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Participatory modelling for conceptualizing social-ecological system dynamics in the Bangladesh delta

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Abstract

The concept of complex social-ecological systems (SES) as a means for capturing system dynamics properties (e.g. interactions and feedbacks) has gained attention in policymaking and advancing evidence in understanding complex systems. In contexts with limited data, conceptual system dynamic models offer a promising entry point to overcome challenges in understanding SES dynamics, which is essential for managing the long-term sustainability of SES and human wellbeing. Here, we build on previous work focused on agricultural production, and use participatory approaches to develop a conceptual System Dynamics (SD) model for the south-west coastal SES in Bangladesh encompassing multiple forms of livelihood (fisheries, shrimp farming and forests, as well as agriculture). Using qualitative methods, including focus group discussions with farmers, fishermen, shrimp farmers and forest people, as well as expert consultations, we identified interactions, feedback loops and thresholds for the SES. The conceptual system model developed independently by stakeholders is consistent with a model developed using an empirical approach and literature review. Feedback loops are identified for the ecological (e.g. climate and water, mangrove and salinity) and social (e.g. shrimp farming and mangrove, agricultural (e.g. crops) production and subsidy) sub-systems in the Bangladesh delta. The biophysical thresholds that impact social conditions, include river water discharge (1500 $m^3 s^{-1}$ to 2000 $m^3 s^{-1}$), climate (28 ^oC) and soil salinity (~4 $dS\ m^{-1}$ to ~10 $dS\ m^{-1}$). Exceeding these thresholds suggest, that SES may lose resilience in the near future, and increase the likelihood of regime shifts. Findings of this study contribute to the management of the deltaic ecosystem and provide specific policy recommendations for improving environmental sustainability and human well-being in the Bangladesh Delta and can be further used as inputs into system dynamic modelling to simulate changes in this SES.

Keywords: Social-ecological systems (SES), feedbacks, thresholds, regime shifts, participatory modelling

1. Introduction

The concept of social-ecological systems (SES) has rapidly gained ground over the recent decades (Liu et al., 2007; Folke et al., 2005) and has become a major research priority for sustainable ecosystem management (Dearing et al., 2015). This management approach requires understanding SES in an integrative way in order to capture the complex interaction between causal factors and responses, as well as lags, feedback and thresholds in social and ecological systems (Biggs et al., 2012). A systems perspective can be used to synthesize all these complex concepts (e.g. lags) (Chen et al., 2009). System Dynamics (SD) modelling is being used more often to capture complexities using a systems perspective (Chang et al., 2008). SD modelling was first developed in the early 1960s by Jay Forrester (Ford 2010; Forrester 1961). This modelling technique provides insight into the behaviour of a system, including feedbacks, delays and nonlinearities (Videira et al., 2009). SD models can be used to explore changes in a SES and the pathways for limits to growth (Meadows et al., 1974). SD modelling has been used for managing eco-agriculture systems (Li et al., 2012), water resources (Beall et al., 2011), wildlife systems (Beall and Zeoli, 2008), and social dynamics of ecological regime shifts (Lade et al., 2015). Although SD has been used as an effective decision-making tool, the testing and validation of SD models remains well debated in SD research (Barlas, 1996).

Testing behaviour validity and structural validity of a model are commonly used validation methods. Validating model generated behaviour against the real behaviour of a system, in order to investigate the accuracy of model output in representing the actual system, is known as validating model behaviour (Hossain et al., 2017a; Khan et al., 2009). Structural validity refers to the validation of assumptions, factors and their interrelationships within the system which can represent the real system. In comparison with behavioural validation, emphasis has been placed on structural validation (Khan et al., 2009), because researchers argue that real behaviour is less important and nearly impossible to validate, whereas it is important to validate the reliability of a model's structure so the model can demonstrate changes in behaviour while testing policies (Barlas, 2000, 1996).

While validating the structure of a system, the use of participatory approaches is becoming more popular. Participatory modelling involves local stakeholders or directly affected people sharing their perceptions, knowledge and understanding about system processes (Jakeman et al., 2006; Cain et al., 2001). A participatory approach can often help address data limitations for ecosystem management (Ritzema et al., 2009); and it has already been used for conceptualizing the system dynamics model of a wetland ecosystem (Ritzema et al., 2009), wildlife management (Beall and Zeoli, 2008), water resources management (Beall et al., 2011) and river basin management (Videira et al., 2009).

Despite growing emphasis on SES dynamics (e.g. Hossain et al., 2018; Biggs et al., 2012; Liu et al., 2007), previous studies (e.g. Shamsuddoha et al., 2013; Datta et al. 2010) focused on sector specific conceptual models (e.g. shrimp, climate change) without considering SES dynamics (e.g. interactions, feedbacks, nonlinearities) and engaging stakeholders in the research process. In this new study, we extend our previous work (Hossain et al., 2017a) on the sustainability of agriculture in Bangladesh by developing several sector specific, participatory system dynamics models that describe the complex dynamics (e.g. interactions, feedbacks) between social and ecological systems for the Bangladesh delta. Here, we have made a first attempt to collect threshold data for the SES for the interacting agricultural, fishery, shrimp and forest sectors in the Bangladesh delta. In addition to discussing policy implications based on the findings of this study, we also discuss plausible methods and challenges in operationalizing conceptual models to understand the sustainability of complex SES.

Our overall objective is to use a participatory approach for conceptualizing the system dynamics model of a SES in the Bangladesh delta by answering the following research questions:

1. What are the key factors that affect livelihoods?
2. How do these factors affect livelihoods?
3. What are the causal interlinkages between those factors?
4. Which are the threshold points in the social-ecological systems?
5. Where are the feedback loops within the SES.

The findings from this study can be fed into a system dynamics model as a structural validation (validation of assumptions, factors and their interrelationships within the system) approach and to help in understanding the complex dynamics of the system in order to simulate changes in SES and tipping points for biophysical and social conditions.

2. Study area and Methods

2.1. Study area

Our study area is the south-west coast of Bangladesh (Figure. 1). This is an area of ~25,000 km^2 (16% of the total land area of Bangladesh), with a total population of 14 million (BBS, 2010; Szabo et al. 2015b) experiencing high out migration and uncertain demographic futures (Szabo et al. 2015b). The ecosystem of this area produces more than 1,300 million USD of Gross Domestic Product (GDP) (BBS, 2010). Inhabitants of this environmentally vulnerable area face significant food insecurity and are dependent on agriculture (~40%), fisheries (~20%) and forestry (~25%) as a source of livelihood (Hossain et al., 2015; Szabo et al. 2015a, Lazar et al. 2015). Moreover, approximately 1.5 million people are directly and 10 million people are indirectly dependent on the world's largest forest mangrove called the 'Sundarban' (Islam and Haque, 2004). Here we assume that, for changes in the ecological system, the livelihoods of agriculture, fisheries and forestry dependent people (~80%) will be directly affected, whilst the remaining people who are dependent on these sources for food security will be indirectly affected. Thus, we focused on four main livelihood sources (agriculture, fishery, shrimp farming and forestry) for modelling the SES.

