Resilience of river deltas in the Anthropocene

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Key Points:

- The predictive capacity of morphodynamic models needs to improve to better anticipate global change impacts on deltas
- Information theory and dynamical system theory offer complementary analysis frameworks to improve understanding of delta resilience
- The sediment balance in a delta channel network needs to be closed such that predictions match with independent observations

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Abstract

At a global scale, delta morphologies are subject to rapid change as a result of direct and indirect effects of human activity. This jeopardizes the ecosystem services of deltas, including protection against flood hazards, facilitation of navigation and biodiversity. Direct manifestations of delta morphological instability include river bank failure, which may lead to avulsion, persistent channel incision or aggregation, and a change of the sedimentary regime to hyperturbid conditions. Notwithstanding the in-depth knowledge developed over the past decades about those topics, existing understanding is fragmented, and the predictive capacity of morphodynamic models is limited. The advancement of potential resilience analysis tools may proceed from improved models, continuous observations and the application of novel analysis techniques. Progress will benefit from synergy between approaches. Empirical and numerical models are built using field observations and, in turn, model simulations can inform observationists about where to measure. Information theory offers a systematic approach to test the realism of alternative model concepts. Once that the key mechanism responsible for a morphodynamic instability phenomenon is understood, concepts from dynamic system theory can be employed to develop early warning indicators. In the development of reliable tools to design resilient deltas, one of the first challenges is to close the sediment balance at multiple scales, such that morphodynamic model predictions match with fully independent measurements. Such a high ambition level is rarely adopted, and is urgently needed to address the ongoing global changes causing sea-level rise and reduced sediment input by reservoir building.

1 Introduction

River deltas are hotspots for economic development, wetland biodiversity and agriculture. Many of the world's mega-cities are located in deltas (Syvitski & Saito, 2007), related to harbor activity, fishing, and the fertility of coastal land. High population densities put deltas under pressure and lead to reshaping of the sedimentary environment (S. Wilson & Fischetti, 2010; Zhang et al., 2015). Under natural circumstances, delta dynamics are primarily governed by riverine sediment supply and subsequent tidal and wave-driven reworking, controlled over larger timescales by fluctuations in mean sea-level and sediment supply. Human activity disrupts these natural dynamics; building of reservoirs in river catchments, for example, has caused many deltas to become sediment starved (Syvitski et al., 2005). While compromising between alternative land use types, delta planforms have increasingly become fixed by embankments (engineered levees) for reasons of land reclamation and flood prevention (Giosan et al., 2013). The embankment obstructs the processes of aggradation that could compensate for subsidence within the embanked interchannel areas (J. Nittrouer et al., 2012), which has been identified as a major factor determining flood vulnerability (Syvitski et al., 2009).

Whether constrained by embankment or not, delta distributary channels typically terminate in mouth bar complexes, where depths are small (Fagherazzi et al., 2015). Fairways crossing these mouth bars require regular dredging to prevent rapid accretion (e.g., Fan et al., 2006). The relatively deep navigation channels convey a comparatively large share of the river discharge, and amplify the tidal motion in the delta channel network. Typically, this leads to import of marine sediment and a reduction of the channel width (Nienhuis et al., 2018). Fine sediment tends to accumulate in deep navigation channels, causing a gradual increase of suspended sediment concentrations. The dredging volumes needed to guarantee sufficient navigation depth can become excessive (De Vriend et al., 2011), which may be traced back to a variety of physical processes including tidal pumping of sediment (Allen et al., 1980) and density driven circulations (Hansen & Rattray Jr, 1966).

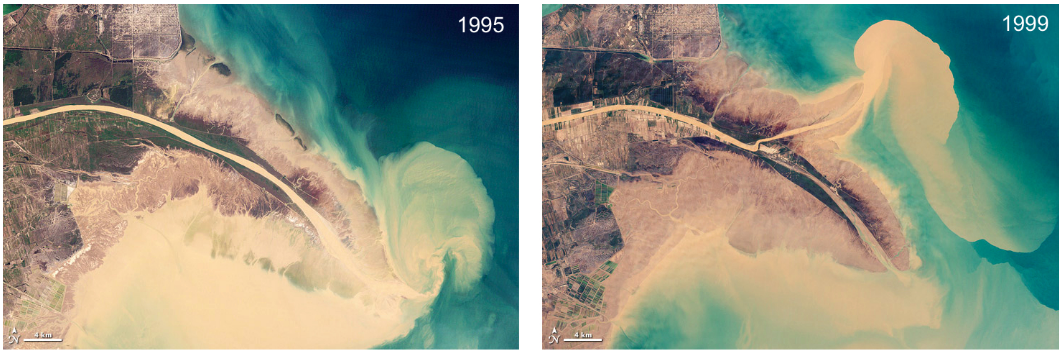

Figure 1. Scientific understanding about the natural process of avulsion has laid the basis for a large-scale human intervention in which a new channel is created in the Yellow River Delta. Image courtesy: NASA Earth Observatory.

Whereas distributary channels inside the delta tend to accrete, delta shorelines of sediment starved deltas show retreat, marking a transition from progradation to erosion such as in the Nile Delta (Stanley & Warne, 1993), the Mississippi Delta (Couvillion et al., 2017), the Ebro Delta (Sanchez-Arcilla et al., 1998) and the Yellow River Delta (Chu et al., 2006). Urban expansion in deltas causes sand to be a valuable resource, up to the point that the entire sediment input to the delta is extracted and used for the foundation of infrastructure and building material. Coastal protection works may arrest the shoreline retreat, but the impacts of sediment depletion may eventually become apparent inside the delta channel network as scour. In deltas with a heterogeneous subsoil lithology, erosion processes lead to the emergence of deep pits in the channel beds, putting the protected embankments at risk (Sloff et al., 2013). Unprotected earthen dikes, such as in the Ganges-Brahmaputra delta, can directly fail as a result of flow reorganization triggered by human modifications (Bain et al., 2019).

Considering that sea-level rise, sand depletion, as well as human pressure on delta land are expected to increase, conventional approaches to control delta landscapes may become unsustainable. River embankments require progressively higher maintenance efforts, as the delta land behind the embankment subsides. Storm surge barriers cannot be easily adjusted to keep up with the rising sea-level. Awareness has grown that in a long-term perspective, hard and inflexible infrastructure in deltas may be inefficient, which motivates the quest for sustainable, nature-based solutions to relieve the pressure on deltas (Temmerman & Kirwan, 2015; Tessler et al., 2015). The development of nature-based solutions, in turn, requires in-depth knowledge about the way in which deltas have gained flood resilience in the geological past (Paola et al., 2011; Hoitink et al., 2017), and about the potential triggers that may force part of the delta to another stable state. This can be illustrated with the case of the Yellow River Delta (Fig. 1), where an uncontrolled rerouting of the river is prevented using knowledge about avulsion (Moodie et al., 2019).

Here, we define a delta morphodynamic system to be resilient when it has the capacity to recover from an extreme forcing at one of its boundaries, and is largely self-sustaining (i.e., not in need of high maintenance). In this context, extreme forcing includes peak river discharges and storm surges. Accordingly, a delta may be considered resilient when after an extreme river discharge event or a storm surge, morphodynamical processes quickly reverse the temporary impacts on the delta morphology, autonomously. A more resilient delta returns more closely to the morphology it had prior to the event, which is dependent on general wave climate, discharge dynamics, tidal regime and the sedimentary and biotic characteristics. In this contribution, we set out to introduce grand challenges that need to be overcome before this form of delta resilience can be fully understood, and eventually quantified.

We focus on emerging processes that are notoriously difficult or costly to reverse, and that are specific to deltas as opposed to coastal plains in general. Within this focus area, four key manifestations of delta instability in an anthropocentric context can be identified: river bank failure, persistent channel incision or siltation, avulsion, and regime change to hyper-turbidity. Each of those four processes occurs both in natural deltas and in human modified deltas. They represent poorly reversible, or even irreversible transformations of the morphodynamic system, at least at the time scale of decades. Both natural and human-modified deltas have variable degrees of resilience, and are subject to study herein. It is our intention to address the weaknesses in current approaches that aim to analyse and quantify delta resilience, and to propose promising analysis tools that may help to improve the predictive power of various types of models. Considering sea-level rise, an improved capacity to predict delta stability is urgently needed.

In section 2, we discuss the knowledge gaps for each of the four selected manifestations of delta instability. In section 3, potential analysis tools are evaluated that can be employed to anticipate and prevent the uncontrolled state changes described in section 2. Such tools allow to quantify resilience, and to identify early warning indicators. Section 4 discusses the key challenges that need to be overcome when applying new analysis tools discussed in section 3.

