Integrated assessment of social and environmental sustainability dynamics in the Ganges-Brahmaputra-Meghna delta, Bangladesh

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Abstract

Deltas provide diverse ecosystem services and benefits for their populations. At the same time, deltas are also recognised as one of the most vulnerable coastal environments, with a range of drivers operating at multiple scales, from global climate change and sea-level rise to deltaic-scale subsidence and land cover change. These drivers threaten these ecosystem services, which often provide livelihoods for the poorest communities in these regions. The imperative to maintain ecosystem services presents a development challenge: how to develop deltaic areas in ways that are sustainable and benefit all residents including the most vulnerable. Here we present an integrated framework to analyse changing ecosystem services in deltas and the implications for human well-being, focussing in particular on the provisioning ecosystem services of agriculture, inland and offshore capture fisheries, aquaculture and mangroves that directly support livelihoods. The framework is applied to the world's most populated delta, the Ganges-Brahmaputra-Meghna Delta within Bangladesh. The framework adopts a systemic perspective to represent the principal biophysical and socio-ecological components and their interaction. A range of methods are integrated within a quantitative framework, including biophysical and socio-economic modelling and analyses of governance through scenario development. The approach is iterative, with learning both within the project team and with national policy-making stakeholders. The analysis is used to explore physical and social outcomes for the delta under different scenarios and policy choices. We consider how the approach is transferable to other deltas and potentially other coastal areas.

1. Introduction

Globally, deltas are a major focus for human settlement with a resident population of 500 million people (Ericson et al., 2006). A number of large deltas such as the Nile, Ganges-Brahmaputra-Meghna and Mekong have high population densities, reflecting the benefits of a delta location, including the significant provisioning ecosystem services of agriculture and fisheries. Many delta regions have emerged as economic growth poles and sites of urban agglomeration, such as Cairo, Dhaka and Shanghai (e.g. Seto et al., 2011; Szabo et al., 2016; Sebesvari et al., 2016). They are also a major focus for development and land use change such as improving agriculture via polders or promoting aquaculture. Delta ecosystems often have important conservation and biodiversity status due to their extensive wetlands (www.ramsar.org) and hence comprise complex socio-environmental systems.

It has long been recognised that deltas are especially vulnerable to sea-level rise (SLR), reflecting their low altitude (Broadus et al., 1986; Milliman et al 1989). However, global SLR is not the only issue of concern. In deltas a range of other drivers are acting on multiple sub-global scales. For example, regional catchment management generally reduces water and sediment input and water extraction, sediment starvation and subsidence operate at the scale of the delta plain (e.g., Woodroffe et al., 2006; Day et al., 2007; Syvitski et al., 2009; Tessler et al., 2015). Hence delta regions globally are experiencing increases in flooding, inundation, salinization and erosion, enhancing hazards and impacting rural livelihoods and food security. Analysis of change therefore requires an integrated or systems analysis of the relevant drivers and their effects, including interactions.

The Ecosystem Services for Poverty Alleviation (ESPA) Deltas Project ("Assessing Health, Livelihoods, Ecosystem Services and Poverty Alleviation In Populous Deltas, 2012-2016") has addressed these issues in the Ganges-Brahmaputra-Meghna delta, Bangladesh (Figure 1). The overall aim is to provide policy makers with the knowledge and tools to enable them to evaluate the effects of policy decisions on ecosystem services and livelihoods by linking science to policy at the landscape scale. In this paper we document the overall integrated method, illustrate its application, and reflect on its efficacy. A large 100-strong multidisciplinary team worked together towards this common goal with integration emphasised from the earliest stages of the project.

The project framework includes governance and stakeholder analysis, scenario development, socio-economic analysis, household surveys and biophysical modelling. Integration of these components required developing an integrated assessment model – the Delta Dynamic Integrated Emulator Model (ΔDIEM) – suitable for assessing potential future socio-ecological trajectories on the delta, including the role of different development and adaptation choices. ΔDIEM's development involved extensive discussion and debate within the research team in terms of formulating ideas on integration. An essential feature of the approach is to ensure the production of timely, useful and coherent results for decision makers. Hence, in addition to a high level of coordination amongst the diverse project partners, the project has an ongoing engagement with national level stakeholders selected to engage with strategic planning. The intra-project interaction ensures that all components follow the same conceptual model and narratives about the future, whereas the external interaction with stakeholders ensures understanding, usefulness and trust of the national decision makers towards the results. As explained in Section 3.7, a learning process iterates between model development/application and structured stakeholder engagement.

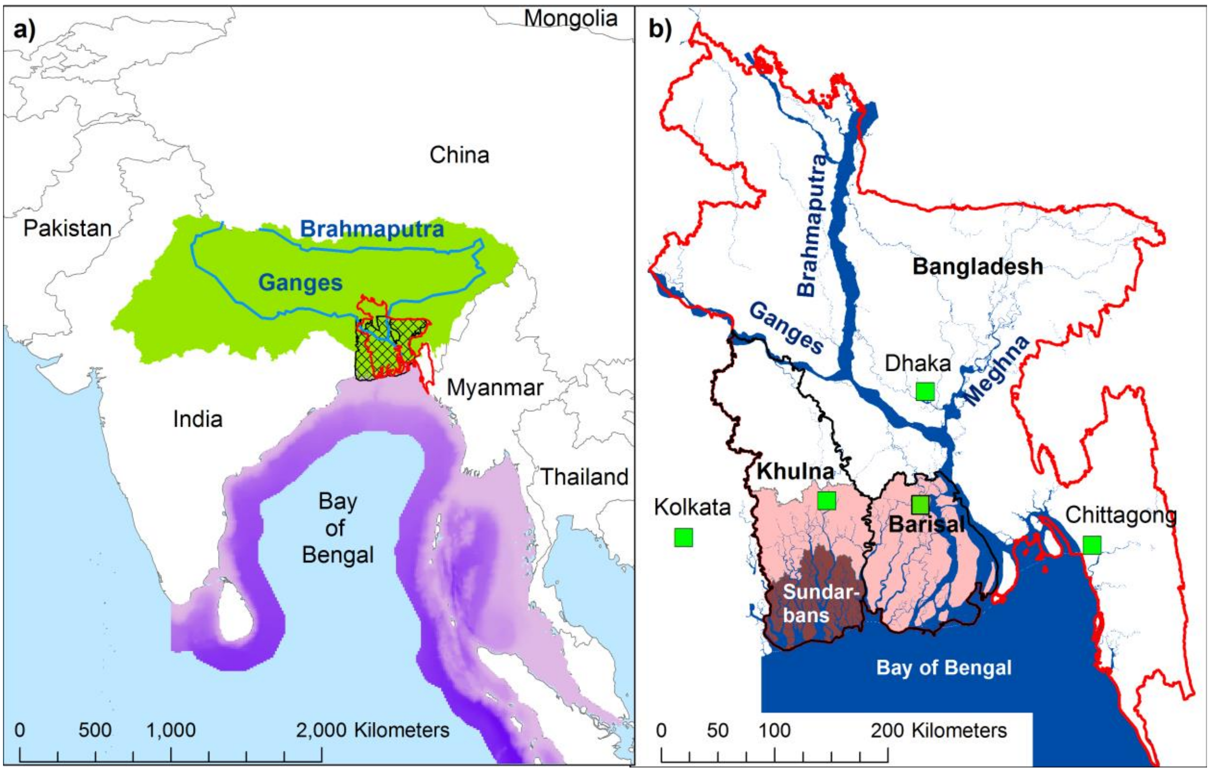

Figure 1: (a) The Ganges-Brahmaputra-Meghna river basin (shaded green), the Holocene delta (shown with criss-cross lines, after Woodroffe et al., 2006) and the Bay of Bengal (shaded purple). (b) The detailed study area (shaded), including the Sundarbans (shaded brown). Selected urban areas are shown as green squares. Khulna and Barisal Divisions are indicated. Bangladesh is shown with a red boundary.