2.2. Methods

2.2.1. Overview

A qualitative research method (Figure 2) has been used to develop the SES model for the study area. In general, our approach comprises five research steps: 1) conceptualizing a sectoral (agriculture, fishery, shrimp and forest) causal loop diagram by identifying factors and mapping the interlinkages and causality of those factors during focus group discussions (FGDs) with farmers, fisherman, shrimp farmers and forest people; 2) conceptualizing the SES (including agriculture, forest, shrimp and fishery) dynamics (e.g. interactions, feedbacks) through expert workshops; 3) conceptualizing a final system dynamics model based on synthesized information from steps 1 and 2; 4) comparing the final conceptualized system model and previous models developed using different approaches (e.g. statistics, literature review); 5) collecting thresholds for biophysical processes using expert interviews and a literature review.

2.2.2. Conceptual system dynamics model

We used a participatory approach to develop a conceptual system dynamics (SD) model for the south-west coastal SES in Bangladesh. System dynamics modelling helps to understand the complex behaviour of a system and to synthesize complex relationships (e.g. feedbacks, nonlinearity) between SES (Ford, 1999; Forrester, 1997). A SD model starts with the conceptualization of a model, which is known as a causal loop diagram or conceptual system dynamics model (Hossain et al., 2017). A causal loop diagram visualizes linkages between variables in a SES that can produce positive or negative feedbacks loops(Sterman, 2000). Positive feedbacks in a SES amplify change and promote system instability, whilst a negative feedback attenuates change and stabilizes a system (Ford, 2010). For example, a positive feedback occurs when an increase in deforestation increases regional temperature which increases fire risk. This in turn, may cause forest dieback and further deforestation (CBD 2010). In contrast, an example of a negative feedback occurs when a rise in shrimp production degrades a mangrove area by increasing local salinity and causes a long-term reduction in the suitability of shrimp production.

Box 1: Definition of key terminologies

Social-ecological systems (SES): Complex and integrated systems in which human and nature are interdependent and shaped by each other.

System dynamics: Understand the behaviour of complex systems over time and synthesize complex relationships (e.g. feedbacks, nonlinearity) between social-ecological systems (Forester, 1962).

Causal loop diagram: Causal refers to causal (cause and effect) relationships and loop refers to closed chain of cause and effect that creates a feedback

Causality: assumes that the value of an interdependent variable is the reason for the changes in value of a dependent variable

Threshold: a critical value of a driver for which a small change can cause a large change in ecological state

Feedback: a causal link that demonstrates a reciprocal relationship (outputs of a system are routed back as inputs) that creates either positive or negative feedback loops.

Positive and negative feedback: when the effect of causality among factors reinforces the initial change. In contrast, a negative (balancing) loop is occurs when the effects of the causality opposes the initial change.

Tipping point: a critical point beyond which an ecosystem shifts to a new state with a significant change, which is typically rapid and hard to reverse once it transgresses a critical (Tipping) point.

Slow and fast variable: Slow variables are controlling and determining the structure of social-ecological systems and shaping variables for system resilience. Fast variable responds over shorter time scales in respond to changes in slow variables which respond slowly over the long term

A conceptual system dynamics model (causal loop diagram) simplifies the real-world SES by conceptualizing the structure of the system by identifying, understanding and evaluating cause and effect relationships between variables (Inam et al., 2015). As such, conceptual system dynamic models offer a promising entry point to overcome challenges in understanding the feedback structure of a SES (Videira et al., 2017). Therefore, the conceptual SD model is recently receiving recognition as a powerful tool for complex issues (Vermaak 2016) and has been increasingly used to promote the participation of environmental decision-making process (Sarriot et al., 2015). Examples where conceptual SD models are applied include water resources (Kotir et a., 2016), industrial ecosystems (Mota-López et al., 2018), agriculture (Robert et al., 2017), geomorphology (Payo et al., 2016), energy (Agnew et al., 2018), coastal (Joakim et al., 2016) and health systems (Littlejohns et al., 2018).

2.2.3. Description of the focus group discussions (FGDs) and workshops

We used a participatory approach as the primary technique of data collection, which includes: 1) focus group discussions (FGD) with farmers, fisherman, forest dependent people and shrimp farmers, and 2) organized workshops in which different stakeholders (academics, representatives of NGOs and other professionals) participated in the discussion. Participants were provided with a summary document which contained a brief description of the study objective, an overview of the workshop's aims and key research questions. Due to the illiteracy of most of the FGD participants, the session chair selected by the participants briefly discussed the aims and key research questions. The discussion, both for workshops and FGDs, was facilitated by a session chair. In addition, student assistants with an academic background in environmental and social sciences facilitated the discussions. The average time for the workshops and FGDs was two and a half hours. Participants were allowed sufficient time for discussions. All participants were informed that their identity would be kept anonymous by removing participant information (e.g. name, list of participants, photo).

In total, seven FGDs were conducted between April and August 2015 in Barisal, Khulna and Patuakhali (Barguna) (Figure. 1). On average, there were 20-24 participants in each FGD, the majority being participants between 30-60 years of age or older and engaged in their profession for at least 10 years. Before starting the discussion, we divided the participants into two groups to ensure saturation of information (e.g. minimize redundancy and disagreements) from the same area. These groups were selected in order to maximize the understanding of SES in the region. During the FGDs, participants were first asked to identify the key factors affecting their livelihoods and provide details how these factors affect their livelihoods. Secondly, participants were asked about interlinkages amongst those factors.

For the workshops, experts from academia and government employees working in environment, fishery, agriculture, forestry, and water resource management were invited.

Additionally, journalists, NGOs, other professionals and students working on environmental and other relevant issues (e.g. development programs, poverty, food security) were also invited. Two workshops were organized in Khulna and Patuakhali to collect qualitative data (Figure. 1). The total participants (n=25) during each workshop were divided in two discussion groups in order to ensure the saturation of information (e.g. minimize redundancy and disagreements) from the same area. The information collected from participants concentrated on feedbacks and thresholds, and this was possible because participants were experts in their respective fields.

