System dynamics across three scales in the Brahmaputra River Basin- Exploring a Himalayan social-hydrological system

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Abstract

The Brahmaputra River Basin (BRB) in the Himalayan landscape has seen a range of issues at multiple scales related to water sharing and dams, political mobilizations related to ethnic identity and sovereignty, flood and riverbank erosion, and population displacement. Current disciplinary knowledge fails to explain persistent policy paradoxes such as the continuation of embankment breaches while the river channel may be stabilizing as well as sudden shifts in problem situations, from annual floods to landlessness. This study uses system dynamics to integrate existing knowledge of river basin hydro-geomorphology and flood protection policy in the State of Assam in India, with issues experienced by a riparian tribal community in the upstream part of the Assam Valley. Simulation analysis indicates the role of feedback relationships between local governance issues and flood control effectiveness and also illustrates a need for studies integrating the dynamics of land along with flows of water and sediment in river channels. Model testing also illustrates the importance of policy alternatives at different scales: i.e., farm-level changes to cropping pattern, integration of land use and land tenure in sub-national disaster management, and basin-scale zoning and culturally acceptable relocation of people.

Introduction

South Asia is incomparable, in terms of availability of water, given the flows of the Indus, Ganga, and Brahmaputra; contributed by the annual monsoon rains and the vast reserves of fresh water in the snow and glaciers of the Hindu Kush-Karakoram- Himalaya (HKH). The annual run-off of one of the most important interlinked basin systems of the region, that is, Ganga-Brahmaputra-Meghna is around 1,150 billion cubic metres (bcm). The water availability in this interlinked system alone, considering only the surface water, is 3 times the water availability for the world (Biswas 2008; Bandopadhyay and Ghosh 2009). However, the entire region suffers from “too much or too little water” given its abundance during the monsoons but scarcity in dry seasons (Wirsing 2008). The management of these major river systems is crucial for provisioning water, energy, and food to the current growing population (projected to reach 2.3 billion by 2050) and also securing crucial ecosystem services to meet the needs of future generations and improve the ecologic health of the rivers (Rasul 2015). At the same time, such management is a complex governance issue due to varying national and sub-national interests, multiple policy priorities and institutional frameworks along with issues of fit between environmental and hydrological processes and epistemic boundaries (e.g., engineering, ecology, and economics) (Biswas 2008; Bandopadhyay 2009; Varma and Mishra 2017; Feng et al., 2019; Varma and Hazarika, 2019; Vij et al; 2020).

Half of the water available in the Ganges-Brahmaputra-Meghna interlinked basin comes from the Brahmaputra which originates from the Chemayungdung glacier in the Tibet Autonomous Region (5300 m elevation) (Pradhan et al.,2021). The Brahmaputra Basin (BRB) has a total population of more than 80 million people, unevenly distributed among the riparian nations with the highest density in the lowest riparian country of Bangladesh, followed by India and then Bhutan, and the least is in the uppermost riparian in the Tibet Autonomous Region (Goswami 2008). In India, the catchment of the Brahmaputra and its tributaries covers the seven States of the Indian polity's North East Region (NER) (i.e. Assam, Arunachal Pradesh, Meghalaya, Mizoram, Manipur, Tripura and Sikkim) along with the northern parts of West Bengal (Goswami, 2008; Das et al. 2014). It is home to around 200 of the 350 ethnic communities of the NER, each of which has its own culture and history which do not always fit well with the political boundaries within the NER (Goswami 2008).

Recent reviews indicate the need for understanding the relationships between basin hydrology, geomorphology, polity and communities at different spatial, temporal and conceptual scales using multiple disciplines and worldviews. There is a dearth of such social-hydrological studies for the region while the persistence of data gaps increases uncertainty for policymakers and enhances mistrust among stakeholders at sub-national, national and transboundary levels (Pradhan et al., 2021; Pandey et al., 2020).

Framing flood and erosion issues in the BRB as a social-hydrological system

The Brahmaputra River accounts for almost 29% of all surface water in India, 44% of India's hydropower potential, and is one of the sources of tension between India and China (Pandey et al., 2020). The BRB has seen a range of complex contestations at the transboundary, national, and sub-national levels over issues related to water sharing and hydropower dams, political mobilizations related to issues of ethnic identity and sovereignty, flood and riverbank erosion, failure of flood control, and population displacement and out-migration (Goswami 2003; Gohain 2008; Das et al. 2009; Hazarika 2009; Lahiri and Borgohain 2011; Baruah 2012; Varma and Mishra 2017; Varma and Hazarika, 2019). The State of Assam within the Indian NER region of the BRB faces the worst impact of flood and bank erosion. Riverbank erosion is a persistent issue due to the dynamic shifting of multiple channels of the river (i.e. braided and anastomosing), unconsolidated sand and mud deposits on the agricultural lands of the floodplain as a result of high overbank sediment discharge and embankment failures. Approximately 83% of the course of the Brahmaputra in Assam is braided, where the flow of the river is divided into several channels at low flow, separated by sand bars (locally called chars). During the 1954–2011 period, 17 out of 34 districts (administrative sub-units) of Assam lost nearly 7% of their land area due to riverbank erosion. This amounts to around 80 square km of land (valued at USD 20 million) lost every year. Such floods and erosion lead to landlessness and socio-economic issues among riparian communities, and the rate of displacement from these areas stands at around 10,000 families annually (Pradhan et al., 2021; Sarma and Acharjee, 2018; Das et al, 2014;).

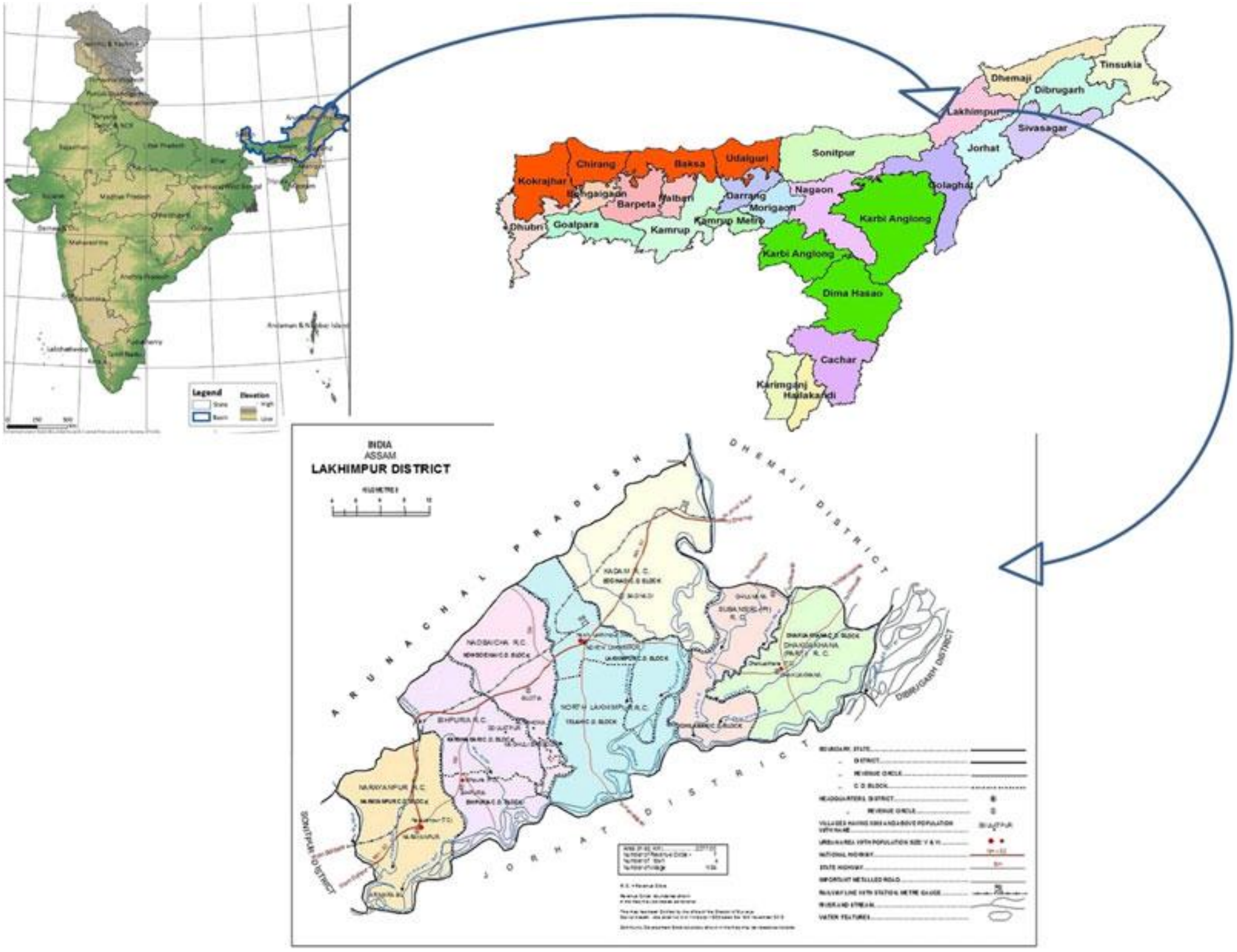
Disaster and governance issues surrounding the BRB have often been framed as problems of the dynamics of basin-level hydro-geomorphology, the evolution of different political-economy regimes (colonial, post-colonial to neo-liberal) influencing policy interventions for extraction of resources from the agro-ecosystems of the basin, and politics of identity and space within and among diverse communities of NER and Indian polity (Varma and Hazarika, 2019; Varma and Mishra, 2017; Varma, 2016). Each of these framings has tried to capture the interplay of factors at scales characteristic of their disciplinary domains (Varma, 2016). The hydro-geomorphology frame draws from the discipline of earth science and hydrology while explaining the changes in flow pattern in different reaches of the river basin and dynamics of sediment transport in different time periods (Goswami and Das, 2003; Sarma, 2005; Goswami, 2008). The political-economy framework, drawing from the disciplines of history, political science and economics, explains the different interventions in the Brahmaputra basin as influenced by the evolution of different resource appropriation regimes from pre-colonial to postcolonial times (Das and Saikia, 2011; Saikia, 2012; Saikia, 2014). Finally, the discipline of political science has been used to explain the defining of political space for the sub-basin and the resulting struggle for identities among ethnic communities (Phukon and Dutta, 1997). Varma and Mishra (2017) and Varma and Hazarika (2019) explain that such studies have helped in understanding the evolution of the flood and social issues in the basin. However, policy paradoxes such as the continuation of flood damage and land loss, allegations of disaster mismanagement in political debates and the popular media, despite new flood and erosion management institutions and external funding need more exploration.