The paper is structured as follows. Section 2 discusses the overall GBM delta, the study area and the challenges to the region over the coming decades. Section 3 explains the integrated assessment, developing a framework of diverse components suitable to analyse the future of provisioning ecosystem services and rural livelihoods and policy choices. Section 4 discusses the implications and Section 5 concludes. The details of the components and analysis are explained elsewhere such as Nicholls et al. (2015), Adams et al. (2016) and Amoako Johnson et al (2016), as well as in forthcoming papers.

2. The GBM delta, coastal Bangladesh and drivers of change

The Ganges-Brahmaputra-Meghna (GBM) Delta is one of the world’s most dynamic and significant deltas. Geologically, it covers most of Bangladesh and parts of West Bengal in India, with a total population exceeding 100 million people (Woodroffe et al., 2006; Ericson et al., 2006). The Ganges and Brahmaputra rivers rise in the Himalayas (collectively with catchments in five countries: China, Nepal, India, Bhutan, Bangladesh) and ultimately deposit their sediments in the GBM delta and the Bay of Bengal (Wilson and Goodbred, 2015) (Figure 1). The Meghna is another major river feeding the delta, which has a smaller catchment in Bangladesh and India. The delta is changing rapidly with a growing urban population, including major cities such as Kolkata, Dhaka, Chittagong and Khulna. At the same time, the delta provides important ecosystem services, especially provisioning services that enhance the well-being of the large population that are dependent on intensive rice paddy and fisheries.

The national population of Bangladesh increased fourfold between 1950 and 2013, from 38 to 157 million and is projected to exceed 200 million by 2050 with continued urbanisation (UN, 2013, Streatfield and Karar, 2008). Despite rapid GDP growth from US$840 (1996-2000) to US$1090 per capita (2011-2015) (http://data.worldbank.org/indicator/NY.GDP.PCAP.CD), Bangladesh continues to be a low income country in UN classifications (Hunt, 2015).

The study area is the seaward part of the delta within Bangladesh, south of Khulna and west of the Meghna to the Indian border (Figure 1). It includes the southernmost Districts of Khulna Division and all Barisal Division. This area comprises one of the world's largest lowlands with an elevation up to three metres – one metre above normal high tides – and it is subject to tidal exchange along the numerous channels. Hence it is the area within Bangladesh most threatened by SLR (e.g., Milliman et al., 1989; Huq et al., 1995; World Bank 2010). The study area population is exposed to a number of hazards, including tidal flooding, riverine flooding, arsenic in local groundwater supplies, salinity in water supplies and in irrigation water, and water logging. However, cyclones and associated storm surge are most damaging. The region remains predominantly rural with extensive agriculture, aquaculture and capture fisheries. There are numerous islands near the Meghna River with isolated resident communities. It also includes the Bangladeshi portion of the Sunderbans, the largest mangrove forest in the world.

The study area population was about 14 million in 2011, approximately 10 percent of the national population (BBS 2012). Demographic projections suggest a likely ageing population of 11.5 to 14.0 million by 2050 with out-migration of working age adults and increasing life expectancy (Szabo et al 2015a; 2015b). Out-migration is principally to urban centres and reflects multiple factors, including salinity impacts on agriculture production and risks from natural hazards. Across the seven divisions in Bangladesh, poverty is second highest in Barisal and third highest in Khulna (BBS, 2011; Adams et al. 2013a), showing that the incidence of poverty in the study zone is higher than the national average. Savings or access to finance are limited for most of Bangladesh's population (Mujeri, 2015), making households vulnerable to economic shocks.

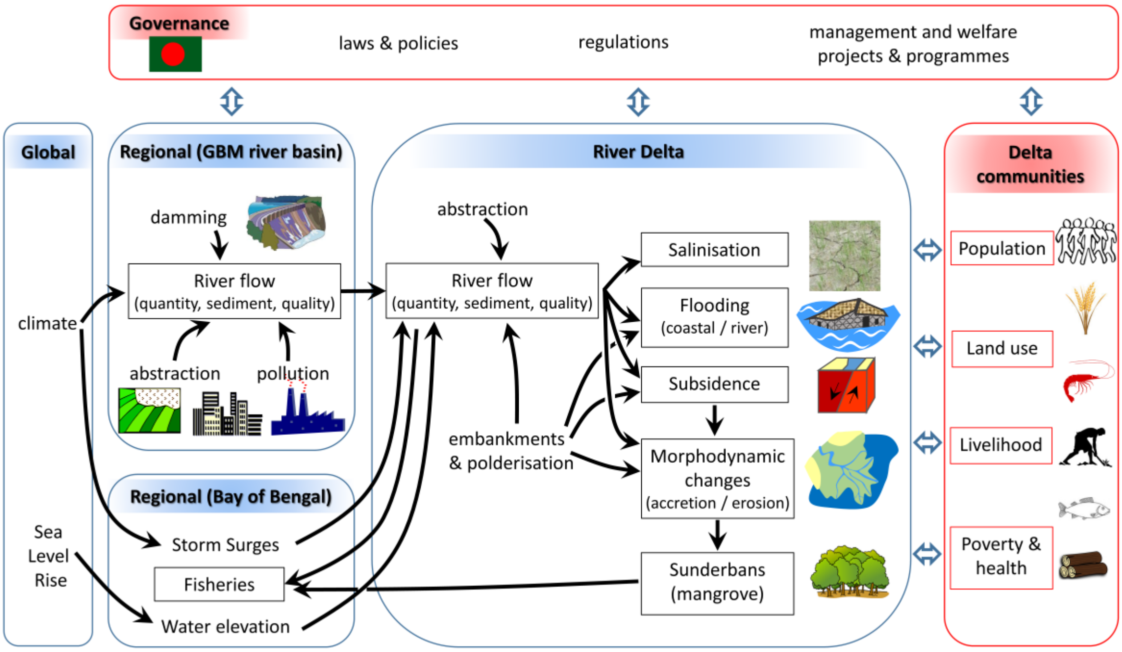

Figure 2: Schematic illustration of the key biophysical factors affecting the study area and their relationship to governance and community/socio-economic factors.

The analysis considers three distinct scales: (1) global; (2) regional, including the river basin and Bay of Bengal; and (3) the delta, including the study area (Figures 1 and 2).