2.2.4. Development of the conceptual system dynamics model

Figure 2 depicts the flow diagram showing the schematic methodology of the study. In summary, both in FGDs and workshops, the development of the conceptual system dynamics model was developed in the following steps:

1. Participants identified key factors affecting their livelihoods (RQ1) and discussed how these factors affect their livelihoods (RQ2).
2. Participants mapped the relationships (RQ3) among factors in terms of interlinkages and causality of those factors. If a change in one factor led to change in another factor, the participants described the link as a causality and drew a line between the factors. In addition, when the first factor was increased, the direction of the change that triggers the increase in the second variable was depicted by putting a positive (+) sign. This was later conceptualized as a solid line when digitizing the conceptual model in STELLA. When an increase in the first factor led to a decrease in the second factor, this was depicted by a negative (−) sign and symbolized using a dotted line between the factors.

   In the workshops, we also followed similar steps from 1 to 2. The expertise of the workshop participants enabled a discussion about plausible thresholds (RQ4) for biophysical processes, such as the temperature threshold for fish production. However, due to the illiteracy of stakeholders in the FGDs, we limited our approach to identifying factors and interlinkages between factors.

3. Workshop participants also identified feedback loops (RQ5) where a causal link demonstrated a reciprocal relationship (outputs of a system are routed back as inputs) that creates either positive or negative feedback loops. They identified the loop as a

positive (reinforcing) feedback loop when the effect of causality among factors reinforces the initial change. In contrast, a negative (balancing) loop was identified when the effects of causality oppose the initial change.

In both the FGD and workshops, each group presented their outputs which were interactively discussed, and lead to the development of a final conceptual system dynamic model in the form of causal loop diagrams. We have used the system dynamics modelling platform STELLA to digitize and visualize the conceptual system dynamic models for the SES in the Bangladesh delta.

2.2.5. Commonalities and differences with other approaches

To identify commonalities and differences we compared the participatory based conceptual system dynamics model in this study with a previously developed conceptual model developed using time series data and regression based methods (Hossain et al., 2017b). In summary, comparison of the final conceptual model developed using a participatory approach comprises two steps (Figure 2): (1) System models developed independently by stakeholders in this study are compared with the system model developed using empirical analysis (e.g. models) and a literature review (Hossain et al., 2017b); 2) The participatory conceptual models was used not only for qualitative assessment of the SES, but also can be used in quantitative assessment of SES dynamics, following the methodology (for just agriculture) developed in Hossain et al. 2017a. Details of both approaches are as follows:
1) Comparisons with empirical analyses: Hossain et al., 2017b developed a conceptual system model, based on a regression (additive, logistic, linear) model and literature review for the SES in the south-west coastal Bangladesh. This earlier work is compared to the systems model developed in this study to identify commonalities and differences between the two system models. The conceptualization of the analysis and detailed methodology to analyse the linkages between social and ecological variables, which served the purpose of conceptualizing a system model with the support from literature can be found in our previous study (Hossain et al., 2017b).
2) Quantitative validation of SES dynamics: The agricultural conceptual model developed by the stakeholders has been used as the basis of a previous study (Hossain et al., 2017a) for developing a system dynamics model, which has been used to investigate whether it can be used to simulate historical behaviour of the system. The overall idea of providing an example (agriculture model) from a previous study (Hossain et al., 2017a) is to show that the

participatory conceptual models can not only be used for qualitative assessment of SES, but can also be used in quantitative assessment of SES dynamics. The SD model platform STELLA has been used to develop the agricultural model further by using the SD modelling components such as stocks (e.g. state variables such as subsidy), flow (rate variables such as inflow of investment) and converters (e.g. factors). As we lacked information to formulate a priori mathematical relationships between variables, a built-in feature of STELLA – the 'graphical function' which fits mathematical relationships between variables based on any existing information, was used to parameterize variables. Available time series data collected from official statistic and literature have been used to parameterize the variables in the graphical functions by inserting the input values (e.g. water) in the x-axis and output values (e.g. crop production) in the y-axis. The detailed model development and parameterization of the system model are provided in our previous study (Hossain et al., 2017a): equations for defining relationships among variables of the system dynamic model in STELLA are reproduced in the SI in Hossain et al., 2017a, the model was run for a period of 50 years and compared the model output with a time series (50 years) of normalized crop production data in order to investigate whether the conceptual system model developed independently by stakeholders can be used to simulate historical behaviour of the system.

3. Results

3.1. Agriculture

SI Figure 2 shows the factors, including quality of seeds, use of pesticides, irrigation and fertilizer, which farmers identified as positively influencing the production of crops. On the other hand, drought, salinity and temperature beyond a threshold negatively affect crop production. Both flood and rainfall have a positive and negative influence on crop production: while floods damage the production of crops, they also improve soil fertility which leads to higher production of crops. According to farmers, crop production is negatively affected by low water availability in the upstream Ganges river, which in turn, increases irrigation demands.

Production from agriculture is directly related to income, which is directly and positively associated with daily food availability and consumption, access to health care and electricity. Although the government and NGOs have constructed community clinics and hospitals where farmers can access inexpensive medical facilities, farmers depend on their income for purchasing medicines and medical tests. For education, sanitation and access to safe drinking water, farmers depend on government and aid from NGOs as well as their personal income. For example, although primary education is free for all, the cost of private tuition to complete education is one of the barriers in attaining primary education.

Furthermore, subsidy and market regulation have a considerable effect on household income. When farmers can purchase subsidised fertilizer, pesticides and irrigation materials (e.g. fuel, pump), they are able to make profits from their production. Similarly, when the market price of selling rice is higher than the production cost, their profit increases. However, farmers often experience financial loss because of poor market regulations that set the price of agricultural commodities equal to, or slightly higher than, their production cost. Possibly for this reason, experts also recognize that national policies such as subsidies for fertilizer and electricity for irrigation substantially affect the production and income of farmers. Finally, greater agricultural production reduces out-migration.

3.2. Fisheries

SI Figure 3 depicts the causal loop diagram for fisheries in the Bangladesh delta. Experts agreed that rising temperature and salinity have a negative effect on fish production. An increase in water flow leads to higher production of fish in rivers; however, a high-water level during flooding reduces fish catches. Similarly, water depth is negatively associated with fish catch. Both water depth and flood, contribute to an increase in the production of fish in rivers and ponds. Fishermen also observed that fish catches increase during natural disasters and tidal flows. Moreover, fishermen and experts have reported that reduced water flow from the northern part of the country is one of the reasons for decreasing fish production.