Some studies have also attempted to understand the complexity across the phenomena of basin characteristics, flood control and community vulnerability using a range of participatory techniques from group modelling to participatory scenario building. Such studies have indicated a lock-in of engineering solutions such as embankments, adaptation deficit among communities amidst new risks and hazard situations, and the role of power and social learning to navigate change (Varma et al 2015; Tschakert et al 2016; Varma and Mishra 2017; Vij et al 2020). However, there is still a lack of exploration of what could be this ‘change’; i.e., a vision for governance and the disaster management policies required to achieve the desired change? This notion of ‘desired change’ itself illustrates the challenge of plurality in society; i.e., the existence of multiple experiences and ideas of change. It is crucial to explore narratives of the problem situation to identify stakeholders, discourses, networks and the role of their interaction in shaping policy interventions or lack thereof; i.e., understanding aspects of power in a society in which the need for change is identified and ‘desired change’ is defined for a particular problem situation (Hoekstra et al., 2018; Mao et al., 2017; Varma and Mishra, 2017; Varma et al., 2015). This gives us an opportunity to use a social-hydrological resilience framework that blends socio-hydrology, social-ecological systems and system dynamics approaches. Resilience here is explained as the capacity of the social/hydrological sub-system or the coupled social-hydrological system to absorb disturbance, adapt, or transform to a different system in response to hazards such that services can flow from the hydrological to the social sub-system (Mao et al., 2017).

Years of understanding and managing river basins through reductionist schemas, through for example government departments of water resources, land revenue and others, as well as form the perspectives of disciplinary expertise such as engineering and ecology have led to consequences often hydrologically and ecologically undesirable but also socially unacceptable. Much mismanagement and misdiagnosis likely arise from ignorance of multi-and-cross scale linkages; e.g., delayed impacts of upstream land-use change on downstream water and sediment discharge or alteration of the fertility of farmlands as embankments control the spread of nutrient-rich floodwaters to flood plains (Pradhan et al., 2021; Pandey et al., 2020, Sendzimir et al.,2018; Cash, 2006). The Panarchy framework from social-ecological systems (Holling et al. .2014) provides a conceptual lens to explore cross-scales interactions whereby a Meso scale can be influenced by the slow-moving processes (*Remember*) at a macro scale but also the fast-moving processes at a micro scale (*Revolt*).

Therefore, exploring narratives of a problem situation is a first step that has to be followed by the application of system dynamics. Such a methodology can integrate the knowledge from multiple sources, identify the complexity within and across different scales of the social-hydrological system, explore dynamics in the behaviour of the system as certain processes change at any of the system scales, and finally provide policy insights for managing resilience (Jose and Kopainsky, 2020; Sendzimir et al., 2018; Mao et al., 2017; Sendzimir et al., 2011). Following the Panarchy framework, this study organizes existing knowledge, from literature, expert interviews, fieldwork and group modelling exercises (Varma et al., 2015) focused on flood and riverbank erosion issues in the BRB, into three distinct scales: Basin hydro-geomorphology (Macro), Flood control policy within the Assam State jurisdiction (Meso), and the socio-economic situation of the *Mising* tribe in the north bank villages in the upper Assam Valley (Micro). It further explores the system dynamics within and across the three scales to understand the shift in problem from one of the annual floods to landlessness. Finally, it analyses the system dynamics model for policy leverage points and discusses ways forward for public policy in the BRB.

Figure 1- Dhakuakhana subdivision within the Lakhimpur District, State of Assam in India. Lakhimpur District is geographically located on the North bank in the upper Assam Valley and the cluster of villages with extreme land loss are within its Dhakuakhana sub-division.



Source – Varma and Mishra, 2017

Methods

The issue of flood and channel widening in the BRB may stabilize according to the theory of the Least Action Principle as well as preliminary data from upstream (see Figure 10). However, land loss persists on the North bank. The policy intervention has shifted from flood protection with earthen embankments to riverbank protection with geotextile embankments due to continuous breaches (see Figure 4 for breaches near the cluster of villages in Dhakuakhana sub-division of Lakhimpur District) as a result of flood and bank erosion and also elsewhere in the BRB. But, discontent continues among the *Mising* community due to landlessness and little scope for livelihoods. Due to a lack of alternatives, there is a massive migration of young men from these villages leaving behind women and the elderly and thus increasing vulnerability to future hazards (Varma and Mishra 2017). This creates the need for exploration of the problem within and across the scales of the BRB and virtual experimentation for policy alternatives.

The next section applies system dynamics, adapting the five steps of Sterman (2018) into the following three stages:

Conceptualization: This stage focuses on the trend of the problem, referred to as reference mode, and identifying the system structure responsible for the situation. Causal Loop Diagrams (CLDs) are used to explore the three scales of the BRB social-hydrological system which is transformed into a Stock and Flow Diagram (SFD) using Vensim software of Ventana systems. Simulation is performed and simulated behaviour is validated against theory and historical trend.

- **Analysis:** This stage involves analysis of the simulation results and conducting a scenario exercise to understand the evolution of the problem, impact of plausible changes and policy leverages. The scenario exercise will be achieved by parametric sensitivity tests.

- **Policy Testing:** This stage will test policy alternatives and gain insights into the management of resilience in the BRB.

The operationalization and results of the three stages are explained in the next section.

Application of system dynamics

Conceptualization

This sub-section explores linkages between existing bodies of knowledge around the issue of flood and riverbank erosion in the study area where braiding and anabranching in the Brahmaputra river are most significant (Figure 2), considering the impact of the current policy response based on flood embankments (Figure 3), and the emergence and persistence of landlessness is a serious problem (Figure 4). Figure 5 illustrates the cross-scale linkages within the BRB social-hydrological system influencing the shift of the problem from floods to land loss. Figure 6 identifies the stock and flow structure used for simulation and Figures 7 and 8 illustrate aspects of model validation. Figure 7 provides a comparison between the trend of key variables of the problem i.e. width of the river channel and high flood level in the upper Assam Valley and events of embankment breaches in the villages of Dhakuakhana sub-division of Lakhimpur district of North bank of the Valley (also see Reference mode in Annex 1) and simulation results. Figure 8 provides results of extreme condition indirect test with selected parameters. A detailed conceptualization of the three scales of the BRB, transformation of the summary Causal loop Diagram (Figure 5) to Stock and Flow Diagram (Figure 6) and model validation is presented below.

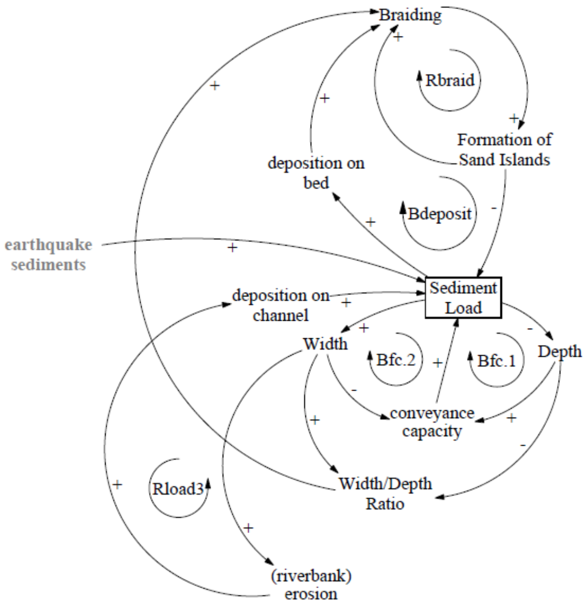
Basin hydro-geomorphology: Dynamics within the Least Action Principle

Pre-1950, the Brahmaputra river was believed to be in a condition of minimal change based on topographic data as well as testimonial narratives from villagers. Based on the Least Action Principle (LAP) (Nanson & Huang, 2018), it is inferred that the river was in an optimal state of maximum flow efficiency (MFE) where minimum energy was expended to move sediment in the river bed and changes in the physical form of the river were at a minimum.

The Great Earthquake in 1950 has deviated the river from this state. There is a shift in width/depth ratio where the huge increase in sediment load from the landslides triggered by the earthquake has caused channel bed aggradation (decrease in depth) and rapid channel widening (increase in width), manifested in the form of channel braiding. The variable of width/depth ratio is representative of the input of sediment, and ultimately, a measurement of the change in the state of the river.

In more recent contexts, it is reported that High Flood Levels are starting to level off after 1996. It can be inferred that channel depth is reaching a steady state. Also, the braiding index, which had on average been increasing, begun to plateau from about 2010 reflecting how the channel width is levelling off as well. Following LAP, it can be safe to assume that the rate of change of the Brahmaputra River channel may decrease and current observations also point out that the river may continue to move towards a new state of minimum change. However, this viewpoint discounts the future uncertainties of earthquakes and climate change and is illustrated in the CLD in Figure 2.

Figure 2- CLD of basin hydro-geomorphology

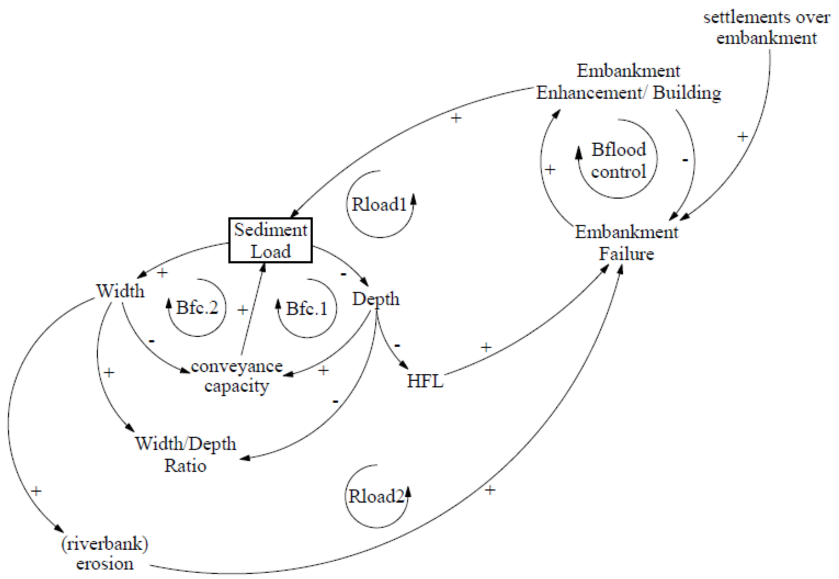


Policy response in Assam: Lock-in of flood control

The policy response in Assam seems to be in a "technological lock-in" and there is policy inertia and resistance to look beyond embankments to find major new initiatives (Wasson et al., 2020). The Assam Embankment and Drainage Act was initiated in 1954 and the State policy still relies heavily on embankments as the dominant solution for flood control. The initial building of 885km of embankments as a response to the 1954 flood triggered the over-reliance on this technical solution. This involves a cyclical behavioural trend whereby the increasing extent of adoption of embankments increases the attractiveness of the solution and subsequently causes further adoption. This provides a theoretical explanation to show how Assam has been confined to this technological frame for about 55 years even when its utility is questionable (Wasson et al., 2020).

The role of embankments for flood control is also questionable worldwide due to the phenomenon known as the 'levee effect' which has been studied in the context of socio-hydrology (Baldassarre et al., 2015) whereby levees (embankments) breed complacency and actually increase risk. Embankments also slow down fine and coarse sediment reaching the flood plain that may increase bed aggradation leading to higher flood levels. In the town of Dibrugarh on the South bank or in the villages of Lakhimpur District on the North bank, embankments are common but they suffer severe flood damage every year. Maintenance and raising of embankments continue (see Figure 3) while breaches due to floods and/or riverbank erosion and channel relocation happen every year. In addition, many embankments become spaces of refuge as floods and bank erosion continue which puts additional pressure on this infrastructure (Varma and Mishra, 2017).