When considering the biophysical processes operating in the study area (Figure 2), they all affect the available land area within the delta plain and its potential uses (Woodroffe et al., 2006). There is a broad regional subsidence of two to three millimetres a year, and more localised hotspots with higher subsidence (Brown and Nicholls, 2015; Higgins et al., 2014). There is both local loss and gain of land, with a net national gain of land over the last few decades, reflecting the large sediment supply (Bammer, 2014; Wilson and Goodbred, 2015). River floods mainly occur during the wet season monsoon, when a large volume of water is received from the upstream catchments. This results in 20-60 percent inundation of Bangladesh annually (Salehin et al. 2007). Cyclones and storm surges regularly make landfall in Bangladesh (mean >one per year for 20th Century). Cyclones and storm surges lead to extreme sea levels, high winds, and potentially coastal (i.e. saline) flooding, which damage crops and properties, and have significant consequences on health, mortality and livelihood security (Alam and Dominey-Howes, 2015; Lewis et al., 2013; Mutahara et al., 2016). However, improved Disaster Risk Reduction by the growth of flood warnings and cyclone shelters has greatly reduced the death toll during extreme floods and cyclones (Shaw et al., 2013).

Coastal Bangladesh has a system of polders built starting in the 1960s where the land is surrounded by embankments with drains to manage water levels and enhance agriculture. In the long-term, polderisation both prevents sedimentation and promotes subsidence due to drainage (Auerbach et al., 2015). This degrades soil quality unless expensive fertilisers are purchased, and makes drainage more difficult and increases potential flood depths when dikes fail. The balance between sea water and freshwater is a critical issue in the study area

(Clarke et al., 2015; Lázár et al., 2015). This balance varies seasonally and salt water encroaches further inland during the low river flow period between the annual monsoon rains, and cyclones can also cause saltwater flooding by generating extreme sea levels (Kabir et al., 2015). If the land becomes too saline, traditional agriculture is degraded. If this persists there are limited options: moving to salt-tolerant crops (which are being continuously developed) or converting to brackish shrimp aquaculture which is usually for export and are associated with negative socio-economic outcomes (Ali, 2006; Islam et al., 2015; Amoako Johnson et al., 2016). Upstream dams and water diversion to irrigation and other uses may enhance salinisation. The Sunderbans are an important buffer against cyclones, but are threatened by SLR and other stresses (e.g. pollution) (Anirban et al., 2015; Payo et al., 2016). They provide a range of ecosystem goods which are available to the poorest, as well as tourism based around the Bengal tiger, an endangered species.

3. The ESPA Deltas Approach

Analysing the future of ecosystem services and human livelihoods in coastal Bangladesh includes integrating the social, physical and ecological dynamics of deltas in the identification and measurement of the mechanisms by which the system components interact to produce human well-being. The approach seeks to determine which physical and biological processes affect life, livelihoods, health and mobility. It then analyses these relationships and builds a predictive model to analyse potential future scenarios in collaboration with those stakeholders responsible for action.

The analysis builds on key insights from the science of ecosystem services. First, economies and societies depend on ecosystems that produce ecological functions and final goods and services (Fisher et al., 2009). Ecosystem services include provisioning services, services from regulating biological and physical processes and diverse cultural ecosystem services (Millennium Ecosystem Assessment, 2005). In deltas, ecosystem services include the processes that bring freshwater, sediments, productive and biologically diverse wetlands and fisheries, and productive land for agriculture (Barbier et al., 2011). Our focus is on provisioning ecosystem services in agriculture, mangroves and fisheries dominated systems, as well as regulating services such as buffering of storms provided by mangroves. The benefits of these to society are considered as multiple dimensions of well-being including health outcomes, material elements of well-being and perceptions of well-being.

The method that we follow to achieve this goal is summarised in Figure 3. Governance analysis and stakeholder engagement occur throughout the project, reflecting its participatory nature. The method develops hypotheses concerning the relationship between ecosystem services and livelihoods; and develops new typologies based on the characteristics of the wider socio-ecological systems in deltas. We analysed population censuses and implemented a household survey to collect data on ecosystem services and livelihoods. In parallel, we analysed a range of biophysical processes in a consistent manner. To apply these results in policy analysis full integration is required. To this end we developed a range of exogenous and endogenous scenarios, including extensive stakeholder participation. We also develop an integration framework and apply this to develop the Delta Dynamic Integrated Emulator

Model (ΔDIEM). ΔDIEM couples relevant biophysical processes and a unique household livelihood module based on the household survey results collected within the project. Figure 3 provides an overview of the approach and each component is addressed in detail below.

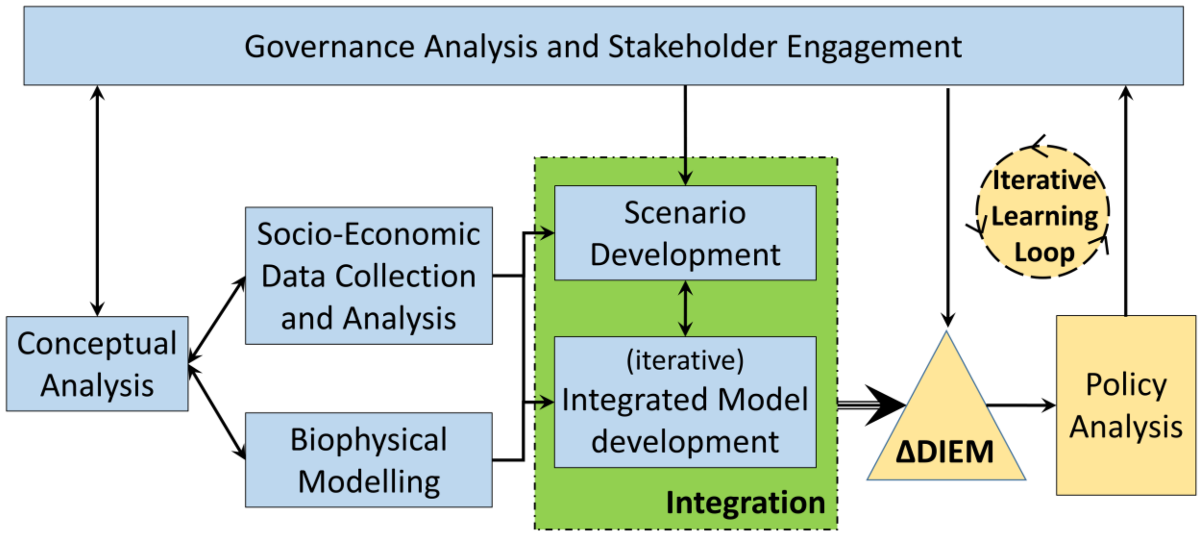

Figure 3. Components of analysis of ecosystem service processes, societal outcomes and governance and scenarios in the GBM delta system.

3.1 **Conceptual Analysis and Framework**

The focus of the ESPA Deltas project is on deltaic ecosystem services, and especially provisioning ecosystem services. Hence, we develop a framework that focuses on the mechanisms that link ecosystem services with social outcomes. These mechanisms are core to all the following research tasks, including the design of the integrated model (Section 3.6). This includes exploring hypotheses concerning the specific nature of development, poverty and environmental trends within the GBM delta.

Explaining social outcomes of ecosystem service use within the GBM delta requires consideration of: (1) the magnitude and mobility of ecosystem services and associated populations; (2) seasonality and other short-term temporal dynamics of ecosystems; (3) social structures such as the debt economy, (4) capital accumulation and reciprocity in economic relations; and (5) the distribution issues associated with ownership and access to land and resources such as fisheries. These mechanisms are persistent and engrained in social-ecological systems and their governance. They have been used to explain the continued presence of poverty, social exclusion and patterns of uneven development in many contexts (see Hartmann and Boyce, 1983; Bebbington, 1999; Ribot and Peluso, 2003). The social mechanisms are manifest in measurable outcomes – notably the material well-being and incomes of populations, their nutritional status and health outcomes, and in so-called subjective well-being – how people perceive their present and futures (Camfield et al., 2009).