Coastguards play an important role in protecting fish from over-exploitation by restricting the catch of egg-bearing female fish during the breeding season. This creates conflict between coastguards and local fishermen, as the fishermen's income is reduced due to limited fish catch during this season. Use of fishing nets (e.g. stick, current, gill nets) has a negative impact on fish production in the long run, as small net sizes trap young fish. Fishermen's income depends on daily fish catch, market price of fish and debt. Debt is incurred to rent boats and other fishing materials. The local mahajon (a group who are financially and politically powerful) often charge a higher rate of interest for loans and force fishermen to sell their fish at the mahajon's desired price. This syndicate often controls the local market and dictate the national price of fish. Fishermen also highlighted that income from fish catches are positively linked with their food consumption, health service (purchasing medicines and medical tests) and electricity. However, primary education attainment, sanitation and drinking water access depended both on household income and support from the government and NGOs.

3.3. Shrimp farming

SI Figure 4 shows the causal loop diagram for shrimp production in the Bangladesh delta. Fertilizer plays a role in preparing the soil of shrimp ponds (gher) and increasing pond fertility. Production of good quality and a high quantity of fingerlings from rivers or hatcheries are a prerequisite for higher production of shrimp. Erratic rainfall patterns, water flow during flood and waterlogging due to heavy rainfall damages shrimp production. Sudden rainfall leads to drops in temperature and reduces the salinity level, which has negative consequences on shrimp production. Farm-raised shrimp often contract viruses, the causes which are unknown to farmers and leads to losses. The occurrence of viruses has become more common in the last five years.

Experts mentioned that because of rising temperature, sudden rainfall and higher levels of salinity, shrimp farming is often threatened by viruses, which reduces total production by at least 50%. In particular, low water depths in shrimp ponds due to synchronous high temperatures and low rainfall increase the vulnerability of cultured organisms to the presence of viruses. Farmers reported that income from shrimp ponds is lower than it was between 1990 and 2000. Experts commented that recently observed reduced income could be explained by loss of soil fertility, rising temperatures and erratic rainfall patterns in the region. Mangrove forest is highly fertile and suitable land for shrimp cultivation. However, the fertility and quality of mangrove soil degrades in response to intensive cultivation of shrimp in the same location for a long time. In turn, shrimp production may also decrease because of the depletion of mangroves, as it reduces the soil fertility and suitability of shrimp cultivation. This was confirmed by the shrimp farmers, who have been experiencing reduced production compared to the period between 1990 and 2000. With regards to linkages between the income of shrimp farmers and other factors affecting human wellbeing, shrimp farmers reported that income directly influences food consumption and health (purchasing medicines and tests) while access to sanitation, education and safe drinking water are dependent on aid from the government and NGOs.

3.4. Forest product collection

Crab, honey and fish fry are the three main products (SI Figure 5) that forest people collect from the mangrove ecosystem. Forest-dependent people explained that there are lower stocks of honey in the mangrove when seasonal temperatures are high and rainfalls are low. Moreover, freshwater flow is required for honey production, as the bees collect fresh water as part of their physiological process. Interviewed farmers perceived that the stock of honey had reduced since they started experiencing reduced water flow from the northern part of Bangladesh. The water scarcity problem has become more severe due to a salinity rise, which also reduces freshwater availability for bees. High levels of salinity influence crab cultivation positively until a high threshold level is reached when crab productivity is reduced.

Experts highlighted that the stock of honey, wood and fish all depend on the stock of mangrove. Water flow reduction and salinity rises are the main causes of top-dying disease in mangrove trees. The government has now banned collection of wood from the mangrove. However, interviewed farmers mentioned that, despite banning wood collection, illegal wood loggers with powerful political connections usually collect wood from the mangrove throughout the entire year. Moreover, besides regulating services, practices such as an increase in forest product collection (e.g. wood, wax) and honey cultivation by forest people in the Sundarbans, are one of the reasons for decreasing wild honey and fish fry collection. Fish fry collection is negatively affected by water flow and salinity rise.

3.5. Interaction, feedbacks and thresholds

Interaction and feedbacks are the prime factors for the dynamics of the SES; they coproduce the services provided by the ecosystem (Biggs et al., 2012). We have mainly used experts' opinions from the workshops to identify feedbacks within and between social and ecological systems.

We have identified seven positive (reinforcing) feedback loops (Table 1) using the participatory approach for the SES in the Bangladesh delta. Though, the participants did not identify negative (balancing) feedback loops, positive feedback loops are the important ones to assess because these loops destabilize the SES. In the case of our study region, participants identified positive feedback (loop 1) between crop production and investment in agriculture (e.g. income, GDP, fertilizer use). Higher profit from the agricultural sector and other sectors (e.g. industry) increases the possibility of more investment in agriculture in terms of subsidizing fertilizer and irrigation facilities including equipment which in turn increases agricultural production. Positive feedbacks also exist between temperature and river discharge (Loop 2), and between shrimp farming and soil salinity (Loop 3). The reduction in water availability due to the diversion of water in the upstream Ganges increases the regional temperature, which in turn increases evapotranspiration from rivers, and thus ultimately, decreases further water availability.

Participants also revealed that not only the increase in salinity creates suitable environment for shrimp farming, but due to the demand for shrimp farming, shrimp farmers also add more salt in the ponds or bring saline water into the shrimp ponds by connecting rivers and ponds with canals. Ultimately, the salinity of soil in the ponds increases which in turn increases the suitability and productivity of shrimp farming. Participants identified this loop (Loop 3) as one of the major reinforcing feedback loops that is linked to other reinforcing feedback loops 4 and 5. In particular, the feedback (Loop 4) between shrimp farming and crop production implies a reduction in crop production because a decline in income from crop production increases the possibility of adopting shrimp farming. An increase in shrimp farming decreases land availability for crop cultivation due to the conversion of rice fields into shrimp farms which causes a salinity rise in both rivers and soils. Moreover, an increase in shrimp farms depletes mangrove forests (Loop 5), which increases salinity, and in turn increases shrimp production in the coastal area. This feedback loop between shrimp farming and mangrove indicates the possibility of future mangrove depletion. However, the feedback loop between shrimp farming and mangrove also depicts a negative (balancing) feedback loop as the depletion of mangrove, reduces the fertility and suitability of shrimp cultivation. The feedback loop between shrimp farming and mangrove could be influenced by the positive feedback (Loop 6) between river water salinity and mangrove forest. Discussion with the expert participants during the workshop and literature review (World Bank 2016; Santini and Reef 2014; Manna et al., 2010) reveal that higher salinity in river water decreases mangrove forest which in turn increases the possibility of a higher river water salinity as the mangrove maintains the estuarine ecosystem by creating an optimum environment for the mixing of fresh and salt water.

