ENVIRONMENTAL RESEARCH
LETTERS

PURPOSE-LED PUBLISHING™

Part of the
ENVIRONMENTAL RESEARCH
SERIES

LETTER • OPEN ACCESS

# From discourses to systems—policymaking for adaptive management in the Brahmaputra River basin

To cite this article: Navarun Varma *et al* 2025 *Environ. Res. Lett.* **20** 064023



ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
20 December 2024

REVISED
11 April 2025

ACCEPTED FOR PUBLICATION
24 April 2025

PUBLISHED
16 May 2025



LETTER

# From discourses to systems—policymaking for adaptive management in the Brahmaputra River basin

**Navarun Varma[1], Ryan Tan[2], Robert J Wasson[3], Cecilia Tortajada[4,*], Raghupratim Rakshit[5] and Abhinandan Saikia[6]**

1 Residential College 4, University Town College Program, National University of Singapore, Singapore
2 International Institute for Applied Systems Analysis, Laxenburg, Austria
3 Fenner School of Environment and Society, Australian National University, Canberra, and College of Engineering and Science, James Cook University, Cairns, Australia
4 School of Social and Environmental Sustainability, University of Glasgow, Dumfries, United Kingdom
5 Department of Geology, Jagannath Barooah University, Assam, India
6 Centre for Ecology, Environment and Sustainable Development, School of Social Sciences and Humanities, Tata Institute of Social Sciences, Guwahati Off-campus, India
* Author to whom any correspondence should be addressed.

**E-mail: Cecilia.tortajada@glasgow.ac.uk**

**Keywords:** adaptive policymaking, systems thinking, Brahmaputra River basin, river science, climate change

Supplementary material for this article is available online

## Abstract

Flood and riverbank erosion management in the Brahmaputra River basin (BRB) has traditionally relied on structural engineering interventions. However, there is growing evidence of their ineffectiveness and the social-ecological concerns they raise, including emergent systemic risks. This paper presents a social-ecological systems approach, offering a model that acts as a boundary object to integrate knowledge, foster stakeholder collaboration to tackle community vulnerability, and facilitate policy experimentation—key elements for advancing adaptive management. Employing systems thinking and system dynamics-based modelling can bridge the divide between science and policy, especially in areas characterized by data limitations and uncertainties like the BRB. This study adopts a nested approach encompassing three scales: macro (basin-level hydro-geomorphology), meso (flood control policies and infrastructure at administrative levels), and micro (village-level socio-economic conditions). The constructed boundary object promotes cross-scale learning and policy experimentation. Model scenarios of policy alternatives demonstrate that an integrated strategy—leveraging land covered with coarse sediment, innovating land use, and redesigning floodplains—significantly enhances effective land use and minimizes embankment failures. The findings emphasize the reinforcing dynamics between embankment degradation and community protests, highlight the limitations of compensation mechanisms, and reveal the erosion of adaptive capacity under the current control-based policy regime. A crucial insight from this study is that flood management strategies must evolve continually, reflecting scientific advancements, assessing policy impacts, and addressing local adaptation needs. Furthermore, a greater focus on riparian land use within development strategies is essential. The model scenarios advocate transitioning from traditional flood control to a landscape design harmonizing cropping practices and floodplain development with river morphology dynamics. While rooted in the Indian BRB context, the modelling framework provides a basis for adaptive water governance in other sediment-rich, politically sensitive, and hydrologically dynamic transboundary basins.

## 1. Introduction

Efforts to manage rivers reflect a public understanding of their functional roles within communities, regions, and nations. However, this understanding can be challenged by events such as extreme floods, riverbank erosion, or sediment deposition, which often result in unexpected surprises and disasters (Best *et al* 2022). Conventional management policies have mostly followed the control and command paradigm of management of river dynamics through engineering structures. Though they may provide short-term protection from extreme events like floods and droughts, they can have trade-offs in long term like loss of essential ecosystem services (Di Baldassarre *et al* 2015, Mao *et al* 2017, Dunham *et al* 2018, Perry *et al* 2024).

It has been seen that efforts to manage disturbances like floods frequently result in bigger disruptions. For instance, policies aimed at controlling flood volumes with dikes or embankments can cause increased crop damages due to water stagnation or lead to larger floods when such structures fail, and even result in higher loss and damages as such structures attract more settlements and infrastructures due to a false sense of safety—a phenomenon typically called the 'levee effect' (Pahl-Wostl *et al* 2007, Buurman and Wasson 2018, Sendzimir *et al* 2018, Fusinato *et al* 2024). Though the volatility of climate, population, and finance may necessitate more flexible management policies, the past decisions of 'control and command' can lead to path dependence, locking strategies into rigid frameworks (Buurman and Wasson 2018, Sendzimir and Schmutz 2018).