2 Manifestations of delta instability

2.1 River bank failure

Failure of river banks may cause catastrophes that are well documented in the memories of communities living in coastal lowlands (Fig. 2). Although the rate of change of channel planforms generally reduces towards the coast (e.g., Hoitink et al., 2017), bank retreat rates of distributary channels can be significant. For example, Pilarczyk (2004) reported retreat rates of up to 20 m a^{-1} on the Mekong River Delta, while J. Walker et al. (1987) observed retreat rates as large as 11 m a^{-1} in the Colville River Delta. Bank erosion is a natural process and most commonly occurs at cut banks of meandering rivers during long-term, gradual adjustment of river planform. Pervasive bank erosion is therefore used as an indicator of channel instability, such as persistent channel incision or siltation (e.g., Schumm et al., 1984), or a precursor of avulsion. River bank retreat is primarily caused by two erosion processes: surface erosion (also termed hydraulic or fluvial erosion) and gravity-induced mass failures or bank collapses (e.g., Langendoen & Simon, 2008). Surface erosion occurs when the forces exerted by surface and groundwater flows exceed the erosion resistance of the bank soils. Stream bank mass failure occurs when the gravitational force, that is the weight of the failing bank, exceeds the shear strength of the bank materials (Thorne et al., 1982; Lawler, 1993; Thorne et al., 1998b,a). The overall erosion resistance and shear strength of bank soils is affected by soil physical and chemical properties, soil organics, soil water chemistry, pore water pressures and the presence of riparian vegetation. Some authors consider subaerial weathering of bank material as a third erosional process or agent (Couper & Maddock, 2001). However, it is typically seen as a preparatory process that makes bank material more susceptible to surface erosion or mass failure.

Papanicolaou et al. (2006) identified key areas in need of further research for the above processes (Table 1), which are similar to those described by Rinaldi & Nardi (2013). At present, limited progress has been made to address these needs. Improvements in high-resolution measurement techniques has resulted in improved quantification of flow resistance provided by bank roughness in general (Konsoer, 2014; Leyland et al., 2015) and by vegetation specifically (e.g., Hopkinson & Wynn, 2009; Nepf, 2012; Aberle & Järvelä,

Figure 2. Catastrophic dike breaches such as near the city of Bemmel in The Netherlands (1799) are engraved into the memories of communities living in river landscapes. Drawing by Christiaan Josi, 1802. Image courtesy: Rijksmuseum Amsterdam.

2013). Unfortunately, these advances have not led to generalized formulations of bank erodibility and surface erosion rates. Soil erodibility is controlled by a multiplicity of soil and soil water physical and chemical properties with varying impacts that make soil erodibility highly variable in space and time, and therefore site specific (Konsoer et al., 2016), which may prohibit the establishment of a universal model. Because of this complexity, research on the lateral dynamics of distributary channels has mainly focused on quantifying the effects of fluvial and tidal hydrodynamics (e.g., Lentsch et al., 2018). However, Motta et al. (2012) showed that floodplain soil erodibility could exert a greater influence on river planform geometry and dynamics than the hydrodynamic processes.

Coupled monitoring of river hydrodynamics and bank erosion (Luppi et al., 2009; Klösch et al., 2015) and the increasing use of computational models that include more processes at smaller scales (Darby et al., 2007; Langendoen et al., 2016) have enhanced our understanding of bank failure processes and their controls. However, the longitudinal (or three-dimensional) extent of a bank failure event and its ensuing impact on reach-scale channel morphodynamics are not taken into account (Klösch et al., 2009). The three-dimensional shape of a bank failure, hydrodynamics at time of failure, and bank soil strength including effects of vegetation largely determine the size distribution and location of failure blocks. Failure blocks are thought to limit long-term bank erosion (Wood et al., 2001; Parker et al., 2011), but they can deflect the flow onto the bank thereby enhancing bank erosion (Hackney et al., 2015). The role of failure blocks is thus ambiguous.

Leyland et al. (2015) showed that bank roughness co-evolves with erosion, possibly limiting bank retreat rates. Understanding this process is further complicated by the wide range in spatial scales of the bank roughness components (Konsoer et al., 2017), which form at different time scales, and the heterogeneity of bank material. The multiplicity of length and time scales in bank erosion (Couper, 2004) has not been adequately resolved to quantify streambank erosion at scales beyond the reach scale. A shift from deterministic to probabilistic approaches may be needed to more accurately predict long-term bank erosion at reach scales. Furthermore, morphodynamic models do not adequately represent feedback mechanisms between vertical and lateral channel adjustment. Ver-

Table 1. Summary of major research needs identified by Papanicolaou et al. (2006). The asterisks after the research needs indicate the level of progress made at this time: **, no or very limited progress; and *, some progress. The absence of an asterisk indicates major progress.

Preparatory	
Experimental quantification of the effects of sub-aerial processes on the reduction of erodibility and shear strength parameters	**
Surface Erosion	
Generalized formulation of erosion rate for both cohesive and cohesionless materials	**
Model for soil detachment or erodibility coefficient of cohesive materials and cemented cohesionless materials	**
Measurement techniques for erodibility coefficient	*
Improved calculation of local applied hydraulic shear stress that accounts for turbulence, 3-D effects, vegetation, etc.	*
Effects of vegetation on erosion-resistance parameters	*
Bank mass failure	
Effects of soil water dynamics on soil shear strength: seepage forces, liquefaction, etc.	*
Longitudinal extent and shape of bank failure	**
Break up and fate of collapsing bank material	**
Root reinforcement provide by both fine (< 1 cm) and coarse (> 1 cm) roots	*
Extending the assessed failure types beyond simple cantilever or planar failure types	*
Combining multi-dimensional computer models of free surface hydrodynamics, soil water dynamics, and slope stability	

tical growth of bars and islands steer flow onto the opposing bank, thereby increasing bank erosion rates resulting in changes in channel planform, such as channel sinuosity and bifurcation asymmetry, which controls distributary channel network growth (Shaw & Mohrig, 2014). Physically-based simulation of bank erosion mechanics in multi-dimensional morphodynamic models is complicated as the bank steepness cannot be represented on the mesh given the horizontal size of deltas, necessitating subgrid-scale models of bank geometry and erosion mechanics (Langendoen et al., 2016).

2.2 Avulsion

River channel avulsions are characterized by rapid channel relocations (i.e., jumping), rather than gradual migration (Slingerland & Smith, 2004). They have been studied extensively in modern environments, using physical experiments, and in the ancient rock record (e.g., Kraus, 1996; Mohrig et al., 2000; Reitz et al., 2010). Channel avulsions are driven by in-channel aggradation that forces the flow out of the channel, as well as through erosion of the river levee induced by overland flow during floods, which generates crevasse splays (e.g Edmonds & Slingerland, 2009; Hajek et al., 2012). These operations may occur mutually, or independently.

Fluvial-deltaic landscapes are heavily relied upon for societal welfare (Vörösmarty et al., 2009) and as such deltaic avulsions (particularly those that are unintended/unpredicted) can profoundly affect people. Numerous engineering practices and scientific studies have been leveraged to better understand avulsions and constrain their mechanics. Efforts have sought to limit the occurrence of natural avulsions, however, deltas inherently grow and maintain through the periodic relocation of the fluvial depocenter, which provides sediment, water and nutrients to sustain coastal landscapes. Hence, an important scientific forefront is identifying a balance between protecting infrastructure located on deltas while continuing to nourish these delicate landscapes. This goal requires physically-based models to better predict and understand avulsions, and the research is motivated by a need to inform a wide-range of scientific communities that aim to sustain deltaic coastlines.

Deltaic avulsions arise over a variety of scales: lobe building avulsions are periodic, and occur near the transition from normal to backwater hydrodynamic flow conditions (Jerolmack, 2009). Here, a decline in water-surface slope lowers sediment transport capacity, resulting in sediment accumulation to the channel bed (J. A. Nittrouer, 2013). The location for this occurrence is estimated using a backwater length scale approximation: $L_b = H/S$, where H is the characteristic flow depth and S is the along-stream slope of the system (Paola & Mohrig, 1996). The characteristic time scale for this type of channel avulsion is estimated as the quotient of the channel depth and rate of channel bed aggradation (Jerolmack & Mohrig, 2007). While this provides a first-order approximation for most deltaic systems, recent investigations have demonstrated that the avulsion timescale is better characterized as half of the channel depth (Ganti et al., 2014; Moodie et al., 2019); in essence, channels do not completely fill with sediment before avulsing. Meanwhile, splays, or incomplete avulsions, may arise during a single flood event. Bay fill avulsion events are essentially sustained splays (over multiple flood cycles), and distributary mouth bar avulsion events can occur at the distal end of fluvial channels entering the marine basin, and these are quite dynamic, particularly during floods (Fagherazzi et al., 2015).