In the case of feedback loop 7, an increase in shrimp production leads to increased income of shrimp farms (due to higher productivity, and price compared to rice), which in turn creates the possibility of investing more (e.g. purchase of more land, more labour, other inputs) on shrimp farming, hence ultimately increasing the production from shrimp farming. A similar description was provided by participants for the feedback loop (Loop 8) between fish production from ponds and income.

Table 2 depicts known biophysical thresholds. Although the threshold for rice depends on specific rice varieties, the physical process (e.g. germination, flowering) of rice production shows a detrimental effect under average temperatures below 20 °C and above 30 °C (Hamjah, 2014; BARC, 2012). However, a modern high-yield and salinity-tolerant rice variety such as BRRI dhan28 responds negatively to temperatures above 28 °C (BRRI, 2015). We have also identified 27 °C as the threshold temperature for rice production using generalized additive models (GAM) in our previous analysis (Hossain et al., 2017b). In addition, models predicted that rice yield will decline by ~18% and ~25% respectively for rising temperatures of 2 °C and 4 °C (Basak et al., 2012; Basak, 2010; Mahmud, 1998; Karim et al., 1996). Therefore, considering these thresholds of temperature for rice and the different growing seasons of different rice varieties (Sarkar et al., 2014; BBS, 2009), it would not be erroneous to assume a threshold for rice production at a mean temperature of ~28 °C and that there would be at least a 10% yield reduction of rice because of the changes in seasonal and annual temperature of 2 °C. Rainfall (1000-1200 mm per year) and soil salinity (2 dS m^{-1}) are also limiting factors for rice production. Although rice production decreases by ~10% for soil salinity greater than 2 dS m^{-1}, some of the modern rice varieties could resist soil salinity up to 4 dS m^{-1} (Mondal et al., 2001).

It was revealed during consultation with stakeholders that forest products in the mangrove forest are highly dependent on water availability from upstream and river salinity in south-west coastal Bangladesh. Islam (2011, 2008) has identified river salinity level ~40,000 dS m^{-1} as a threshold value for the Sundarban mangrove forest which also requires maintaining at least of 2000 m^3 s^{-1} water flow in the dry season, otherwise, the sustainability of mangrove forest may be jeopardized.

Despite decreasing fish production from rivers (Hossain et al., 2015), Bangladesh became one of the major (fifth largest) fish producing countries in the world in 2014 due to a transformation in fish production occurring in ponds (FAO, 2014). However, this progress in fish production from ponds may be limited by the rising temperature, reduced water availability and salinity rise. Experts from fisheries stated that the optimum temperature for some of the major produced and consumed fish such as Rohu (*Labeo Rohita*) and Catla (*Catla Catla*) is 27-29 °C, beyond which there is a detrimental effect on the physiology of the fish for egg hatching. Fish production reduces by at least 50% at a temperature of 32 °C and shows at least a 15% reduction when 29 °C is exceeded. However, some fish species, such as Tilapia, can tolerate a temperature range of 22-25 °C. A salinity level of 12 dS m^{-1} to 15 dS m^{-1} is the limit for fish production in ponds. Experts also reports that, at least ~1500 m^3 s^{-1} of water flow is required for fish production in rivers, otherwise the breeding ground and production of fish may be hampered. Stakeholders perceived that rising temperature and other consequences of environmental and climate change will favour shrimp farming in coastal Bangladesh. However, the field level data collected from Bangladesh Fisheries Research Institute (BFRI) show that there is an optimum water temperature (25-32 °C) and soil salinity (8-39 dS m^{-1}) for the production of shrimp. Experts and shrimp farmers have stated that above these threshold ranges, shrimp production declines by at least 50% because of virus outbreaks in shrimp farms.

4. **Discussion**

4.1. Conceptual system dynamics model and policy implications

Based on consultation with stakeholders, we have developed a conceptual system dynamics model (Figure 3) for the SES in the Bangladesh delta. We combined all the information from the causal loop diagrams (SI Figure 3 to Figure 5) developed by different stakeholders during FGDs and workshops in the study area.

The positive feedback loop between shrimp farming and crop production constitutes a trade-off between food security and unsustainable land use; as the increase in shrimp production reduces the land suitable for crop production. Similarly, higher profits from shrimp farms increase the possibility of further conversion of mangrove into shrimp farms (Azad et al., 2009). Such unsustainable conditions, coupled with the higher temperature and salinity due to climate change impacts (World Bank 2014, Szabo et al. 2015a), call for proactive adaptive strategies. Management strategies thus need to consider external controls on river discharges as they not only threaten the wild fisheries from rivers, but also increase mangrove depletion (Islam 2011), regional temperature (Adel 2002) and salinity (Hossain et al., 2015).

The threshold range and negative (balancing) feedbacks identified for shrimp farming negate the possibility of adopting shrimp farming as an alternative livelihood option in response to climate change. For example, depletion of mangrove forest due to salinity means the fertility and suitability of shrimp production may decrease in the long run.

Similarly, the threshold range of fish production from ponds, reduced water availability and salinity rise could limit the progress made in fish production from ponds in the future. In such a case, the interaction between the slow variables (e.g. temperature, rainfall, water availability) that shape and control the system resilience may lead to a gradual decline of resilience in the social and ecological systems (Hossain et al., 2017b; Zhang et al., 2015). In addition to the interactions in the SES, feedbacks identified in the SES may also cause a decline in resilience and raises the prospects of leading the SES towards a tipping point in the near future (CBD, 2010).

Evidence of the high dependency of human development (e.g. sanitation, education) on development aid and the dependency of crop production on subsidies indicate that the SES in the Bangladesh delta may be in a transition phase as it is adapting well (improvement in human wellbeing) to changes (worsening) in regulating services (e.g. climate, water quality) (Hossain et al., 2015; Renaud et al., 2013). Moreover, the nonlinearity (physical thresholds) identified for slow variables (e.g. temperature, salinity and water availability), interaction and feedback loops suggest that in the near future, the SES of this region, may transgress the safe operating space (point beyond which becomes dangerous to humanity), meaning the risk of unpredictable and damaging change to the SES will become too high for sustainable ecosystem management (Hossain et al., 2017a; IPCC 2013). Thus, it is essential to investigate how the social system will respond to changes in the ecological system.