Sendzimir *et al* (2018) suggest expanding our perspectives both 'horizontally and vertically' to develop an adaptive management (AM) paradigm for managing river channels and their floodplains. Horizontal expansion involves moving beyond both disciplinary and interdisciplinary perspectives to recognize riparian communities as integral parts of social-ecological systems (SESs). This calls for a transdisciplinary approach that incorporates the lived experiences of local communities and the interests of a diverse range of stakeholders, including those from academia, government, civil society, and the business sector. Vertical expansion, on the other hand, emphasizes the need to consider different management levels and scales of analysis. Many issues shift across scales and do not fit to one administrative scale or a scale of analysis of a study (Cash *et al* 2006, Herrfahrdt-Pähle 2014), e.g. the overdevelopment in the upstream can lead to increase of surface run-off downstream or raising of embankments to protect infrastructure in one bank can lead to bank erosion in the opposite bank. AM treats policies as hypotheses that must be tested, emphasizing the need for flexibility in policymaking to acknowledge, rather than reduce, ambiguity and uncertainty. Additionally, AM emphasizes incorporating different levels of learning throughout processes of policy formulation, implementation, and assessment, supported by monitoring and evaluation (Sendzimir *et al* 2018, Caccamo *et al* 2023, Lazurko *et al* 2023).

AM draws from many other experimental approaches that have aimed for adaptability in decision-making processes in business and natural resource governance (Senge 1990, Vennix 1996, Checkland 2000). It offers analytical methods like systems thinking and system dynamic modelling (STSDM) as boundary objects to facilitate collaboration among scientific and extra-scientific actors and serving as guidelines for problem-solving (Sendzimir *et al* 2018, Biggs *et al* 2021). Such boundary objects can help in exploring interdependencies of factors across different spatial, temporal, and conceptual scales, integrating knowledge from different sources, and can progress towards experimentation to discover multiple policy options, instead of an optimal solution, for managing resilience in uncertain contexts (Holling *et al* 2014, Mao *et al* 2017, Hoekstra *et al* 2018, Herrera de Leon and Kopainsky 2020, Biggs *et al* 2021, Lane 2024).

Research on the Himalayan Rivers highlights gaps in hydrological information, leading to uncertainty and mistrust among stakeholders (Pandey *et al* 2020, Pradhan *et al* 2021). Further, the flows of water and sediment are intertwined with human needs and ecosystem services, requiring an understanding of their socio-geomorphic context (Best *et al* 2022, Gamble *et al* 2024). Studies in the Indian section of the Yarlung-Tsangpo-Brahmaputra River basin (Brahmaputra River basin, or BRB) have examined river morphology, flood control, and community vulnerability using inter-and-transdisciplinary methods. These studies reveal an over-reliance on engineering solutions, such as embankments, and highlight the adaptation deficits of communities facing new risks and hazards, emphasizing the role of power dynamics in policy change (Varma *et al* 2015, Tschakert *et al* 2016, Varma and Mishra 2017, Vij *et al* 2020). However, there remains a significant gap in exploring what such policy change should encompass, indicating a missed opportunity to develop a shared vision for comprehensive alternatives to engineering interventions. This study aims to contribute to the development of a boundary object—an accessible model based on STSDM—that can aid in envisioning alternative policy options. This is a crucial component for transitioning to an AM approach in policymaking.

## 2. Methodology

### 2.1. Study area

The Brahmaputra River in India contributes to almost 29% of all surface water of the country and 44% of its hydropower potential. The river along with its tributaries cover seven states of the Indian Northeast Region (NER)—Assam, Arunachal Pradesh, Meghalaya, Mizoram, Manipur, Tripura, Sikkim, and the northern parts of West Bengal. It is also a source of tension between India and China (Pandey *et al* 2020). The river has been the centre of various disputes at the transboundary, national, and sub-national levels, regarding water sharing, hydropower dam construction, political mobilizations related to ethnic identity and sovereignty, flood and riverbank erosion, failure of flood control, and population displacement and out-migration (Gohain 2008, Das *et al* 2009, Hazarika 2000, Lahiri and Borgohain 2011, Baruah 2012, Varma and Mishra 2017, Varma and Hazarika 2019, Dekaraja and Mahanta 2021).