It has been recognized that rivers maintain an avulsion "clock" (Chadwick et al., 2019), but the occurrence of avulsions is stochastic and, as such, difficult to predict. While lowland deltaic river systems typically avulse during major flood events, not every flood causes an avulsion. As an example, consider the Mississippi River delta, one of the most studied coastal deltas of the world. Avulsions in this river indeed constitute a threat to stable human habitation in deltas: this landform is occupied by approximately 1.5 million people, and the Port of Louisiana is one of the largest in the Western Hemisphere (in volume trade). As such, levees have been built to corral river flooding and prevent an avulsion. The time scale of avulsion for the Mississippi system, over the Holocene, is approximately every millennium. As the U.S. Army Corps of Engineers is keenly aware, the Mississippi River channel is due for an avulsion into the Atchafalaya distributary channel. Such a disturbance has been deemed unacceptable because of its potential impact on society, and so significant resources have been expended to install infrastructure to prevent this avulsion. Specifically, the Old River Control Structure, constructed in the 1960s and modified onward for several decades, presently maintains a 70-30% split between the Mississippi and Atchafalaya Rivers (respectively). However, as a consequence of the design and operation of this diversion, the proportional volume of sediment necessary to maintain equilibrium transport conditions is not properly allocated between the two subordinate channels, and so over the past several decades, the mainstem Mississippi River has experienced significant sedimentation (Heath et al., 2015). Ironically, over time, the Old River Control Structure is rendering the system even more susceptible to natural failure by shortening its avulsion timescale.

This lesson offers insight into a conundrum of fluvial-deltaic science, particularly as applied to societal sustainability: as a consequence of the non-linear relationships that exist between water discharge, boundary shear stress, and sediment transport, it is challenging to partition water at a bifurcation and expect the transport capacities between the two subordinate channels to match the main stem (i.e., the sum of the parts often does not match the total). Hence, sediment deposition may arise at channel bifurcations (Dong et al., 2016). In turn, engineering a bifurcation (e.g., the Old River Control Structure) proves complicated, because it necessitates extracting bed material sediment (the fraction of sediment most susceptible to variable boundary stress conditions) and water at controlled ratios. This is difficult, however, because bed material is in highest concentration in proximity to the channel bed, and so appropriately partitioning this sediment necessitates building deep diversions (Kenney et al., 2013).

As was postulated by Edmonds & Slingerland (2008), asymmetrical apportioning of water at a delta bifurcation (i.e., to maintain stability) approaches stability at approximately a 60-40% split, and this ratio could help maintain morphodynamic stability at a delta bifurcation. However, as delta systems in nature possess a wide-range of bifurcation orders, and as a universal theory for bifurcation order for a given deltaic system remains elusive, there still exists uncertainty about the extent to which engineering delta bifurcations (i.e., for the sake of nourishing coastlines) can maintain equilibrium transport conditions and maximize water and sediment distribution to the coast.

2.3 Persistent channel incision or siltation

Processes of persistent channel incision and siltation in alluvial channels have long been studied to better understand landscape evolution, where the coastal connection is typically represented as a constant or slowly varying mean sea-level (e.g., Pritchard et al., 2009). The stability of channel beds in delta areas is complicated by the tidal motion and other causes of sea-level fluctuations, forcing the surface level in the region where alluvial sediment reaches the coast. This triggers backwater and drawdown conditions of the mean water level profiles (Chatanantavet et al., 2012), which are influenced by the tides (Kästner et al., 2019). Recent studies have addressed the equilibrium of longitudinal profiles of tide-influenced fluvial channels based on one-dimensional models, assuming uniform sediment and neglecting the effects of density differences imposed by the freshwater-saltwater interface (Guo et al., 2014; Canestrelli et al., 2014; Bolla Pittaluga et al., 2015). Generic understanding of bed level profiles in tide-influenced delta channel networks is largely limited to those idealized conditions. The long-term consequences of changes in river discharge regime, reduced sediment supply, sea-level rise, infrastructure and subsidence are therefore uncertain. It is unclear towards which new state a real world delta channel that shows persistent channel incision or siltation will develop. Hereafter, we briefly review examples from the Ganges-Brahmaputra-Meghna Delta and the Rhine-Meuse Delta, illustrating how a myriad of factors complicates disentangling causes and effects.

Starting in the 1960s, about 5000 km^2 of tidal deltaplain in the Ganges-Brahmaputra-Meghna Delta in Bangladesh have been embanked for agricultural use (C. Wilson et al., 2017), resulting in a vast poldered area which neighbors the near-pristine Sundarbans to the North. The construction of the embankments has caused widespread sedimentation and channel infilling (Addams Williams, 1919; Mahalanobis, 1927; Mukerjee, 1938; Alam, 1996). The presence of polders has led to an amplification of the tidal range inland and has immediately affected the connectivity of the tidal deltaplain, by cutting off more than 1000 km of tidal creeks once responsible for connecting the islands to the main tidal channels (Pethick & Orford, 2013). The presence of the embankments and their alterations to the hydrodynamics of the tidal plain have resulted in the infilling of more than 600 km of channels, impacting navigation pathways in the area (C. Wilson et al., 2017). This has led to the creation of more than 90 km^2 of new land since the embankments have been built, land that is referred to as “Khas”, meaning new (C. Wilson et al., 2017). To arrest the infilling of channels, tidal river management strategies are being developed, which rely on temporary removal of an embankment to increase the volume of water moving in and out the adjacent tidal channel over a tidal cycle. Tidal river management counteracts channel siltation and raises the polder level, which mitigates subsidence (van Staveren et al., 2017).

Similarly, the Rhine-Meuse Delta accommodates a branching channel network where human controls over channel morphology has systematically increased over the past centuries, while sediment supply has dropped. The engineering measures include normalization, creation of new rivers, construction of a storm surge barrier and deepening of the main navigation channel, which altogether overwhelm the effects of sea-level rise on the mixed fluvial-tidal hydrodynamics and the associated morphodynamic developments (Vellinga et al., 2014). Harbors connected to the main navigation channel are efficient mud traps, where fine sediment originating from the rivers Rhine and Meuse accumulate (De Nijs et al., 2009). The storm surge barrier has closed off the main estuarine branch in the delta, whereas a subordinate channel has been incrementally deepened to facilitate shipping. The channels connecting the closed estuary and the shipping channel are subject to incision in a heterogeneous subsoil by strong tidal currents (Sloff et al., 2013; Huismans et al., 2016). Gaps in a poorly erodible top layer lead to deep scour holes, jeopardizing the embankment. The storm surge barrier is partly being reopened, albeit insufficiently to alleviate the problems of scour. Currently, the sediment capturing capacity of intertidal areas is gaining recognition, leading to small-scale “depoldering” projects (van der Deijl et al., 2019). Re-opening of storm surge barriers and returning previously reclaimed land to the marine environment reveal a paradigm shift in delta management (Wesselink et al., 2015; Warner et al., 2018). The pragmatic approach to counteract problems of channel incision and siltation is in need of a stronger scientific substantiation.

2.4 Turbidity regime change

If the tendency for accretion is counteracted by dredging, instability of the sedimentary system may still manifest itself in the form of extremely high concentrations of suspended sediment. The resulting hyperconcentrated flow conditions and the associated layers of fluid mud covering channel beds (Talke et al., 2009) pose a serious threat to the ecology of modern estuaries and deltas. In general, channel deepening to accommodate larger ships is considered the main cause of such unfavourable conditions. Larger depths typically amplify the tidal range and enhance flood dominance, up to a tipping point for which the system undergoes a critical transition to a high-turbidity state (Winterwerp & Wang, 2013; Winterwerp et al., 2013; van Maren et al., 2015). This regime change is attributed to a positive feedback cycle between tidal amplification, flood dominance, mud accumulation, and reduced hydraulic drag caused by mud at the bed.

The state switch from moderate suspended sediment concentrations to a hyperconcentrated state is critically dependent on the threshold for erosion, whereas there is no consensus on the best theoretical description of erosion (Sanford & Maa, 2001; Mehta, 2013). Hyperconcentrated flow may occur if this threshold is persistently exceeded and supply-limited conditions are prevalent (Dijkstra et al., 2018). The possible switch to hyperturbidity will then depend on the availability of fine-grained material, which can be limited. The regime transitions between the two states show hysteresis, which can be attributed to hindred settling. Once a sufficiently large amount of fine material has accumulated within the system, the transition becomes nearly irreversible. Switching back to the previous regime may require not only restoring the former shallow bathymetry, but also the removal of all accumulated fine sediment.

The loss of intertidal area has the same qualitative effect as channel deepening and narrowing: enhanced flood dominance and reduction of the accommodation space where fine sediment can settle. Beyond this, little is known about how geometrical properties of intertidal areas control the propensity for attaining a possible tipping point where the system switches to hyperconcentrated flow conditions. Altough the basic mechanism that leads to hyperturbidity recently has been captured in idealized models (Dijkstra, Schuttelaars, Schramkowski, & Brouwer, 2019; Dijkstra, Schuttelaars, & Schramkowski, 2019b), and used to estimate the propensity for a regime shift (Dijkstra, Schuttelaars, & Schramkowski, 2019a), the predictive capacity of those tools is yet to be confirmed and may be limited by a large number of simplifications. There is a need to quantitatively explain how alternative geometrical configurations of channels with intertidal areas influence the critical transition between regular and hyperconcentrated flow conditions.

