shoreline either advanced or was stable along most of its delta coast prior to the 1950s; since the late 1950s, the western coast has receded at rates of ~50 m year^{-1} [40]. The greatly reduced fresh water delivery and heavy seawater intrusion has destroyed large areas of prime agricultural land, including submersion of some villages in the coastal belt of these districts — causing desertification and displacement of several hundred thousand local residents who had been living there for many generations [41]. Herds of cattle, sheep and goats that used to be kept in the delta are no more, and only herds of camel are still found there [45]. It is unlikely that these trends can be reversed given the large population of the Indus basin and the deterioration of the delta will likely continue unabated.

Mekong delta

The Mekong delta begins in Cambodia at Phnom Penh, where the river divides into the Mekong and the Bassac. The delta area is mainly located in southern Vietnam where the distributaries of the Mekong drain into the South China Sea. The catchment area has a size of 0.76 M km^2 while the delta itself encompasses an area of approximately 55 000 km^2 [46] forming the third largest delta plain of the world [47]. The typical discharge is around 15 000 m^3 s^{-1} while peak discharges can be well above 50 000 m^3 s^{-1} [46] with an estimated sediment load of ca. 160 Mt year^{-1} [48]. The delta's climate is tropical monsoonal. A large part of the delta is influenced by tides [46].

In the Mekong delta in Vietnam, large-scale human interventions such as channel construction, flood and coastal protection are relatively recent, mainly starting in the 17th century [49]. For example, the establishment of channels started in 1824, was continued in late 19th century by the French, and have been considerably extended during the 1930s [50]. A more recent phase of channel construction started in 1975, when a large number of irrigation and land reclamation schemes have been put in place for irrigation purposes [49,50]. Despite considerable bank erosion and high rates of channel migration (up to 20 m year^{-1} in the upper delta region), bank stabilization via technical engineering measures has not been applied on a large scale [49] meaning that the natural delta dynamics are fundamentally intact. Existing engineering structures contribute to flood hazards by elevating flow velocities and thus bank erosion as well as the likelihood of flooding in the non-protected areas of the delta including the risk of dyke failures in protected areas [51]. Rice is the main crop in this agriculturally-dominated delta [52]. Yet, this rice production is increasingly under threat by salinity intrusion partially induced by climate change related to sea level rise. The delta is also extremely vulnerable to changes brought about by human activity upstream such as dam construction, which are likely to change the hydrology, sedimentation processes, nutrient transport as well as the status of the aquatic ecosystems [53,54]. Other examples of human impacts include extension of engineered infrastructure against seawater intrusion, coastal and riverbank erosion, intensification of agriculture and aquaculture with resulting pollution of freshwater resources [55]. Further concerns involve riverbank erosion [50], increasing flood variability [56•], coastal erosion and the resulting human migration in response to these changing environmental and economic conditions [57].

In summary, the relatively recent history of human interventions in the Mekong delta is approaching a point where the function of the delta as an enabling environment for agricultural and aquaculture production could be significantly threatened in the future. The Mekong is an Anthropocene delta that could tip into an unfavorable system state should water and sediment fluxes be further altered via either climate change and/or upstream dam construction. Fully engineered solutions might not be achievable or even desired but an adaptation of agricultural production systems to the consequences of coastal erosion and salinity intrusion might be a viable option [58], which could constitute a different development pathway, increasing the resilience of the Mekong delta SES.

Danube delta

The Danube river is the second largest river in Europe (2857 km in length), it connects 11 riparian countries, and provides 77% of the total freshwater input to the Black Sea. The 817 000 km^2 watershed is currently inhabited by over 100 million people. The Danube delta begins in Romania near Tulcea, where the river's main channel divides into the northern Chilia, the central Sulina and the southern Sfântu Gheorghe branches. Covering an area of 4080 km^2 [59], the Danube delta is the second largest river delta in Europe.