Assam faces the most severe impact of floods and riverbank erosion in NER. After the 8.6 magnitude earthquake in 1950, large amounts of sediment were added to the Brahmaputra River, causing it to aggrade (the riverbed rose due to sediment deposition) (Sarkar and Thorne 2006). The river can only transport more sediment by widening, which has led to the formation of sand islands known as 'chars' (Sarma and Acharjee 2018) and redirected water towards the riverbanks (Thorne *et al* 1993). The river's active braided channel (multiple channels separated by sand islands) width increased by 63% from 1912 to 2020, with a significant rise in Rohmoria of 106%. From 1954 to 2011, 17 of Assam's 34 districts lost about 7% of their land due to erosion, owing to such dynamic shifts of the river, translating to around 80 km$^2$ annually, valued at USD 20 million in 2021. This loss has caused landlessness and socio-economic issues among riparian communities, displacing roughly 10 000 families each year (Das *et al* 2014, Sarma and Acharjee 2018, Pradhan *et al* 2021).

Embankments have not significantly reduced economic damage (Wasson *et al* 2020). After the completion of the embankment lengthening, there was an increase in damages between 1985 and 1990, and again between 1997 and 2003. This escalation is partly attributed to major floods, particularly in 1988, and embankment breaches. Since the 1990s, measures were implemented to control riverbank erosion by constructing spurs or groynes as extensions from the bank into the river to redirect its flow away from the bank (Baruah 2023). However, there has been no assessment of the effectiveness of such erosion control. Although one might argue that the lack of change in the average width of the Brahmaputra River between 2009 and 2020 is due to riverbank erosion control, this seems unlikely. The treated sections of the river are limited in length, the structures often fail, and the river is probably tending towards a new equilibrium in width following the disturbances that occurred in 1950 (Sarker and Thorne 2009).

Our fieldwork in the Brahmaputra Valley reveals ongoing ambiguities regarding the causes of flooding in various areas (Tortajada *et al* 2024, figures A1 and A2 in appendix 1). In the Nagaon district of Assam, downstream of the tributary named Kopili, riparian communities reported a lack of communication about excess water releases from the Kopili dam during the 2022 monsoon, greatly impacting them. However, satellite imagery has shown imbalances between the riverbed, embankment heights, and floodplains, which can lead to overtopping and delayed drainage of trapped water. Upstream in North Lakhimpur district of Assam, the morphology of the tributary named Ranganadi River has been changing since the mid-1980s, with an eastern shift of a side channel (locally referred to as 'xuti') since the mid-2000s. In response, an embankment was constructed to redirect water, coinciding with increased human settlements nearby, illustrating the 'levee effect' phenomenon (Tortajada *et al* 2024).

Despite evidence raising serious doubts about the effectiveness of current flood and erosion control measures, discussions in the Indian Parliament and Assam Legislative Assembly focus on immediate concerns such as loss and damage, funding for flood control and relief efforts, demands for 'national disaster' status for Assam floods, and general awareness of the situation (figure B and table 1 in appendix 1). Unfortunately, this narrow focus overlooks failures of flood control, lessons learned, and alternative approaches (Buurman and Wasson 2018, Fusinato *et al* 2024) such as flood-resilient structures, enhancing warning systems with community participation, and implementing flood insurance—all of which have been established or are in planning stages in the downstream riparian nation of Bangladesh (Byatt 2023).

### 2.2. Application of STSDM

This study expands on the work of Varma *et al* (2015), Varma (2016) and Varma and Mishra (2017), which involved ethnographic fieldwork and series of stakeholder workshops related to flooding and erosion in the northern bank of the upper Brahmaputra Valley (Assam) (figure 1), and builds on the ST based maps that was co-created with stakeholders. The following two steps were adapted from Sterman's (2000) modelling cycle for this study (see figure 1)

Step 1: Systems Thinking of three scales of analysis. This study begins by categorizing existing knowledge (Varma *et al* 2015, Varma 2016, Varma

