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Earth system governance for transformation towards sustainable deltas: What does research into socio-eco-technological systems tell us?

Anna Wesselink [1], Oliver Fritsch [a, *], Jouni Paavola [b]

[a] Murdoch University, Environmental and Conservation Sciences & Sir Walter Murdoch School of Public Policy and International Affairs, 90 South Street, 6150, Murdoch, WA, Australia
[b] University of Leeds, School of Earth and Environment, Sustainability Research Institute, LS2 9JT, Leeds, UK

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ABSTRACT

Increased river flows and sea level rise in a changing climate are of great concern in deltas and makes sustainability particularly important for delta societies. This article reviews current approaches to assess delta sustainability, results of these assessments and what they mean for policies regarding deltas. We particularly ask whether deltas need transformations in order for delta living to be feasible in the future. The reviewed literature is mostly based on socio-ecological systems theory with small contributions from socio-technical systems theory, and struggles to take account of all relevant interrelationships. The technological interventions that shape the relationships between societies and delta environments should be highlighted by considering deltas as complex socio-ecological-cum-technical systems, in part because technological interventions are the most feasible societal response to secure delta living in the short term. The reviewed research suggests that most deltas are locked-in to an irreversible path towards unsustainability. We examine the pathways for transformation offered by socio-ecological systems and socio-technical systems research, and we assess whether they are technically and politically sufficient, feasible and acceptable to achieve the required transformations. We conclude that while the experimentation advocated in research may support local adjustments, their up-scaling to delta level is challenged by political disagreement and societal resistance.

1. Introduction

Sustainability[1] is of particular importance for delta societies since the presence and impact of water from rivers and seas is overwhelming, both as live-giver and a threat. The predicted increases in peak river flows and sea level rise due to climate change are therefore of great concern in deltas (Nicholls et al., 2019). However, sustainable delta living also depends on many social and technological factors that influence each other in complex ways: water management technologies sometimes change ecosystems unexpectedly; restructuring of economies due to increased connectedness nationally and globally affects societies' impact on delta systems; cultural, social and societal modernization changes expectations about protection and predictability; migration transforms rural and urban areas into metropolises. In order to move beyond generic statements about the (un)sustainability of current delta living and accurately diagnose the state of deltas, a systems-based approach should therefore be used that takes into account the interdependence between delta societies, their natural environment and the technological interventions that enable delta living.

This article reviews the research on deltas that does use a systems-based approach. We ask whether this research shows that deltas need transformations in order to be sustainable in changing climate and, if so, how these transformations could unfold. Past delta studies have mostly focused on a limited range of relationships, and usually examine only one direction of the society-nature interactions in deltas. We identified three major strands of delta

* Corresponding author.
E-mail addresses: a.j.wesselink@outlook.com (A. Wesselink), oliver.fritsch@murdoch.edu.au (O. Fritsch), j.paavola@leeds.ac.uk (J. Paavola).
[1] Independent scholar

[1] We recognise that the notion of sustainability is multi-interpretable and contested, so what sustainability will look like varies according to different actors. However, this ambiguity does not distract from the general argument we make.

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scholarship which are briefly discussed below in order to set the scene for the systems research that we focus on in the remainder of the article.

The first strand of delta research looks at mitigating the impact of nature on delta societies through human interventions. Much of this research examines flood risk management, e.g. the design of embankments, low-tech measures such as homestead protection by raised platforms, and agricultural adaptations such as floating rice and aquaculture. This research is often characterised by technological optimism that delta environments can be adjusted indefinitely to societal needs, dismissing concerns about sustainability. Responding to this critique, recent proposals involve interventions based on 'nature-based solutions', 'building with nature' and eco-engineering (Van Staveren et al., 2014; Smajgl et al., 2015; Wesselink et al., 2015; Nesshöver et al., 2017). This new nature-based orientation is expected to foster the sustainability of interventions and to help preserve the delta system. But because these experiments started only a few years ago, it is too early to assess them.

The second strand of delta research examines the impact of flood risk management interventions on natural delta systems. This quest stems from a concern regarding natural systems' carrying capacity that arose in the 1970s and that has gained prominence with the rise of climate change (Ibáñez et al., 2014; Day et al., 2016). Of particular interest here is the research on sediment balance in delta systems, since sustainable delta systems are argued to depend on a zero or positive sediment balance (Ericson et al., 2006; Syvitski et al., 2009; Tessler et al., 2015). A related area of research focuses on ecological systems of deltas such mangroves which can be an important stabilizer of delta systems (e.g. Bosma et al., 2012).

The third strand of delta research focussing on livelihoods of delta communities is more cautious about the sustainability of delta living. It considers human society adaptable and inventive (Musa et al., 2016; Vogt et al., 2016), but emphasises the vulnerability of resource-poor delta inhabitants (Chapman et al., 2016; Bosma et al., 2012; Fenton et al., 2017).

In the context of climate change, flood risk management and livelihood studies help understand 'how societies can continue to live in deltas by adapting their own practices and/or the delta', while sediment balance and ecological research ask 'how climate change and societal developments will impact on the functioning of deltas'. But the reviewed research typically examines only one direction of the society-nature interactions in deltas and thus omits issues such as emergence, tipping points and unpredictability due to complexity that are key in systems analysis (Kay et al., 1999; Holling, 2001; Urry, 2005). Delta studies should address both directions of interaction simultaneously to better understand the complex interactions of physical and social factors in deltas when assessing their sustainability. In Section 2 we will review how the socio-ecological systems (SES) approach and its cousin, socio-technical systems (STS[2]) approach, have been employed to understand deltas, and what they conclude about the sustainability of delta living.

