Imperatives for sustainable delta futures

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River deltas are significant in the global economy and support large human populations and biodiversity. Hence, they are now recognized as central to research and policy in the context of environmental change and regional sustainability (Vörösmarty *et al.,* 2009; Kuenzer & Renaud, 2012; Szabo *et al*., 2015a). Human interventions and climate change are increasing environmental risk in many deltas of the world (Blum & Roberts, 2009; Overeem *et al*., 2009; Syvitski *et al*., 2009; Renaud *et al.,* 2013). Land use transition, changing livelihoods and the proliferation of engineering approaches for water management and coastal protection produce unintended outcomes (Giosan *et al.,* 2014; Auerbach *et al.,* 2015). It is essential to integrate our understanding of the physical, ecological and socio-economic dynamics of deltas to develop systemic understanding and sustainable delta futures (Foufoula-Georgiou *et al*., 2013; Ramesh *et al.,* 2016).

A global initiative, "Sustainable Deltas 2015" supported by the Belmont Forum funded DELTAS project and endorsed by the International Council of Scientific Unions (ICSU), spearheads global efforts towards improving the integrated understanding of deltas. Deltas, due to their global relevance, require targeted attention and action to achieve the Sustainable Development Goals (SDGs).

"Anthropogenic modifications of the deltaic regions can interfere with SDGs 1.5, 2.4, 11.5, 11b and must be addressed"

The impacts of climate change and sea level rise (SLR) tend to be intensified by direct anthropogenic modifications (e.g. river control structures, coastal embankments, and upstream reservoirs) on the delta plain.

Key messages

1) Changes in river discharge and sediment loads are of comparable importance to SLR in assessing delta sustainability (Blum & Roberts, 2009; Wilson & Goodbred, 2014; Tessler *et al.,* 2015).

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2) In many deltas, subsidence may pose a greater threat than SLR (Driel *et al.*, 2015). Reducing human-accelerated subsidence (Higgins *et al.*, 2013; Rogers *et al.*, 2013) will maintain delta stability (White & Tremblay, 1995), and lower disaster risk.
3) River and tidal sediment supply to deltaic landscapes can maintain elevation and nutrient supply, even under subsidence and SLR (Rogers *et al.*, 2013; Brammer, 2014; Auerbach *et al.*, 2015; Ramesh *et al.,* 2015).
4) The long-term sustainability of current coastal risk-reduction strategies must be assessed against the points above.

"Avoiding ecological regime shifts will contribute to achieving SDGs 6, 14 & 15"

Deltas support biodiversity and supply many ecosystem services (Russi *et al.*, 2013). However, these coastal systems are being widely degraded (Leadley *et al*. 2015; Hossain *et al.* 2015; de Araujo Barbosa *et al*., 2016).

Key messages

1) Investment in natural capital supplied by relatively intact deltaic ecosystems provides the least expensive and most sustainable management opportunities (Vörösmarty *et al*., 2010).
2) Implementing improved environmental regulations for resource use and designating protected areas for conservation measures are priorities.

"The negative impacts of environmental change on food security, health and socioeconomic equality need to be addressed to achieve SDGs 2, 3 and 1."

Individuals' socio-economic status and health conditions are linked to the state of the delta environment (Szabo *et al*., 2015b).

Key messages

1) Poorest households are at greatest risk of food insecurity and loss due to natural hazards, requiring increased policy attention (Szabo *et al*., 2015b; Hajra *et al.,* 2016).
2) Health conditions are linked to environmental factors in deltas and need to be addressed in a targeted way (Costello *et al.,* 2009).
3) Land loss and submergence increases human migration, raising important challenges and questions (Ghosh *et al*., 2014).

"Deltaic cities deserve more attention in sustainability discussions to accelerate progress towards SDGs 6, 9 & 11"

Deltas often have high levels of urbanization and poverty, and low levels of infrastructure provision, raising many challenges.

Key messages

1) Disaggregated data and downscaled model results are needed to provide more accurate information of exposure and vulnerability patterns, and better inform policies and planning for urban areas within delta regions (García *et al.,* 2014; Mansur *et al*., 2016).
2) Creating a sustainable transition of urban infrastructure and governance is a challenge for successfully integrating climate change mitigation as a measurable target of SDGs 6, 9 & 11 (Mansur *et al*., 2016).

“Working in collaboration with indigenous and local knowledge (ILEK) will help reach SDGs 1, 2, 11, 13, 14 & 15”

Indigenous populations are disproportionately vulnerable to impacts of deltaic change, but also a rich resource for identifying more sustainable alternatives, e.g. to intensifying crop production.