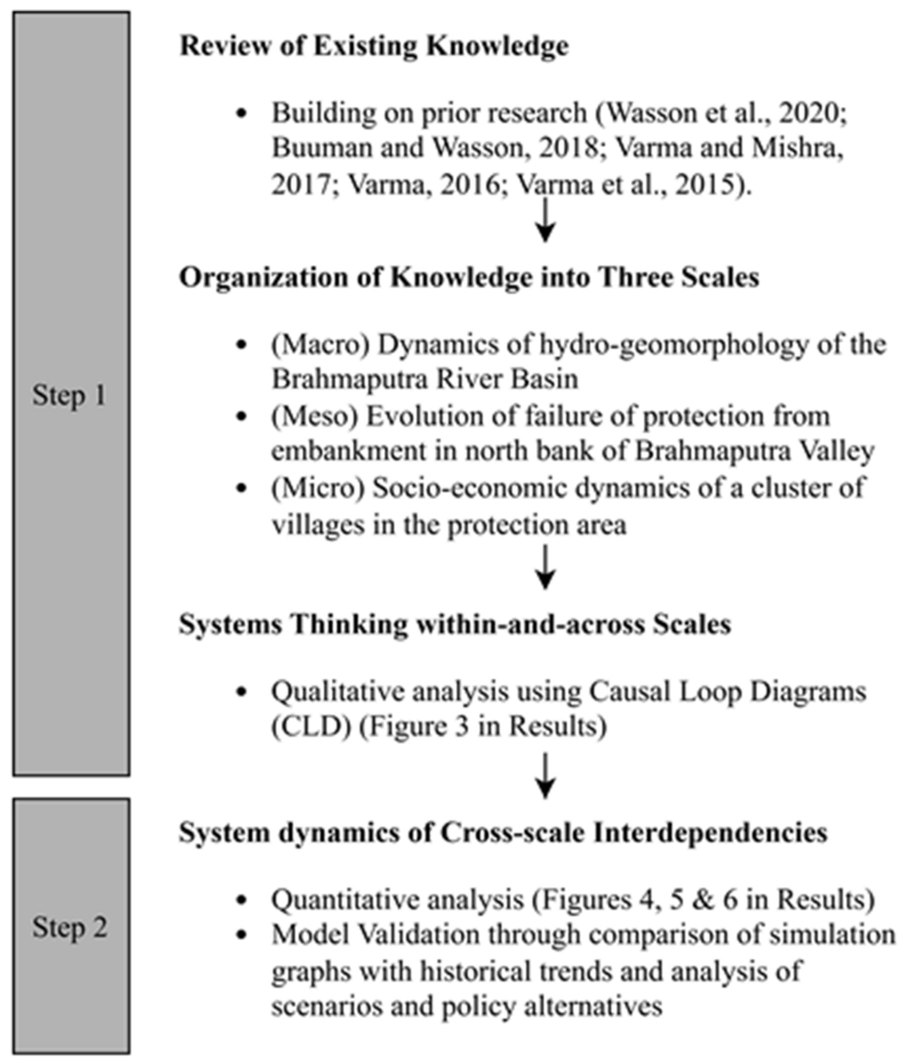


**Figure 1.** Schematic of the methodological steps followed in the study adapting Sterman's (2000) modelling cycle.

and Mishra 2017, Buurman and Wasson 2018, Wasson *et al* 2020) on the dynamics of the hydro-geomorphology of the BRB (macro scale), the evolution of flood control through the *Sissirkolghor-Tekeliphuta* embankment that traverses several administrative districts in Assam (north bank of upper Brahmaputra Valley) (meso scale), and the socio-economic dynamics of select protected villages by the embankment (micro scale) within a sub-division (Dhakuakhana) of one of the districts (Lakhimpur) (figure 2). This categorization follows the 'Panarchy' theory of multi-and cross-scale SES dynamics (Holling *et al* 2014). The complexity within each scale, macro-meso-and-micro, is examined using Causal Loop Diagrams (CLDs)—a ST mapping tool, with the VENSIM modelling software (Ventana Systems, Inc) (detailed explanation of CLDs with figure C in appendix 1). The study then employs the qualitative analysis to investigate the interdependencies across these scales to understand the issue of embankment failure and emerging landlessness in the riparian community.

Step 2: System Dynamics across the three scales of analysis. In this step, the summary CLD that emphasizes cross-scale interactions from Step 1 is transformed into a SD simulation (quantitative) model using the VENSIM software. All the primary stocks (accumulation and delays) and flows (rates of de/accumulation) are identified in the model, with summary CLD guiding the formulation of the auxiliary variables, parameters and the feedback loop mechanisms (Sterman 2000). A significant challenge in quantifying the model is the limited availability of datasets. This limitation arises from the ethnographic nature of the primary data in the micro scale (Varma 2016, Varma and Mishra 2017) as well as the general dearth of secondary data in BRB context. However, this is not a critical issue, as the model is primarily backward-looking, emphasizing the explanation of historical behaviour rather than forecasting future