In Section 3 we review the governance prescriptions arising from the SES and STS framing of societal responses to climate change. The initial emphasis in this literature was on *resilience* as an overall goal and strategy. When doubts about resilience started to emerge, *adaptation* entered the scene. In response to worries that adaptation does not always enable societies to cope with climate change, *transformation* has become the new buzzword (Gillard et al., 2016). The three concepts have their origins in SES research (Holling, 1978; Berkes and Folke, 2000; Walker et al., 2004), which offers different views on how these concepts relate to each other (e.g. Folke et al., 2010; Pelling, 2010). The notions of resilience and adaptation have been widely adopted inside and outside the academia, and the scientific meaning of the terms has become blurred in common usage.[3] Yet their wide adoption indicates that they are useful for many actors. Transformation has not yet gained the same status, but is being promoted by a growing research and practitioner community. To complicate matters further, in environmental governance research resilience, adaptation and transformation are used both as analytical or descriptive terms to study the state of a system and its changes, and as the basis for normative governance recommendations for what should be done to achieve a more sustainable system state (see e.g. Moon and Blackman, 2014). The most prominent of the latter kind to emerge from the SES and STS communities are adaptive management (AM) and transition management (TM) approaches. We will discuss them in Section 3.

Based on our review we conclude that deltas should be considered complex socio-ecological-cum-technical systems and that transformations are needed to achieve sustainability in deltas. The interdependency between societies, their natural environment and technological intervention is evident in deltas, since humanity has long tried to manage them with technological interventions. As we will argue in Section 2, technology is also the most realistic short-term intervention to achieve sustainability when abandonment of existing technologies is considered one alternative. Technology thus has to be taken into account for delta studies to be useful for society. Finally, in Section 4 we ask whether the recommendations from the SES and STS approaches for AM or TM are technically and politically sufficient, feasible and acceptable for the required transformations. We suggest that most deltas are locked-in to an irreversible path towards unsustainability. While the experimentation advocated by AM and TM may support local adjustments, their up-scaling to delta level is prevented by political disagreement, controversy and societal resistance. We conclude that the future of delta living looks bleak, unless societies can drastically reduce their impact on natural processes.

2. Deltas as complex socio-ecological-technical systems

We suggested above that the sustainability of deltas should be assessed on basis of a complex systems approach that considers the interdependence between delta societies, their natural environment, and the technological interventions that enable delta living in most deltas. In what follows, we will review how SES and STS approaches have been employed to understand deltas, and what they conclude about the sustainability of delta living.

The SES paradigm's ontology considers the earth a self-organising complex system. It originates from IIASA's work in the late 1970s on structural change and ecosystem functioning (Holling, 1978). The scope of this work expanded later to include societal phenomena (Berkes and Folke, 2000). Complex systems are considered sensitive to initial conditions, to have emergent properties and to experience sudden systemic changes to new equilibria (transformations) when tipping points are reached (Holling, 2001; Urry, 2005); such changes may also lead to perceived collapse, a form of equilibrium. Classic SES models require the formalisation of system processes and their interconnections, which means that they can contain hundreds of parameters and variables (Kay et al.,

[2] We use 'STS' for socio-technical system, although we recognise that STS refers to science and technology studies in other contexts.

[3] Many presentations at the flagship Transformations conference http://www.transformations2017.org/did not distinguish transformations from change. This highlights that the meaning of the concept has not yet settled, and that scholars may be riding the wave of the mounting popularity of the concept.

1999). One branch of SES research focuses on perfecting formal SES models rather than calibrating them, since it is often impossible to collect the breadth and volume of data needed to calibrate complex systems models, even for a geographically limited area (Pulver et al., 2018).

The STS approach is also based on a complex systems ontology (Geels and Schot, 2007; Fischer-Kowalski and Rotmans, 2009, De Haan and Rotmans, 2011). Accordingly, a system is delineated around a certain technology: in deltas this may include flood risk management technologies such as large or small dikes or levees, groins, sluices and pumps. STS scholars explore why technological change happens and what role economic, political and societal actors play in it. They use the term transitions when referring to system change. STSs are seen to consist of macro, meso and micro levels. The macro-level refers to the economic, physical and political structures that organise the society as a whole. The meso-level refers to the norms, values and paradigms that constitute sectoral cultures. Finally, the micro-level refers to the patterns of behaviour on the ground (Geels and Schot, 2007, De Haan and Rotmans, 2011). Patterns across the levels of a STS then form a *regime*, defined as a “rule-set or grammar embedded in a complex of engineering practices; production process technologies; product characteristics, skills and procedures; ways of handling relevant artefacts and persons; ways of defining problems; all of them embedded in institutions and infrastructures” (Foxon et al., 2009, p.5).