A key insight of the approach here is that deltas are a mosaic of diverse social-ecological systems. Various studies on social-ecological systems show that the well-being and health status of populations coming from ecosystem services do not depend on individual elements of ecosystems, but rather on bundles of ecosystems that collectively produce desirable and socially useful outcomes. The people, ecosystems, services and mechanisms used to access these services together combine to create distinct socio-ecological systems, unique to each bundle of services. The characteristics of co-production of ecosystem services at the landscape scale lead, it is suggested, to significant trade-offs between types of ecosystem services (Raudsepp-Hearne et al., 2010). In the GBM delta, such trade-offs are apparent, with Hossain et al. (2016) demonstrating how land use intensification over the past 50 years has significantly increased provisioning ecosystem services per capita, but with a concurrent decline in natural habitats and regulating services.

The dynamics of deltaic social-ecological systems are such that trends are not easily identifiable in simple deterministic relationships. In the GBM case, for example, populations in poverty persist despite the presence of diverse, highly productive ecological systems (Adams et al., 2013b). Similarly, land conversion from agriculture to brackish (Bagda) shrimp aquaculture produces high value commercial products, yet has not transformed the economic fortunes of the localities in which it is practiced (as it reduces employment by 90 percent and the profits are narrowly distributed). Rather aquaculture is co-located with areas of persistent poverty, with the health and economic well-being of associated populations being negatively affected by salinization (Amoako Johnson et al., 2016).

In summary, the conceptual framing of social-ecological systems within the GBM delta explains how social phenomena and environmental drivers combine to constraint well-being, health and pathways of development. The approach incorporates multiple elements of well-being including objective measures of material outcomes such as income and assets; health outcomes; and so-called subjective well-being. The absence of well-being represents multi-dimensional poverty: alleviation of poverty is often stated as a major goal of development policy and hence understanding the contribution ecosystem services make to the well-being of poor populations and their contribution to poverty alleviation has high societal and policy relevance.

3.2 Governance Analysis and Stakeholder Engagement

The incorporation of stakeholder views and developing a detailed understanding of the role and gaps of governance in connecting ecosystem services and poverty alleviation are fundamental to our methodology. A highly structured approach was adopted to ensure that the project was able to respond to stakeholder priorities and knowledge, and that stakeholder expectations were realistic. Understanding the reality of how legal, institutional and policy frameworks can mediate the translation of ecosystem services to benefits that could affect poverty were again stakeholder-driven. In the early stages of the analysis, key issues were identified for further analysis, and these issues also inform the scenario development process (Section 3.5).

In Bangladesh, we selected national planning and policy processes as our target: this provided an effective and manageable group of national stakeholders. Representatives from approximately 60 relevant institutions were actively involved, primarily through semi-structured one-to-one interviews, but also through broader workshops, with key stakeholders being identified via an initial mapping process (Marchrzak, 1984; Reed et al, 2009; Gooch et al, 2010). These stakeholders comprised: (1) government ministries and international organisations; (2) donor agencies; (3) academics and experts; and (4) representative NGOs. This process was bolstered through enhanced engagement with a small number of super-stakeholders, whose interests aligned most closely with the project's aims and objectives from the perspective of use and uptake, data provision and cross-sectoral relevance.

Ecosystems are governed by different legal regimes, often confined within sectoral boundaries (Greibner et al, 2011). Laws and institutions often fail to accommodate cross-cutting issues and are frequently fragmented and incomplete. Weaknesses in government planning structures in Bangladesh, combined with heavy reliance on donors, could result in donor-initiated projects that are not optimally aligned with the achievement of national goals and policies (Rouillard et al, 2014). Our governance analysis focused on around 80 pieces of relevant legislation and policy across multiple sectors relevant to the sources of ecosystem services and to the protection and improvement of livelihoods (including water and land use management, fisheries, environmental protection, human rights and rural development). Preliminary efforts aimed to produce a baseline multi-sector, multi-scale analysis of relevant documentation, from the transboundary scale (i.e. across the whole GBM basin) through the national and sub-basin scales and down to the local, concentrating on those administrative areas where decision-making is of relevance (cf. Figures 1 and 2). This was buttressed by a further analysis of the factors that influence the implementation and achievement of policy objectives, and the extent to which legal and institutional frameworks are capable of supporting policy (Hill et al, 2014). This analysis of barriers was extended to cover informal governance systems where relevant, in order to understand the cogency of local customary systems and more formal frameworks (Greibner et al, 2011).

Additional efforts were made to incorporate governance metrics and indicators into the integrated modelling process in order to try to capture the governance situation in future projections, though significant difficulties were encountered with respect to linking these in a meaningful way to biophysical, poverty and health-related indicators. As one approach to overcome these problems, a post-hoc assessment of modelled interventions was performed in the light of the governance findings, highlighting key steps that should be taken from a legal, policy and institutional perspective to facilitate implementation of the specific intervention.

3.3 Socio-economic Data Collection and Analysis

Building on the conceptual framework, a range of socio-economic analyses were conducted (Figure 4) including an analysis of demographic trends and scenarios (Szabo et al., 2015a), an analysis of macro- and national economic trends (Hunt, 2015) an analysis of poverty indicators from the census (Amoako Johnson et al., 2016) and as little empirical data existed, an innovative household survey on ecosystem services in the study area. This survey is explained in detail below. Combined, these data provided an understanding of: baseline conditions and scenarios; empirical linkages between the environment and poverty; and a detailed causal analysis of the links between the environment and poverty and environmental factors, respectively. These all informed the ΔDIEM model (Section 3.6).

To investigate the relationship between ecosystem services and human well-being across diverse socio-ecological systems a qualitative and a quantitative household survey are conducted. The qualitative survey aimed to conceptualise the socio-ecological system, and the quantitative survey ensured that this information can be integrated with the biophysical models to answer specific questions regarding the ecosystem-poverty relationship. Within the quantitative household survey, approximately 1500 randomly selected households were visited in three seasons, across the socio-ecological systems of the study area. This allowed capturing the temporal and spatial dynamics at multiple scales. The questionnaire collected data on livelihoods, diverse forms of well-being (assets, income, expenditure, food consumption, satisfaction with life, blood pressure, nutritional status) and the characteristics of ecosystem service use. In addition, the survey collected information on the mechanisms that facilitate or hinder well-being from ecosystem services: debt and debt relations; land ownership and access mechanisms; shocks and coping strategies; and mobility.

The highest level of stratification for sampling was based on the seven most important socio-ecological systems in the region, identified through land cover maps, verified through extensive qualitative fieldwork, and based on dominant land use: (1) irrigated agriculture, (2) rain-fed agriculture, (3) saline aquaculture (4) freshwater aquaculture, (5) mangrove forest dependence, (6) offshore fisheries and (7) locations with riverbank erosion. Stratification was carried out using land use maps generated from satellite imagery. Further stratification was then carried out using administrative districts (Unions), lists of villages (Mouzas) and a household listing in selected villages. Adams et al. (2016) provides full details of the survey design and data collection and the associated data is available at http://dx.doi.org/10.5255/UKDA-SN-852179.