Human settlements in the Danube delta are documented since the Roman Empire and the Little Ice Age [59,60,61•]. Rapid deforestation in the watershed led to increased sediment transport and rapid Holocene delta growth [59,60]. Hence, in light of the Anthropocene [62••], the human influence dates back to before the industrial era. During the last century, human pressures on the Danube delta have included the creation of polders for agriculture — some of which have been abandoned due to restoration measures, channel deepening for navigation (Sulina channel), introduction of alien fish species for fishery, and eutrophication resulting from agriculture. However, the lack of continuous dikes in the delta allows the river to spread over the delta. Since the 1970s, rapidly accelerating water and energy demands in the upland basin led to the construction of water engineering facilities like the Iron Gates I and II reservoirs, which together have reduced the suspended sediment load reaching the Danube delta from 40 to 100 000 ton year^{-1} to less than 20 000 ton year^{-1} [61•], resulting in erosion in the southern part of the delta. Despite the decreased sediment loads, low subsidence rates counteract the threat of increasing inundation. However, while these recent pressures affect the geographic shape of the delta (Figure 1 in Giosan *et al.*, 2012 [60]), its geomorphological stability and Holocene ecological functioning have not been driven past a tipping point of resilience.

The Danube delta thus can be categorized as being in-between a 'Holocene-modified delta SES' and an 'Anthropocene delta SES' state. The variety of environments and high biodiversity in the Danube delta would not exist in its current form without the massive interventions that started during the Roman Empire and the increasing population pulses during the Little Ice Age [60,61•]. Today, the Danube delta provides vital ecosystem goods and services, such as surplus nutrient uptake and recycling, which benefits the catchment–Black Sea coast continuum [63•,64].

A central tipping point cannot easily be applied to the Danube delta SES. To date, we have no indication that the Danube Delta features a certain 'point of no return'. In addition, the often negative connotations associated with the words 'tipping point' do not seem to apply to the Danube delta, particularly when discussing historical human impacts on the environment. We observe, instead, the emergence of a relatively young SES that provides a highly valuable set of socio-environmental goods and services. Without anthropogenic forcing over the last two Millennia, it is unlikely that the current system and its socio-environmental services would exist. The socio-economic processes that led to today's Danube delta have created an ecosystem that is among the top European points of biodiversity.

In considering the Danube delta, we can introduce the notion of a 'positive tipping point' leading to an 'Anthropocene delta SES' that is currently the focus of European efforts toward increased socio-economic development and protection. In 2011 the EU, through its Joint Research Centre (JRC), called for an initiative providing scientific support of a Danube-wide development strategy. Among the six scientific clusters launched in Brussels in May 2013, four (water, land and soil, bioenergy, and air) directly underscore the importance of material and energy flows and the transboundary nature of the drivers affecting the Danube-Black Sea SES and, thus, the delta (http://ec.europa.eu/regional_policy/cooperate/danube/index_en.cfm).

Applying a historic and geochronological view, we see the central role of land-based processes driven by socio-economic development (land-use and cover change, urbanization, and industrialization); additionally, post 1990, we see demographic and societal transformation (the socio-political 'tipping point') and the rapid transition from a planned economy to a market economy in many riparian states to be key factors in defining the SES state of the Danube. Determining and measuring the growing role of political and transnational institutions, such as the EU, in providing scientifically informed governance frameworks remains a challenge, particularly when it comes to applying the term 'tipping point' in a meaningful way to deltas, and to other SES.

Conclusions

Many of the world's deltas are regions of intensive agricultural production and in more recent times, of rapid urbanization. These local transformations often occur synchronously with transformations in the upland contributing drainage basins. Many deltas around the world have now been or are being transformed from a Holocene state to an Anthropocene state and these transformations, when combined with the effects of climate change, could push some deltas past tipping points toward an unfavorable SES state.

The deltas presented in this paper are all subject to regime shifts. The three Asian deltas that we considered are currently among the most rapidly changing. The example of the Rhine-Meuse and Danube delta shows that the highly managed state can be relatively stable, and may give rise to interventions leading to an increasingly resilient system. This, in theory, is dependent on availability of cheap energy resources and the Rhine-Meuse delta could actually prove to be poorly resilient in light of anticipated, rising energy costs over the long-term. However, despite increasing energy prices, the cost of water management in the Netherlands constitutes a decreasing part of national spending [65], and thus preserving delta integrity becomes an issue of political willpower and willingness to make requisite financial investments. Water systems themselves will be a basis for a transition to more sustainable energy sources (already 110 GWh per year is gained from water power opposed to 176 GWh needed for water management [66]).