Key message

ILEK is a rich resource for identifying how to maintain flexibility of food and income production under different environmental conditions (Vogt *et al.,* 2015, 2016).

“Novel approaches are available to support delta management and track progress towards SDGs”

Space-based approaches

Integrated observational networks of ground observations, and air- and space-borne observation, allow tracking environmental processes and human activities affecting delta sustainability.

Key messages

1) Spaceborne Earth observations can be used to define baselines and monitor change, e.g. precipitation, urbanization, or subsidence rates on the scale of the entire basin or delta (Overeem *et al*., 2009; Higgins *et al*. 2013; Kuenzer *et al*., 2013a,b, 2015; Ebtehaj *et al.,* 2015).
2) Such information products can be displayed in delta information systems to support informed, spatially-targeted decision making (Kuenzer *et al*., 2016).
3) Repeated mapping (i.e. LIDAR data collection) is needed to accurately represent the dynamic topography in these low-lying regions (e.g. Steckler *et al*., 2010).

Modelling approaches

Imposing upstream changes in flow and sediment within delta regions has downstream effects, including the flow and sediment that reach the coast and sustain deltas against SLR.

Key messages

1) Drainage basin scale models are needed to constrain future water and sediment flux scenarios. These large-scale frameworks can be used to evaluate scenarios and to inform management and planning (Darby *et al.,* 2015; Whitehead *et al.,* 2015).
2) Physically-based, highly resolved, morpho-dynamic models including ecosystem processes are necessary tools for disaster risk reduction, and restoration efforts with sound information on the balance between contributing and erosive fluxes at the local scale.
3) Engagement of stakeholders via simplified delta models allow to interpret and assess areas most vulnerable to change (e.g., Tejedor *et al.,* 2015a,b), and can foster dialogue for understanding the complexity of delta systems and evaluating delta futures.

Vulnerability and risk assessments

To promote risk informed decision-making for the sustainable development of deltas, it is necessary to monitor the vulnerability of deltaic social-ecological systems, by tracking achievements against the SDGs and the targets of the Sendai Framework for Disaster Risk Reduction 2015-2030 (UN, 2015).

Key messages

1) Assessment frameworks must capture social, ecological, and geophysical elements and their interactions; currently such integrated assessments are rare (Lazar *et al*., 2015; Tessler *et al.* 2015; Wolters and Kuenzer, 2015; Sebesvari *et al.,* 2016).
2) Risk and its underlying drivers often show strong spatial and temporal variability. Sub-delta scale vulnerability assessments and frequent updates are required using multi-hazard approaches (Sebesvari *et al.,* 2016; Wolters *et al*., 2016).
3) Vulnerability and risk information can be used for adaptation planning as well as for disaster risk reduction, e.g. for planning of evacuation routes (Saxena *et al.,* 2013).

"It is critical to invest in improved accountability mechanisms"

Given the complexity of deltas, and their importance for achieving multiple SDGs locally and at broader scales, improved accountability mechanisms are critical in formulating viable sustainable development strategies.

Key messages

1) The design of data collection needs to be comprehensive and linked to the analysis needs and frameworks across environmental and socioeconomic dimensions, and at appropriate scales.
2) Data must be collected and made available for transboundary deltas which might not follow spatial SDG reporting units.

"A new approach to delta planning is needed"

In light of the uncertainties decision-makers are facing, a new approach is needed that results in plans which perform satisfactorily under a wide variety of possible future pathways, are adaptive over relatively short time scales (5 to 10 years), and support long term planning under different plausible scenarios (Haasnoot *et al*., 2013; BanDuDeltAS, 2015; Nicholls *et al.,* 2015), as applied for example in the Bangladesh Delta Plan 2100 and in the Dutch Delta Programme and Thames 2100 study (Haasnoot, 2013). Good governance and transboundary cooperation in a multi-sectoral approach, aligned with economic and technical capacity is essential to achieve delta sustainability (Bucx *et al*., 2015; UNEP and UNEP-DHI, 2015). Knowledge and best practice transfer among deltas are needed to support the development and implementation of adaptive measures (Driel *et al*., 2015). Increased attention of the public, academia and policy makers to the challenges and opportunities in deltas is essential and can be facilitated by global programs and initiatives such as "Sustainable Deltas 2015". With effective delta planning, ecologically-informed improvements to infrastructure, and investments in social well-being, long-term sustainability of deltas can be achieved.

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