4.2. Comparison and operationalization of social-ecological systems (SES) models

Previously developed models (Hossain et al., 2017b) used statistical approach (additive and logistic regression models) to develop a conceptual system model (SI Figure 7), which has been compared with the participatory system model developed in this study. The overall idea of comparing between the system models developed in this study and the previous (Hossain et al., 2017b) study is to identify the commonalities and differences between the two system models, which use two different approaches.

In summary, besides the interactions among variables (e.g. rainfall and crop production) in the two system models, commonalities are identified in terms of feedback loops, such as shrimp farming and salinity, temperature and river water flow. In case of non-linear relationships, the threshold temperature of ~ 28 °C for crop production reported by the stakeholders, and water salinity for forest production coincide with the observation through empirical analysis.

This study adds value to the knowledgebase for ecosystem management. For example, the influence of salinity and temperature on shrimp production up to a certain point negates the possibility of the previous assumption (e.g. Ahmed et al., 2015) of an increase in shrimp production due to climate change. The threshold temperature (water and air) and salinity level for fisheries and shrimp production reported by the stakeholders were not observed in the previous study (Hossain et al., 2017b), which used statistical analysis to identify threshold in SES. The dependency of fish production on temperature and salinity was excluded in the previously developed statistically based (Hossain et al., 2017b) conceptual model, which also excluded the influence of debt and market regulation on fish, subsidy on crop production and freshwater flow on honey production. This is because our previous work (Hossain et al. 2017b) depends on the statistical analysis of historical data, which provides the evidence of an aggregated view and what has already been experienced in the SES. In contrast, the participatory approach used in this study, adds value to other approaches, as stakeholders could provide new information based on perceptions, reconstructing knowledge and current experience, and as such is very useful in relatively data poor regions such as Bangladesh.

Besides comparing the two conceptual system models, we provide an overview of the results from the previous study (Hossain et al., 2017a), in which, SD modelling used an agriculture model developed by the stakeholders as a basis for system dynamics modelling, and was compared (SI Figure 8) against a time series (50 yrs.) of normalized crop production data. This validation based on a previous study (Hossain et al., 2017a) implies that a system model developed by stakeholders can be used as an input to simulate the changes in SES and managing the ecosystem in the Bangladesh delta. Though, based on the previous study, we have compared the full conceptual model (the present study) against the empirical study (Hossain et al., 2017a), and the agricultural conceptual model against historical behaviour using a system dynamics model (Hossain et al., 2017b), testing and validation of the full conceptual model using any modelling approach, is beyond the scope of this paper, and can be further improved by using the full conceptual model developed in this study as an input in system dynamics modelling.

This study attempts a qualitative operationalization of complexity science concepts using a participatory approach for managing a SES. Overall, this study contributes to the management of the ecosystem by; 1) increasing the understanding of the SES in the Bangladesh delta; 2) operationalizing qualitatively the sustainability science concepts such as tipping points and feedbacks in the real world SES; 3) collecting threshold information for the SES (shrimp, forestry and fishery); 4) modelling the SES in data-poor areas using a participatory approach instead of time consuming data collection and analysis. In addition, the use of participatory approach can serve the purpose of structural validation in SD modelling as the stakeholders are free to structure the process through an active participation without concerns about the parametrization and outputs of modelling (Leenhardt et al., 2017).

However, the wide range of stakeholders with diverse interests and knowledge can often be challenging (e.g. resolving conflict and seeking consensus) and time consuming in participatory modelling of a SES (Leenhardt et al., 2017). Though we experienced similar challenges (e.g. conflicts) in one workshop, the organization of a presentation for each group at the end of the group discussion and finalization of the conceptual system model based on the interactive discussion and feedbacks helped resolve conflicts and seek consensus in the workshop.

The level of challenge increases when operationalizing the conceptual system models using existing modelling approaches for policy implications. In particular, the lack of spatial components in system dynamics modelling limits the application of SD modelling in policy analysis (Hossain and Speranza Submitted). For example, shrimp is widely cultivated in this region, however, saline water shrimp is mostly cultivated around the Sundarbans mangrove forest. Therefore, the impacts of shrimp farming will not be homogenous across the regions and a model that excludes spatial heterogeneity, may mislead the policy at the region, in which (e.g. Barishal region) freshwater fish is mainly cultivated compared to shrimp farming.

The highly complicated modelling processes in the approaches such as agent-based and integrated modelling (Verburg et al., 2015) limits the model in capturing two-way feedbacks in SES, as well as validating and analysing the uncertainty of model structure and outputs (Kelly et al. 2013; Voinov and Shugart 2013). Ultimately, all these could reduce the acceptability of adopting this modelling approach in analysing policies for sustainable ecosystem management. In particular, the uncertain nature of the SES such as the possibility of both positive and negative feedback loops for shrimp farming and mangrove forest, indicates the level of challenges in capturing feedbacks and dealing with uncertainties while operationalizing the SES models for the sustainability of complex SES.

5. Conclusion

This study represents a regional scale qualitative operationalization of complexity science concepts and collection of thresholds data using stakeholder consultation for managing a SES. The identified interactions and feedbacks in the SES provide dynamicity in the system. In particular, the eight reinforcing loops identified subsequently intensifies an increasing or decreasing growth in a SES. The positive feedbacks loops (shrimp farming and mangrove forest, shrimp farming and crop production) imply that uncontrolled expansion of shrimp farms may reduce crop production and cause mangrove depletion, which can be accelerated by increasing trends in salinity and temperature due to climate change impacts in this region. However, the possibility of balancing feedback loop between mangrove and shrimp farming, may limit the growth of shrimp farming in the long run. Both the agriculture and fishery (shrimp and fish) systems are sensitive to 28/29 °C, beyond which production may decrease by at least 10%. Our conceptual system dynamics model implies that interactions and feedbacks may reduce the resilience of the SES and may lead it towards tipping points.

The findings from this study can be fed into system dynamic modelling as a structure validation approach (validation of assumptions, factors and their interrelationships within the system) to simulate the changes in a SES. The use of threshold data for biophysical and social conditions support ecosystem management by understanding when and how rapidly the system may cross the thresholds, which ultimately may help acting in time to avoid severe social-ecological impacts.

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Table 1 Feedback loops identified for the social-ecological systems (SES) in the Bangladesh delta. The factors marked with a star are also dependent on other external factors which are explained in the text.