Figure 3- CLD of policy response in Assam



Landlessness and discontent among Mising community: Socio-economic situation of villages in North bank of upstream Assam Valley

The culture of the *Misings*, a riparian tribe of the North bank villages, with shifting cultivation and settlements, was one of adaptation with annual floods involving movement between cultivated areas and stilt houses designed for floods. However, a colonial land revenue system, population increase, and post-independence protection by embankments facilitated a switch to more settled agriculture and prosperity. Household incomes and land availability are both declining as a result of land loss due to riverbank erosion, government acquisition for building embankments closer to villages as branches of the river channel move away from the main channel, and finally from coarse sediment deposition after the recession of flood waters. In the absence of formal communication from government sources, many villagers still hope for compensation for land lost by bank erosion. In reality, there is no scope for such compensation as riverbank erosion is not recognized as a disaster in Indian disaster management policies. However, there exists an opportunity to claim compensation for land acquired by the government to re-build embankments after breaches (Varma and Mishra, 2017; Varma, 2016).

A cultural inhibition to pay land revenue, owing to a pre-colonial legacy of riverbank spaces being regarded as "waste-lands", has led to a lack of individual landholdings among the tribe. This situation questions the validity of compensation claims for the land acquired by the government for embankment maintenance work. This uncertainty around claims and lack of formal communication about the non-disaster status of riverbank erosion drives a narrative of irregularity in the payment of compensation among the villagers. Even if land is provided for resettlement in a different area of the same or opposite bank, there is an inhibition to move to a new area as either the land does not suffice for the joint family culture of the *Mising* households or there are perceived risks of moving to a non-tribal area. The discontent due to persistence of landlessness, ineffective embankment maintenance and its contribution to land loss, lack of compensation and lack of livelihood opportunities are leading to protests in villages. Such protests in turn delay the maintenance and re-construction activities of the flood control infrastructures (see Figure 4).

Figure 4- CLD of landlessness and discontent among *Mising* tribe

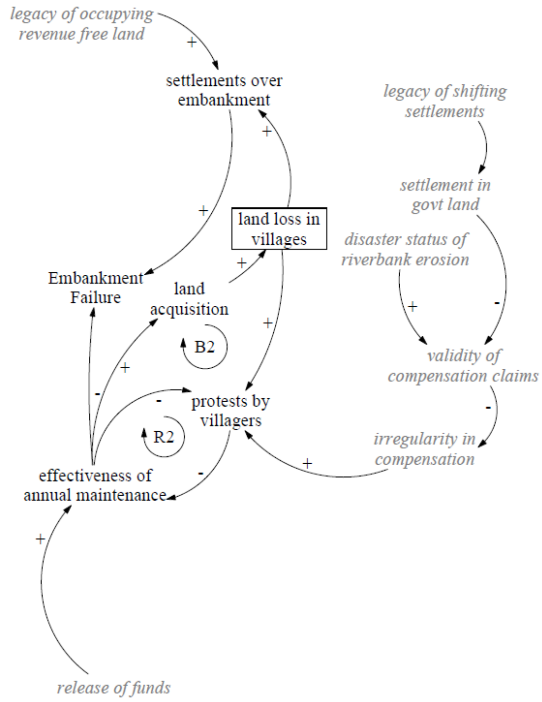


Figure 5 – CLD exploring cause-effect-feedback relations within the BRB driving a shift from flood to land loss problems in villages on the North bank in the upstream Assam Valley. Please see the explanation of feedback loops in Table 1.

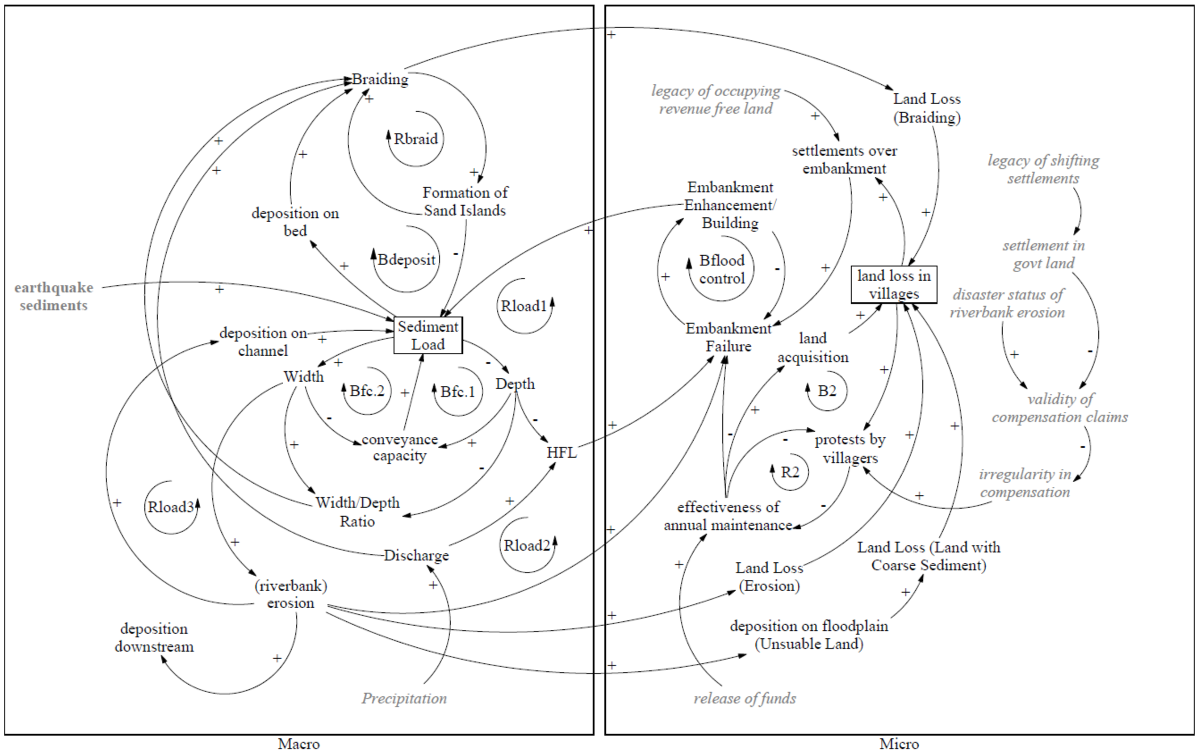


Table 1- Feedback Loops explaining the structure of the CLD

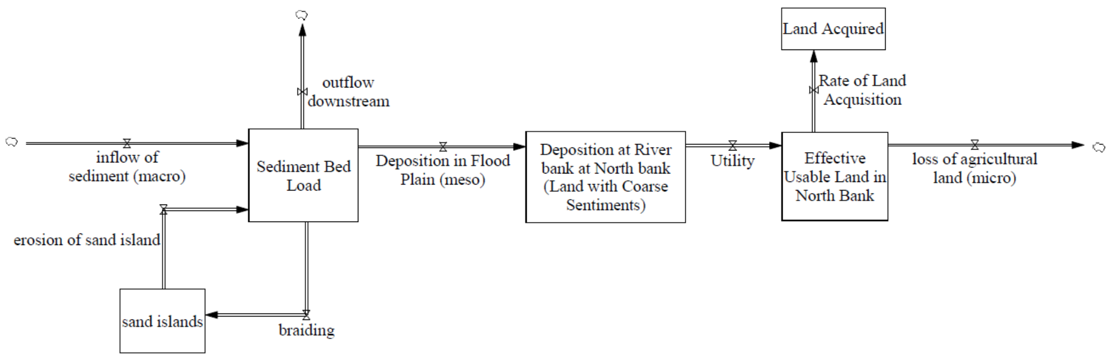
Macro-Scale Loops (Basin Hydro-Geomorphology)			
Action	Loop	Type	Process
W/D Morphology	Bfc.1	Balancing	**Sediment Load -> Depth -> Conveyance Capacity -> Sediment Load** The increase in sediment load causes aggradation of the channel bed (a decrease in depth). This directly decreases the flushing capacity of the channel. Based on LAP/MPE, the river will work against this to decrease the sediment load.
	Bfc.2	Balancing	**Sediment Load -> Width -> Conveyance Capacity -> Sediment Load** The increase in sediment load causes widening of the channel (an increase in width). This directly decreases the flushing capacity of the channel. Based on LAP/MPE, the river will work against this to decrease the sediment load.
	Rload3	Reinforcing	**Sediment Load-> Width -> Riverbank Erosion -> Deposition on Channel -> Sediment Load** The increase in sediment load causes a widening of the river which then causes extensive riverbank erosion. Eroded sediments are deposited on either floodplains, downstream or on the channel. The deposition in the channel will add to the sediment load.
Braiding	Bdeposit	Balancing	**Sediment Load -> Deposition on bed -> Braiding -> Formation of Sand Islands -> Sediment Load**

			The increase in sediment load causes a situation where the channel input is higher than the discharge. This results in a decrease in the rate of flow, and sediments tend to get deposited on the bed. This causes channel braiding which increases the formation of sand islands and decreases the sediment load slowly.
	Rbraid	Reinforcing	**Braiding -> Formation of Sand Island -> Braiding** This describes the braiding process where braiding gives rise to the formation of Sand Islands which then causes more braiding.
Meso-Scale Loops (Policy Response)			
	Rload1	Reinforcing	**Height&Number of Embankments -> Sediment Load -> Depth -> HFL -> Embankment Breaches -> Height&Number of Embankments** The establishment of embankments for flood control is counterproductive. Flood embankments slow down the fine sediment reaching the flood plain (Rload1). This effectively increases the sediment load in the channel. Bed aggradation will occur (decrease in-depth), and as a result, HFL increases. Finally, the embankment breaches are more common, which is then responded to with more flood embankments and more breaches.
	Rload2	Reinforcing	**Sediment Load-> Width -> Riverbank Erosion -> Embankment Breaches -> Height&Number of Embankments -> Sediment Load** In addition, Riverbank erosion also adds to the problem by adding to the vulnerability of embankments. This will likewise result in more embankments being created which, as explained above, will effectively increase the sediment load in the channel.
	Bfloodcontrol	Balancing	**Embankment Breaches -> Height&Number of Embankments -> Embankment Breach** This illustrates the technological lock-in where embankment breaches are responded to by building more embankments.
Micro-Scale Loops (Socio-Economic Situation of Villages)			
Village Disruptions	R2	Reinforcing	**Effectiveness of Annual Maintenance -> Protest by Villagers -> Effectiveness of Annual Maintenance** With the delays and the decrease in funding, the progress of maintenance is further obstructed, causing sentiments toward the government to worsen. The resultant protests disrupt annual maintenance. The politically modulated limitations on annual maintenance will be exacerbated by the cyclical trend of villagers putting pressure on government bodies for their incompetence.

	B2	Reinforcing	**Land loss in villages -> Protests by Villagers -> Effectiveness of Annual Maintenance -> Land Acquisition -> Land loss in villages** Land loss accompanied by the irregularity in governmental compensations drives village dissatisfaction. Protests are carried out which hinders the annual maintenance of embankments through delays. The land acquisition process during annual maintenance is delayed and the villagers get to keep their land. This hinders progress in annual maintenance, causing difficulty for the government to pursue solutions. This demonstrates the inflexibility of the villagers adapting to formal interventions.