The household survey found livelihoods in the study area to be complex and diversified (Adams et al., 2016). Of the survey households, only 3.5 percent worked exclusively (all three seasons) in agriculture/fisheries, 75.9 percent worked one or two out of three seasons in agriculture/fisheries, and the remainder (20.6 percent) worked exclusively in non-agriculture/fisheries sectors. Similarly, 15.0, 2.4 and 82.6 percent of the surveyed households practiced only one, two or 3 or more livelihood types throughout the year, respectively. The data has been analysed in multiple ways in order to illuminate the relationship between ecosystem services and well-being in the context of diverse socio-ecological systems. The results reinforce the importance of ecosystem services as a safety net for the poorest, since those without ecosystem services are those most likely to be both materially poor and experience low satisfaction with life. They also reveal that poverty-environment linkages differ across the socio-ecological systems. These spatially differentiated effects extend to health-related components of well-being such as nutritional status and blood pressure.

The objective of the data collection was not only to dissect the present-day ecosystem services – poverty nexus, but also to ensure that the baseline conditions, parameters and behaviour that inform the integrated model are realistic (Section 3.6). The surveyed ~1500 households were grouped into 37 household archetypes based on seasonal livelihoods and land ownership and these archetypal households were characterised by utilising this unique dataset: assets, income, expenditure, levels of debt, diversity of and seasonality of livelihoods and associated incomes/costs, food intake (among other factors) in ΔDIEM are all based on this empirical data.

In addition, to supporting the development of ΔDIEM, the survey data has many other potential applications, and there is potential to repeat the survey to understand inter-annual trends and variability (Adams et al., 2016).

3.4 Biophysical Analysis and Models

The ecosystem services available in the study area depend in large part on the biophysical environment. A quantitative approach using state-of-the-art models was adopted. While this has a time penalty when setting these up, it allows us to explore and understand coupling and feedbacks between different processes and drivers, as well as consider different policy interventions. Hence, a range of relevant state-of-the-art biophysical process models have been selected, implemented and validated for the GBM delta and/or surrounding region. In general, each of these models had been developed previously, for different locations and applications. After being implemented appropriately for the study area, they were loosely coupled to provide a cascade of information and insight. They have been run for a range of future climate and socio-economic scenarios (Section 3.5) and the outputs have also been used to build the integrated ΔDIEM model as explained in Section 3.6. If further queries arise during the integration, the detailed models are available for further analysis.

Quantitative process models are often applied to individual components of a biophysical system in isolation. However, we take the novel and challenging approach of attempting to link a suite of models of different parts of the system and allowing them to interact with each other as illustrated in Figure 4. This allows insight into the complex inter-dependencies and relationships within the biophysical system. Once these models were implemented and validated against historical data, we assume that the underlying physics/biology is unchanged and make future projections based on changing input data and forcing. To a great extent the natural ecology and human utilisation of the delta system is determined by the physical characteristics of the region. Thus, the underpinning nature of the topography and climate of the region is paramount. Human intervention is the next most important driver of change, at a range of time and space scales, from land use to water abstraction and anthropogenic climate change.

The model system comprises component models or groups of models to simulate climate, catchment hydrology, water quality and sediment load, delta study area hydrodynamics, morphodynamics and groundwater, the Bay of Bengal, and fisheries, agriculture and mangroves in the study area.

For climate, three of the UK Met Office's HadRM3/PRECIS Regional Climate Model simulations (Q_0, Q_8, Q_{16}) are used to capture future climate variability under an A1B emissions scenario. Climate projections indicate a consistent trend towards increasing temperatures and precipitation over the region by the end of the 21st century. Heavy rainfall events are projected to become more frequent, with lighter and moderate rainfall becoming less frequent (Caesar et al., 2015). Consistent climate-induced SLR scenarios are available (Church et al., 2013), together with subsidence scenarios (Brown and Nicholls, 2015).

For catchment hydrology, the semi-distributed INCA model is applied to the entire GBM river system. This shows that climate change is likely to increase the peak flows into Bangladesh during the monsoon period, but that low flows may be more variable and more extended. There is a major threat to water availability from the water transfer plans for the upstream rivers, which could divert water away from the delta region (Whitehead et al 2015b). For water quality and sediment load, simulations with the INCA-N and HydroTrend models are used. The nutrient loads to the delta region from the GBM rivers will vary in the future as climate and socio-economic conditions change. Increased monsoon flows will dilute sources of N and P resulting in reduced concentrations flowing into the delta region. The implementation of the Ganga Management Plan (improved water treatment) will also reduce nutrient loads moving into the delta in the longer term, although increased agricultural development may generate a higher nutrient load depending on the use of fertilisers in upstream catchments. Simulations of sediment flux reveal that the delivery of fluvial sediment to the GBM delta is likely to increase with increasing flows under climate change (Darby et al., 2015; Whitehead et al., 2015a).

Hydrodynamics and morphological changes at the delta scale are captured with the FVCOM (Chen et al., 2003) and Delft-3D models (Haque et al., 2016). Water levels in the delta are controlled by a balance between river and tidal flow, acting on different timescales. Throughout the year the situation can change; from tides controlling the water levels in the dry season, to dominance by river flow during the monsoon. The salinity penetration is controlled by sea level and freshwater flow. The MODFLOW groundwater model (Harbaugh, 2005) is coupled with the SEAWAT water quality model (Langevin et al., 2007) to approximate the groundwater hydrology and salinity of the coastal zone. The groundwater seawater interface has attained its current position over a period of tens of thousands of years. Hence, the direct impact of SLR on the lateral movement of this seawater interface is minimal over the next 50/100 years. However, the indirect impact of SLR is via the increase in surface river salinity which in turn contributes to groundwater salinity. In addition, another potential driver of groundwater salinity change is increased groundwater abstraction in the areas north of the study area.

The GCOMS global framework has been adapted for the Bay of Bengal and simulations to 2100 have been completed for three climate and three socio-economic scenarios. These long time series outputs were required to model fisheries, as fisheries are influenced by processes with a time-scale of 10-30 years. It also enabled an assessment of the increased likelihood of extreme sea level events in the study area (Kay et al., 2016). For coastal fisheries, all simulations project decreases in potential catches comparing present conditions and future scenarios. However, while climate change impacts negatively on Bangladeshi fisheries, good management can mitigate these declines (Fernandez et al. 2015).

For agriculture, he improved CROPWAT model has been developed and fully coupled in ΔDIEM (Lázár et al. 2015). Thus it is possible to run complex scenarios with ΔDIEM and interpret the results by considering the uncertainties of the crop model. Field trials and the Aquacrop model have been used in parallel (Mondal et al. 2016).

Changes in mangrove forest area have been estimated using the Sea Level Affecting Marshes Model (SLAMM) (Payo et al., 2016). By 2100, the net loss was estimated as a maximum of 3, 6 and 24 percent of the present mangrove area for SLR of 0.46m, 0.75m and 1.48m, respectively. The higher losses could reduce the buffer protection provided to upstream areas by the Sunderbans against storm surges (Sakib et al., 2015).