STS are seen to constantly adapt to internal and external stimuli, and greater adaptations involving changes to all three levels amount to a transition. External stimuli include shocks from outside the system; internal stimuli emerge from incompatibilities between structures, norms and practices. Niches are spaces where alternatives to the prevailing regime may emerge and grow. These alternatives challenge existing structures, norms and practices and may replace the regime if supported by entrepreneurs who act as brokers between the niche and the system (Geels and Schot, 2007, De Haan and Rotmans, 2011). There is debate on whether transitions are more successful if sought top-down (macro, imposing new structures) at regime level (meso, popularise novel, convincing norms) or bottom-up (micro, using innovative, functioning practices) (Pelling et al., 2015; Abson et al., 2017). In deltas, eco-engineering and soft flood risk management are examples of niche developments (often instigated top-down) that may have potential to change flood risk management regimes (Wesselink et al., 2015).

2.1. Literature search method

Our overall aim was to find research that considers two-way interactions between physical and social delta features and that is recognisably based on the SES or STS complex systems paradigm, although maybe not explicitly so. We used the Web of Knowledge database to search for articles applying an SES or STS approach to deltas. Search terms *delta AND socio-ecological system* or *delta AND socio-technical system* in the title, abstract or keywords yielded few articles (see results below), so we expanded the search to *delta AND (sustainability OR resilience OR transformation OR transition)* to capture aligned research not explicitly mentioning SES or STS. We then filtered the results based on the abstracts, and added further relevant papers that were cited in the selected papers and removed some that were found not relevant after closer scrutiny. In earlier work we found another body of research that fulfilled our overall criteria: socio-hydrology (Wesselink et al., 2017), which we added to the review. Our purpose was not to find and review all potentially relevant papers, but to obtain an overview of the types of research assessing the sustainability of delta living. The 32 individual papers reviewed below (labelled with * in the reference list) illustrate the research on deltas; they do not provide an exhaustive list. We distinguish four different categories in this delta research, which is performed by different research communities and, judging from the separate bodies of references they use, do not generally interact:

1. Modelling of deltas as SES
2. Integrated assessment of sediment, technology, society and climate change
3. Socio-hydrology of floodplains
4. Delta trajectories research

We found only six papers that explicitly refer to deltas-as-SES (labelled ‘explicit SES papers’) but many more papers that are based on the SES paradigm without mentioning it explicitly. Only the fourth category uses insights from STS research. We will review these explicit and implicit SES articles together, indicating to which category they belong.

2.2. Modelling of deltas as socio-ecological systems

The subset of delta-SES research most closely aligned with the ‘classic’ SES research revolves around conceptual models of delta-SES in which the elements of the SES and their interrelations are presented in a diagram (see Fig. 1, which is explained below). The ultimate goal is to predict future states of the delta-SES so as to inform policy making, which requires translating the conceptual relationships into quantitative ones.

Four explicit SES-papers use conceptual models, albeit differently. Sebesvari et al. (2016) employ their conceptual model to categorise 236 indicators that have been used to assess the vulnerability of delta-SES. They observe that small-scale studies in a single delta dominate the literature and that there is a lack of multi-risk and multi-level studies. They conclude that delta-SES studies rarely offer a balanced social and ecological assessment, typically focussing on the former and seldom on the latter. These constraints, they argue, limit the usefulness of such indicators for policy making. We suggest that the opposite is the case: the usability of the indicators and models for policy making increases by tailoring them to local policy questions, but this represents a barrier to comparative research or whole-delta assessment.

A small scale delta-SES study by Nicholls et al. (2016) seeks to capture socio-ecological relationships. A multi-scale, semi-determinist model including governance arrangements is used for scenario modelling of climate change adaptation options in two coastal locations in Bangladesh (Fig. 1). Unfortunately, they do not report the outcomes of the scenarios. Szabo et al. (2016) and De Araujo Barbosa et al. (2016) conduct their assessments at the whole delta scale. Szabo et al. (2016) use their conceptual delta-SES model in combination with available time-series data on demography, economy, health, climate, food, and water to shed light on the social-ecological system dynamics and drivers of change in the Amazon, Ganges–Brahmaputra–Meghna and Mekong deltas. Because of missing data and incompatible time periods, the interrelation of parameters is inferred by visual inspection of graphs, not by using statistical cross-correlation or other quantitative techniques. Thus the outcomes are rather tentative, although the authors conclude that the “observed changes in many key indicators of ecosystem services point to a changing dynamic state and increased probability of systemic threshold transformations in the near future” (De Araujo Barbosa et al., 2016, p.555) which can only be prevented by “the decoupling of local economic growth from local resource use before irreversible ecological shifts develop” (De Araujo Barbosa et al., 2016, p.574).