The question of whether the Anthropocene will be a major threat to coastal deltas and their inhabitants or a major achievement in terms of taming nature and supporting human development will depend largely on whether a 'safe operating space for humanity' can be maintained [67]. We argue that there is a severe, but perhaps poorly calculated, risk in believing that engineering solutions can fully control Anthropocene delta SES. Sustaining the integrity of coastal deltas and the associated human well-being that they are capable of conveying will be questionable, however, given our lack of knowledge on basin states, feedbacks, and non-linear responses in their dynamics. The examples of the Mekong and Danube deltas show that the non-systematic reliance on engineering structures allow (in the case of the Danube) or could potentially allow (in the case of the Mekong) economic development and increased resilience.

Many initiatives are in place or planned to address the specific constraints that some major world deltas are facing: we mention two here. First, the new global Future Earth research for global sustainability program (http://www.icsu.org/future-earth) is expected to address the complexity of questions such as delta sustainability. The themes of Future Earth provide a framework for capturing the three spatial and fourth temporal dimension of drivers and pressures of deltaic change. They also reflect the sensible interplay of markets, governments and civil society in defining the value systems and social choice for riparian system development. They provide the socioeconomic boundaries for management in the water cascade and thus the delta SES, and will largely influence if a system stays within its sustainable limits or not.

These themes, as we interpret them, capture the spatial temporal and institutional dimension of drivers and pressures of deltaic change. They may help explore the sensible interplay of markets (such as through global, regional and national energy, food and water prices), governments and civil society including welfare aspirations that determine the value systems and social choice in riparian system development. A key is to include the socio-economic boundaries and limitations as well as scientifically sound risk assessments to inform integrated upstream–downsteam management in the water cascade and to figure out under which socio-environmental and economic conditions could a deltaic system be sustained while simultaneously remaining within associated, stable geophysical and biological limits.

A second initiative is a proposal for an International Year on Deltas [68•], aiming to increase awareness of and attention to the value and vulnerability of deltas worldwide, promote and enhance international and regional cooperation at the scientific, policy, and stakeholder levels, and focus and accelerate a comprehensive research agenda toward understanding and modeling these complex SESs.

The need for knowledge on deltas is particularly crucial as we have generated so far little information about the long term impacts of human interventions in these environments — the Anthropocene is a new era that is characterized by rapid changes in our environment. It is not only a question of how to best implement adaptive management of environmental resources in these rapidly changing interface systems between land and ocean but also to characterize their social tipping points or turning points in order to avoid unacceptable changes, if these can be avoided at all.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Ericson JP, Vörösmarty CJ, Dingman SL, Ward LG, Meybeck M: **Effective sea-level rise in deltas. Sources of change and human-dimension implications**. *Global Planet Change* 2006, **50**:63-82.

2. • Kuenzer C, Renaud FG: **Climate and environmental changes in river deltas globally: expected impacts, resilience, and adaptation**. In *The Mekong Delta System. Interdisciplinary Analyses of a River Delta.* Edited by Renaud FG, Kuenzer C. Springer Environmental Science and Engineering XV; 2004:7-47.
The authors review the most prominent challenges that threaten delta development worldwide and discuss possible mitigation and adaptation options. Furthermore, the authors describe deltas with different resilience and address the challenges induced by environmental and climate change.

3. •• Overeem I, Kettner Albert J, Syvitski J: **Impacts of humans on river fluxes and morphology**. In *Treatise of Geomorphology, Volume 9, Fluvial Geomorphology.* Edited by Wohl E. New York: Elsevier; 2013:828-842.
The paper describes the human impact on the river fluxes through engineering, and indirectly through land-use and climate change and describes the extent of the human influence. The paper argues that the effects of the combined human actions are multi-directional and complex and calls for a quantitative mapping of the human influences on rivers for achieving an integrated river and delta management.