Land cover/Land (LCLU) of the study area is also required and was measured using Landsat 5TM remote sensing images combined with field observations. This classified the study area into nine LCLU categories for three time slices (1991, 2001, 2011): (1) Water, (2) Bagda (saline shrimp farming), (3) Golda (freshwater prawn farming), (4) Agriculture (non-waterlogged), (5) Agriculture (waterlogged), (6) Wetlands and mudflats, (7) Mangrove, (8) Rural settlements, and (9) Major urban areas (see Amoako Johnson et al., 2016). Based on these observations, annual land use scenarios were developed. For the historical period, gaps were filled with linear interpolation. The future LULC scenarios were developed based on stakeholders' scenario narratives for 2050 (e.g. saltwater shrimp area slightly increased due to conversion of natural vegetation under BAU). The narratives were quantified, and after a final stakeholder workshop, where the quantified scenarios were discussed, the 2011 LULC data were projected to 2050. Beyond 2050, no further change in LULC is assumed due to the huge uncertainties.

3.5 Scenario Development

The project utilised climate, environmental and socio-economic scenarios. The climate, environmental, land use and demographic scenarios were developed by experts as explained in Sections 3.3 and 3.4. Below the development of endogenous socio-economic scenarios is explained.

Adopting a scenario-based narrative of possible (and plausible) futures allows responses to environmental and social changes over time to be explored in a way that addresses the huge levels of uncertainty. It also facilitated the integration of the views of stakeholders with the scientific findings. The approach that was adopted was inspired by the new Shared Socioeconomic reference Pathways (SSPs) approach (Arnell et al, 2011; O'Neill et al., 2014). We developed three future socio-economic scenarios: Less Sustainable (LS); Business As Usual (BAU); and More Sustainable (MS). These scenarios are devices for engaging with stakeholders, and no absolute inferences were made with respect to the actual sustainability of any of these scenarios: this is assessed with ΔDIEM. BAU is defined as the situation that might exist if existing policies continue and development trajectories proceed along similar lines to the previous 30 years. LS and MS are alternatives that are broadly less or more sustainable than BAU. The scenario approach allowed us to take the stakeholder issues of concern and project how they might look in 2050, on the basis of the ensemble of downscaled climate models defined in Section 3.4.

As part of the stakeholder engagement process described in Section 3.2, the main issues in the delta that were of concern to stakeholders were derived through a series of interviews and local level workshops held over two years (2012 to 2014). Each of the resulting issues – including salinization, erosion and sedimentation, and shrimp versus agriculture - were categorized into four issue groups: (1) Natural Resource Management; (2) Food Security; (3) Poverty / Health / Livelihoods; and (4) Governance. During a workshop held in October 2013, these were broken down by participants into almost 100 separate elements. Within the limits of a series of rather conservative boundary conditions, attendees ranked the extent of improvement/deterioration of these elements they expected by 2050 using a six point scale. Consensus (or at least majority agreement) was achieved, and significant efforts were made to ensure internal consistency across categories. Stakeholders were also asked to identify, where possible, the elements of the other issues where the impact of governance would be significant. The resulting table, roughly quantifying the constituent elements, allowed a detailed qualitative narrative of the BAU scenario in Bangladesh to be prepared, and corresponding narratives were developed for the other two scenarios (LS, MS). These were forensically evaluated by almost 100 experts at a workshop in Dhaka in May 2014, and revised narratives agreed subsequently.

A Qualitative-to-Quantitative process was required so that ΔDIEM could utilise the scenarios (Sections 3.6 and 3.7). This required the quantification of as many scenario elements as possible. In order to maximise stakeholder ownership of the scenarios (and subsequent results), stakeholder experts agreed on values of key model input parameters consistent with the narratives at a workshop held in November 2014, and through completion of a dedicated questionnaire. These results were then applied within the iterative learning loop (Section 3.7). Note that there were limits to the incorporation of a significant proportion of the scenario elements in the quantitative analysis, especially those related to governance. This is a topic for further research.

These socio-economic scenarios are linked to the expert demographic and land use scenarios. Hence, the climate and socio-economic scenarios are combined in a three by three matrix, giving nine plausible sets of scenarios (Q_0-LS, Q_0-BAU, Q_0-MS, Q_8-LS, etc.). By constantly considering nine plausible futures, the simulation results immediately indicate the uncertainty of the results and the robustness of interventions. While these are the scenarios used at present, the framework is flexible and other scenarios could be utilised as appropriate, as long as they provide the appropriate parameters for ΔDIEM.

3.6 Integrated Model Development (ΔDIEM)

As already noted, integration within the ESPA Deltas project faced multiple challenges: (1) multiple scientific disciplines, (2) multiple scales of analysis, (3) varying analytical methods, and (4) different computational power and run time requirements. For example, the Delft-3D model takes two days to simulate one year for one scenario, whereas the INCA model simulates all nine scenarios over 100 years within an hour. Thus, the first step of integration is to build on the earlier components and develop a conceptual diagram of the coupled biophysical-human system (Figure 4). This includes issues raised by the stakeholders and identifies the required processes and model elements. At the same time, the spatial and temporal scales of the biophysical models and all analytical methods are mapped, including the schematics of the integrative model. The integration aims to develop a rapid assessment framework which can simulate many future cases, and hence explore policy choices. This was based on a new meta-model that fully couples the required system elements and harmonises across the spatial and temporal scales. The current version of the model considers the upstream river basin and the Bay of Bengal as boundary conditions (although these can be replaced by dynamic counterparts, if required), because the focus of the analysis is on the Bangladesh coastal zone as defined in Figure 1 and on the environment – human interaction. Thus, the boundary conditions are currently represented by look-up tables of scenarios (climate, upstream hydrology and water quality, Bay of Bengal sea elevation and fisheries), whereas the coastal system has fully coupled representation.

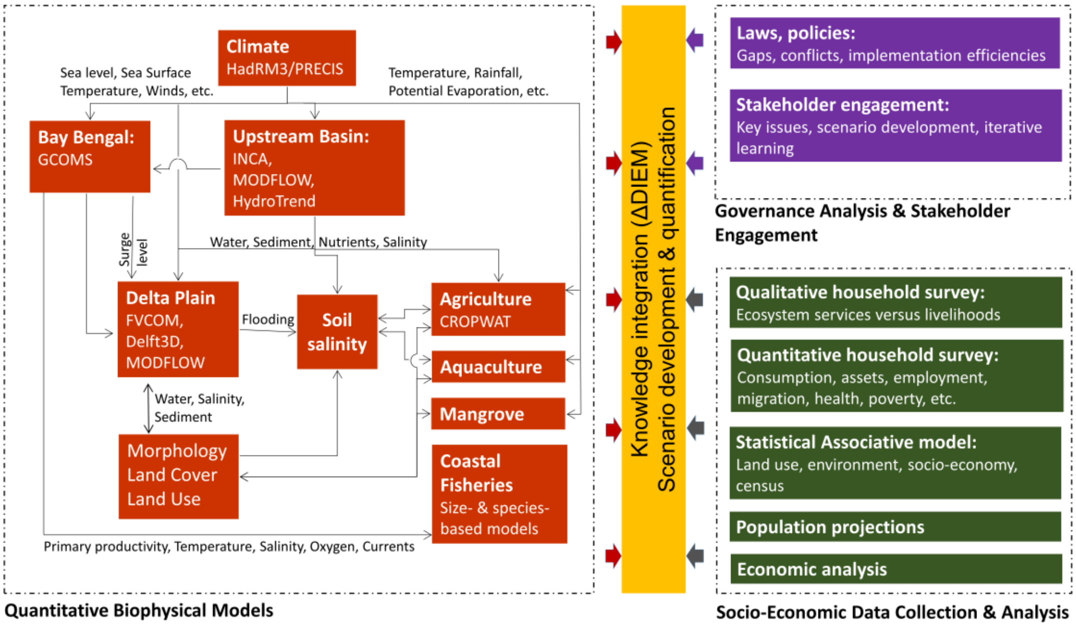

Figure 4. A conceptual diagram showing the flow of information to knowledge integration, which is encapsulated in ΔDIEM.