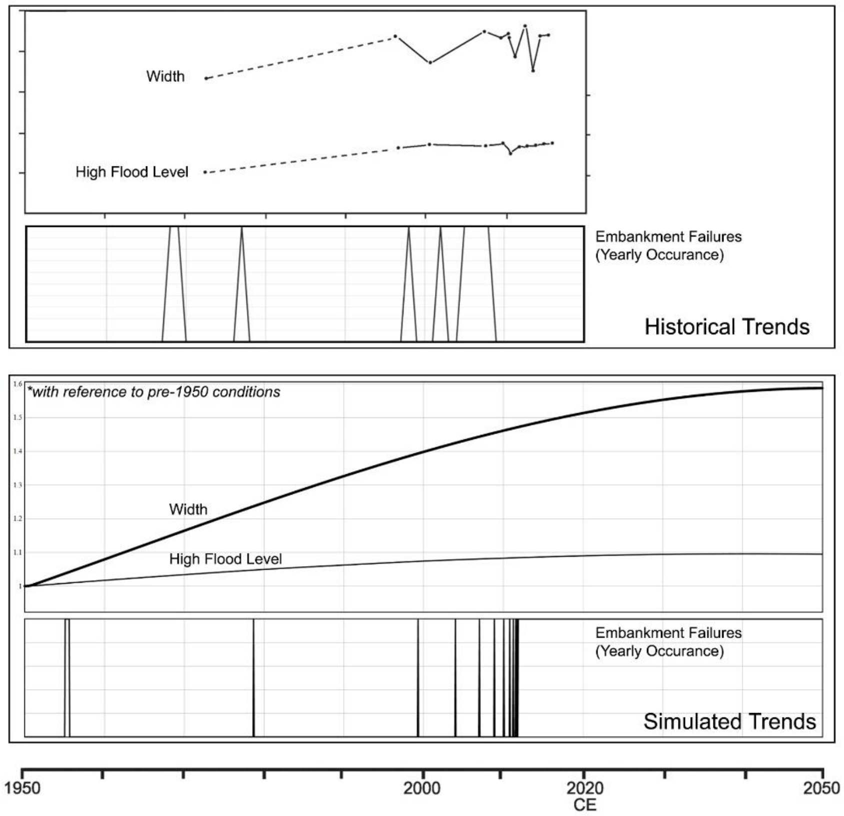
The Stock and Flow diagram in Figure 6 offers a bird's eye view of the subsystems across the scales. It illustrates the main stock and flow stem of the model (please see Appendix 2 for a detailed description of the simulation model using this structure) i.e. Inflow of sediment (macro) > sediment bedload > deposition in flood plain (meso) > Land in North bank villages > loss of agricultural land (micro). The figure also illustrates that tracking the sediment movement from Basin to Valley to Villages provides an entry point to explore the cross-scale relationships within a social-hydrological system such as the BRB in the Himalayan landscape.

Figure 6- Transforming CLD (figure 5) into Stock and Flow Diagram. For a detailed description please see Appendix 2.



The width and High flood level trends in Figure 7 are from ongoing research at Dibrugarh University, Assam, to triangulate information from GIS-based surveys and actual measurements. Though the trends are preliminary findings and there is a need for more empirical research for validation, it is safe to assume that the trends concur with the LPA theory. The embankment breach incidents are from the area of the village cluster on the North bank (See Map for Dhakuakhana subdivision within Assam), as published in Varma and Mishra (2017) and also recorded by the Government of Assam. Historical data from 1970 to 2016 highlights the behavioural changes in the river channel from the great earthquake in 1950. The system dynamics model is simulated for another 40 years to experiment with three scenarios and analyse the changes. The goal-seeking behaviour of width and high flood level (which can also be used as a proxy for channel depth) in the simulation complies with the LPA theory whereas the frequency of embankment breaches tallies with the actual cases of breach.

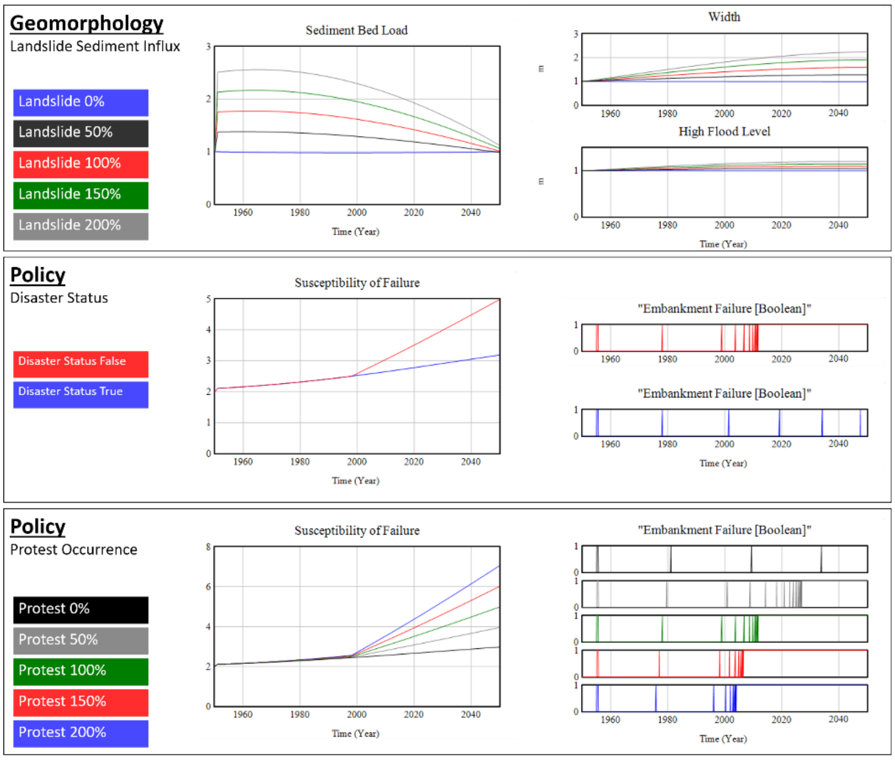
Figure 7 – Comparison with historical trends of river channel width, high flood level in the Dibrugarh area of Assam (upper Assam Valley) and embankment breach incidents in the North bank villages of the same upstream region of the Valley.



Figures 5 and 6 indicate that the approach used in this research i.e. integrating logic and narratives of the problem situation using system dynamics can be useful as a transdisciplinary framework for understanding multi-and cross scale dynamics in any Himalayan river basin context. The conceptual relationships in each of the three scales of the model structure (see sections explaining Figure 2 to 4) are from established theory and empirical work in which the authors participated. The application of system dynamics (see Appendix 2 for a detailed explanation of equations and parameters used, and also evidence of dimensional consistency) to explore the plausible cross-scale linkages provides a novel perspective to science and policy in the Himalayan region. In many such data-scarce as well as ambiguous problem situations of South Asia, this framework can be applied to guide policy dialogue.

Beyond the visual comparison of the historical, theoretical and simulation trends (Figure 7), Figure 8 provides results of the extreme condition tests and Figure 9 illustrates simulation behaviour with changes in time steps used for simulation as part of structure-oriented behaviour tests for model validation (Barlas, 1996).

Figure 8- Extreme condition tests explore extreme values of important parameters and evaluate if the model continues to exhibit behaviour that is anticipated.

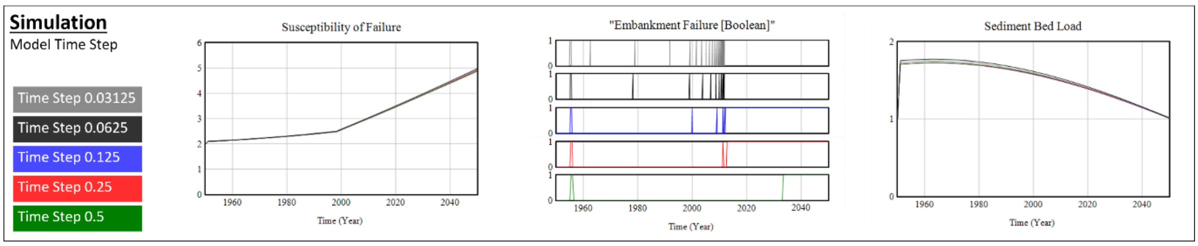


One geomorphological and two policy parameters - (1) landslide sediment influx, (2) disaster status and (3) protest were tested for extreme values (Figure 8 and 9). They were chosen because of their structural influence on the real system context in their respective scales.

1) Landslide sediment influx was tested to evaluate the robustness of the geomorphological system. Even with extreme values, the self-organizing behaviour of the geomorphological system (characterized by B.fc1 and B.fc2 in Table 1) is retained, as illustrated from the goal-seeking behaviour of *sediment bed load*, *width*, and *high flood level*.

2,3) Disaster status and protest occurrence was tested to evaluate the indirect link between the policy system and the village system. It exhibits an anticipated behaviour where the influence on the crucial variables such as *susceptibility of failure* and *embankment failures* are confined to scale changes and not behavioural changes.

Figure 9 – Time step test explores variation in the simulation time steps and understands how it will affect the modelled system.



Various possible values of simulation time steps were tested. As indicated in Figure 9, the majority of crucial variables of various scales in the system experience little to no changes. The only observed change lies in embankment *failure* which simulates discrete data – this is expected since time steps would alter the underlying function of this variable. This is unimportant as the variable functions to illustrate the occurrences of embankment failure but the crucial underlying quantities of this simulation *susceptibility of failure* and *rate of maintenance* stays largely the same.

Analysis

This sub-section presents findings from an analysis of simulation results and scenario testing which provide insights relevant for flood disaster management policy in Assam and the BRB. Policy design might have to look beyond basin-scale hydro-geomorphology and also integrate village-scale human dimensions for effectiveness. Moreover, beyond flows of water and sediment in the river channel, land in the riparian zone needs to receive more focus for policy design. The findings are explained in detail in the following paragraphs.

Influence of cross-scale linkage: Impact of village-level dynamics on embankment effectiveness

As illustrated by feedback loops R2 and B2 of the CLDs in Figures 4 and 5, the village-scale events influence the effectiveness of embankments i.e. the number of breach events. We test this further (see Annex 2 for details) to investigate the extent to which embankment breaches are influenced by actions in villages. After minimizing the 'effect of protests by villagers' by 80%, the difference in breaching occurrences is stark. As shown by the blue line in Figure 10, the breach events remain but their frequency decreases post-1998. Thus, the effectiveness of embankment policy is disrupted by actions in villages. Such an increase of embankment breaches post-1998 can be due to an increase in protests owing to discontent driven by the narrative of irregularity of compensation for land loss (see Figure 11).