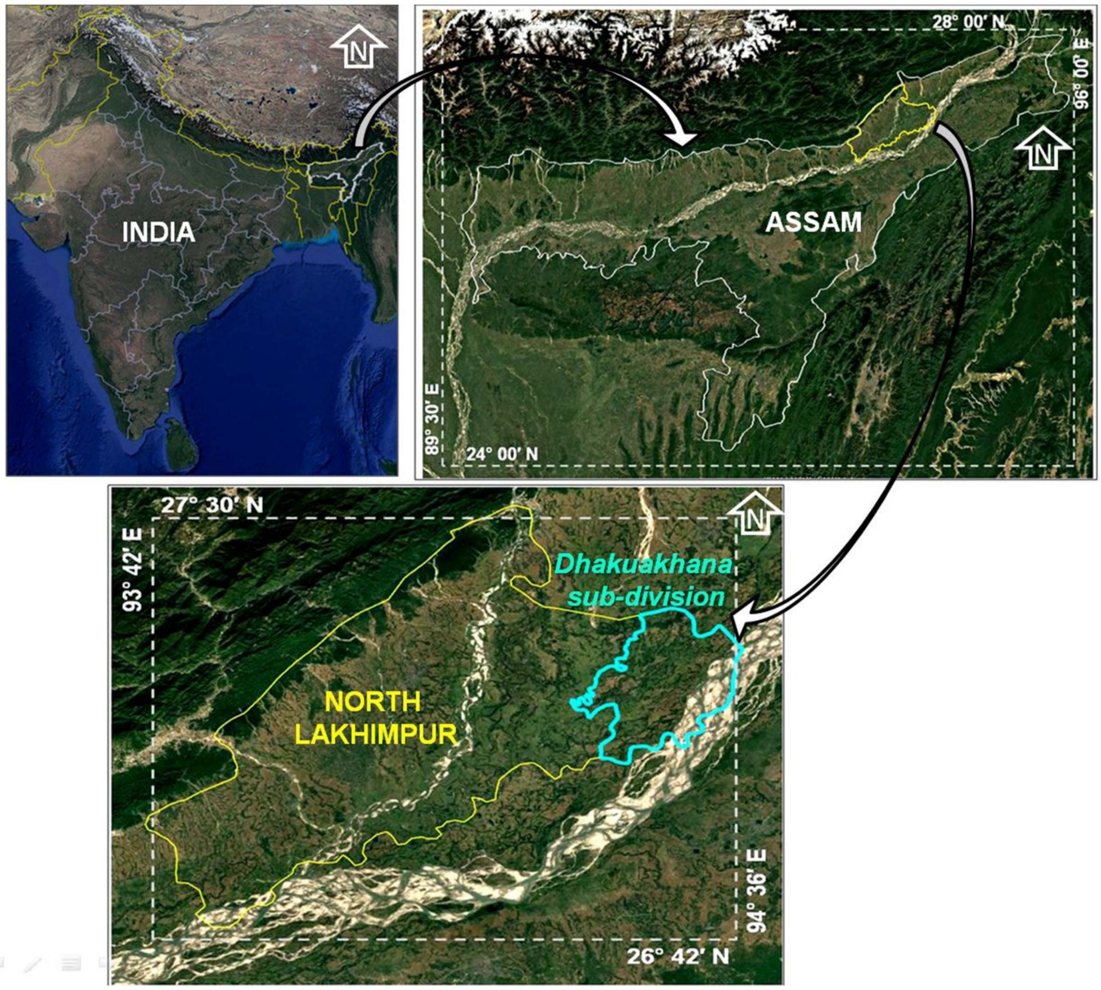


**Figure 2.** Micro: Dhakuakhana subdivision within the Lakhimpur District of Assam in India. Lakhimpur District is geographically located on the North bank of the upper Brahmaputra Valley and the cluster of villages with extreme land loss are within its Dhakuakhana sub-division. Map Data © 2024 Google Earth; Attribution: Google (2024), Landsat/Copernicus (imagery date: 5/14/2024); https://earth.google.com/web/@27.20609151,93.88668302,186.85349748a,83396.35193769d,35y,356.79955011h,0t,0r/data=CgRCAggBMikKJwolCiExLUdhWGNudHh0TlpFdm80UGo2LS1XbmV5N2t1NWVLanEgAToDCgEwQgIIAEoICMfWt8UFEAE.

behaviour. Parameters were determined through manual calibration against historical data, followed by expert evaluation from co-authors to ensure empirical plausibility. At least 20 parameters were calibrated, based on historical trends related to channel width, flood levels, and embankment failures (figure 5 and Documentation of the Model in appendix 2). Although automated calibration techniques offer better replicability and statistical fit, a manual qualitative calibration approach was chosen balancing the challenge of lack of quantitative data, the need for falsification over confirmation, and the opportunity of validation by the multidisciplinary team of co-authors. Such calibration approach may be less efficient but not necessarily less accurate (Lyneis and Pugh 1996, Oliva 2003, Ibrahim *et al* 2023). This process begins with direct calibration of parameters against closely associated variables (typically within the same scale) and extends to indirect calibration involving variables influenced by multiple parameters (often operating at different scales).

Overall, the calibrated model exhibited some numerical sensitivity but maintained behavioural robustness, confirming its effectiveness in investigating the underlying system structure and past dynamics. Therefore, the validation of the model is not focused on statistical fit but rather on structural and behavioural validity through various methods, such as extreme condition testing and behaviour sensitivity analyses (Barlas 1996, Kotir *et al* 2016), all of which involved contributions from the co-authors. The aggregated SD model from the cross-scale conceptualization (the summary model from Step 1) provides a novel simulation-based learning environment, a boundary object where scenario experiments can be conducted through parametric sensitivity tests to further explore the role of feedback loops across scales as well as policy alternatives (Sterman 2000, Naugle *et al* 2024).