Loop No.	Description	Balancing or reinforcing
1	Crop production → Gross domestic production (GDP) shared by agriculture* → Subsidy → Fertilizer and irrigation → Crop production	Reinforcing
2	Temperature → Water availability* → Temperature	Reinforcing
3	Shrimp farming → Soil salinity → Shrimp farming	Reinforcing
4	Shrimp farming → Land availability → Crop production → Income → Shrimp farming	Reinforcing
5	Shrimp farming → Mangrove forest → Shrimp farming	Reinforcing/ Balancing
6	River salinity → Mangrove forest → River salinity	Reinforcing
7	Shrimp farming → Income → Shrimp farming	Reinforcing
8	Fish production → Income → Fish production	Reinforcing

Table 2. Biophysical thresholds for four livelihood sources in the Bangladesh delta

Livelihood sources	Thresholds	Source
Agriculture	28 ^{0}C (Air temp) 4 dS m^{-1} (Soil salinity)	Stakeholders (This study) & Basak et al., 2012; Basak 2010; Mondal et al., 2001; Mahmud 1998; Karim et a., 1996
Forest (mangrove) product	~40,000 dS m^{-1} (Water salinity) 2,000 m^3 s^{-1} (Water flow) 25-28^o C , 35 ^{o} C (Air temp)	(Islam 2011 and Islam 2008) Nandy and Ghose (2001); Field (1995); Wong and Tam (1995)
Fisheries	27 ^{o}C to 29 ^{o}C (Water temp) 0-5 ppt (Soil salinity) ~1,500 m^3 s^{-1} (Water flow)	Stakeholders (This study)
Shrimp	25 ^{o}C – 32 ^{o}C (Water temp) 7.80-39 dS m^{-1} (Soil salinity)	Stakeholders (This study)

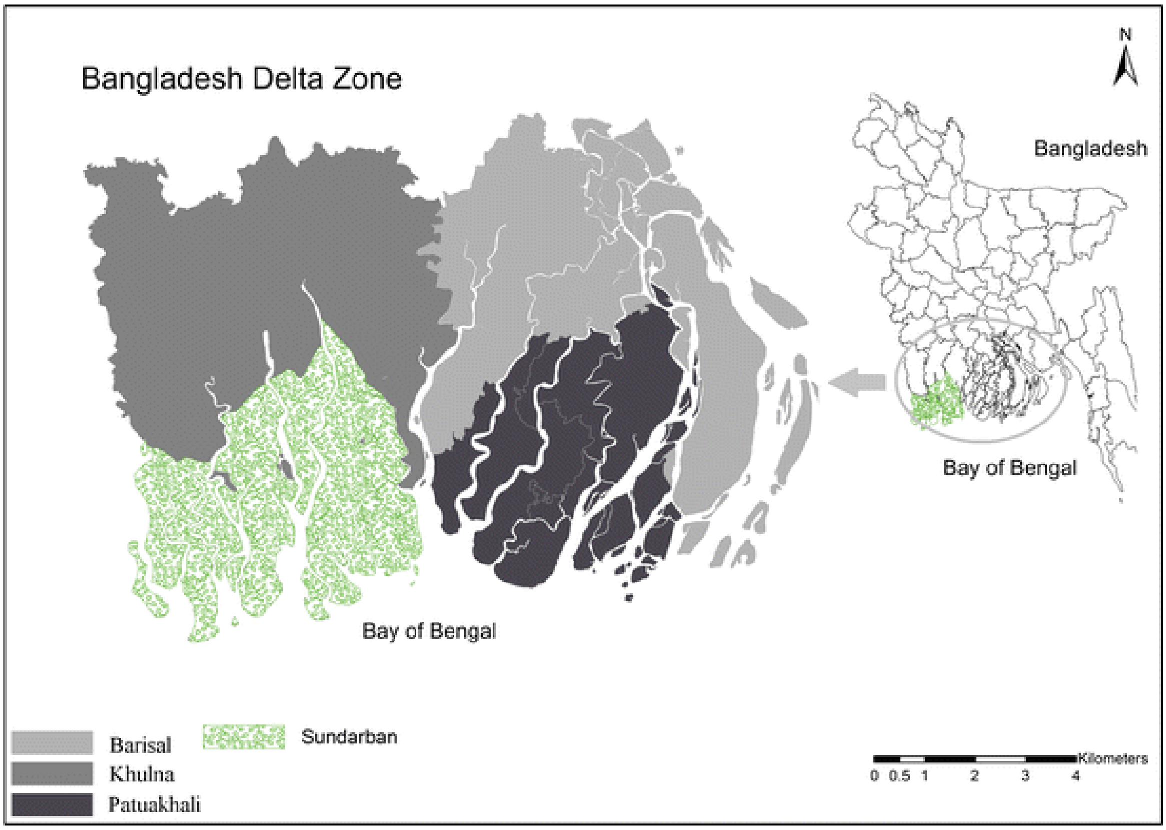

Figure 1 Study area showing location in Bangladesh (inset), the three greater districts and the Sundarbans.