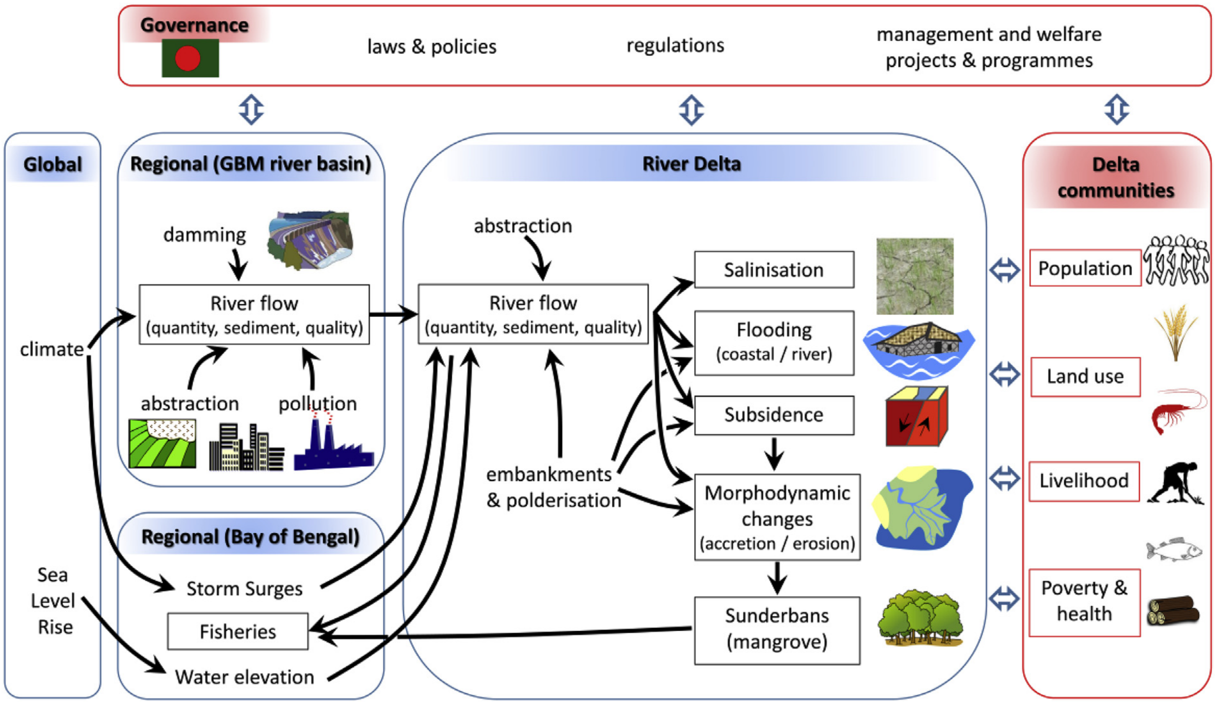

Fig. 1. Example of delta-SES conceptual model (Fig. 2 from Nicholls et al., 2016).

Brondizio et al. (2016) build a generic conceptual delta-SES model, which they argue can be used everywhere to diagnose and examine a focal problem. Their model incorporates insights from the Institutional Analysis and Development framework (Ostrom et al., 1994) to identify possible 'action situations'. They illustrate their approach by assessing the sustainability of the fisheries subsystem in the Amazon delta. The authors conclude that although this delta is considered among the most preserved and resilient, its long term sustainability is challenged by changes in infrastructure, urban growth and pollution, and growing demand for resources is creating pressure on local ecosystems and livelihoods.

2.3. *Socio-hydrology of floodplains*

Socio-hydrology is inspired by the SES paradigm although this is not explicitly acknowledged in the socio-hydrological literature, which originates in the field of hydrology. The approach aims to understand the dynamics and co-evolution of coupled human-water systems (Sivapalan et al., 2012). Socio-hydrological interaction in floodplains is the most studied topic (Di Baldassarre et al., 2013a, 2013b; 2014a, 2014b; O'Connell and O'Donnell 2014; Cuillo et al., 2017; Yu et al., 2017). Its objective is to investigate "how different sociotechnical approaches in floodplains are formed, adapted, and reformed through social, political, technical, and economic processes; how they require and/or entail a reordering of social relations leading to shifts in governance and creating new institutions, organizations, and knowledge; and how these societal shifts then impact floodplain hydrology and flooding patterns" (Di Baldassarre et al., 2014a, p.137).

A study of the Po floodplain examines the historical co-evolution of settlement patterns and technological choices (Di Baldassarre et al., 2013a, 2014a). It highlights the 'adaptation effect' which occurs with limited use of flood defences, resulting in frequent flooding and decreasing vulnerability; and the 'levee effect' which occurs when flood defences lead to less frequent but more severe flooding and increased vulnerability. Di Baldassarre et al. (2013b, 2015) use this analysis to construct a conceptual model of human-nature interactions in a floodplain. The input of fictive time series and an assumed decision model on when to construct levees and when to move away "shows that the conceptual model is able to reproduce reciprocal effects between floods and people as well as the emergence of typical patterns [adaptation and levee effects]" (Di Baldassarre et al., 2013b, p.3295). Using the same conceptual model Viglione et al. (2014) explore how the size and wealth of settlements will change over time with six ideal-types of risk-coping cultures. The representation of human-nature interactions is more limited in the Bangladeshi case study (Di Baldassare et al., 2014b) which focuses on statistical relationships between the occurrence of flooding and patterns of human settlements.

Although its goals resemble those of the delta-SES research, socio-hydrology is not (yet) studying deltas-as-SES because of its limited focus on human response patterns in floodplains. Therefore, it cannot really assess the sustainability of delta-SES, although Ciullo et al. (2017) come close with a comparison of the resilience of the two response patterns.

2.4. *Integrated assessment of sediment, technology, society and climate change*

A third strand of delta-SES research asks whether the sediment balance of deltas will be sustainable given increasing societal impacts and sea level rise. This research is not explicitly labelled as SES research, and some studies only look at one way impacts. However, the most integrative studies consider two-way feedbacks and therefore included here. These studies perform integrated assessments that compare the sustainability of deltas worldwide or examine a single delta (e.g. Ngom et al., 2016; Twilley et al., 2016; Bao and Gao, 2016). We will not discuss single delta studies here as their approaches and conclusions are similar to those of the comparative studies discussed below.