## 3. Results

### 3.1. Qualitative analysis: exploring the macro-meso-and-a micro scale of BRB

*Macro* (figure C(a) in appendix 1): Before 1950, the Brahmaputra River experienced minimal change, as indicated by topographic data and local accounts. According to the least action principle (LAP) (Nanson and Huang 2018), the river operated at maximum flow efficiency, using minimal energy to transport sediment with few physical changes. After the 1950 earthquake, the river's conditions changed significantly. The increased sediment load from landslides led to a shift in the width-to-depth ratio, causing channel bed aggradation (decreased depth) and rapid widening, evident in channel braiding. This ratio serves as an indicator of sediment input and reflects the river's altered state. Our observations show that high flood levels have stabilized since 1996, indicating that channel depth is reaching a steady state. The braiding index peaked around 2010, suggesting a levelling of the channel width. While the LAP implies that changes in the Brahmaputra River channel may slow down, future uncertainties related to earthquakes and climate change remain a concern.

*Meso* (figure C(b) in appendix 1): The Assam Embankment and Drainage Act, initiated in 1954, led to the extensive use of embankments for flood control, totalling 885 km once it was implemented. The dependence on embankments for 55 years is not only questionable, but they can also slow down fine sediment reaching the flood plain (Varma and Mishra 2017, Wasson *et al* 2020). In many districts of Assam, have become spaces of refuge for riparian communities during flood disasters putting additional pressure on this infrastructure (Varma 2016, Varma and Mishra 2017).

*Micro* (figure C(c) in appendix 1): The *Misings* are a tribe living along the northern riverbank, with a culture adapted to annual floods. They traditionally kept shifting between cultivated fields in the river (*char)* islands and riverbanks, using boats and stilt houses, but factors such as a colonial land revenue system, population growth, a sense of safety from the embankments have prompted a shift to more settled agriculture. Despite this, household incomes and land availability are declining due to riverbank erosion, government land acquisition for embankment reconstruction every flood cycle, and coarse sediment deposition after floods. Villagers can claim compensation for land acquired for rebuilding embankments after breaches but not for lost land due to erosion, as this is not recognized as a disaster in Indian disaster management policies (Varma *et al* 2015, Varma and Mishra 2017).

A cultural aversion to paying land revenue, stemming from the historical belief that riverbank areas are 'waste lands,' has resulted in a lack of individual land ownership among the tribe. This raises doubts about compensation claims for land acquired by the government for embankment. Uncertainty around these claims and poor communication about lack of compensation from riverbank erosion contribute to perceptions of irregular compensation payments in the community. Furthermore, there is reluctance to move to resettlement areas due to inadequate land for the *Mising* tribe's join family structure and/or fears of relocating to non-tribal regions. Ongoing problems of landlessness, ineffective embankment maintenance, insufficient compensation, and limited livelihood opportunities are leading to protests, which further delay the maintenance and reconstruction of flood control infrastructure (Varma and Mishra 2017).

The interdependencies between the macro, meso, and the micro scales are further explored in a Summary CLD, figure 3 (explanation of feedback loops in table 2 in appendix 1).

### 3.2. Quantitative analysis: formulating and experimenting a SD model to explore cross-scale dynamic complexity

The summary CLD (figure 3) is then transformed into a Stock and Flow diagram (figure 4) which is used for formulation of a SD model (appendix 2). Figure 4 illustrates the main structure of the model 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-hydro-geomorphological system such as the BRB.

To validate this SD model (Barlas 1996), we compared the model generated simulation graphs of the width and HFLs of the river (macro) with the real-world graphs constructed through the triangulation of historical, theoretical, and current observed patterns of the main channel of the river in the upstream Brahmaputra Valley (figure 5). A similar comparison was conducted for observed patterns (Varma and Mishra 2017) and simulation graphs of embankment breach events in the village cluster on the North bank (micro) (figure 5). The real-world patterns for width and HFLs were developed by combining GIS-based surveys with actual measurements conducted