3 Potential resilience analysis tools

3.1 Numerical modelling of deltas

A wide range of numerical modelling tools exist to analyze and predict the manifestations of delta instability discussed in the previous section. Simulation models have been proposed for all hydrodynamic, sedimentologic, biotic and biogeochemical processes. The time and space scales resolved in those models are coupled: relatively small-scale processes such as bank failure, channel scour and dredging operate on seasonal to yearly timescales, whereas avulsion and turbidity regime changes, which act over a larger region, occur on periods of years to centuries. The largest scale delta developments such as delta lobe switching are regulated by boundary conditions fluctuating over timescales ranging from centuries to millennia. Within this spectrum, model approaches covering timescales up to hundreds of years are most directly relevant in the context of analysing delta resilience.

Numerical models strongly vary in their degree of complexity. More complex models are less suitable for long-term simulations, because of the associated large computational effort, and also because they are prone to error accumulation (Hajek et al., 2012). High complexity models have traditionally been designed as engineering tools to investigate the short-term impacts of local interventions, and may reveal the dominant sediment transport mechanisms in delta channel networks. They are increasingly used in an exploratory mode as well, combining complex formulations and non-linear interactions with simplified geometries to investigate morphodynamic processes in rivers (van Maren, 2007; Schuurman et al., 2013), estuaries (Hibma et al., 2003; Marciano et al., 2005; Van der Wegen & Roelvink, 2008), or the dynamics of mouth bars (Nardin & Fagherazzi, 2012; Nardin et al., 2013; Mariotti & Fagherazzi, 2013).

Idealized models are specifically designed to focus on processes that are considered essential to describe a particular phenomenon under consideration (e.g., Kim et al., 2009; Schuttelaars et al., 2013). Such a phenomenon is described with mathematical equations that capture the response of specific processes to changes, such as channel deepening. Idealized models are fast, and enable to study model responses to a broad domain of the parameter space; however, these models lack complex physics and topography. It is therefore not obvious to what extent schematised models truly mimic the natural system they represent. Reduced complexity models are placed in between these process-based and idealized models, and are based on rules designed to mimic physics. For example, DeltaRCM (Liang, Voller, & Paola, 2015; Liang, Geleynse, et al., 2015) has been used to quantify the response of delta systems to sea-level rise (Liang, Van Dyk, & Passalacqua, 2016) and subsidence (Liang, Kim, & Passalacqua, 2016). In a similar fashion, the Coastal Evolution Model (Ashton et al., 2001) quantifies the response of the coast to waves. The majority of these model studies address abiotic processes only, but since the work of Temmerman et al. (2005), the important role of biology is increasingly accounted for (Fagherazzi et al., 2012).

Whether or not a model is appropriate to quantify delta resilience in terms of the capacity to recover from extreme events depends on the time-scales related to the investigated changes (T_c) and the time-scale at which the model attains dynamic equilibrium (T_e), which is referred to as the morphological spin-up time. Dynamic equilibrium is of minor relevance when $T_c \ll T_e$. The latter may often apply when investigating the short-term impact of direct human interventions such as sand extraction on tidal dynamics, allowing the use of high complexity numerical models. Changes in natural systems, or long-term effects of external changes (often resulting from human interventions), are governed by time-scales larger than the equilibrium time-scales. Turbidity regime changes, as well as delta planform topology developments, typically respond at time-scales $T_c \geq T_e$. Such processes can only be addressed with reduced complexity or idealized models, forced with simplified initial and boundary conditions.

Reduced complexity models resemble river deltas or estuaries in a qualitative sense, but their spatial resolution is typically too limited to implement local human interventions. Multiple human interventions are often carried out simultaneously, or at least within a period shorter than the morphological adaptation time scale T_c. For instance, in many deltas, the channels have been deepened, bends were straightened, intertidal areas have been reclaimed and the discharge distribution is modified by upstream dams in a period spanning several decades, each of which may have morphological timescales of decades or more (depending on the system size). The fact that such interventions can only limitedly be quantified with equilibrium models (as these lack the required spatial resolution), and often operate together, complicates identifying causes and effects. The synthetic equilibrium morphologies generated by numerical models may strongly differ from real-world topographies. The alternative, using realistic topography as a starting point in morphologic calculations, is hampered by the spin-up time, which may exceed the response period associated with an isolated intervention (T_c). Idealized models are in essence equilibrium models, and therefore their response is not influenced by spin-up time. However, they suffer from the same drawback as reduced complexity models. Their topography differs too much from reality to implement detailed measures and they miss part of the physics, such that the applicability is uncertain.

The morphological imprints of an extreme event can be widespread, and depend on the detailed human interventions designed to counteract the negative effects of extremes. To date, state-of-the-art high complexity numerical models are mainly used to analyse flood resilience based on hydrodynamic simulations, without resolving morphological developments (e.g., Islam et al., 2019; Ferrari et al., 2020). The use of flexible meshes, in which the resolution is high in a focus area and low in the rest of the delta, has the potential to adopt a hybrid approach in morphodynamic modelling, to bridge the gap between local processes such as a dike breach and the delta-scale effects on delta morphology. Other promising developments include increased data availability and improved data quality, which may reduce the spin-up time by enhancing the agreement between initial and boundary conditions, and help validating all three types of models.

3.2 Use of empirical relations

The process-based modeling approaches described in Section 3.1 are complemented by empirical studies that use field data from modern (and ancient) river systems, to constrain delta behavior. Deltas that have evolved over the past millennia may inform about delta resilience, as they experienced multiple extreme events. The famous tripartite delta classification diagram by Galloway (1975) distinguishes form and morphology of delta systems based on the influences of the fluvial system, delivering water and sediment to the delta, relative to the influences of tides and waves. With the accessibility of global remote sensing databases, the physical attributes of deltaic systems are becoming increasingly better quantified (Syvitski et al., 2005; Syvitski & Saito, 2007; Caldwell et al., 2019; Nienhuis et al., 2015, 2018). Empirical trends emerge that may serve to validate the outcomes of physical and numerical modeling experiments. In this regard, it is possible to use "space for time" substitution, insofar that at a given site it is possible to map a trajectory of future change by modifying particular boundary conditions (e.g., relative sea-level rise, temperature, wave climate), using examples provided from other sites that maintain similar environmental conditions to render comparisons. Hence, by investigating a large empirical dataset of deltas that are currently experiencing a set of predicted conditions, it is possible to estimate future change for a particular site in question.

Information from global remote sensing images adds to stratigraphic records, which have proven paramount in developing emprical relations to describe avulsion dynamics. For example, as described in Section 2.2, field evidence indicates that the delta apex is set by the onset of backwater flow, where sedimentation facilitates avulsions (Jerolmack & Mohrig, 2007; Jerolmack, 2009; Chatanantavet et al., 2012). Despite the importance of the backwater length scale for deltas emerging from rivers over a range of sizes (laboratory to continental-scale), empirical evidence, bolstered by theoretical improvements, indicates that the location of the avulsion node varies by a factor of three (Shaw, Mohrig, & Wagner, 2016; Ganti et al., 2016; Moodie et al., 2019). This suggests that a zone rather than one particular spot is susceptible to avulsion.

Sediment transport and the associated bedform dynamics are key processes governing delta resilience that remain heavily reliant on empirical relations. Sediment transport algorithms typically require inputs for boundary shear stress, or grain shear stress (i.e., boundary stress adjusted for form drag), and critical shear stress of particle mobility, but are modified depending on size and scale of the system from which they were developed. These modifications typically emerge as "tuning parameters"; for example, exponents and coefficients that may be adjusted to match theory and measurements. Sometimes, forcing algorithms to fit an ensemble of data for which they may not have been expressly developed can lead to insight regarding system operations. An example is found for the Yellow River Delta (China), a large and lowland sand-bed system with high sediment concentration. The best tested semi-empirically based total load equation developed to estimate bed material sediment discharge, the Engelund-Hansen sediment transport formula (Engelund & Hansen, 1967), under predicts sediment load for the Yellow River by a factor of twenty (Ma et al., 2017). Based on a compilation of data, Ma et al. (2020) introduced an alternative, universal relation for sediment transport in fine-grained environments typically found in deltas. Predicting delta response to changes in boundary conditions implies predicting sediment transport rates, which is still a field where leaps forward can be made.