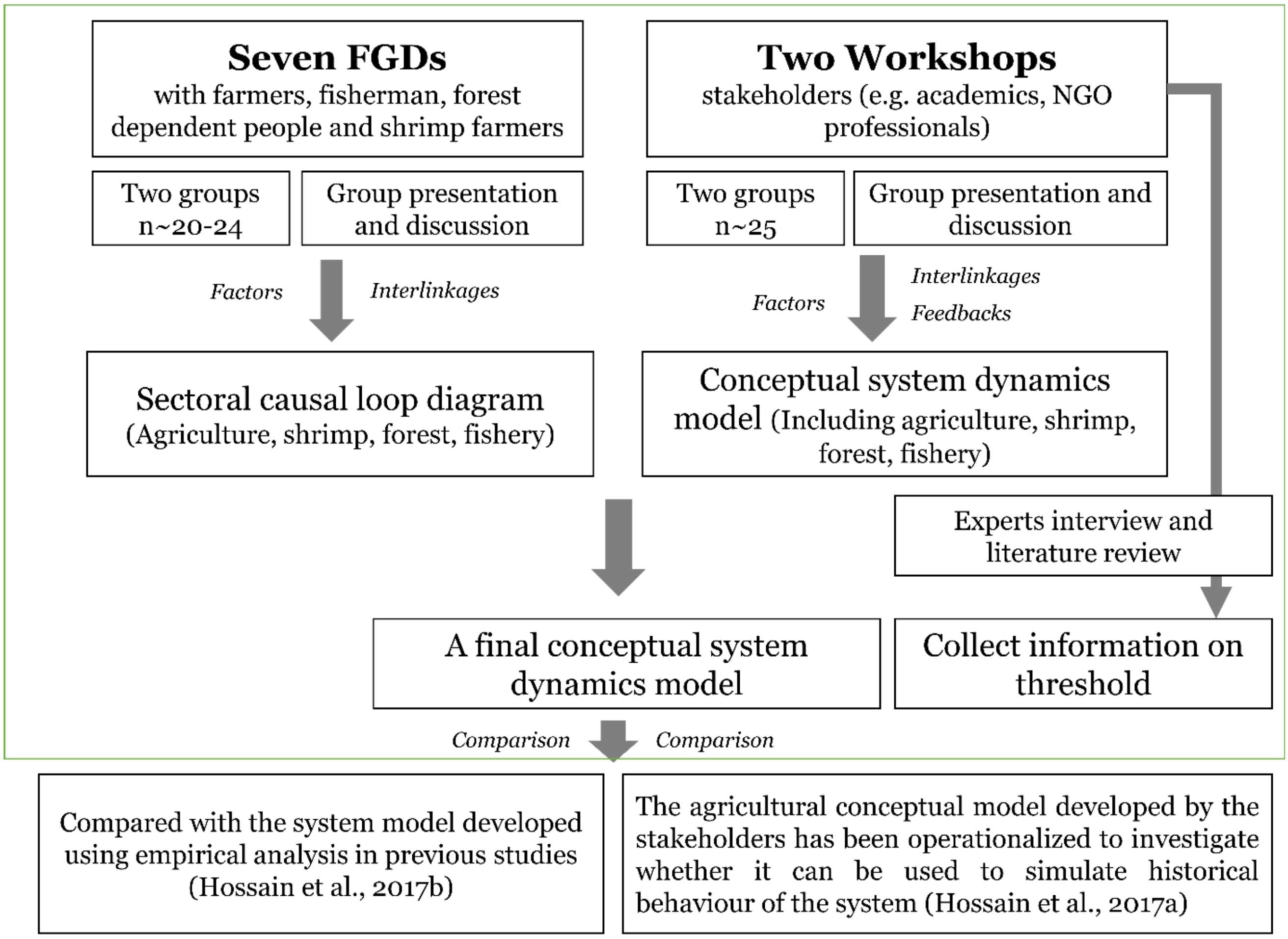

Figure 2 Flow diagram showing schematic methodology of the study. The green lines denote the contribution of this study and indicate how the previous studies are complemented by the findings of this study. (FGD: Focus Group Discussion and NGO: Non-Governmental Organisation)

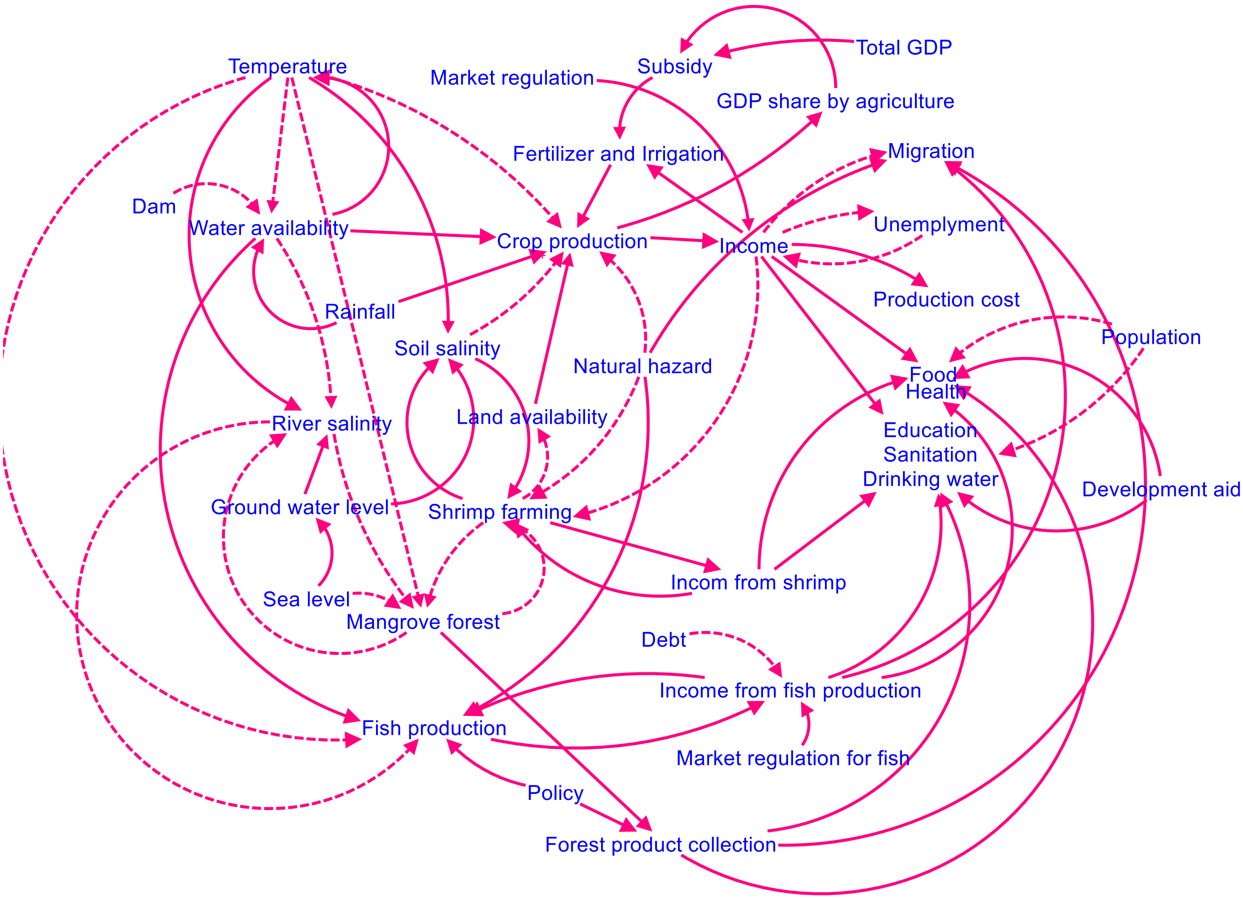

Figure 3. Conceptual system dynamics model for the social-ecological systems (SES) based on stakeholder's consultation in the Bangladesh delta. We combined the information from focus group discussion (FGDs) with farmers, fishermen, shrimp farmers and forest people, as well as the experts' consultation in workshops. The solid lines and dots line depict the positive (+) and negative (−) relationships between the variables. (GDP: Gross Domestic Products)