Only Renaud et al. (2013) comparative study explicitly considers deltas as SES and that they can have four system 'states': holocene, modified holocene, anthropocene, and collapsed. A change of state is argued to happen when a tipping point is reached. Ibáñez et al. (2014) similarly investigate whether different types of deltas can cope with sea level rise by changed sedimentation processes and what this implies for management strategies, which they summarise as 'rising dykes' or 'rising ground'. Day et al. (2016, p.275) suggest that "deltaic sustainability can be considered from geomorphic, ecological, and economic perspectives, with functional processes at these three levels being highly interactive". They present a classification of 24 deltas according to high, moderate, low and inexistent potential for sustainability. Other studies have calculated the sediment balance to assess and compare deltas worldwide. Ericson et al. (2006) compare 40 deltas, Syvitski et al. (2009) 33 deltas. However, these two articles only discuss one side of the society-nature relationship in deltas and thus are not true SES studies. Seijger et al. (2018) report a qualitative comparison of delta regions in Asia, Europe, and the US based on subsidence characteristics to conclude that most deltas are trapped in a dual lock-in of technology and institutions that both act as constraints for moving into a more sustainable direction over longer term.

Tessler et al. (2015) offer the most comprehensive delta SES assessment and a large sample of 48 deltas, using the concept 'risk trend'. They define a risk trend as the product of natural hazards, anthropogenic drivers and vulnerability. Each of these factors is quantified, enabling the ranking of deltas with regard to the current situation with and without substantial investments in FRM infrastructure, and for a future scenario of reduced investment. The results indicate how some deltas reduce risks by investing in infrastructure (Rhine, Mississippi) and how in others such investments would hardly make a difference (Ganges).

To conclude, delta researchers working with sediment models in a SES-like manner all argue that deltas will only be sustainable in the long term if the sediment balance that underpins their existence is preserved or restored, which for some means eco-engineering or "rising grounds" (Ibáñez et al., 2014, p.127). Otherwise undesirable developments could lead to "collapse" (Renaud et al., 2013, p.644) or loss of integrity (Tessler et al., 2015).

2.5. Delta trajectories research

The final area of delta-SES research aims to describe path dependencies of delta systems as a whole, often with a view to exploring options for future governance choices. The research stream originates from the Netherlands and is closely linked with the Dutch policy agenda. One part of the trajectories research is quantitative, based on integrated assessment meta-models and overlapping with the approaches described in Section 2.4. Another part of the stream is qualitative and describes the development of delta systems narratively.

2.5.1. Integrated assessment meta-models

Haasnoot et al. (2011, 2012, 2014) developed an integrated assessment meta-model to assess the costs and benefits of water management strategies in the Dutch delta programme (2014–2019). The model uses existing computer modules describing the water system in terms of water availability and demand, and modules describing the economic and societal impacts of flooding and water scarcity. The considered management options are technical, focussing on the strengthening of dikes and widening of rivers, alongside with adaptations to houses. The delta programme aims to prepare the Netherlands for climate change over the next century, enabling adaptation to changed circumstances as time goes by. The authors demonstrate how preferred management options change over time using what they call 'adaptation pathways': in them future options depend on antecedent choices. While originating from the Netherlands, the high profile of Dutch water management research has fostered the adoption of the approach in other deltas as well (Al Hossain et al., 2018).

2.5.2. Delta trajectories narratives

Van Staveren's work is based on narratives (Van Staveren and Van Tatenhove, 2016; Van Staveren et al., 2014). Its analytical framing goes beyond SES to include an understanding of deltas as STS to acknowledge the prominent role of technology in many delta systems. Van Staveren's narratives of 'delta trajectories' aim to 'assess and understand the evolution of a delta-SES over time under the influence of mutually interacting social, ecological, and technological systems (Van Staveren and Van Tatenhove, 2016, p.1). His narratives of the Mekong, the Rhine and the Ganges-Brahmaputra-Meghna deltas include not only a rich description of the social and physical developments and their interaction, as in SES, but also an analysis of the path dependencies and technological and institutional lock-ins that is informed by STS analysis. Other researchers have also qualitatively described delta trajectories implicitly as SES-cum-STS, including Bao and Gao (2016) for the old Huange delta, Benedikter (2014) for the Mekong delta, Day et al. (2006) for the Ebro delta, Twilley et al. (2016) for the Mississippi delta and Wesselink et al. (2007) for the Rhine-Meuse delta. Likewise, Haasnoot et al. (2019) distinguish generic coastal archetypes in order to identify possible governance choices for sustainable development, which again yields narratives.

2.6. Discussion: socio-ecological systems as models or metaphors

We reviewed the merits of strands of delta-SES research for assessment of delta sustainability. Sections 2.2 and 2.3 indicated that translating conceptual models into predictive ones (as in Nicholls et al., 2016) requires vast effort and data even for a small area, and is therefore highly challenging at whole-delta scale. Even semi-quantification (Sebesvari et al., 2016; Brondizio et al., 2016; De Araujo Barbosa et al., 2016) requires substantial reduction in the number of considered variables and relationships. None of the reviewed papers does justice to deltas as complex systems with emergent properties, because simplified assessment of ecosystem services and livelihoods is typically used to proxy the overall state of the delta. The use of concepts like ecosystem services and livelihoods can also be criticised for omitting what counts for citizens or ecosystems (Turnhout et al., 2013; Coffey, 2016). Finally, each study adopts its own conceptual delta-SES model linked to the expertise of involved researchers which again undermines the collective research effort.