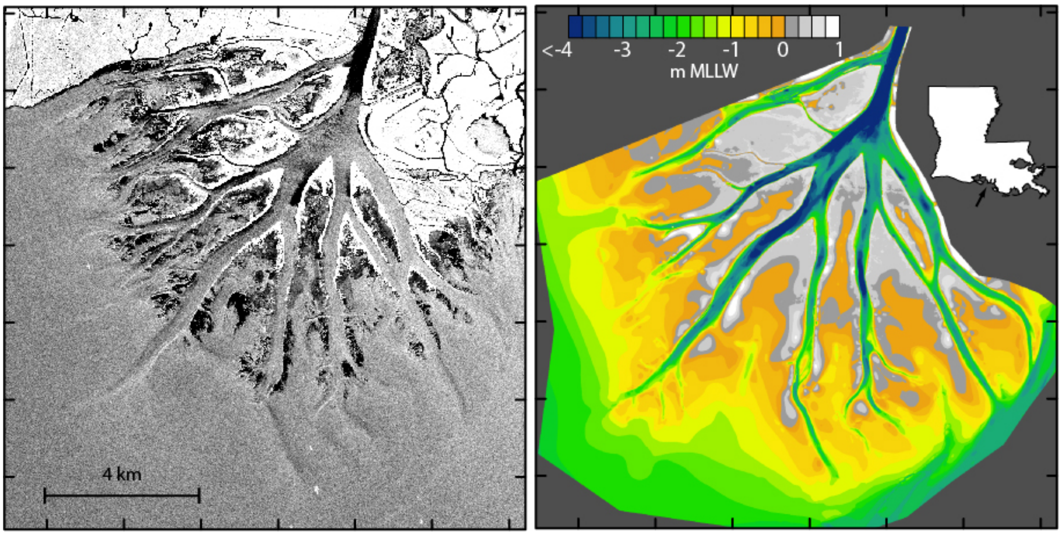

Figure 3. Airborne radar allows to monitor shallow bathymetry at high resolution, complementing shipborne hydrographic surveys. Left: image of Wax Lake Delta from an Uninhabited Aerial Vehicle Synthetic Aperture Radar (May 6, 2015). Right: Corresponding image based on a single beam sonar surveys (February 2015). Adjusted from Shaw, Ayoub, et al. (2016)

3.3 Continuous observation

High resolution, continuous monitoring allows direct observation of the hydrodynamic and morphodynamic responses to abrupt and gradual changes in boundary conditions. Modern monitoring is being accomplished through distributed networks of in situ sensors, and through a variety of space-based remote sensing techniques. For example, a new approach to continuous monitoring of flow and discharge exploits measurements from a horizontal acoustic Doppler profiler, which can collect horizontal flow profiles across dynamic delta channels (Sassi, Hoitink, & Vermeulen, 2011; Kästner et al., 2018). A diverse array of sensors on satellites provide ways of sensing wetland land-use, suspended sediment, topography, and their changes in time (Xia, 1998; Klemas, 2013). Such data sets have been important for recent analyses of water surface change and inundation patterns in delta systems (e.g., Brakenridge et al., 2013; Donchyts et al., 2016; Wagner et al., 2017; Besset et al., 2019), which contributes to an understanding of recovery after extreme events.

While spatial and temporal resolution of remote sensing platforms continues to improve, the resolutions and degree of precision depend on the environment. In particular, airborne remote sensing techniques are limited beneath the water surface in turbid conditions associated with river deltas. This is a persistent problem for shallow coastal and deltaic systems. Widespread use of Light Detection and Ranging (lidar), structure-from-motion, and other techniques in terrestrial environments can produce high-resolution digital elevation models interpolated from over one thousand measurements/m^2 (Passalacqua et al., 2015). Lidar and multispectral techniques can also work well to measure bathymetric surfaces in clear-water systems, where it is possible to measure up to 70 m deep (e.g., Wedding et al., 2008; Brock & Purkis, 2009). However, because light passing through water is both attenuated as a function of water depth and color, and scattered by particles, measurements are limited to less than 6 m, where turbidity is affected by sediment concentrations of 0.2 - 9 mg/l (Gao, 2009). Considering that suspended sediment concentrations in most delta systems regularly exceed 100 mg/l (N. D. Walker & Hammack, 2000; Falcini et al., 2012; F. Buschman et al., 2012; Hale et al., 2019; Eidam et al., 2019), optical sensing of the water-sediment interface in deltaic systems is rarely possible below a few decimeters. This limitation severely hinders the ability to detect rapid changes in shallow bathymetry, which can include erosion and deposition exceeding 1 m over a single flood or storm event (Jaramillo et al., 2009; Khan et al., 2013; Hale et al., 2014; Shaw & Mohrig, 2014).

The limitations of remotely sensing the subaqueous portion of deltas means that data must be collected through slow and costly boat-based surveys, or autonomous waterborne vehicles. Multi-beam echosounding is the current state of the art, and can map the water-sediment interface at high resolution (J. Nittrouer et al., 2011; Maloney et al., 2018). While the resolution of multi-beam bathymetry can approach that of lidar, data collection rates are orders of magnitude slower due to vessel speed limitations. Further, the utility of a multibeam system decreases as shallow water constrains its survey footprint. Surveying in very shallow regions is limited to single-beam sounding (Shaw & Mohrig, 2014) or walking RTK GPS campaigns (Eekhout et al., 2014; Olliver & Edmonds, 2017; Ritchie et al., 2018). Distributed networks of monitoring stations in coastal marshes, such as the Coastwide Reference Monitoring System (CRMS) in coastal Louisiana, are becoming an essential tool for monitoring wetland resilience and sustainablility in many deltas (Hensel et al., 1999; Jankowski et al., 2017; Ibáñez et al., 2010; Auerbach et al., 2015). However, such networks have not yet been extended to the delta front or open bays, where bathymetric change can be far more rapid (Ganju et al., 2017; Eidam et al., 2017).

These practical limitations in resolution have important implications for coastal digital elevation models of river deltas, which ideally span the subaerial and subaqueous environments. Coastal DEMs integrate measurements collected with many different survey techniques with varying resolution, and use datasets collected decades apart. The state-of-the-art USGS CoNED DEM of the northern Gulf of Mexico[1] integrates measurements collected between 1880 and 2013. NOAA navigation charts show that it is generally the shallow coastal regions away from shipping lanes where decades-old measurements continue to be used (NOAA Chart 14852, NOAA Chart 11351). The resolution is relatively weak in the shallow coastal zone below 0 m, yet this is precisely where significant bathymetric change should be expected. These topobathymetric digital elevation models form an essential boundary condition for many hydrodynamic models, including hurricane storm surge (Hope et al., 2013; Xing et al., 2017), and flood and tidal modeling (Xie et al., 2017; Vinh et al., 2014; Gaweesh & Meselhe, 2016). While such models are validated to varying degrees, it is likely that modeling can be improved, particularly in very shallow regions, with improved DEMs.

The need for direct remote sensing of the water-sediment interface has been circumvented by several creative techniques that use knowledge of coastal hydrodynamics to obtain estimates of bathymetry based on water surface features. One well-established example of this involves using synthetic aperture radar (SAR) backscatter to estimate shallow bathymetry. While radar cannot penetrate water, radar backscatter can quantify water surface roughness (Alpers & Hennings, 1984; Alpers et al., 2004). SAR can potentially resolve uneven bathymetry in turbid environments and has been used to detect large shallow marine sand banks (Fu & Holt, 1982; Hennings, 1998) and tidal bar features (Vogelzang, 1997; Calkoen et al., 2001). Videos of depth-limited breaking waves can be used to estimate subaqueous topography and evolution (Harrison et al., 2017), and streaklines composed of thin films on the water surface allow the ability to map the flow direction field in aerial or satellite imagery (Shaw, Mohrig, & Wagner, 2016). By interpreting the divergence of the flow direction field, the location of subaqueous channel tips can be estimated from streaklines (Shaw et al., 2018). The resolution produced by these new techniques is low compared to direct altimetry, and ideal hydrodynamic

[1] https://topotools.cr.usgs.gov/topobathy_viewer/dwndata.htm

conditions are required (Cathcart et al., 2020). Even so, the shallow coastal zone on river deltas is vast and difficult to measure, so the systematic use of these techniques has the potential to significantly improve coastal digital elevation models.

The extensive data sources from remote sensing increases the need for the development of automatic tools capable of extracting relevant information without or with limited user intervention. Most of the existing empirical studies discussed in section 3.2 focus on a few deltaic systems, or require extensive manual operations. With the aid of machine learning techniques, and multiple sources of available data, the mapping of surface water change is now possible (Donchyts et al., 2016; Pekel et al., 2016; Isikdogan et al., 2017b), and deltaic networks can be extracted from remotely sensed observations (Isikdogan et al., 2015, 2017a, 2018; Nienhuis et al., 2020). The automatic extraction of river networks in deltaic environments remains a challenge, but there are no inherent obstructions to developing such tools.

3.4 Information theory

Whether it be modelling or observational data, the analysis strategy requires careful consideration. Processes in deltas are active over a wide range of spatial and temporal scales; couplings are usually nonlinear, thus challenging the use of classic statistical approaches such as linear correlation analyses (Passalacqua, 2017). Yet, quantifying these couplings is fundamental to understanding how deltas respond to gradual and abrupt changes in forcing. The manifestations of delta instability discussed in Section 2 are no exception, as they will be the net outcome of multiple processes acting at various scales. Part of the solution to this issue is in linking causes and effects at their scales. As couplings are nonlinear, mathematical approaches such as network and graph theory and information theory are emerging as valuable approaches.