4. Syvitski JPM, Kettner AJ, Overeem I, Hutton EWH, Hannon MT, Brakenridge GR, Day J, Vörösmarty C, Saito Y, Giosan L, Nicholls RJ: **Sinking deltas due to human activities**. *Nat Geosci* 2009, **2**:681-686.

5. Vörösmarty CJ, Meybeck M, Fekete B, Sharma K, Green P, Syvitski J: **Anthropogenic sediment retention: major global-scale impact from the population of registered impoundments**. *Global Planet Change* 2003, **39**:169-190.

6. Syvitski JPM, Vörösmarty CJ, Kettner AJ, Green P: **Impact of humans on the flux of terrestrial sediment to the global coastal ocean**. *Science* 2005, **308**:376-380.

7. Syvitski J, Saito Y: **Morphodynamics of deltas under the influence of humans**. *Global Planet Change* 2007, **57**:261-282.

8. • Dasgupta S, Laplante B, Murray S, Wheeler D: **Exposure of developing countries to sea-level rise and storm surges**. *Clim Change* 2011, **106**:567-579.
The paper reports the outcome of a global GIS analysis conducted to estimate the exposure to future storm surge increases associated with more intense storms and a 1 m sea level rise. The results point out areas of the developing world which may be more exposed to these climate changes than others.

9. Crutzen PJ, Stoermer EF: **The 'Anthropocene'**. *Global Change News* 2000, **41**:17-18.

10. Biggs R, Carpenter SR, Brock WA: **Turning back from the brink: detecting an impending regime shift in time to avert it**. *PNAS* 2009, **106**:826-831.

11. Möllmann C, Müller-Karulis B, Kornilovs G, St. John MA: **Effects of climate and overfishing on zooplankton dynamics and ecosystem structure: regime shifts, trophic cascade, and feeback loops in a simple ecosystem**. *ICES J Mar Sci* 2008, **65**:302-310.

12. Lenton TM, Held H, Kriegler E, Hall JW, Lucht W, Rahmstorf S, Schellnhuber HJ: **Tipping elements in the Earth's climate system**. *PNAS* 2008, **105**:1786-1793.

13. Lindsay RW, Zhang J: **The thinning of Arctic sea ice, 1988–2003: have we passed a tipping point?** *J Clim* 2005, **18**:4879-4894.

14. Secretariat of the Convention on Biological Diversity: *Global Biodiversity Outlook 3*. 2010:. Montréal, Canada.

15. Walker B, Meyers JA: **Thresholds in ecological and social-ecological systems: a developing database**. *Ecol Soc* 2004, **9**:3 http://www.ecologyandsociety.org/vol9/iss2/art3 (online available).

16. IPCC (Intergovernmental Panel on Climate Change): *Special Report — Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)*. Cambridge University Press; 2012.

17. Overeem I, Syvitski JPM: *Dynamics and Vulnerability of Delta Systems, LOICZ Reports & Studies No. 35*. Geesthacht: GKSS Research Center; 2009, .

18. Kwadijk JCJ, Haasnoot M, Mulder JPM, Hoogvliet MMC, Jeuken ABM, van der Krogt RAA, van Oostrom NGC, Schelfhout HA, van Velzen EH, van Waveren H *et al.*: **Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands**. *Wiley Interdiscip Rev: Clim Change* 2010, **1**:729-740.

19. •• Werners SE, Pfenninger S, Swart R, van Slobbe E, Haasnoot M, Kwakkel J: **Thresholds, tipping and turning points for sustainability under climate change**. *J Curr Opin Environ Sustain* 2013, **5**:334-340 (in press).
The authors shows how thresholds, tipping and turning points are important focal points for sustainability under climate change that can help to bridge the science-policy interface.

20. Renaud F, Birkmann J, Damm M, Gallopín GC: **Understanding multiple thresholds of coupled social-ecological systems exposed to natural hazards as external shocks**. *Nat Hazards* 2010, **55**:749-763.

21. Folke C, Chapin FS III, Olsson P: **Transformation in ecosystem stewardship**. In *Principles of Ecosystem Stewardship: Resilience-Based Natural Resource Management in a Changing World.* Edited by Chapin III FS, Kofinas GP, Folke C. Chapin, MC: Springer; 2009:103-128.