Figure 10- Simulated impact of fewer village-level protests on embankment breaches

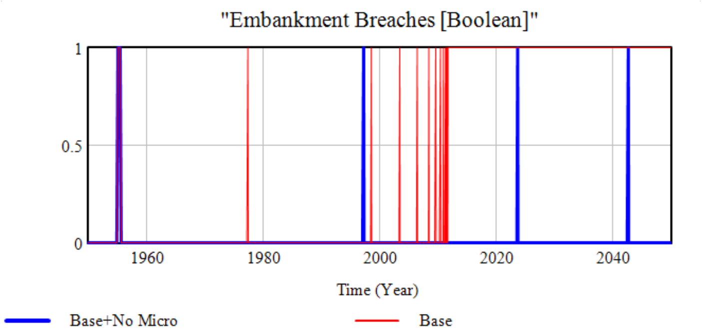
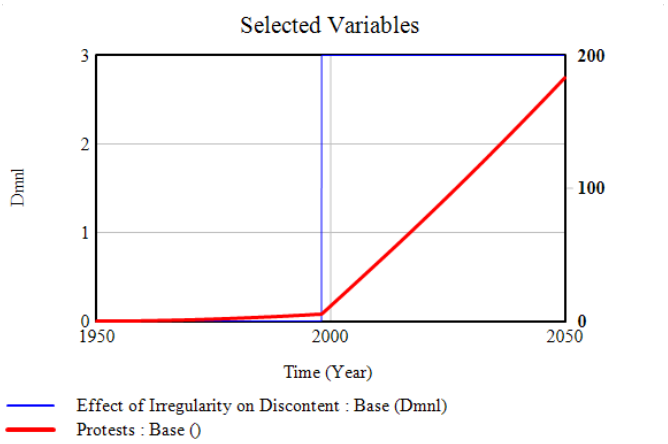


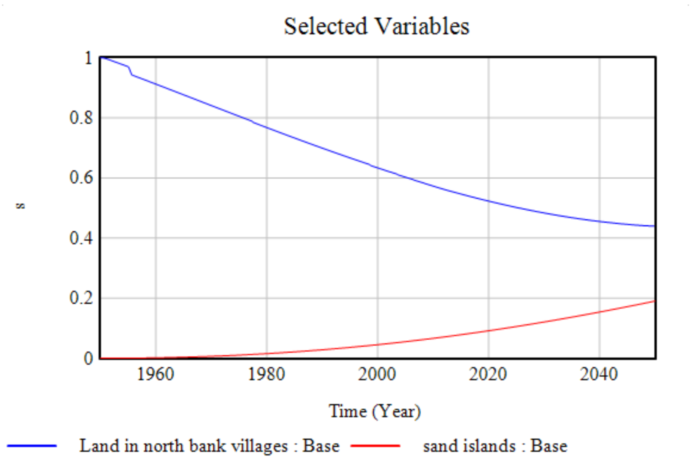
Figure 11- Increase in discontent among *Misings* and village level protests



A relook at land in a riparian context: Need for innovations in land use policy

There is an increase in the accumulation of sand islands in the simulation model as illustrated by the red trend in Figure 12. This can also be interpreted as not just an increase in the number of sand bars/islands but starting the process of re-connection of such spaces with flood plains as already observed in many areas in the upper river as a result of fieldwork and examination of satellite images. However, due to a lack of land surveys (Anand, 2017), there is no actual record of such emergence in the BRB. A decreasing trend of productive land in villages (see blue line in Figure 12 and also Varma and Mishra, 2017) and an increase in islands and bars and/or their connection with flood plains creates a need for innovative land use. Such a need was also found acceptable among the *Mising* leaders who participated in a group model building workshop (Varma, 2016; Varma et al., 2015). Moreover, technological innovations such as farming new type of crops, solar-powered irrigation on sand islands, as well as innovations in land tenure are seen in similar contexts in Bangladesh (Krishnamurthy, 2014; Rehman and Reza, 2012). However, precise policy recommendation will depend on the quality of sediments of the sands bars and islands and this creates the need for more empirical research on land use and land tenure institutions in Assam Valley.

Figure 12-



Policy testing

The model is tested with four policy alternatives to examine the changes in ‘effective usable land’ in villages and ‘embankment breaches’; i.e., policy pathways for not only flood protection in the villages but also means for the *Mising* community to come out of landlessness. The results of the tests are summarized in Figure 13 and Table 2-

Figure 13-

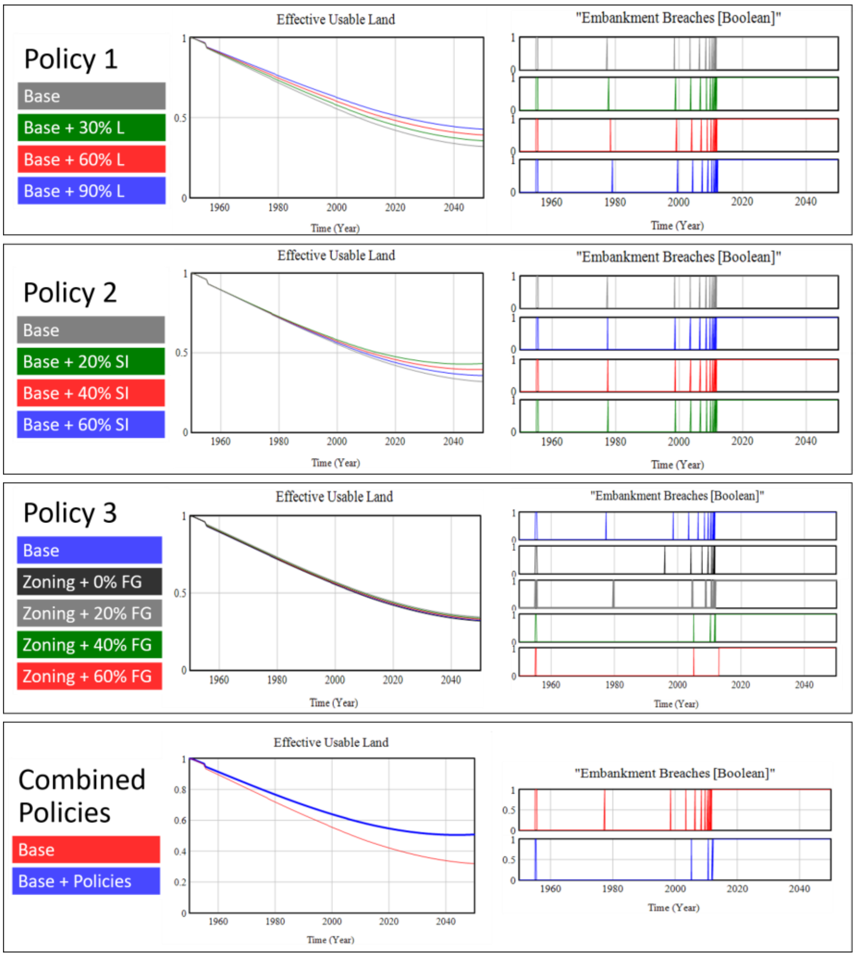


Table 2-

s/n	Policy Name	Rationale and description of policy strategy	Testing principle
1	Crop Diversification	Sediment deposited on the north bank is coarse sand, as it is not deposited by the usual overtopping of fine silt containing floodwater from the river channel to the flood plain. Sand deposition occurs during channel relocation by anabranches (secondary or tertiary branches) from the braided river channel and by embankment breaches. Land covered by coarse sediment is perceived by the community as well as recorded by the Government as land loss due to loss of the agricultural utility of the land.	Increasing *fraction of land with coarse sediment utilized* (30,60,90%)

		A plausible solution would be to change cropping patterns; e.g. paddy to pumpkins, to utilize some of these unused areas.	
2	Innovations in land use	The model simulation suggests an increase in the accumulation of sand islands, which as explained before, may also mean a connection with the flood plain if the width and depth continue a goal-seeking behaviour. *Mising* culture (e.g. type of housing, cultivation practices and so on) facilitated their pre-colonial shifting lifestyle in the riparian zone by using sand islands while settled agriculture is recent. To some extent, the legacy of this culture continues as observed by Varma and Mishra, (2017). A blend of such traditional practices into formal institutions of land use and customization of lessons of technological and land tenure innovations in similar contexts in Bangladesh can be examined for policy design.	Increasing *fraction of Sand Islands Utilized* (30,60,90%)
3	Floodplain design	As the effectiveness of flood protection with embankments is questionable in the BRB and elsewhere, the flood plain can be designed to absorb instead of fully resist flood disturbances. Floodgates (FG) can be envisaged to drain out a portion of the floodwater to designated areas of the floodplains to relieve stress from existing embankments. This would also require zoning of the floodplain to regulate areas for flood runoff. Zoning would also facilitate de-congestion over embankments; i.e., reduce settlements on embankments which is one of the factors for failure of maintenance work of flood control infrastructure. Runoff from floodgates can be connected to wetlands which can act as buffers for flood water and also sources of fishes. In reality, the implementation of such a design is complex as it would also require effective management of floodgates, restoration of wetlands and planned relocation of people for zoning.	Decreasing *Susceptibility to Breaching* (20,40,60%). Prohibiting *Settlements on Embankments* by Zoning
4	Combination of policies	The most significant results for an increase in effective usable land as well as decrease of embankment breaches is through a combination of crop diversification in areas of sand deposition, innovation in land-use practices integrating productive and regulated use of sand islands and	[Policy 1 & 2] Increasing *utility of land with coarse sediment* and *sand island (50%)*

		design of flood floodplains with floodgates and zoning.	[Policy 3] Reducing *Susceptibility to Breaching (50%)* and Prohibiting *Settlements on Embankments*

Ways forward for social-hydrological resilience: Recommendations for policy and research in the BRB and similar Himalayan river basins

The application of the system dynamics method helped in exploring the cross-scale dynamics across hydro-geomorphology of the BRB, the flood protection policy of Assam State of the Indian polity, and issues experienced by a riparian community in the upper Assam Valley. The research approach used in this study can be applied as a framework to similar data constrained and ambiguous problem situations of Himalayan river basins. The simulation analysis pointed to the role of feedback between village-scale governance issues of landlessness, lack of communication and awareness of disaster compensation rules and resulting discontent and protests on the effectiveness of flood protection through embankments. This creates the need for flexibility in disaster management institutions in the BRB to recognize social needs and facilitate adaptation to novel hazards. This is important as climate change impacts on discharge in Himalayan rivers can lead to more surprise events at local scales which are currently discounted and a limitation of this study. Beyond the role of feedback from community action to policy effectiveness or lack of it, the simulation results also illustrate a need to integrate studies of dynamics of land and land use in Himalayan river basin contexts such as the BRB. But to enable such science to impact policy, there will be a need for flexibility in disaster management institutions.

Policy testing of the system dynamics model illustrates the importance of combining interventions at different scales; i.e., farm-level interventions such as a change of cropping pattern which is more attuned to different levels and types of river sediment, flexibility at the sub-national policy level to integrate changes in land use and land tenure with disaster management policy and basin level zoning policy to operationalize the set of proposed policies: floodgate-wetland restoration-culturally acceptable planned relocation.

This study started with the prior knowledge of narratives of the social-hydrological issue of flood and riverbank erosion in the BRB and has produced new policy insights by integrating this knowledge using system dynamics. From this analysis, we argue that a transformation of the policy paradigm from flood control with embankments to one of multi-scale disaster management will require capacity building for social hydrological resilience among sub-national and national policymakers, regional academia and civil society in Himalayan nations. Systems thinking and system dynamics are best suited as a pedagogic tool in such capacity-building programs which can help in the integration of actors’ voices as well as lead to change in mindsets and protocols through iterations, dialogue and simulations. This research also contributes to science as it points to the elements of hydro-geomorphology which are yet to be quantified. More empirical research is required for science and policy in the region to validate such integrative approaches and increase their confidence in policy design.