Network and graph theory are helpful to represent a system as complex as a delta as a set of links and nodes, whose connectivity is captured in the adjacency matrix. Recent work has quantified delta network complexity based on this approach (Tejedor et al., 2015a,b), the signature of sediment composition on this complexity (Tejedor et al., 2016), and the signature of delta forming processes on network structure (Passalacqua et al., 2013). In the classical sense of sets of links and nodes, network representations may be too simple to capture how fluxes are transported through delta networks. Observations from the Wax Lake Delta in coastal Louisiana, for example, have shown that a large portion of the channel discharge is transferred to the island interiors via secondary channel and over-levee flow (Hiatt & Passalacqua, 2015), thus suggesting that delta networks are leaky and the classic network model may not be always appropriate (Passalacqua, 2017). More complex network representations, such as a *multiplex* may help in this regard as they allow the representation of a system as a set of multiple networks in which links are allowed within each layer and between layers. This approach has been recently used to represent the transport of fluxes in channels and islands in delta systems (Tejedor et al., 2018).

Another helpful concept is that of Entropy (Shannon, 1948), which is a measure of the uncertainty contained in a variable. A nonlocal entropy rate has been recently applied to modeled and natural deltas to quantify the self organization of delta networks and to suggest an optimality principle behind it (Tejedor et al., 2017). Entropy is also the basis for information theory metrics, such as Mutual Information (MI) and Transfer Entropy (TE), where information is defined as a reduction in uncertainty. In other words, knowledge of how a variable (or more than one) reduces the uncertainty of another. MI is similar to the classic definition of correlation, although based on the probability density function (pdf) of the variable rather than on the observations themselves. MI thus measures how synchronized variables are. TE instead measures how knowledge

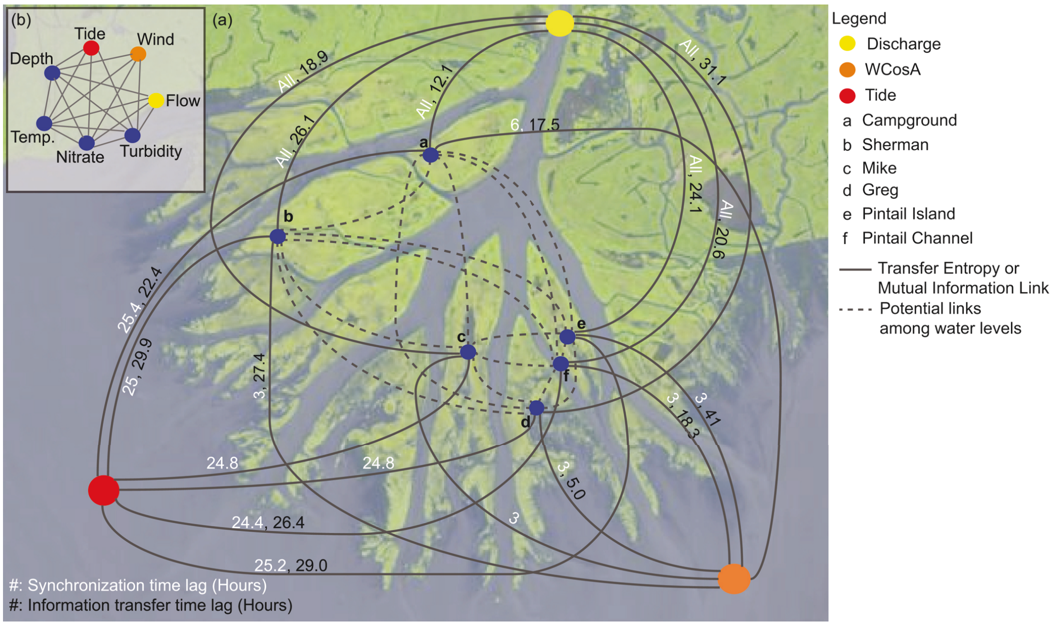

Figure 4. Connectivity of processes can be quantified from information theory applied to time series of key variables in a delta. Relationships are quantified in terms of the synchronization among variables (how much information they share) and their information transfer (how much one variable contributes information to the other). (a) Measured links among water level, discharge, wind, and tides at the Wax Lake Delta (LA, USA) from time series observations collected over three months. (b) Other possible connections of interest in deltas. Adjusted from Sendrowski & Passalacqua (2017).

of a variable and its past helps reduce uncertainty of another variable, by adding information that was not contained in the past of the variable itself.

A first application of these tools to deltaic environments is that of Sendrowski & Passalacqua (2017) for the analysis of water level fluctuations on the Wax Lake Delta in coastal Louisiana in response to wind, discharge, and tides (Fig. 4). The approach allows the quantification of process connectivity: viewing the variables as nodes of a network whose links are the couplings between these variables at a given scale or range of scales (Passalacqua, 2017). This operation is important in deltaic systems were a given change in water level or another variable may be caused by different factors at different scales; for example, on the WLD, which maintains a micro-tidal regime, water level fluctuations result from discharge, wind, and tide variability are on the order of decimeters, and are often compounding, regardless of the cause (Geleynse et al., 2015). Through an analysis of process connectivity, it is possible to capture the response of water level to each factor independently through time. Spatial differences can also be captured, with hydrologically connected locations in the delta (e.g., an island with secondary channels) responding at much faster scales than more hydrologically disconnected islands (e.g., islands with subaerial levees).

When applied to sediments, rather than water level fluctuations, it is more likely that forcing factors may act simultaneously. Another available approach, still based on the same mathematics, is to separate the synchronous, redundant and unique information from the MI, computed among sources and a sink. This approach has been successfully used with eco-hydrology variables (Goodwell & Kumar, 2017a,b). The main constraint for applying these tools is the requirement on the length of the time series (200-

300 to 500 data points depending on the method used for computing the probability density function). Thus, there is a need for identifying areas experiencing change, for example via remotely sensed observations, and then for focused collection of time series data for the quantification of couplings.

A great advantage of applying information theory statistics to observations is also validating numerical modeling results so as to guarantee that an answer is obtained for the right reason. Sendrowski et al. (2018) compared the couplings among water level and forcing factors measured in the field to those measured from numerical modeling results obtained by running Delft3D under the same conditions as those experienced in nature. The results showed that, while the model was able to capture well the transport over channels, the couplings with islands were not fully captured, particularly those related to small time-scale wind speed fluctuations. The advantage of validating numerical modeling results based on couplings is that it is possible to quantify the capability of a model to capture the dynamics of a system under analysis, even if processes are missing, or its representation needs to be improved.

Additionally, once validated, numerical models can be used for measuring the effect of a disturbance (e.g., changes in incoming sediment input, construction of embankments) by comparing the process network of a healthy system to that of a system under disturbance (quantified from synthetic data generated with the validated model). This analysis can provide information on which parts of the system would be most affected by the disturbance and at what scale. Similarly, an information theory analysis in combination with numerical modeling could be used to assess the predicted efficacy of a restoration design, by comparing the process network of the current system to that of the restored one.

3.5 Dynamical system theory

Towards predicting the key manifestations of delta instability as described in section 2, a strong focus on thresholds is warranted. Thresholds beyond which a positive feedback mechanism comes into force are generally referred to as tipping points, which may lead to bank collapse, avulsion, persistent channel depth change, or hyperturbidity. Dynamical system theory (DST) is a generic scientific framework to analyze tipping points, broadly applied to explain resilience versus abrupt changes in nature and society (Scheffer, 2009). The use of concepts from DST in delta geomorphology has largely remained limited to studies focussing on self-organization (Coco & Murray, 2007; Fagherazzi, 2008; Rodriguez-Iturbe & Rinaldo, 2001) and biogeomorphology (Marani et al., 2010, 2013), but is rarely employed in its full extent.

In DST, regime shifts are known as catastrophic bifurcations, which can be illustrated by the classical theory of a fold catastrophe (Figure 5, Scheffer (2009)). The equilibrium state of a system can respond in different ways to a change in conditions (left hand panels). Systems can respond smoothly, as in panel (a), or abruptly, as in (b). Critical transitions occur if the equilibrium curve is folded (panel c). Three equilibria can then exist for a given condition. When the system is close to a bifurcation, as in F2, a subtle change may cause a large shift to the lower limb. Close to such a bifurcation, a perturbation can easily push the system across the boundary between the attraction basins, as illustrated by the stability landscapes in the right hand graph. These bifurcation points are tipping points where runaway change can produce a large transition in response to a perturbation, referred to as a critical transition. Over the past decades, it has become clear there are multiple symptoms that announce if a critical transition is approaching. In a wide range of complex systems, the value of generic indicators has convincingly been demonstrated (Scheffer et al., 2009), which confirms that critical transitions are indeed related.