This leads us to conclude that it is not really possible to capture the complexity of whole deltas adequately in quantitative SES or socio-hydrology models except at a rather coarse scale, with questionable outcomes (cf. Wesselink et al., 2017). Quantitative models are too challenging if not impossible to use at this scale, which together with the assumptions they require render value judgements that are inevitably incorporated in the models opaque to political scrutiny. The preservation of complexity in SES models could be an aim for more manageable case studies of single deltas and their context (e.g. Nicholls et al., 2016). For larger-scale delta-SES assessments, the SES should really be considered a metaphor calling for all elements of delta living to be taken into account. At the same time, SES analysis could sometimes be simplified to the essential relationships, as in the delta assessments based on the sediment balance (see further below in Section 4.3) – where 'simple' does not mean 'easy'.

Narratives play a key role in conveying the results in much of the sediment balance research (Section 2.4) and the trajectories research (Section 2.5). They corroborate Phillips (2012) point about the prevalence of narratives (or storytelling) in Earth Sciences. While narratives are key to Van Staveren's work, most sediment balance articles also use narratives to describe the history of deltas or the types of deltas to convey their results (e.g. Day et al., 2016; Ibáñez et al., 2014; Ericson et al., 2006; Renaud et al., 2013); so do Haasnoot et al. (2019) to describe possible delta trajectories. For policy engagement and uptake of results, Epstein et al. (2014) advocate narrative as a complement to technical information, for overcoming substantive and aspirational barriers between science, policy making and civic society, as narratives are easier for non-experts to understand and emotionally and morally more engaging. Fincher et al. (2014) and McEwen et al. (2017) offer examples where narratives were key to the engagement with local delta communities in delta research.

Sediment balance and trajectories research also share an interest in technological interventions because “past hydraulic interventions are still profoundly shaping the present-day delta” and can inform “in an extrapolative fashion, possible future delta-SES pathways” as a result of changing conditions and potential threats (Van Staveren and Van Tatenhove, 2016, p.1). For example, Tessler et al. (2015) include technology into their investment capacity index. While technological interventions feature in many SES studies, only the trajectories analysis (Section 2.5) conceives deltas as complex socio-ecological-cum-technical systems. Research on deltas could therefore benefit from a further combination of insights from SES and STS research: a hybrid of SES and STS appears desirable due to the interdependency between societies, their natural environment, and technological intervention in deltas. In research on urban water management, SES and STS concepts have been combined well. Building on more than a decade of action research in Melbourne and elsewhere in Australia, Ferguson et al. (2013) constructed a conceptual model combining SES insights about systemic change with a multi-layer STS model to diagnose the current state of the urban water management system and to suggest pathways toward sustainability. This research also included experimental action research to bring about desired changes such as infiltration of storm water. Rather than considering technology an element of the social system, as SES research does, we therefore propose that deltas should be conceptualised as hybrid socio-eco-technical systems in line with Van Staveren and Van Tatenhove (2016).

Special attention to technology should also be given because technological interventions are within the scope of immediate political agency (Ibáñez et al., 2014; Mitsch, 2014) unlike deliberate steering of an entire socio-eco-technical system. After all, the design and implementation of measures to conduct water is straightforward compared to changing other system elements such as population density, agricultural systems or urbanisation processes – let alone global economic developments or climate change. So, if technological choices are within reach, how to achieve sustainability? To answer this question, we return to the generic SES and STS literature to see which normative recipes they offer.

3. Transformation: whence and whither

The results that emerge from the four research strands together generate a powerful message that most delta systems are in a systemic lock-in and moving towards a collapse because of unsustainable human interventions. Gradual adaptation may not be enough, and transformative action may be needed. Transformation is a concept that attracts attention in ecology, institutional theory, organisational studies, policy studies, and science and technology studies, all of them drawing from their own ontological and epistemological tenets (Markard et al., 2012; Frantzeskaki et al., 2016). An alternative term, transition, is used by STS researchers to refer to comparable phenomena (Geels and Schot, 2007, De Haan and Rotmans, 2011). We will examine here how SES research prescribes AM to achieve such systemic changes (Section 3.1), and how STS research prescribes TM (Section 3.2).

There is a broad agreement that transformation and transition refer to fundamental systemic changes (Fischer-Kowalski and Rotmans, 2009; Markard et al., 2012; Manuel-Navarrete and Pelling, 2015; Abson et al., 2017). However, many ambiguities remain (Brand, 2016). Complex systems science language is used to talk about “the fundamental system-wide change in the structure and functioning of a system” (Ferguson et al., 2013, p.1), suggesting that system complexity underpins the uncertain, contested and pluralistic nature of our knowledge about the physical and social environment (Foxon et al., 2009). Others use a system metaphor to refer to any combination of two or more phenomena (Brand, 2016). Importantly, transformations may be intentional or not, occur incrementally or radically, and take place at high or low speeds. That is, transformations are not always fast and intentional, or voluntary, as seems to be assumed at times (Markard et al., 2012; Feola, 2015). For Pelling et al. (2015) what distinguishes transformations from other notions of change is their magnitude and depth. ‘Transformation’ is thus a typical example of a boundary concept (Star and Griesemer, 1989) which is vague in general use but acquires a specific local meaning.