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Appendix 1

<u>Authorization Letter for Figure 1</u>

To Authors of *System dynamics across three scales in the Brahmaputra River Basin- Exploring a Himalayan social-hydrological system*

I, Navarun Varma, first author of the paper: *Discourses, Narratives and Purposeful Action –Unraveling the Social–Ecological Complexity within the Brahmaputra Basin in India* published in Environment Policy and Governance in 2017, give permission to Ryan and his co-authors to use the Map from Figure 1 in the published paper as it is.

Navarun Varma

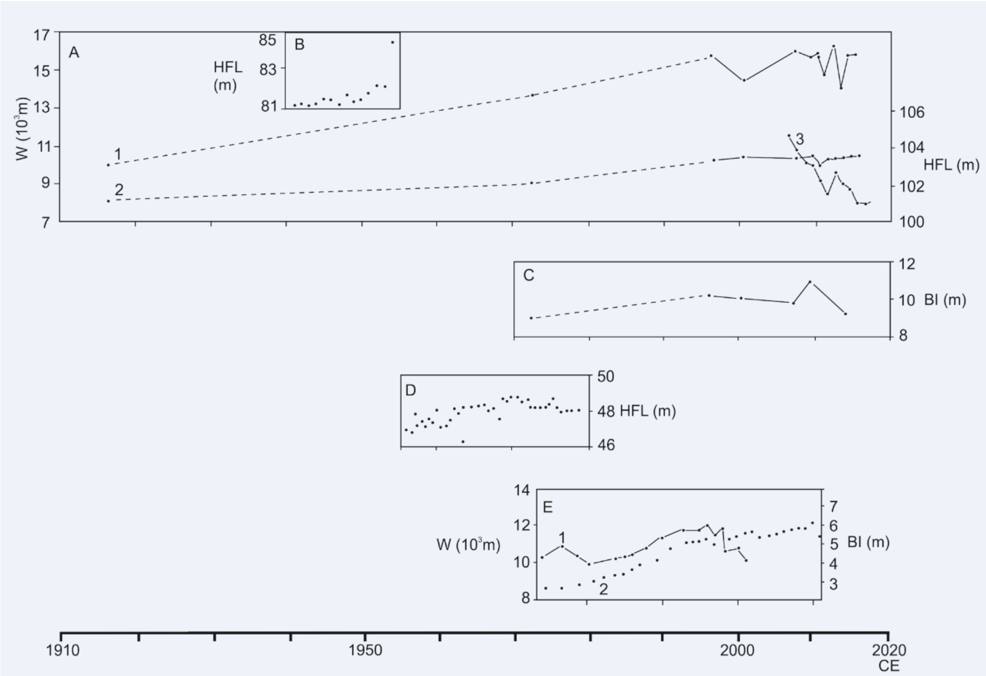
Navarun Varma

Lecturer (Resident Fellow)

Residential College 4, University Town College Program,

National University of Singapore

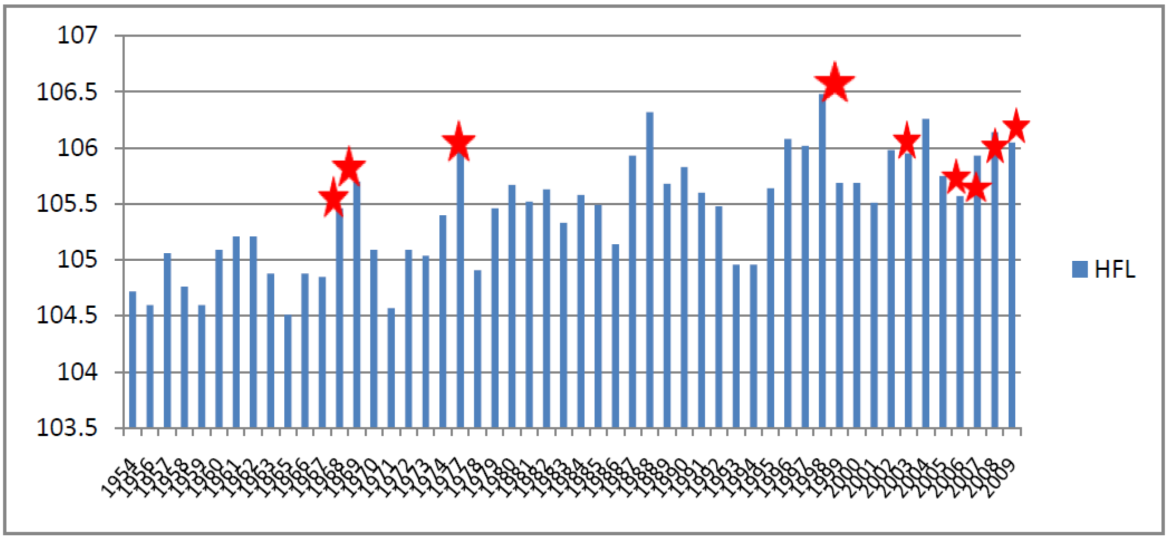
Reference Mode (Width, High Flood Level)



"A #1 -Mean Width at Dibrugarh. #2 HFL at Dibrugarh. #3 HFL at Dholla."

Reference Mode (Embankment Failures)

Figure 2.4 of High Flood Level (HFL) in meters and ★ denotes embankment breaches in Sissirkolghor-Tekeliphuta embankment.



Appendix 2

These are fundamental assumptions within the scales:

Macro

1. The landslide sediment influx is a unit-step function representing a singular event that happened during the Year of the Great Earthquake : 1950. It assumes that the sediment has reached the river within the same year. The influx increase is approximately 71% as estimated by Prof Wasson (unpublished).

2. The estimate of Discharge is 4%. Based on Prof Wasson's estimates, the following calculations were made deposition rate = 7.13, sediment load = 180. Discharge flow is 7.13/180 = 4%.

Meso

3. There is a constant rate for the building of embankments, and an absence of time delays between building and functioning state.

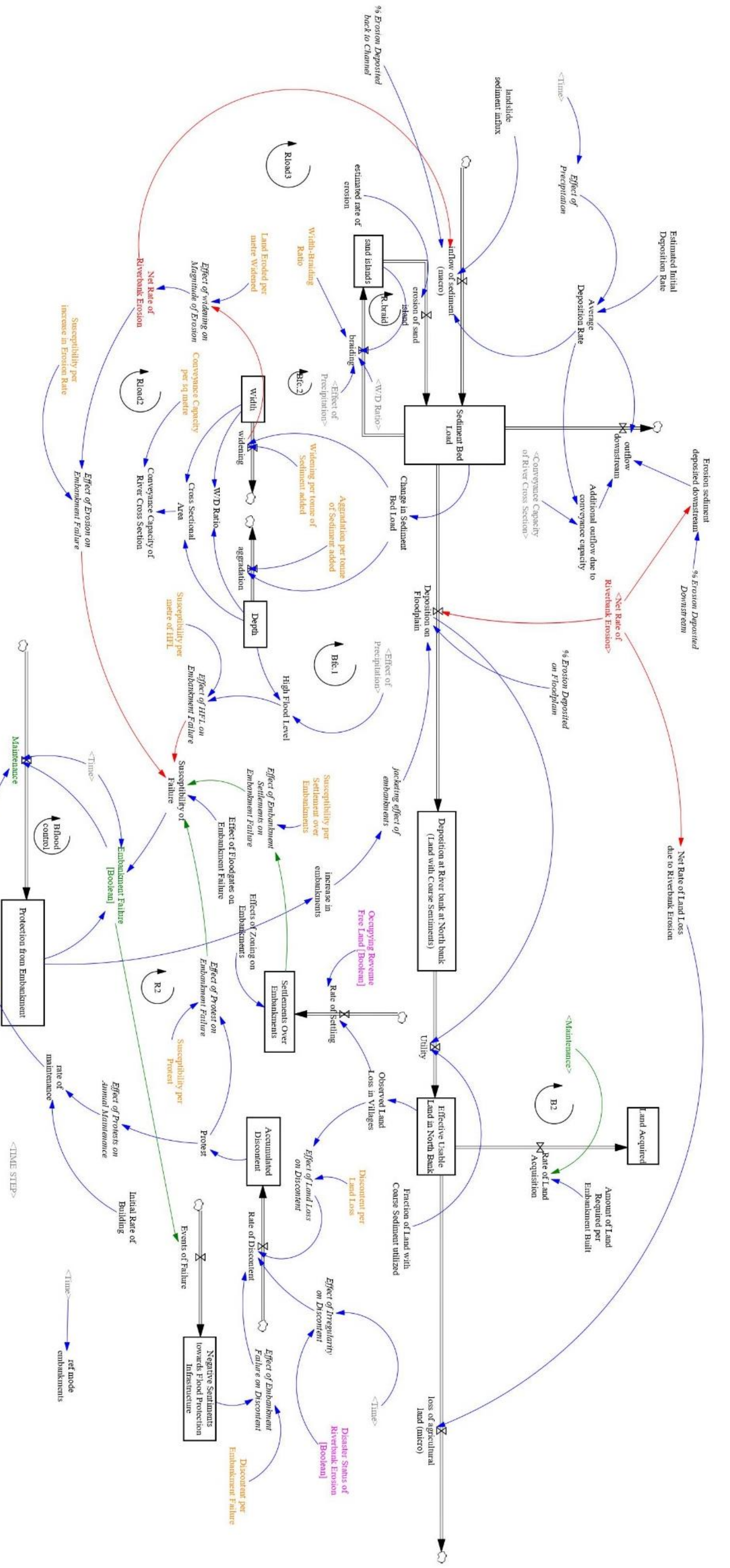
4. Embankment breaches are assumed to be caused by the following factors: HFL, Riverbank Erosion, Embankment Settlements, and Village Protests.

Micro

5. Discontent due to irregularities of compensation is a constant and only starts in 1998 when major disruptive events started to occur within the villages.

6. Amount of land acquired by the government is linearly proportional to the extent of embankments construction and maintenance.

Blown-Up Figure of Stock and Flow Diagram



Documentation

(01) "% Erosion Deposited back to Channel"=
0.75
Units: Dmnl
[Constant] The numerical value is estimated with insights from knowledge accumulated on hydro-geomorphology of Himalayan rivers by the third author of this research and further calibrated with the reference mode. There is also no general theory to estimate this parameter because of the complexity of braided rivers and monitoring of the fluxes of sediment into and out of the channel has not occurred. It is likely however that most sediment derived from riverbank erosion will be deposited in the channel because much of this erosion occurs by bank slumping as the water level falls. However, some of the bank material deposited in the river may be spread overbank on the floodplain during subsequent floods. This may explain the curious feature of the Brahmaputra where the floodplain consists of flood couplets; that is sandy units capped by fine sediments as a result of single floods.

(02) "% Erosion Deposited Downstream"=
0.05
Units: Dmnl
[Constant] The numerical value is estimated with insights from knowledge accumulated on hydro-geomorphology of Himalayan rivers by the third author of this research and further calibrated with the reference mode. As noted in variable (01), an accurate numerical value is unavailable due to lack of monitoring and general theory, but it is likely that most of the products of riverbank erosion are deposited in the channel, followed by floodplain deposition and then deposition downstream.

(03) "% Erosion Deposited on Floodplain"=
0.2
Units: Dmnl
[Constant] The numerical value is estimated with insights from knowledge accumulated on hydro-geomorphology of Himalayan rivers by the third author of this research and further calibrated with the reference mode. As noted in above variable (01) and (02), an accurate numerical value is unavailable due to lack of monitoring and general theory, but it is likely that most of the products of riverbank erosion are deposited in the channel, followed by floodplain deposition and then deposition downstream.