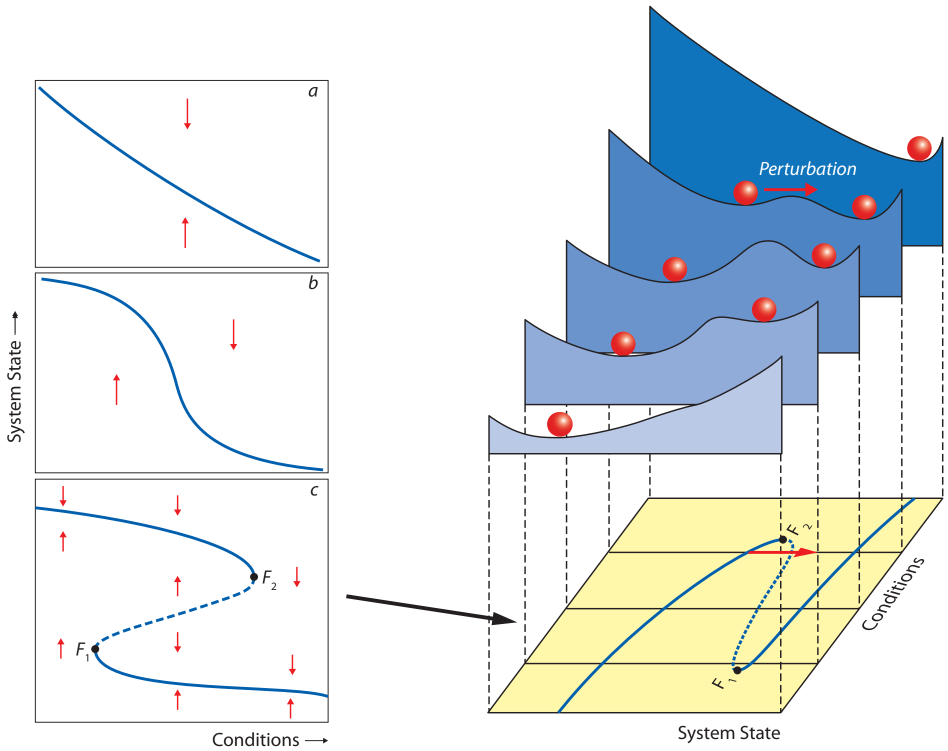

Figure 5. Regime shifts in deltas may be interpreted as critical transitions in a fold system. Curves in the left panels depict equilibrium conditons as a function of forcing conditions. If the curve is folded, as in c, alternative equilibria exist for the same conditions. The arrows illustrate in which direction the system moves if it is not in equilibrium, showing all curves to be stable except for the dashed line in c. The dashed line can be interpreted as the border between two basins of attraction, as illustrated in the right figure. Adopted from Scheffer (2009)

Prior to a regime change, the temporal dynamics in key variables typically changes, because the system is too far off from a stable state in which the system is resilient to perturbations. This leads to critical slowing down (Strogatz, 2018), which refers to a marginally stable situation for which rates of recovery are small. Slowing down tends to increase the autocorrelation in temporal patters of fluctuations. In addition to an increased autocorrelation, the reduction in the rates of recovery manifests as an increase in the variance of fluctuations, which has been formally demonstrated. In marginally stable situations, perturbations are not anymore firmly attracted back to the stable state. The resulting increase in memory of a system can be quantified from wavelet analysis of time-series characterizing the system, which will reveal the loss of resilience.

Next to indicators in time-series that yield an early warning of critical transitions, there exist a variety of spatial indicators (Kéfi et al., 2007; Maestre & Escudero, 2009; Dai et al., 2013; Kéfi et al., 2014). The increased recovery time to local equilibrium after a perturbation, caused by slowing down, leads to an increase of spatial coherence in the system. The spatial coherence, in turn, can be quantified from the cross-correlation using various types of metrics. An associated type of indicator is based on changes in the characteristic shapes and sizes of patches in images (Rodriguez-Iturbe & Rinaldo, 2001). Close to a systemic transition, the increased coherence results in scale-invariant distributions of patch sizes and other metrics that parameterize patch shape. In systems characterized by self-organized regular patterns, specific spatial patterns that can be recognized from an image may announce a critical transition.

The dynamical systems theory explained above offers a powerful framework to analyse the resilience of deltas. Delta channels are continuously exposed to a variable river discharge, which is a stochastic forcing that can be used to investigate the rates of recovery in turbidity regimes and channel morphology, even in absence of direct observations during critical transitions. Long-term data series of hydrodynamic variables and turbidity can be used for this purpose, collected in regions where a regime shift may have occurred. Now that available idealized models are capable of simulating a turbidity regime change and the transition from a stable tidal channel to a channel that tends to silt up, it is possible to establish if these critical transitions are predictable from auto-correlation and cross-correlation metrics. Using the modelling results and satellite images for delta channels showing bank retreat, it is worth investigating if channel bank instability is preceded by changes in hydrodynamic fluctuations and flow coherence.

4 Grand challenges

4.1 Closing the sediment balance on an annual time-scale

Several overarching challenges can be formulated that may steer the development of analysis tools as described in the previous section. A primary target is to gain confidence in the fluxes, sources and sinks in the sediment balance of a delta channel over an annual cycle, and to quantify how low impact-high probability conditions compare to high impact-low probability events (e.g., Castagno et al., 2018). Such a comparison is crucial in analysing delta resilience, as they inform about regime change thresholds. Typically, in-situ collected data fails to cover the spatial and temporal resolution and accuracy necessary to explain morphodynamic changes from differences in estimated sediment transport rates. Even in the Rhine-Meuse Delta in The Netherlands, an example of an intensively monitored delta system, the data on sediment transport across the boundaries and sediment extraction by dredging are still insufficient to explain the sediment volume changes inferred from comprehensive, frequent, high quality multibeam measurements.

Compared to alluvial environments where unimodel sediment prevails, deltas represent complex transitional environments with mixtures of sand, silt, clay and organic material. Each of those fractions may contribute to the sediment balance, which is often simplified to a sand balance. For silt and clay, the degree in which deltas act as a filter remains difficult to quantify. The finer fractions not only contribute to the total sediment volume, but may also impact sand transport and bed morphodynamics, indirectly affecting the sand budget of the delta. Models are typically calibrated to data within a confined calibration realm in which available data may be reproduced by the model through alternative model settings, which is referred to as equifinality (van Maren & Cronin, 2016). These different settings may lead to very different model behavior outside the calibration bounds, and imply uncertainty about the sediment balance for various fractions.

Remote sensing has potential to help meeting the data demands, for example with the upcoming NASA SWOT mission that will provide water fluxes in channels larger than 100 m. This will allow establishing sediment balances at multiple scales, which may lead to contrasting insights. In the Ganges-Brahmaputra-Meghna Delta, for example, the large scale system may be in balance, in the sense that sufficient sediment input is available to keep up with sea-level rise. At the scale of individual channels, domains exist where channels are silting up, whereas in other domains incision occurs (Auerbach et al., 2015; C. Wilson et al., 2017). There is a need to quantify how much sediment is being transferred to the interior of islands via secondary channels, and flow over levees. Advances in continuous observations, outlined in section 3.3, provide new means of quantifying erosion, deposition, and associated sediment fluxes. Some field observations for shallow flow (< 1 m) exist (Hiatt & Passalacqua, 2015), but this needs to be carried out over large spatial extents. The upcoming NASA NISAR mission will provide differences in water level over short windows of time, from which hydrological connectivity metrics may potentially be inferred.

Having acknowledged the potential of remote sensing, and satellite remote sensing specifically, in situ monitoring remains indispensable. With decreasing width-to-depth ratio of a channel, the flow and sediment dynamics becomes evermore three-dimensional in character, and suspended sediment concentration at the surface becomes less strongly correlated to depth averaged concentration. In situ observations of channel junctions remain crucial, as they exert a key control in partitioning sediment fluxes over the delta channel network, and the flow and sediment partitioning processes are particularly complex (F. A. Buschman et al., 2010; Sassi, Hoitink, de Brye, et al., 2011; F. A. Buschman et al., 2013; Salter et al., 2018; Kästner & Hoitink, 2019).