22. Huntington HP, Goodstein E, Euskirchen E: **Towards a tipping point in responding to change: rising costs, fewer options for arctic and global societies**. *Ambio* 2012, **41**:66-74.

23. Day JW Jr, Boesch DF, Clairain EJ, Kemp GP, Laska SP, Mitsch WJ, Orth K, Mashriqui H, Reed DR, Shabman L, Simenstad CA, Streever BJ, Twilley RR, Watson CC, Wells JT, Whigham DT: **Restoration of the Mississippi delta: lessons from hurricanes Katrina and Rita**. *Science* 2007, **315**:1679-1684.

24. Paola C, Twilley RR, Edmonds DA, Kim W, Mohrig D, Parker G, Viparelli E, Voller VR: **Natural processes in delta restoration: application to the Mississippi delta**. *Ann Rev Mar Sci.* 2011, **3**:67-91.

25. Werners SE, Sandt Kvd, Jaspers F: **Mainstreaming climate adaptation into water management in the Netherlands: the governance of the Dutch delta program**. *Conference on the Human Dimensions of Global Environmental Change*; *Amsterdam: 2009*.

26. Delta Commissioner: *The 2011 delta programme working on the delta; investing in a safe and attractive Netherlands, now and in the future*. Ministry of Transport Public Works and Water Management, Ministry of Agriculture Nature and Food Quality, and Ministry of Housing Spatial Planning and the Environment, Dutch National Government; 2010.

27. Jian J, Webster PJ, Hoyos CD: **Large-scale controls on Ganges and Brahmaputra river discharge on intraseasonal and seasonal time-scales**. *Q J R Meteorol Soc* 2009, **135**:353-370.

28. Coleman JM: **Brahmaputra river: channel processes and sedimentation**. *Sediment Geol* 1969, **3**:129-239.

29. Sarkar SK, Bhattacharya A, Bhattacharya B: **The river Ganga of Northern India; an appraisal of its geomorphic and ecological changes**. *Water Sci Technol* 2003, **48**:121-128.

30. Moors EJ, Groot A, Biemans H, van Scheltinga CT, Siderius C, Stoffel M, Huggel C, Wiltshire A, Mathison C, Ridley J *et al.*: **Adaptation to changing water resources in the Ganges basin, northern India**. *Environ Sci Policy* 2011, **14**:758-769.

31. Misra AK: **Climate change impact, mitigation and adaptation strategies for agricultural and water resources, in Ganga Plain (India)**. *Mitig Adapt Strateg Glob* 2012. (published online, online available: http://dx.doi.org/10.1007/s11027-012-9381-7).

32. Gain AK, Immerzeel WW, Sperna Weiland FC, Bierkens MFP: **Impact of climate change on the stream flow of the lower Brahmaputra: trends in high and low flows based on discharge-weighted ensemble modeling**. *Hydrol Earth Syst Sci* 2011, **15**:1537-1545.

33. Iftekar MS, Islam MR: **Degeneration of Bangladesh's Sundarbans Mangroves: a management issue**. *Int For Rev* 2009, **6**:123-135 (Online available: http://dx.doi.org/10.1505/ifor.6.2.123.38390).

34. Barua P, Chowdhury SN, Sarkar S: **Climate change and its risk reduction by mangrove ecosystem of Bangladesh**. *Bangladesh Res Pub J* 2010, **4**:218-225.

35. Mohammed MR, Rahman MM, Islam KS: **The causes of deterioration of Sundarban mangrove forest ecosystem of Bangladesh: conservation and sustainable management issues**. *AACL Bioflux* 2010, **3**.

36. Loucks C, Barber-Meyer S, Hossain MdAA, Barlow A, Chowdhury RM: **Sea level rise and tigers: predicted impacts to Bangladesh's Sundarbans mangroves**. *Clim Change* 2010, **98**:291-298.