In ΔDIEM the hydrodynamics of the coastal zone was captured by the three-dimensional Delft-3D, FVCOM and Modflow-SEAWAT models for three time-slices, and sophisticated emulators (cf. Hotelling, 1936; Clark, 1975; Challenor, 2012) were created to represent these (surface and groundwater) hydrological and water quality processes within ΔDIEM. Emulation of these complex model results was essential to reduce the computational time and to interpolate the available simulations. A novel, regional soil salinity component of ΔDIEM was also developed that fully couples the climatic, hydrological and land management drivers of soil salinity change and links these with a process-based agriculture model (i.e. the improved CROPWAT model; Lázár et al 2015). Thus climate change, flooding, salinization, and land management has a direct impact on crop productivity in the simulations. All these biophysical calculations are done at the Union level (i.e. the smallest planning unit in Bangladesh) and at a daily time step (note that there are 653 Unions in the study area). Annual fish catches estimated by the coastal fisheries model are downscaled to the Union scale and a monthly time step by utilising a new fish market survey conducted within the project. Other livelihoods (i.e. small business, small-scale manufacturing, salaried employment) are less important in rural Bangladesh, and were not studied in detail. Thus in ΔDIEM, they are represented with observation-based look-up tables.

One of the most novel aspects of the approach is the explicit inclusion of poverty and health in ΔDIEM, rather than as an external piece of analysis. These issues are integrated in two distinct ways, both building strongly on the biophysical simulations of ΔDIEM. The first method uses a spatial statistical asset-poverty model (aggregated to the Union Level and on an annual time step) to directly estimate asset poverty (Amoako Johnson et al., 2016). This is based on biophysical state indicators and some socio-economic scenarios of employment rate, access to education and travel time to cities and markets. The second method approximates household livelihoods, poverty and health from the household survey (Section 3.3) using an agent-based-type household economy model. Within this process-based calculation, the simulation follows the virtual lives of 37 household archetypes (union-based, monthly time step). These archetypes are identified and parametrised using the household survey. Calculations in the household component are driven not only by the biophysical changes, but also by the demographic, land cover and economic scenarios (Section 3.5). Incomes and remittances are matched with direct livelihood costs, affordable household expenditure and farm labouring opportunities. The output of the calculation is household welfare and food intake. A range of governance interventions can be tested with this model framework such as: land use restrictions, subsidies, income taxes, market price policies, new crop varieties, embankment projects, infrastructure development, etc. Such a detailed household economy model also produces regional economic indicators (e.g. GDP/capita, GINI coefficient), food security indicators (e.g. rice production, hunger periods) and national poverty indicators. These two contrasting methods, the statistical associative model and the household survey model, allow preliminary consideration of uncertainty in the simulations, robustness of governance interventions and identify further research areas.

3.7 Policy Analysis and an Iterative Learning Loop

Our integrated methodology is built on ongoing stakeholder engagement and iterative learning through the project (Sections 3.2 and 3.5). This includes involving an innovative learning process where stakeholders (from government to civil societies) are involved in all stages of the research starting from the identification of research questions to developing scenarios and exploring these within the ΔDIEM framework. This ensures stakeholder trust, interest and willingness to participate.

While stakeholder engagement and learning was embedded in the whole project, the iterative learning loop in Figure 3 is critical to engaging with the policy process and is expanded in Figure 5. This provides a process for decision makers to engage and adaptively test outcomes from the implementation of individual policies or rafts of policies into the future. The practicalities of this approach involve a series of workshops which initially provide information on the simulated outcomes across a range of scenarios. The process is initiated by the earlier stakeholder engagement and scenario development described in Section 3.5. Stakeholders are informed of ΔDIEM capabilities and formulate inputs to ΔDIEM based upon scenarios already discussed (Step [1] in Figure 5). These inputs are in the form of narrative statements and so the process of Qualitative to Quantitative transformation is required with expert technical input (Step [2] in Figure 5). These inputs are used in ΔDIEM to produce a range of output simulations of future states of the delta study area. (Step [3] in Figure 5). These simulations are then reviewed at a further stakeholder meeting and adaptation responses can be proposed (Step [4] in Figure 5). The loop can then be re-iterated multiple times, allowing investigation of the problems of the GBM delta, and possible solutions including trade-offs.

We have worked with stakeholders to define the types of intervention that could be represented in ΔDIEM. A diverse range of socio-environment and socio-agricultural interventions can be addressed and simulated in the ΔDIEM system, ranging from soft policy tools such as natural flood management (forestry and land use management mangrove development, and land use planning and zonation), to harder more substantial engineering interventions such as the development of water management and storage systems (dams, barrages, polders, pumping systems, water treatment). The credibility of a simulation always needs to be considered, and for some measures additional model simulations including the interventions to retrain ΔDIEM emulators may be required.

As such ΔDIEM is an iterative learning instrument to explore the impact of a range of climate, social and governance interventions in close collaboration with decision makers. The main focus is up to 2050, as the socio-economic scenarios are most credible over this time frame and there is stronger interest in the next 30 years. However, longer simulations are feasible and desirable from a policy perspective, especially for the biophysical indicators if not for the socio-economic context. For example, the Bangladesh Delta Plan 2100, which is currently being developed to steer strategic development of Bangladesh, has a strong focus on the next few decades but also considers a maximum time frame of 2100 (see http://www.bangladeshdeltaplan2100.org/).

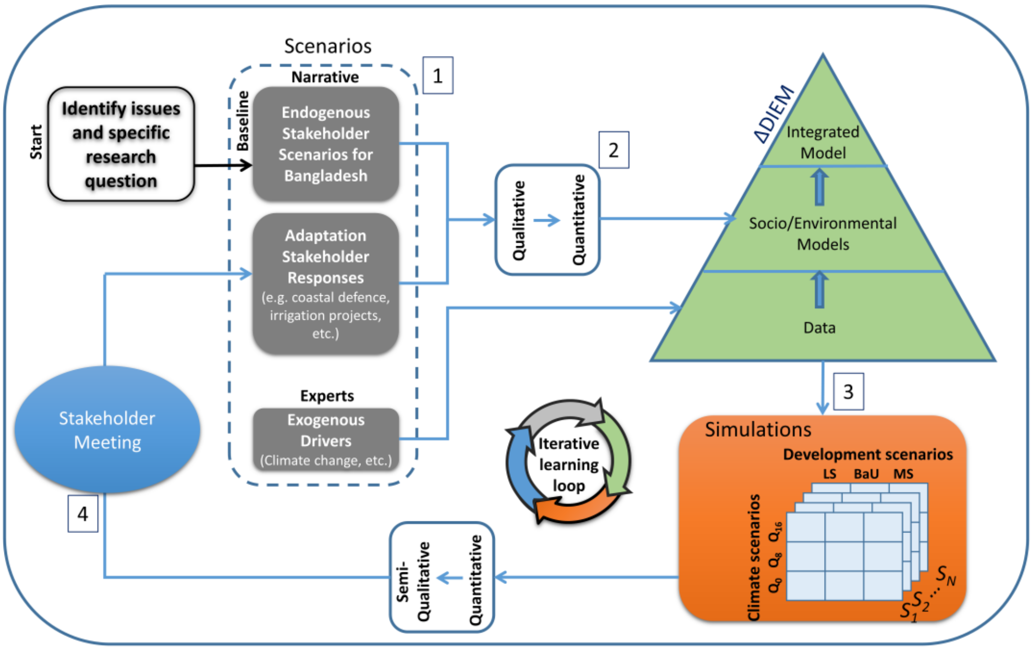

Figure 5. Concept of the iterative learning loop using ΔDIEM for policy analysis. Reference numbers describe the loop are referred to in the text: (1) scenario development, including adaptation responses; (2) qualitative to quantitative translation to ΔDIEM inputs; (3) simulations using ΔDIEM; and (4) stakeholder review of the simulations.