3.1. Adaptive management

The governance approach advocated by SES research, AM, is based on complex systems ontology and ideas about how humans can handle complexity through experimentation. For quantative SES modellers, iterative modelling, monitoring and matching responses enable learning from new data and models and from policy implementation; their goal is to design a solution based on quantitative, predictive modelling. The models aspire to be deterministic and universal, to allow making the predictions needed to inform action (Lee, 1999; Benson and Stone, 2013). This looks remarkably like a reductionist experiment, although such experiments seldom lead to the conclusive answers that politicians request (Medema et al., 2008). Moreover, the view held by proponents of AM that their results will be taken up by policy makers in a rational and linear model of science-to-policy transfer is naïve (Shove and Walker, 2007; Voss and Bornemann, 2011).

Governance scholars in the SES community consider that polycentric governance, public participation, experimentation, and a bioregional approach are the cornerstones of AM (Huitema et al., 2009, p.11). Options for human responses are often presented as scenario analyses (Van Asselt and Rotmans, 2002, Pahl-Wostl, 2007, for an overview see Rounsevell and Metzger, 2010). Scenario analysis can be used in participatory science-cum-policy making processes where social learning accounts for different opinions, values and knowledges in the society. These scholars consider that top-down policy approaches are doomed to failure. This pessimism could be interpreted as a strategy to maintain and justify the status quo (Gillard et al., 2016). However, it resonates with dominant discourses in political and social sciences suggesting that late-modern economies and societies are increasingly difficult to govern and require new modes of governance that better harness bottom-up action and include actors that could otherwise remain veto players (Goetz, 2008). AM researchers have recognised these pitfalls though perhaps not their profoundly political origin. They acknowledge that AM ”is relatively simple in theory [sic!] and considerably more difficult in practice" (Curtin, 2014, p.1, see also Lee, 1999). Galat and Berkley (2014) recently evaluated the experience to date, concluding that institutional barriers are the main obstacle to AM. This is elsewhere identified by SES researchers as a "lack of knowledge about how to manage the human dynamics of [adaptive] co-management" (Beratan, 2014, p.1). This raises the question: who are the actors that make decisions on AM and manage humans, and are thereby implicitly considered external to the system? Voss and Bornemann (2011, p.2) speak of AM as "design for governance" – of the system, but also of those living in it. We will return to this question of politics and power in Section 4.

3.2. Transition management

The STS literature has also set out to inform policy makers about how to initiate and steer transitions (Foxon et al., 2009) through its normative variant TM. This approach promotes the creation of niches and empowerment of front runners through access to decision makers, funding, knowledge, and training (Geels and Schot, 2007; Avelino, 2009; Fischer-Kowalski and Rotmans, 2009).

Experimentation and participation are central elements of TM, as in AM. Small-scale experiments help to test the feasibility of alternative structures, norms, practices or technological innovations to see 'what works'. If the experiment is successful, another further-reaching test will be conducted. Thus a series of small-scale tests may lead to large-scale and long-term transitions (Fischer-Kowalski and Rotmans, 2009). Participatory forums can be established to involve technology developers, industrial partners, local authorities and community groups (Foxon et al., 2009) from all three levels, to inform the direction of small-scale experiments and to assess them, resulting in a cycle of experimentation and participatory deliberation.

Governance arrangements thus look remarkably similar to those advocated by AM scholars. Both approaches rely on a combination of small-scale experiments and participation of non-researchers to achieve system change.

4. Transformations for delta living?

Deltas are dynamic because they vary at different temporal and spatial scales due to changing river flows, tides and sea currents, and varying sediment loads and depositions associated with them. Climate change is an additional driver to such changes. From a sediment balance point of view "a reduction of this dynamic nature by human activities lies at the heart of many problems facing deltas" (Renaud et al., 2013, p.646). The research discussed above finds that human actions often exacerbate such physical changes to their own detriment. The research concludes that most deltas have reached, or will soon reach, a tipping point where remedial action is no longer possible within the current system state: delta systems will likely shift into another state that may not be advantageous for societies.

The reviewed literature highlights how difficult it is to escape from unsustainable development due to path dependency and technological and institutional lock-ins. Ibáñez et al. (2014) go as far as to say that a retreat may be the only alternative over long term. Mitsch (2014) remains cautiously optimistic although he observes that most restoration projects have not achieved their aims. Only profound systemic changes to societal pressures can preserve sustainable delta living, yet they are hardly within the reach of day to day political decision making. AM and TM advocate small scale experiments to achieve system change. The literature on local transformations and their facilitation is growing (e.g. Musa et al., 2016; Vogt et al., 2016; Chapman et al., 2016; Bosma et al., 2012; Fenton et al., 2017). It is questionable whether a) enough small experiments can be set up to achieve critical mass, and whether regime change is possible given the sunk costs and vested interests in the FRM infrastructure; b) transformations to sustainability will emerge from these experiments because of the unpredictability of complex systems, and c) priority is given to sustainability as the goal of these experiments.