37. Bandyopadhyay K: *Mangroves Sprout in Kolkata*. Kolkata: The Times of India; 2008, .

38. Mitra A, Banerjee K, Sengupta K, Gangopadhyay A: **Pulse of climate change in Indian Sundarbans: a myth or reality?** *Natl Acad Sci Lett* 2009, **32**:19-25.

39. Milliman JD, Quraishee GS, Beg MAA: **Sediment discharge from the Indus river to the ocean: past, present and future**. In *Marine Geology and Oceanography of Arabian Sea and Coastal Pakistan.* Edited by Haq BU, Milliman JD. New York: Van Nostrand Reinhold; 1984:66-70.

40. Giosan L, Constantinescu S, Clift PD, Tabrez AR, Danish M, Inam A: **Recent morphodynamics of the Indus delta shore and shelf**. *Continent Shelf Res* 2006, **26**:1668-1684.

41. Inam A, Clift P, Giosan L, Tabrez AR, Tahir M, Rabbani MM, Danish M: **The geographic, geological and oceanographic setting of the Indus river**. In *Large Rivers: Geomorphology and Management.* Edited by Gupta A. Chichester: John Wiley & Sons; 2007:333-346.

42. Memon AA: **Devastation of the Indus river delta**. In *Proceedings, World Water & Environmental Resources Congress 2005, American Society of Civil Engineers, Environmental and Water Resources Institute*; *Anchorage, Alaska, May 14–19: 2005*.

43. Kamal S: **Area water partnerships (AWPs) and their potential for community-based action in IWRM**. *International Symposium on Community Based Approaches for Integrated Water Resources Management*; *Islamabad, February 16–17: 2004*.

44. Fahlbusch H, Schultz B, Thatte CD: *The Indus Basin: History of Irrigation, Drainage and Flood Management*. New Delhi, India: International Commission on Irrigation and Drainage; 2004, .

45. Asianics Agro-Dev. International (Pvt) Ltd. (2000) Tarbela dam and related aspects of the Indus River basin, Pakistan, a WCD case study prepared as an input to the World Commission on Dams, Cape Town.

46. Mekong River Commission: *Overview of the hydrology of the Mekong basin*. Vientiane: MRC; 2005, .

47. Coleman JM, Roberts HH: **Deltaic coastal wetlands**. *Geologie enMijnbouw* 1989, **68**:1-24.

48. Milliman JD, Syvitski JPM: **Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers**. *J Geol* 1992, **100**:525-544.

49. Hashimoto T: *Environmental Issues and Recent Infrastructure Development in the Mekong Delta: Review, Analysis and Recommendations with Particular Reference to Large-scale Water Control Projects and the Development of Coastal Areas. Working paper No. 4*. Australian Mekong Resource Centre; 2001.

50. Hung NN, Delgado JM, Tri VK, Hung LM, Merz B, Bárdossy A, Apel H: **Floodplain hydrology of the Mekong delta, Vietnam**. *Hydrol Process* 2012, **26**:674-686.

51. Le TVH, Nguyen HN, Wolanski E, Tran TC, Haruyama S: **The combined impact on the flooding in the Mekong River delta, Vietnam, of local man-made structures, sea level rise, and dams upstream in the river catchment**. *Estuar Coast Shelf Sci* 2007, **71**:110-116.

52. FAOSTAT [Food and Agriculture Organization of the United Nations, Statistics Division] (2013): http://faostat.fao.org/ [accessed 30.01.13].

53. I.C.E.M. International Center for Environmental Management: *MRC Strategic Environmental Assessment (SEA) of Hydropower on the Mekong Mainstream*. . Hanoi, Vietnam 2010.

54. Kuenzer C, Campbell I, Roch M, Leinenkugel L, Vo Quoc T, Dech S: **Understanding the impacts of hydropower developments in the context of upstream-downstream relations in the Mekong river basin**. *Sust Sci* 2012. [Online available: http://dx.doi.org/10.1007/s11625-012-0195-z].

55. Sebesvari Z, Le TTH, Toan PV, Arnold U, Renaud FG: **Agriculture and water quality in the Vietnamese Mekong delta**. In *The Mekong Delta system. Interdisciplinary Analyses of a River Delta.* Edited by Renaud FG, Kuenzer C. Dordrecht: Springer Environmental Science Engineering; 2012:331-361.