The output simulations can be evaluated in a number of ways. Rather than seeking *optimum* solutions the notion of *robustness* is favoured by the authors. This explores what interventions work best across a wide range of plausible futures, as robust interventions are more likely to be applicable in an uncertain future. This is an important point, as ΔDIEM does not provide forecasts of future states, but rather allows an exploration of possible futures, which constitutes appropriate information for a robustness assessment. One question of interest is testing grey versus green infrastructure approaches, as well as hybrid grey/green approaches. Given the large amount of output from ΔDIEM, other decision analytic approaches could be considered.

4. Discussion

Our analysis started with broad qualitative assessment of the system of interest. It progressed with a range of socio-economic analysis and surveys and biophysical modelling. These were developed with integration in mind and also informed scenario development. National-level stakeholders were consulted throughout this process including within the scenario development. This has culminated in the ΔDIEM model, which offers a practical assessment tool for scientific and policy assessment designed with and for stakeholders in a complex socio-environmental context. The ΔDIEM model is now beginning to be used in analysis of the development choices for coastal Bangladesh.

In terms of the question concerning the physical and biological processes which affect life, livelihoods, health and mobility, important insights have emerged as outlined below, and will continue to emerge from this analysis. With respect to the stability of the relationships as regards biophysical process, and hence predictability over time, our assumption that they are unchanging is reasonable and normal. For socio-economic issues this assumption is less justifiable and we have had to review the literature in order to inform our understanding of the stability of the relationships over time. These assumptions are explicit and will be investigated into the future both in Bangladesh and using appropriate analogues elsewhere. However, we recognise that the timeframes at which the socio-economic results are useful is much shorter than for the biophysical results.

This hybrid integrated framework has allowed a move away from an ad hoc, external expert or purely indicator-based approach and provided an opportunity to explore the interactions between domains of knowledge as diverse as oceanographic modelling and perception-based assessments of well-being. In this approach, while the analysis is complex, the assumptions are explicit and have been debated, challenged and changed as our knowledge grows and the detailed questions being posed evolve with this understanding. Hence, it provides an explicit analytical framework and forces the user to identify, consider and explore the limits to knowledge.

ΔDIEM depends upon systems analysis and simulation modelling. Given the difficulty of predicting change in all of the systems considered here, such simulation modelling could be regarded as being almost naïve. We recognise the limits to what we represent in our models, but we sought to represent all the relevant processes and their interactions. Developing and linking models was a key process within the project team that facilitated development of our conceptual ideas, promoted detailed discussion between different discipline experts, as well as developing the ΔDIEM software. As we gain experience we will continue to explore the complexities, interdependencies and uncertainties of our study area. This includes considering a wide range of possible strategies for development within the context of an uncertain future.

Many improvements are possible. This includes provision of better basic data such as bathymetry and elevation or surface water salinity in the short- and long-term. The household survey might be repeated to explore how these factors and relationships change over a number of years, addressing the issue of the stability of relationships/predictability over time. Moreover, the ΔDIEM framework is flexible and can be adapted to analyse additional issues. So, while we have primarily focussed on provisioning ecosystem services in a deltaic environment, the models used could readily be extended to analyse regulating ecosystem services (cf. Hossain et al., 2016).

Building these types of co-produced analytical tools represents a significant amount of effort and resource, but we would argue that the new insights, capacity building, scientific and policy applications and understanding generated justify this approach. The model framework structures our diverse knowledge and understanding of the relevant processes, information and data. Indeed, the level of integration accomplished in this research is novel and unusual and possibly unique in its strong quantitative coupling of biophysical changes to household livelihoods related to provisioning ecosystem services. This research has already provided important insights about the socio-ecological processes operating in the study area and in the wider region. The integration provides synergistic insights for national policy processes such as the Bangladesh Delta Plan 2100. This is providing a practical test of the real world application of this approach in a policy context.

5. Conclusion

This research provides a comprehensive approach that utilises a highly diverse range of data, models and treatments intersected with strong and sustained participatory interaction with stakeholders. The approach offers a transparent methodological approach to the analysing the interface between diverse socio-economic and biophysical components – in this case sustainable livelihoods and ecosystem services in deltas – issues that have often proven a stumbling block for integration. One of the strengths of the approach is that it provides a platform for further refinement and development. The models and data are modular and can be easily changed or extended.

This research has already come to a number of important conclusions for the GBM delta, such as the spatially-variable drivers of poverty in the study area (Amoako-Johnson et al., 2016), or the likely amplification of the seasonal river cycle due to climate change (Whitehead et al., 2015a). Importantly, we have organised our understanding of the GBM delta, both in terms of recent history and prognosis. This helps to understand how the different drivers are shaping the biophysical landscape and ecosystem services and their implications for the resident's well-being. It also makes the development choices and possible trajectories more explicit and empowers national decision-making. Our preliminary analysis shows that decisions made in Bangladesh will have important implications for these trajectories.

Looking to the future, these methods could be applied more widely across other deltas, as many issues are common. Cross-fertilisation with other research efforts in deltas such as the Dutch delta plan (Van Alphen, 2015) and habitat restoration in the Mississippi delta (Coastal Protection and Restoration Authority, 2013) may also be fruitful. As already noted, the methods described are not delta-specific and could be applied in other coastal and non-coastal contexts where strong socio-ecological coupling exists. As such, the spatial domain covered in Bangladesh could be expanded and a national application has been discussed.

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Figure 1: (a) The Ganges-Brahmaputra-Meghna river basin (shaded green), the Holocene delta (shown with criss-cross lines, after Woodroffe et al., 2006) and the Bay of Bengal (shaded purple). (b) The detailed study area (shaded), including the Sundarbans (shaded brown). Selected urban areas are shown as green squares. Khulna and Barisal Divisions are indicated. Bangladesh is shown with a red boundary.

Figure 2: Schematic illustration of the key biophysical factors affecting the study area and their relationship to governance and community/socio-economic factors.

Figure 3. Components of analysis of ecosystem service processes, societal outcomes and governance and scenarios in the GBM delta system.

Figure 4. A conceptual diagram showing the flow of information to knowledge integration, which is encapsulated in ΔDIEM.

Figure 5. Concept of the iterative learning loop using ΔDIEM for policy analysis. Reference numbers describe the loop are referred to in the text: (1) scenario development, including adaptation responses; (2) qualitative to quantitative translation to ΔDIEM inputs; (3) simulations using ΔDIEM; and (4) stakeholder review of the simulations.