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## The Ganges–Brahmaputra–Meghna delta system: biophysical models to support analysis of ecosystem services and poverty alleviation†

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Deltas have been recognised as some of the most vulnerable coastal environments for the last 30 or more years, following initial concerns about climate-induced sea-level rise.<sup>1–3</sup> However, this is just one driver, and it is increasingly recognised that deltas are vulnerable to multiple drivers of change at multiple scales.<sup>4</sup> These include changing catchment management upstream of the deltas, subsidence within the delta, land cover change within the delta and marine processes such as ocean circulation, cyclones and storms. At the same time, many deltas contain large populations of (often very poor) people who depend on ecosystem services for their livelihoods: globally it is estimated that deltas are home to 500 million people. This presents a complex development challenge: how to develop deltaic areas in ways that are sustainable in the long-term, and benefit all the residents, including the poorest. The 'Assessing Health, Livelihoods, Ecosystem Services and Poverty Alleviation in Populous Deltas' (or ESPA

Deltas) Project (<http://www.espadelta.net/>) is a large multi-disciplinary project which is addressing this challenge within the world's largest delta – the Ganges–Brahmaputra–Meghna (GBM) Delta. ESPA Deltas brings together natural and social scientists, engineers and policy analysts to develop an integrative and participatory method to assess the future of coastal Bangladesh, and the role that policy and development can have in shaping that future. The approach views the delta as a series of interacting systems: this systemic perspective is critical to represent all the processes that are shaping the delta. The ESPA Deltas approach emphasises understanding the changing environment and resulting ecosystem services, and their linkages to human wellbeing, poverty and development.

In this issue we explore the environmental science and related components of the ESPA Delta Project, through implementation of sophisticated, quantitative bio-physical models which have been tested against data and are then used to inform an integrated model – the Dynamic Integrated Delta Model (ΔDIEM) – which uses a simpler hybrid model approach, including statistical emulators where appropriate. These papers address key environmental science components across scales from the Ganges–Brahmaputra catchments, down to the delta plain, and smaller to

field and farm scale effects of increasing salinity. Collectively they provide important new insights into the present and future status of the GBM delta. The resulting ΔDIEM model will be utilized together with policy stakeholder understanding to support strategic decision-making and planning.

Caesar *et al.* (DOI: 10.1039/C4EM00650J) consider the downscaling the SRES A1B climate scenario to the South Asia Region, including for the GBM catchment, including exploring the uncertainties within different realisations of this climate. These downscaled climate scenarios are used to drive both catchment and delta-scale changes. Whitehead *et al.* (DOI: 10.1039/C4EM00619D) uses the INCA model to examine changes in the flows in the Ganges and Brahmaputra under climate change and plausible socio-economic change. The results suggest that river flows will increase under all variants of the climate change scenarios, especially during the monsoon. However, the major uncertainty is in human-induced catchment changes which have the potential, in the extreme, to counter this change and even reduce flows relative to today. Futter *et al.* (DOI: 10.1039/C4EM00613E) use the PERSIST model to examine these issues in more detail and show that land use, changes in water management and a changing climate can all be expected to have significant impacts on river flows

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† In memory of Prof Mike Edmunds (1941–2015).



from the Himalayan catchments. Whitehead *et al.* (DOI: 10.1039/C4EM00616J) and Jin *et al.* (DOI: 10.1039/C5EM00092K) then consider the trends in the future of nitrogen and phosphorous in the rivers, and estimate the large fluxes of nutrients entering the Bay of Bengal. These will change with climate and socio-economic futures, with the planned clean-up of the Ganges reducing nutrient loads, but with changes to agriculture, industrial development and atmospheric pollution increasing nutrients as population increases.

Kay *et al.*<sup>5</sup> examine increases in the sources of coastal floods under simulations of climate change and delta plain subsidence. The rise in relative mean sea level combined with episodic extreme events (cyclones) in the Bay of Bengal leads to higher extreme water levels and hence more likelihood of flooding, unless the defences can be upgraded to address this challenge. Edmunds *et al.* (DOI: 10.1039/C4EM00673A) review arsenic and its impacts in groundwater of the GBM Delta, Bangladesh. This is a major present environmental challenge in Bangladesh as a whole, and provides an important backdrop and context to the research of the ESPA Delta Project. While it is nationally significant, arsenic is less of an issue in coastal Bangladesh than further inland due to the (young) age of the deltaic sediments. Mukhopadhyay *et al.* (DOI: 10.1039/C4EM00611A) examine historic trends in the mangroves of the Sundarbans, the largest surviving mangrove forest in the world. They find evidence of important changes in the last few decades. Projection of these changes suggests an increase in salt-tolerant species and a decline in the mangrove areas of 17%. This has important implications for ecosystem services, but it is important to note that the mangrove system is expected to largely survive.

The last three papers consider agriculture in coastal Bangladesh. Mondal *et al.* (DOI: 10.1039/C5EM00095E) consider simulations of yield response of rice to salinity stress, using the AquaCrop model. This was the first demonstration of the model in this setting and it was found to be appropriate and useful.

Clarke *et al.* (DOI: 10.1039/C4EM00682H) examines the effects of changing environmental conditions on farm yields in coastal Bangladesh. The dry season may be extended and combined with greater salinity intrusion due to sea-level rise, and increasingly brackish water may be used for dry season irrigation. If the salinity crosses a threshold of 5 ppt the next wet season is insufficient to flush the salt from the soil. Hence, salt accumulation becomes significant and farm productivity will reduce by as much as 50%, threatening the livelihoods of farmers in coastal Bangladesh. Lastly, Lázár *et al.* (DOI: 10.1039/C4EM00600C) presents a novel integrated model framework which allows changing agriculture and its livelihood consequences to be simulated across coastal Bangladesh. Hence, both biophysical and socio-economic aspects are modelled to link agriculture to farmer's livelihoods and poverty. It illustrates an interim version of one component of the developing  $\Delta$ DIEM model.

These are snapshots of our progress as a project and further important results are emerging within ESPA Deltas, including governance analysis, participatory scenario development, household surveys on ecosystem services and livelihoods and participatory modelling linked to national policy analysis. The application of  $\Delta$ DIEM with stakeholders in Bangladesh is particularly noteworthy. We are also engaging in a complementary manner with other research projects in Bangladesh and across deltas.<sup>6,7</sup> Collectively, this issue and these wider efforts are significantly increasing our understanding of the GBM delta, as well as providing methods that can be applied more widely.

This issue is dedicated to Prof. Mike Edmunds (1941 to 2015).

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