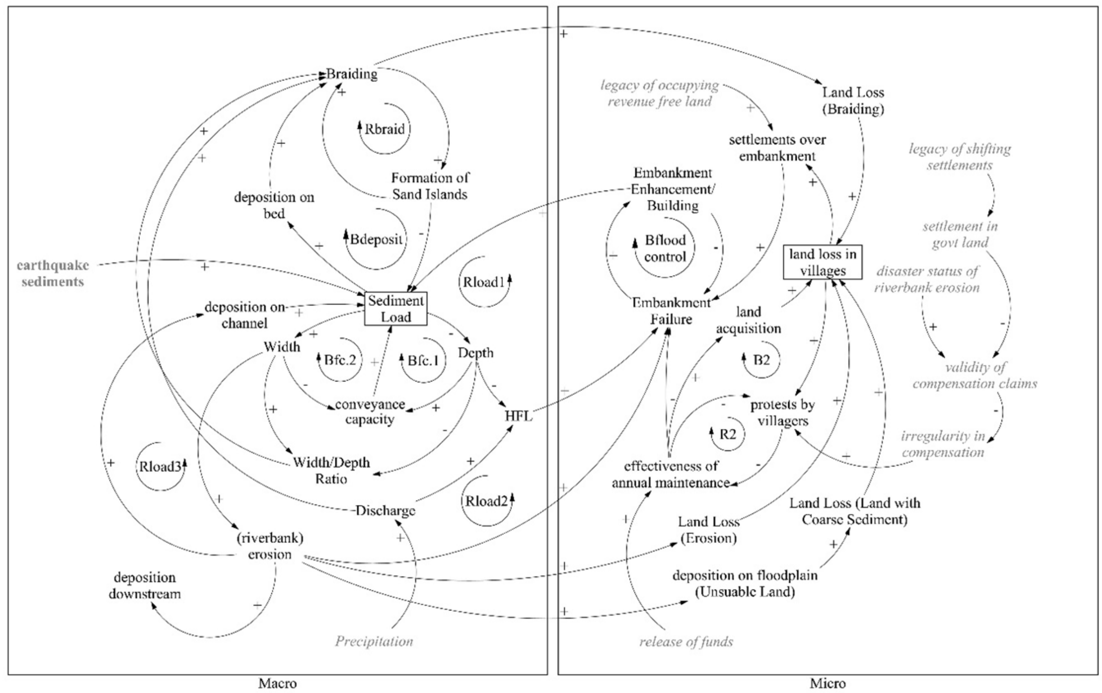


**Figure 3.** Summary CLD exploring cross-scale cause-effect-feedback loop relations (system structure) driving a shift from flood to land loss problems in villages on the North bank in the upstream Brahmaputra Valley. See the explanation of feedback loops in table 1 (appendix 1).

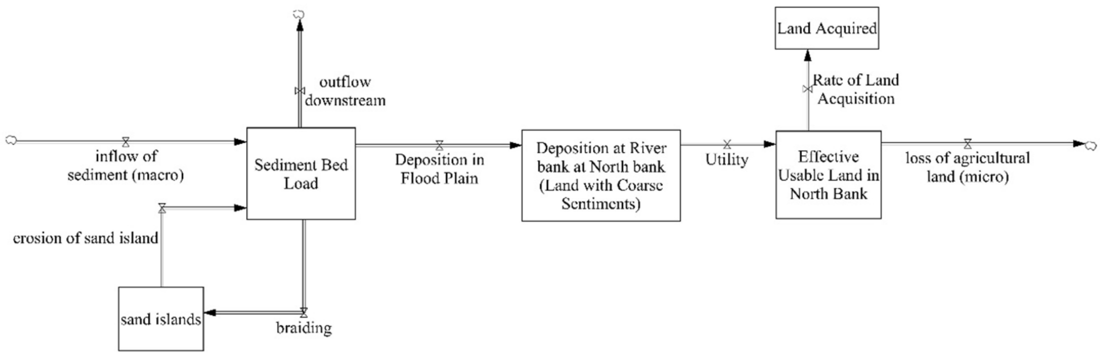


**Figure 4.** Stock and flow diagram (see details of system dynamics model in appendix 2).

as part of ongoing research by a co-author in collaboration with regional experts at Dibrugarh University in Assam. Historical data from 1970 to 2016 reveal behavioural changes in the river channel that follow the great earthquake of 1950. While the patterns require further validation through empirical research, they align with the LAP theory (see macro of quantitative analysis). The system dynamics model was simulated for an additional 40 years to explore scenarios and analyse changes.

The goal-seeking behaviour of the width and HFLs in the SD simulation (figure 5) adheres to the LAP theory, and the frequency of embankment breaches corresponds with actual breach cases (figure 5). Beyond visual comparisons of real-world patterns and simulation trends, we conducted an extreme condition test as part of structure-oriented behaviour validation (Barlas 1996) (figure D in appendix 1).

Three most important findings from the scenario experiments, performed after validation of the SD model, are categorized below as (1) cross-scale impact, (2) need for innovations, and (3) policy alternatives.