4.2 Impacts of sea-level rise and reduced sediment supply

In parallel to setting up the sediment balance at an annual time-scale, there is a need to address the delta mass balance over longer time periods, to anticipate the consequences of sea-level rise and reduced sediment input to deltas as a result of reservoir building. At the centennial scale, river delta stability is often conceived as a simple volume balance comparing sediment accumulation (both mineral and organic) to the accommodation space produced by relative sea level rise (RSLR; eustatic sea level plus subsidence (Blum & Roberts, 2009; Kim et al., 2009; C. Wilson & Goodbred, 2015)). A function for equilibrium delta area A_d can be expressed as (Paola et al., 2011):

$$A_d = \frac{kQ_s(1+r_0)}{C_0(\sigma_c + RSLR_b)} \tag{1}$$

where k is the fraction of sediment retained within a delta (trapping coefficient, dimensionless), Q_s is the mineral sediment discharge (L^3/T), r_0 is the volume ratio of organic to mineral sediment (dimensionless), C_0 is the sediment mass fraction of the deposit (1-porosity, dimensionless), σ_c is subsidence from variable sediment compaction (L/T), and $RSLR_b$ is delta-wide relative sea level rise due to tectonic or isostatic subsidence plus eustatic sea level rise (L/T). When accommodation increases relative to accumulation, the land area near sea level (A_d) must diminish, as is currently predicted for many of the world's deltas (Anthony et al., 2015; Blum & Roberts, 2009; Erban et al., 2014). However, a closer look reveals three important feedbacks that influence this accounting. First, subsidence rates from compacting coastal deposits near the sediment surface, which are spatially and temporally variable, tend to dominate the eustatic sea level rise and delta-wide, deep-seated subsidence rates during the Holocene on the worlds large deltas (Higgins et al., 2014; Jankowski et al., 2017; Rogers et al., 2013; Wolstencroft et al., 2014). Such compaction makes C_0 variable. Indeed shallow river delta sediments range from well-packed ($C_0 \sim 0.6$) to extremely diffuse ($C_0 \sim 0.1$). Hence, the behavior of coastal sediments may exert a primary control on delta morphodynamics through the rates which they compact (Keogh & Törnqvist, 2019). A second feedback is that a significant fraction of sediment accumulation can be organic, which can make up 11-15% of the deposit for some large river deltas ($r_0 \sim 0.12-0.18$; Gouw, 2008; Holmquist et al., 2018). However, such organic deposition is understood to occur only when a delta is starved of mineral sediment, but not fully inundated and abandoned (Bohacs & Suter, 1997; Kosters et al., 1987; Lorenzo-Trueba et al., 2012). Third, the trapping efficiency (k) of mineral sediment varies significantly depending on the delta morphology and characteristics of coastal plain (Nardin & Edmonds, 2014; Nardin et al., 2016; Nienhuis et al., 2018) and material properties of the unchannelized delta deposits (Straub et al., 2015).

It is a grand challenge to find new, physics-based empirical relations that account for the feedbacks in Eq. 1, because they are strong. A recent survey of areal change on 54 deltas over the last 30 years by Besset et al. (2019) found that losses in delta area have been rather small, considering the significant reduction in sediment supply, combined with sea-level rise and sediment compaction, over the same time period. Based on a study of the morphology of nearly 11,000 coastal deltas worldwide, Nienhuis et al. (2020) also found net land gain. This underlines the need to better understand the basic response of deltas to sea-level rise and reduced sediment input. The semi-empirical framework by Nienhuis et al. (2015, 2018, 2020) is a step forward in this respect, as it predicts delta response in terms of dominance of waves, tides and river discharge in shaping the delta planform. This approach adds nuance to Q_s and k in Eq.1, capturing delta buildup and decay governed by a variable river discharge, shoreline change by wave reworking, and tidal controls on channel dimensions, but it does not address sea-level rise. Reduced complexity models are potential tools to investigate the role of sea-level rise (e.g., van der Wegen, 2013). Sea-level rise is associated with time-scales exceeding equilibrium time-scales, as discussed in Section 3.1. Such delta-scale models can provide boundary conditions for realistic models that can capture the topographic detail that is needed to anticipate the impacts of sea-level rise and reduced sediment supply on delta resilience against extreme events and maintenance needs.

4.3 Synergy between approaches and cross-links between disciplines

At a scientific community level, the main challenge is to combine approaches and create cross-links between disciplines. Fig. 6 illustrates how synergy can be achieved between field monitoring, high and reduced complexity modelling, information theory, idealized modelling and stability analysis. Comprehensive field data can be used to set-up a detailed, realistic numerical model, which can represent the dynamics of a specific delta. Such numerical models can be used to optimize a field monitoring program, and be analysed and validated using techniques available from information theory. The collective understanding from field observations and high or reduced complexity models can inform the development of idealized models that capture the essential mechanisms of delta morphodynamic change. Idealized models are less computationally intensive, which allows for the exploration of a much larger domain of the parameter space. When an idealized model has been established that captures the nonlinear feedbacks in a morphodynamic system that includes critical transitions as described in section 3.5 on dynamic system theory, it may be possible to identify early warning indicators for an abrupt change in sedimentary regime, based on variables that are being monitored continuously, such as water levels and discharges.

A contemporary, realistic representation of delta morphodynamic change includes the role of anthropogenic and ecological influences, which are still underrepresented in morphodynamic models developed by earth scientists, civil engineers and physical oceanographers. This requires the disciplinary input from ecologists and landscape architects. Deltas have evolved over centuries as a geological unit in the landscape, but now fulfill a vast number of ecosystem services including shipping, agriculture and biodiversity reserves, which act as constraints to the system. Humans are capable of safeguarding those ecosystem services. Successful interdisciplinary collaboration is therefore needed, which requires common sources of data, accessible and understandable to all communities involved. Terminology has to be uniform. Social scientists play an increasingly important role in coupling the natural and human aspects in delta systems. For an effective interface between delta science and delta management, research efforts have to become not only interdisciplinary, but also transdisciplinary, i.e. involving stakeholders. With the involvement of differnt disciplines, the narrow interpretation of resilience we adopt here can become more general. Interventions have become part of the morphologic equilibrium of deltas. Typically, a natural morphodynamic equilibrium no longer exists, and because of continuous interventions, deltas will not reach morphodynamic equilibrium

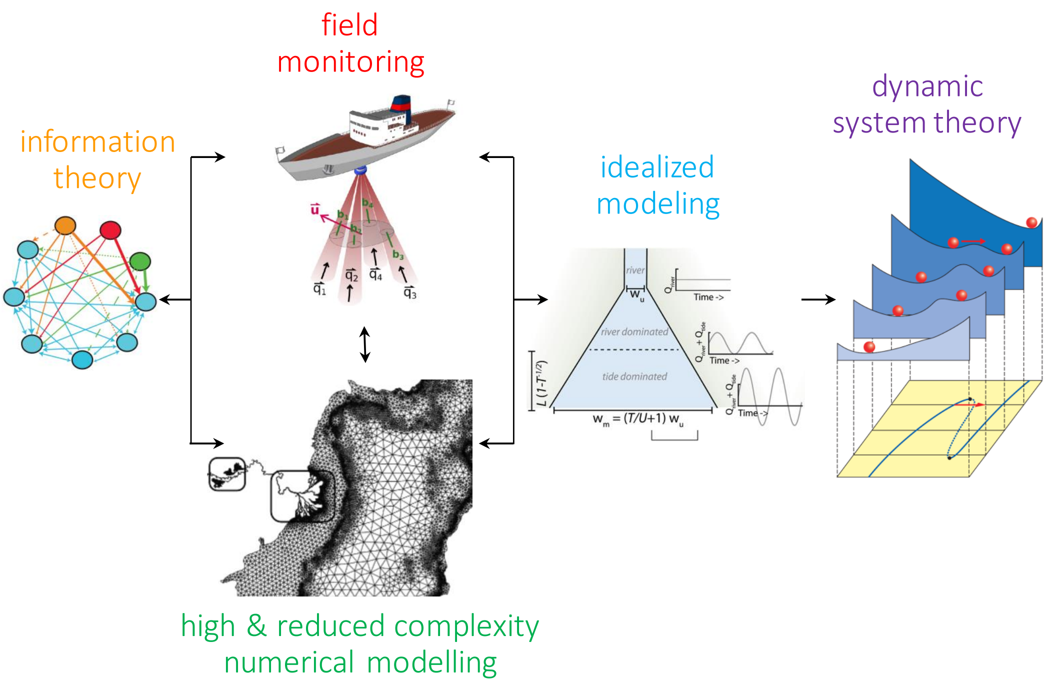

Figure 6. Synergy between alternative approaches to quantify morphodynamic stability of deltas. Field measurements are used to calibrate high complexity models. In turn, modelling results help to optimize a monitoring plan. Information theory can be applied to test the degree in which high complexity models correctly represent the information exchange between field stations in a delta. Using the collective understanding inferred from field observations and complex models, idealized or simplified models can be set-up that capture basic mechanisms that can lead to instability. When the key mechanisms are understood, dynamic system theory can be employed to identify thresholds for regime shifts, and to develop early warning indicators. Graphs obtained from Sendrowski & Passalacqua (2017); Sassi, Hoitink, de Brye, et al. (2011); Vermeulen et al. (2014); Nienhuis et al. (2018); Scheffer (2009)

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as long as human interventions take place. Human occupation of deltas and the loss of pristine conditions cause a lack of in situ views on natural, robust delta systems that have evolved over centuries. When seeking nature based solutions to create delta resilience, a fundamental understanding of morphodynamic equilibrium conditions remains essential. The last near-pristine systems on the globe need to be cherished and analysed, because they may reveal unknown mechanisms of resilience (Kästner & Hoitink, 2019). Besides those, the stratigraphic record provides an abundant archive of pristine delta behavior, which can further be explored.

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