(04) Accumulated Discontent= INTEG (
Rate of Discontent,
0)
Units: Dmnl
[Stock] Discontent is Accumulated and was found as a strong element among Misings of the study area villages in previous work by the second author (Varma and Mishra, 2017)

(05) Additional outflow due to conveyance capacity=
(Conveyance Capacity of River Cross Section-1) * Average Deposition Rate
Units: t/Year
[Auxiliary] Additional Outflow is the product of the net change in conveyance capacity (with reference to the pre-1950s conditions) and average deposition rate.

(06) aggradation=
Aggradation per tonne of Sediment added*Change in Sediment Bed Load
Units: m/Year
[Flow] Aggradation is assumed to have a linear relationship to the change in Sediment Bed Load (pre-1950s conditions).

(07) Aggradation per tonne of Sediment added=
0.0025
Units: m/(t*Year)
[Scaling Constant] Aggradation is assumed to have a linear relationship to the change in Sediment Bed Load (pre-1950s conditions). This value estimates the extent in which change in Sediment Bed Load affects the channel characteristics (also see 'widening').

(08) Amount of Land Required per Embankment Built=
0.01
Units: t
[Scaling Constant] Land Required is assumed to have a linear relationship to the area of Embankment Built. This constant estimates a theoretical amount of land acquired (t) for each embankment built.

(09) Average Deposition Rate=
Effect of Precipitation * Estimated Initial Deposition Rate
Units: t/Year
[Auxiliary] Average Deposition Rate is estimated by multiplying the Precipitation (change in rainfall) with the Initial Deposition Rate.

(10) braiding=
"Width-Braiding Ratio" * (1 + sand islands) * "W/D Ratio" * Effect of Precipitation
Units: t/Year
[Flow] Formula assumes that the braiding rate is a function of the Width/Depth (W/D) Ratio and they have a linear relationship. It also takes into account the insights from the third and fourth authors' knowledge of braided rivers that the increasing formation of sand islands will likely lead to more braiding (reinforcing loop). This is derived from {Sarma, J. N., & Acharjee, S., 2018). A study on variation in channel width and braiding intensity of the Brahmaputra River in Assam, India. Geosciences (Switzerland), 8(9), 1–19. https://doi.org/10.3390/geosciences8090343}.

(11) Change in Sediment Bed Load=
Sediment Bed Load-1
Units: t
[Auxiliary] This variable quantifies the change from the initial simulated Sediment Bed Load representing pre-earthquake conditions.

(12) Conveyance Capacity of River Cross Section=
Cross Sectional Area*Conveyance Capacity per sq metre
Units: Dmnl
[Scaling Constant] Conveyance Capacity is assumed to have a linear/direct relationship with Cross Section Area.

(13) Conveyance Capacity per sq metre=
1
Units: 1/m/m
[Scaling Constant] Conveyance Capacity is assumed to have a linear/direct relationship with Cross Section Area. This value estimates the extent in which a Sq Metre of the Cross Sectional Area will affect its Conveyance Capacity.

(14) Cross Sectional Area=
Width*Depth
Units: m*m
[Auxiliary] Cross Sectional Area is directly proportional to the product of Width and Depth.

(15) "Deposition at River bank at North bank (Land with Coarse Sentiments)"
= INTEG (
Deposition on Floodplain-Utility,
0)
Units: t
[Stock] This stock measures the effective loss of Crop Area, which is land that is effectively present but unable to be used for agriculture purposes.

(16) Deposition on Floodplain=
(Net Rate of Riverbank Erosion*"% Erosion Deposited on Floodplain")
*
jacketing effect of embankments
Units: t/Year
[Flow] The quantity of Deposition in Floodplain is a product of the rate of erosion, and the proportion of that erosion deposited on the floodplain. This formula also accounts for the jacketing effect caused by the embankments.

(17) Depth= INTEG (
-aggradation,
1)
Units: m
[Stock] The initial value of Channel Depth was set as 1 (m) to
represent the pre-earthquake conditions (pre-1950s).

(18) "Disaster Status of Riverbank Erosion [Boolean]"=
1
Units: 1/Year
[Constant] This has a Boolean (True 1 / False 0) value.

(19) Discontent per Embankment Failure=
0.01
Units: 1/Year
[Scaling Constant] Discontent is assumed to have a linear
relationship with Embankment Failure. This value estimates the
extent in which Embankment Failure affects Discontent (also see
Discontent per Land Loss). This is calibrated with the reference
mode of embankment failures.

(20) Discontent per Land Loss=
0.47
Units: 1/Year/t
[Scaling Constant] Discontent is assumed to have a linear
relationship with Land Loss. This value estimates the extent in
which each unit(t) of Land Loss affects Discontent (also see
Discontent per Embankment Failure). This is calibrated with the
reference mode of embankment failures.

(21) Effect of Embankment Failure on Discontent=
Discontent per Embankment Failure * Negative Sentiments towards Flood Protection Infrastructure
Units: 1/Year
[Auxiliary] Land Loss is one of the factors which influences
Discontent. Formula assumes that Land Loss and Discontent have a
linear relationship.

(22) Effect of Embankment Settlements on Embankment Failure=
Susceptibility per Settlement over Embankments*Settlements Over Embankments
Units: Dmnl
[Auxiliary] Embankment Settlements is one of the factors which
influences Susceptibility of Embankment Failure. Formula assumes
that Embankment Settlements and Susceptibility of Embankment
Failure have a linear relationship.

(23) Effect of Erosion on Embankment Failure=
Susceptibility per increase in Erosion Rate*Net Rate of Riverbank Erosion
Units: Dmnl
[Auxiliary] Erosion Rate is one of the factors which influences
Susceptibility of Embankment Failure. Formula assumes that
Erosion Rate and Susceptibility of Embankment Failure have a
linear relationship.

(24) Effect of Floodgates on Embankment Failure=
1
Units: Dmnl
[Constant] It holds a value [0-1] to vary the extent in which
floodgates can be used to alleviate the stress on embankments
for protection. It is used for policy testing.

(25) Effect of HFL on Embankment Failure=
Susceptibility per metre of HFL * High Flood Level
Units: Dmnl
[Auxiliary] High Flood Level is one of the factors which
influences Susceptibility of Embankment Failure. Formula assumes
that High Flood Level and Susceptibility of Embankment Failure
have a linear relationship.

(26) Effect of Irregularity on Discontent=
IF THEN ELSE(Time > 1998,
3 * "Disaster Status of Riverbank Erosion [Boolean]"
, 0)
Units: 1/Year
[Auxiliary] Irregularity of Compensation is one of the factors

which influences Discontent. This variable is influenced by the Disaster Status of Riverbank Erosion which implicates the eligibility for the compensation of land loss. This value estimates the extent in which this Irregularity affects Discontent which is further calibrated with the reference mode of embankment failures. Formula only allows values after 1998 to align with the historical context of compensation claims which began around then.

(27) Effect of Land Loss on Discontent=
Discontent per Land Loss* Observed Land Loss in Villages
Units: 1/Year
[Auxiliary] Land Loss is one of the factors which influences Discontent. Formula assumes that Land Loss and Discontent have a linear relationship.

(28) Effect of Precipitation = WITH LOOKUP (
Time,
([(1950,0.7)-(2050,1)],(1950,1),(1960,0.95),(1970,0.91),(1980,0.88),(1990
,0.84),(2000,0.82),(2010,0.79),(2020,0.77),(2030,0.75),(2040,0.73),(2050,0.71
)))
Units: Dmnl
[Exogenous Data] Formula represents 10 yearly changes rainfall (see Appendix). The data starts with the value of 1 at 1950 to represent pre-earthquake conditions.

(29) Effect of Protest on Embankment Failure=
Susceptibility per Protest * Protest
Units: Dmnl
[Auxiliary] Protest is one of the factors which influences Susceptibility of Embankment Failure. Formula assumes that Protest and Susceptibility of Embankment Failure have a linear relationship.

(30) Effect of Protests on Annual Maintenance=
0.02 * Protest
Units: Dmnl
[Auxiliary] Formula assumes that Protests and its effect on Annual Maintenance have a linear relationship. This is calibrated with the reference mode of embankment failures.

(31) Effect of widening on Magnitude of Erosion=
Land Eroded per metre Widened * widening
Units: t/Year
[Auxiliary] Channel Widening is assumed to have a linear relationship with Magnitude of Erosion.

(32) Effective Usable Land in North Bank= INTEG (
Utility-"loss of agricultural land (micro)"-Rate of Land Acquisition,
1)
Units: t
[Stock] This stock represents the effective usable land available after Land Erosion and Land Acquisition.

(33) Effects of Zoning on Embankments=
1
Units: Dmnl
[Constant] It holds a Boolean (False 0 / True 1) value to represent the prohibition of settling on embankments. It is used for policy testing.

(34) "Embankment Failure [Boolean]"=
IF THEN ELSE((Time > 1955) :AND: Susceptibility of Failure > Protection from Embankment
, 1 , 0)
Units: 1/Year
[Auxiliary] Formula is a Boolean function, simulating the discrete event of an embankment failure if the Susceptibility of Embankment Failure exceeds the Protection it provides.

(35) erosion of sand island=
estimated rate of erosion
Units: t/Year
[Flow] It is assumed that all sediment from the Erosion of Sand Islands will return to the Bed Load.

(36) Erosion sediment deposited downstream=
"% Erosion Deposited Downstream"*Net Rate of Riverbank Erosion
Units: t/Year
[Auxiliary] Net amount of eroded sediment that is deposited downstream.

(37) Estimated Initial Deposition Rate=
0.04
Units: t/Year
[Constant] Based on previous knowledge of the third author, the deposition rate (pre 1950s conditions) =7.13 and sediment load= 180. Hence it is estimated that the Initial Deposition Rate is 0.04 which represents 4% of the initial simulated Sediment Bed Load of 1 (t).

(38) estimated rate of erosion=
0.004
Units: t/Year
[Constant] Sand islands are not permanent land forms, forming, changing and disappearing. Due to lack of availability of any empirical numerical value a calibrated value is used for their rate of erosion. This calibration leads to an increase in sand islands which appears to match the observation that sand islands are increasingly becoming attached to riverbanks and therefore to flood plains which further leads to a hypothesis of increase in availability of land area.

(39) Events of Failure=
"Embankment Failure [Boolean]"
Units: 1/Year
[Flow] Discrete simulated data of Embankment Failure is represented as an inflow.

(40) FINAL TIME = 2050
Units: Year
The final time for the simulation.

(41) Fraction of Land with Coarse Sediment utilized=
0
Units: Dmnl
[Constant] This variable conceptualizes the possibility that a proportion of Land with Coarse Sediment can be used by the villagers. It follows the second author's field observations (Varma and Mishra, 2017) where government, civil society and community engage in different experiments with land use. This quantity will be varied for policy testing.

(42) High Flood Level=
1 - (Depth-1) * Effect of Precipitation
Units: m
[Auxiliary] High Flood Level is inversely proportionate to Depth. High Flood Level also assumes a linear relationship to the effect of precipitation (% change in discharge).