56. Delgado JM, Apel H, Merz B: **Flood trends and variability in the**
• **Mekong River**. *Hydrol Earth Syst Sci* 2010, **14**:407-418.
Based on a review of geochronological and historical data this paper documents the impact of humans on the largest southern European deltas during the Roman Empire and the Little Ice Age. These deltas were formed almost synchronously during these two short intervals of enhanced anthropic pressure on landscapes.

57. Dun O: **Migration and displacement triggered by floods in the Mekong delta**. *Int Migr* 2011, **49**:200-223.

58. Renaud FG, Le TTH, Lindener C, Guong VT, Sebesvari Z: **Resilience and shifts in agro-ecosystems facing increasing sea-level rise and salinity intrusion in Ben Tre Province, Mekong Delta**. *Clim Change* 2013. (submitted for publication).

59. Giosan L, Coolen MJL, Kaplan JO, Constantinescu S, Filip F, Filipova-Marinova M, Kettner AJ, Thom N: **Early Anthropogenic transformation of the Danube–Black Sea System**. *Sci Rep* 2012, **2**.

60. Giosan L, Donelly JP, Constantinescu S, Filip F, Ovejanu I, Vespremeanu-Stroe A, Vespremeanu E, Duller GAT: **Young Danube delta documents stable Black Sea level since the middle Holocene: morphodynamic, paleogeographic, and archaeological implications**. *Geology* 2006, **34**:757-760.

61. Maselli V, Trincardi F: **Man made deltas**. *Sci Rep*
• 2013, **3**.
Based on a review of geochronological and historical data this paper documents the impact of humans on the largest southern European deltas during the Roman Empire and the Little Ice Age. These deltas were formed almost synchronously during these two short intervals of enhanced anthropic pressure on landscapes.

62. Steffen W, Grinevald J, Crutzen P, McNeill J: **The Anthropocene:**
•• **conceptual and historical perspectives**. *Philos Trans R Soc A* 2011, **369**:842-867.
The authors argue that the Anthropocene should be formally recognized as a new epoch in Earth history. The paper provides a history of the human–environment relationship and suggests the Industrial Revolution around 1800 as a start date for the new epoch.

63. Capet A, Beckers JM, Grégoire M: **Drivers, mechanisms and**
• **long-term variability of seasonal hypoxia on the Black Sea**

northwestern shelf — is there any recovery after eutrophication? *Biogeosciences* 2013, **10**:3943-3962.

This paper looks at drivers and mechanisms of hypoxia on the northwestern Black Sea shelf, and whether there is a recovery from eutrophication. One of the major findings in this paper is that annual river nitrate load together with 3 other predictors explains 82% of the hypoxia intensity, and hence, underlines the impact of the Danube river nutrient loads on the Black Sea ecosystem.

64. Friedrich J, Dinkel C, Grieder E, Radan S, Secrieru D, Steingruber S, Wehrli B: **Nutrient uptake and benthic regeneration in Danube delta lakes**. *Biogeochemistry* 2003, **64**:373-398.

65. De Nederlandsche Bank: *Consequences of Climate Change for the Dutch Government Finances (In Dutch: Gevolgen van klimaatverandering voor de Nederlandse overheidsfinancien). Quarterly Report, September*. 2007:. Amsterdam.

66. Dahm R, Bruggers M, Clevering-Loeffen P, Kamermans J: **Energy use of the Dutch water management (In Dutch: Energieverbruik van het Nederlandse waterbeheer)**. *H2O* 2010, **17**:20-21.

67. Rockström J, Steffen W, Noone K, Persson Å, Chapin FS III, Lambin E, Lenton TM, Scheffer M, Folke C, Schellnhuber H *et al.*: **Planetary boundaries: exploring the safe operating space for humanity**. *Ecol Soc* 2009, **14**:32.

68. • Foufoula-Georgiou E: **International Year of Deltas 2013: a proposal**. *Eos* 2011, **92**:340-341.

The paper describes the global importance of deltas and proposed that 2013–2014 be designated as the International Year of Deltas (IYD).