More generally, the prescriptions for AM and TM underestimate how difficult it is to implement their recommendations because they downplay socio-political variables (Brand, 2016; Gillard et al., 2016; Warner et al., 2018). The prescriptions arising from AM and TM have been criticised for this deficiency (e.g. Nadasdy, 2007; Meadowcroft, 2009; Brand, 2016; Gillard et al., 2016; Nightingale, 2017; Van Assche et al., 2017; Dewulf et al., 2019). Space does not allow us to lay out these critiques here in detail but one of them is that the systems analyses of AM and TM involve a limited understanding of politics as a driver of social change and the role that beliefs, norms and values play therein (Cote and Nightingale, 2012; Gillard et al., 2016). Their complex systems ontology conceptualises transformations as (quasi-)automatic adaptations to internal or external stimuli. The agency of actors plays a negligible role, actors are just executing the system imperatives to maintain or regain stable system state. In TM, political alternatives are imaginable, but will only emerge and be selected if they are required to stabilise the system. AM sees human action as a continuous Sisyphean attempt, through experimentation and goal-oriented deliberation, to bring a SES back to stability. Both therefore consider humankind to be sensitive and responsive to the greater systemic (ecological) goal (Warner et al., 2018). As Section 2 demonstrated, reality does not align with these assumptions, which is why deltas continue to risk tipping into undesirable states.

In contrast, in most of the more governance-oriented literature on AM and TM the importance of social choices is recognised (Huitema et al., 2009; Norgaard et al., 2009). However, an implicit distinction is made between actors (engineers, scientists and other members of the elite) who can interpret the system imperatives and translate them into a societal vision, and actors who are expected to accept, work towards and implement that societal vision. Participatory arrangements and 'social learning' are advocated for implementation, but the goal to achieve AM or TM prescriptions turns them into instruments of acceptance management and arenas of technocratic input to operational decisions omitting that values, interests and priorities of actors rarely reflect system imperatives.

The fact that human beings are political animals also casts a shadow on the positionality of those who claim to speak for the system and the planet: their views merely represent one political position amongst many. Phenomena such as climate change produce winners and losers, and it is patronising and depoliticising to assume that everyone should subscribe to a transformative agenda, since some will actually benefit from climate change. Those promoting AM and TM generally fail to fully understand the patterns of resistance in attempts to implement transformations. Power inequalities do not matter if everyone works towards the same goal. Yet structures, norms and practices are expressions of power. If AM and TM do not conceptually account for power they also fail to appreciate the political science findings on public participation (Goodin and Dryzek, 2006; Wesselink and Hoppe, 2011). AM and TM conceptualise participatory arrangements as forums that enable the design and analysis of sustainability experiments, assuming that actors work towards the common good defined by the researchers. However, participatory governance is an arena of power struggle just like any decision making arena.

Some authors in the TM field have recognised this and advocate the analysis of the impact of power relations (Avelino, 2009; Avelino et al., 2016). Understanding the role of power helps to identify potential for the promotion of transformative change (Foxon et al., 2009; Pelling et al., 2015). Finally, the recognition of socio-political factors in the assessment of transfer of policy solutions to other regional, national, continental or cultural contexts, necessitates context-sensitivity (Foxon et al., 2009). STS already contains an in-built warning device: for a system to be stable, structures, norms and practices must be interrelated. Importing one of these elements into a new context can result in incoherence, thereby destabilising rather than stabilising the system by ignoring the political views and power positions of varied actors. Social scientific research on policy transfer (Benson and Jordan, 2011), norm diffusion (Finnemore and Sikkink, 1998) and policy implementation (Hill and Hupe, 2002) have come to similar conclusions, emphasising the need for congruence between imported policies (structures, norms and practices) and receiving contexts. This research provides much evidence that a disregard of political factors can lead to a failure to initiate and implement reforms and larger-scale transformations.

5. Conclusions

Transformation as a profound system change is a new buzzword in environmental governance for dealing with climate change that emerged from the SES research community. Its close cousin, transition, describes similar processes in STS research. We examined whether transformations or transitions are needed in deltas and how they could be achieved from the SES and STS viewpoints. We found a relatively small number of articles that implicitly or explicitly applied a SES or STS perspective to deltas. They included articles using a 'classic' SES approach of conceptual and sometimes quantitative systems modelling, including some where this is labelled socio-hydrology; articles focused on sediment balance using semi-integrated assessments; and articles presenting narratives on past and future delta trajectories. Despite their different approaches, the articles conclude that most deltas are on a path to irreversible system change due to human interventions in the essential ecological processes that maintain deltas: river flows, sediment load and deposition, and coastal erosion, both in the delta and upstream. While the immediate impacts on delta systems are caused by technical interventions that could be reversed or changed, these interventions are embedded in, and originate from, wider system characteristics such as population growth, intensive agricultural production systems, economic development, and urbanisation processes. These system characteristics are in turn embedded in global economic developments and affected by climate change.

The SES and STS prescriptions for AM or TM generally advocate participation and bottom-up experimentation to overcome resistance to their transformative prescriptions, seemingly advocating democratic decision making. However, these deliberative processes do not overcome the real politics and power struggles of setting goals and negotiating compromises. Only if powerful actors subscribe to requirements for a stable system state can sustainable delta living be achieved. Instead, many of the technological solutions that are currently implemented to avoid taking transformative choices make delta ecosystems more unsustainable in the long run, either ecologically (e.g. the increasing height of flood defences) or socio-economically (e.g. the abandoning of flood defences).

Declaration of competing interest

All co-authors confirm that there is no conflict of interest.

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