(43) increase in embankments=
Protection from Embankment-1
Units: Dmnl
[Auxiliary] The net increase in embankments can be characterized by the change in protection from embankment.

(44) "inflow of sediment (macro)"=
landslide sediment influx + Average Deposition Rate + "% Erosion Deposited back to Channel" * Net Rate of Riverbank Erosion
Units: t/Year
[Flow] Inflow of Sediment into the Bed Load coming from upstream sources (Average Deposition Rate) as well as deposition from riverbank erosion.

(45) Initial Rate of Building=
4.085
Units: Dmnl
[Constant] This is calibrated with the reference mode of embankment failures.

(46) INITIAL TIME = 1950

Units: Year
The initial time for the simulation.

(47) jacketing effect of embankments=
1- increase in embankments * 0.05
Units: Dmnl
[Auxiliary] Value is calibrated based on expected behavioural trend (Least Action Principle Theory) of Sediment Bed Load.

(48) Land Acquired= INTEG (
Rate of Land Acquisition,
0)
Units: t
[Stock] This stock represents the Land Acquired to build Embankments/Flood Protection Infrastructure

(49) Land Eroded per metre Widened=
1.013
Units: t/m
[Scaling Constant] Land Erosion is assumed to have a linear relationship with Widening. This value estimates the extent in which each Sq Metre of Widening will affect Land Erosion. It is calibrated based on the reference mode of High Flood Level and Channel Width.

(50) landslide sediment influx=
0.71 - STEP(0.71, 1951.04)
Units: t/Year
[Auxiliary] Formula simulates a spike of sediment contribution to the bed load after the great earthquake of 1950. From insights of the third author's knowledge of the Brahmaputra's hydro-geomorphology, it is estimated that there was a 71% increase in sediment load.

(51) "loss of agricultural land (micro)"=
Net Rate of Land Loss due to Riverbank Erosion
Units: t/Year
[Flow] Loss of Agriculture Land is due to Riverbank Erosion

(52) Maintenance=
IF THEN ELSE(Time > 1955 :AND: rate of maintenance >= 0 ,
"Embankment Failure [Boolean]"*rate of maintenance,
0)
Units: 1/Year
[Flow] Maintenance refers to act of building more embankment/flood protection infrastructure. Formulae restricts maintenance to only occur after the Embankment Act in 1955, and only accept positive values as maintenance can only increase embankment protection in real world contexts.

(53) Negative Sentiments towards Flood Protection Infrastructure= INTEG (
Events of Failure,
0)
Units: Dmnl
[Stock] Negative Sentiments towards Flood Protection Infrastructure is approximated from the total embankment failures that had occurred prior to a date.

(54) Net Rate of Land Loss due to Riverbank Erosion=
Net Rate of Riverbank Erosion
Units: t/Year
[Auxiliary] Rate of Riverbank Erosion approximates the loss of Agricultural Land in the Villages.

(55) Net Rate of Riverbank Erosion=
IF THEN ELSE (Effect of widening on Magnitude of Erosion > 0 ,

(Effect of widening on Magnitude of Erosion) ,

0)
Units: t/Year
[Auxiliary] Value represents the Rate of Riverbank Erosion in units of sediment (t). Formula only allows zero or positive values of erosion.

(56) Observed Land Loss in Villages=
1- Effective Usable Land in North Bank
Units: t
[Auxiliary] Land Loss is approximated by the change (decrease) in usable land.

(57) "Occupying Revenue Free Land [Boolean]"=
1
Units: 1/t/Year
[Constant] This holds a Boolean (True 1 / False 0) value.

(58) outflow downstream=
Average Deposition Rate
+
Erosion sediment deposited downstream
+
Additional outflow due to conveyance capacity
Units: t/Year
[Flow] Outflow downstream is the sum of the Average Deposition Rate, Sediment Deposition from Riverbank Erosion and the Additional Outflow due to change in Conveyance Capacity.

(59) Protection from Embankment= INTEG (
Maintenance,
0)
Units: Dmnl
[Stock] Protection from Embankment is enhanced through maintenance.

(60) Protest=
Accumulated Discontent * 2
Units: Dmnl
[Auxiliary] Protest is conceptualized to be directly proportional to the existing State of Discontent

(61) Rate of Discontent=
Effect of Irregularity on Discontent + Effect of Embankment Failure on Discontent
+ Effect of Land Loss on Discontent
Units: 1/Year
[Flow] Rate of Discontent is a function of Land Loss, Irregularity of Compensation and Embankment Failure.

(62) Rate of Land Acquisition=
Maintenance * Amount of Land Required per Embankment Built
Units: t/Year
[Flow] Land Acquisition is assumed to have a linear relationship to Maintenance (the rate at which embankments are being built).

(63) rate of maintenance=
Initial Rate of Building * (1- (Effect of Protests on Annual Maintenance)
)
Units: Dmnl
[Auxiliary] The Rate of Maintenance is modelled as a fraction (Effect of Protest on Annual Maintenance) of the Initial Rate of Building

(64) Rate of Settling=
Observed Land Loss in Villages

*"Occupying Revenue Free Land [Boolean]"
Units: 1/Year
[Flow] Rate of Settling on Embankments is affected by the Land Loss observed in the Villages. This variable is influenced by the land revenue system which implicates the settlement on embankments.

(65) ref mode embankments = WITH LOOKUP (
Time,
([(1955,0)-(2009,1)],(1955,0),(1967,0),(1968,1),(1969,1),(1970,0),(1976,
0),(1977,1),(1978,0),(1997,0),(1998,1),(1999,0),(2001,0),(2002,1),(2003,0)
,(2004,0),(2005,1),(2008,1),(2009,0)))
Units: **undefined**
[Auxiliary] Lookup Function - reference mode of embankment failures.

(66) sand islands= INTEG (
braiding-erosion of sand island,
0)
Units: t
[Stock] Sand Islands form through braiding and erode over time.

(67) SAVEPER =
TIME STEP
Units: Year [0,?]
The frequency with which output is stored.

(68) Sediment Bed Load= INTEG (
"inflow of sediment (macro)"-outflow downstream
+ (erosion of sand island-braiding-Deposition on Floodplain),
1)
Units: t
[Stock] The initial value of sediment bed load was set as 1 (t) to represent the pre-earthquake conditions (pre-1950s). Formula accounts for the river dynamics (inflow and outflow), and the braiding/ formation of sand islands.

(69) Settlements Over Embankments= INTEG (
Rate of Settling * Effects of Zoning on Embankments,
0)
Units: Dmnl
[Stock] This stock measures estimates the behavioural trend of Settlements over Embankments.

(70) Susceptibility of Failure=
(Effect of Embankment Settlements on Embankment Failure
+Effect of Erosion on Embankment Failure
+Effect of HFL on Embankment Failure
+Effect of Protest on Embankment Failure)
* Effect of Floodgates on Embankment Failure
Units: Dmnl
[Auxiliary] Susceptibility of Failure is a function of HFL, Erosion Rate, Settlements over Embankments and Protest

(71) Susceptibility per increase in Erosion Rate=
12.8
Units: Year/t
[Scaling Constant] Erosion Rate is assumed to have a linear relationship to Susceptibility of Embankment Failure. This value estimates the extent in which Erosion Rate affects Susceptibility of Embankment Failure (also see Susceptibility per - High Flood Level, Settlement over Embankments, Protest). This is calibrated with the reference mode of embankment failures.

(72) Susceptibility per metre of HFL=
2
Units: 1/m
[Scaling Constant] High Flood Level is assumed to have a linear relationship to Susceptibility of Embankment Failure. This value estimates the extent in which High Flood Level affects Susceptibility of Embankment Failure (also see Susceptibility per - Erosion Rate, Settlement over Embankments, Protest). This is calibrated with the reference mode of embankment failures.

(73) Susceptibility per Protest=
0.011
Units: Dmnl
[Scaling Constant] Protest is assumed to have a linear relationship to Susceptibility of Embankment Failure. This value estimates the extent in which Protest affects Susceptibility of Embankment Failure (also see Susceptibility per - High Flood Level, Settlement over Embankments, Erosion Rate). This is calibrated with the reference mode of embankment failures.

(74) Susceptibility per Settlement over Embankments=
0.02
Units: Dmnl
[Scaling Constant] Settlement over Embankments is assumed to have a linear relationship to Susceptibility of Embankment Failure. This value estimates the extent in which Settlement

over Embankments affects Susceptibility of Embankment Failure (also see Susceptibility per - High Flood Level, Erosion Rate, Protest). This is calibrated with the reference mode of embankment failures.

(75) TIME STEP=
0.0625
Units: Year [0,?]
[Constant] Simulation Time Step. Varied for model validation.

(76) Utility=
(Fraction of Land with Coarse Sediment utilized*Deposition on Floodplain)
Units: t/Year
[Flow] This flow represents the proportion of Land with Coarse Sediment used by the villagers.

(77) "W/D Ratio"=
Width/Depth
Units: Dmnl
[Auxiliary] Width/Depth Ratio is a key characteristics of a river's cross section.

(78) widening=
Change in Sediment Bed Load*Widening per tonne of Sediment added
Units: m/Year
[Flow] Channel Widening is assumed to have a linear relationship to the change in Sediment Bed Load (pre-1950s conditions).

(79) Widening per tonne of Sediment added=
0.011
Units: m/(t*Year)
[Scaling Constant] Channel Widening is assumed to have a linear relationship to the change in Sediment Bed Load (pre-1950s conditions). This value estimates the extent in which change in Sediment Bed Load affects the channel characteristics (also see 'aggradation').

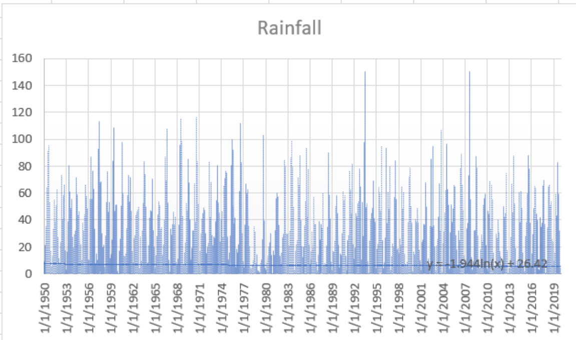
(80) Width= INTEG (
+widening,
1)
Units: m
[Stock] The initial value of Channel Width was set as 1 (m) to represent the pre-earthquake conditions (pre-1950s).

(81) "Width-Braiding Ratio"=
0.005
Units: 1/Year
[Scaling Constant] The parameter is an estimation of the extent to which width may affect the rate of braiding. This calibration leads to an increase in sand islands which appears to match the observation that sand islands are increasingly becoming attached to riverbanks and therefore to flood plains which further leads to a hypothesis of increase in availability of land area.

Precipitation Data (Personal Communication with Saurabhardwaj, TERI India)

Average RF	Date	% Change
7.34	1/1/1950	1.00
6.99	1/1/1960	0.95
6.69	1/1/1970	0.91
6.43	1/1/1980	0.88
6.20	1/1/1990	0.84
6.00	1/1/2000	0.82
5.81	1/1/2010	0.79
5.64	1/1/2020	0.77
5.49	1/1/2030	0.75
5.34	1/1/2040	0.73
5.21	1/1/2050	0.71

y = -1.944ln(x) + 26.42



Rainfall recorded at Lakhimpur, Assam