(1) Cross-scale impact (micro to meso): Feedback loops R2 (R-Reinforcing change) and B2 (B-Balancing change) in the Summary CLD

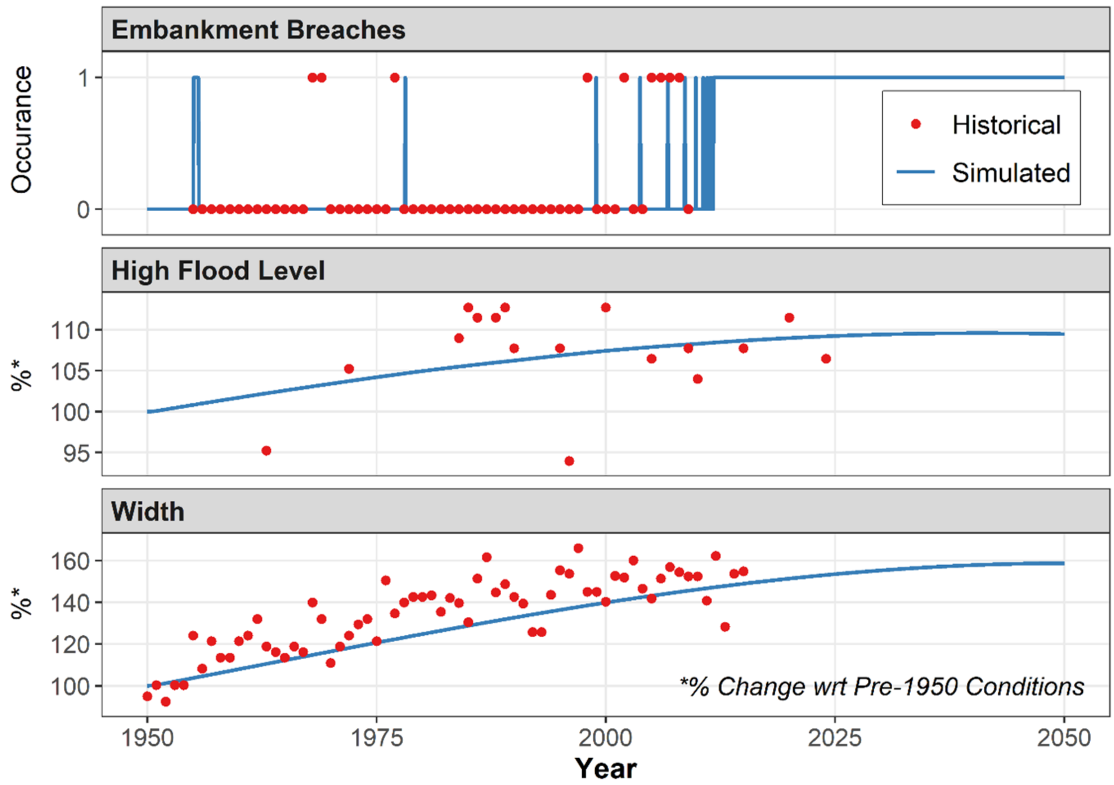


**Figure 5.** Comparison of the patterns of river channel width, HFLs in the Dibrugarh area of Assam (macro scale) and embankment breach incidents in the North bank villages of the same upstream region of the Valley (micro scale) with the model generated simulation graphs.

(figure 3 here and table 2 in appendix 1) and SD model (appendix 2) demonstrate that village-scale (micro) events can affect the effectiveness of embankments (meso), particularly regarding embankment breach occurrences. The simulation shows that after reducing the impact of village protests by 80% in the model, the frequency of breaches decreases significantly after 1998, as illustrated in scenario 1 (figure E1 in appendix 1). This suggests that local actions can disrupt embankment policy effectiveness. The embankment breaches can increase the protests due to discontent driven by embankment failures, land loss and inconsistencies in compensation for land loss (R2 loop in table 2, and figure E2 in appendix 1).

(2) Need for innovations: The model simulation shows an increase in sand islands (figure E2 in appendix 1), which maybe be interpreted as an increase in total land area by a reconnection of such islands with the floodplains, a phenomenon observed by co-authors with expertise in geology, but the lack of land surveys makes it uncertain. At the same time, simulations illustrate the decline of productive land in villages which is consistent with Varma and Mishra (2017). This decline, along with the growth of islands, underscores the need for innovations in land use strategies.

(3) Policy alternatives: The above two scenarios further motivated towards testing the SD model with four policy alternatives (figure 6):

- Policy 1: Utilization of land deposited with coarse sediment.
- Policy 2: Innovations in land use.
- Policy 3: A re-design of flood plains with range of options ranging from embankments with floodgates to relieve the thrust of flood water, restoration of wetlands to create a buffer for flood, and land use planning by separation of zones for intentional floods and settlements.
- Policy 4: Combination of all the above three.

The results of the policy experiments, summarized in figure 6 (table 3 in appendix 1), show significant improvements in effective usable land and a reduction in embankment breaches when implementing the combination of policy alternatives (referred to as Policy 4 above).

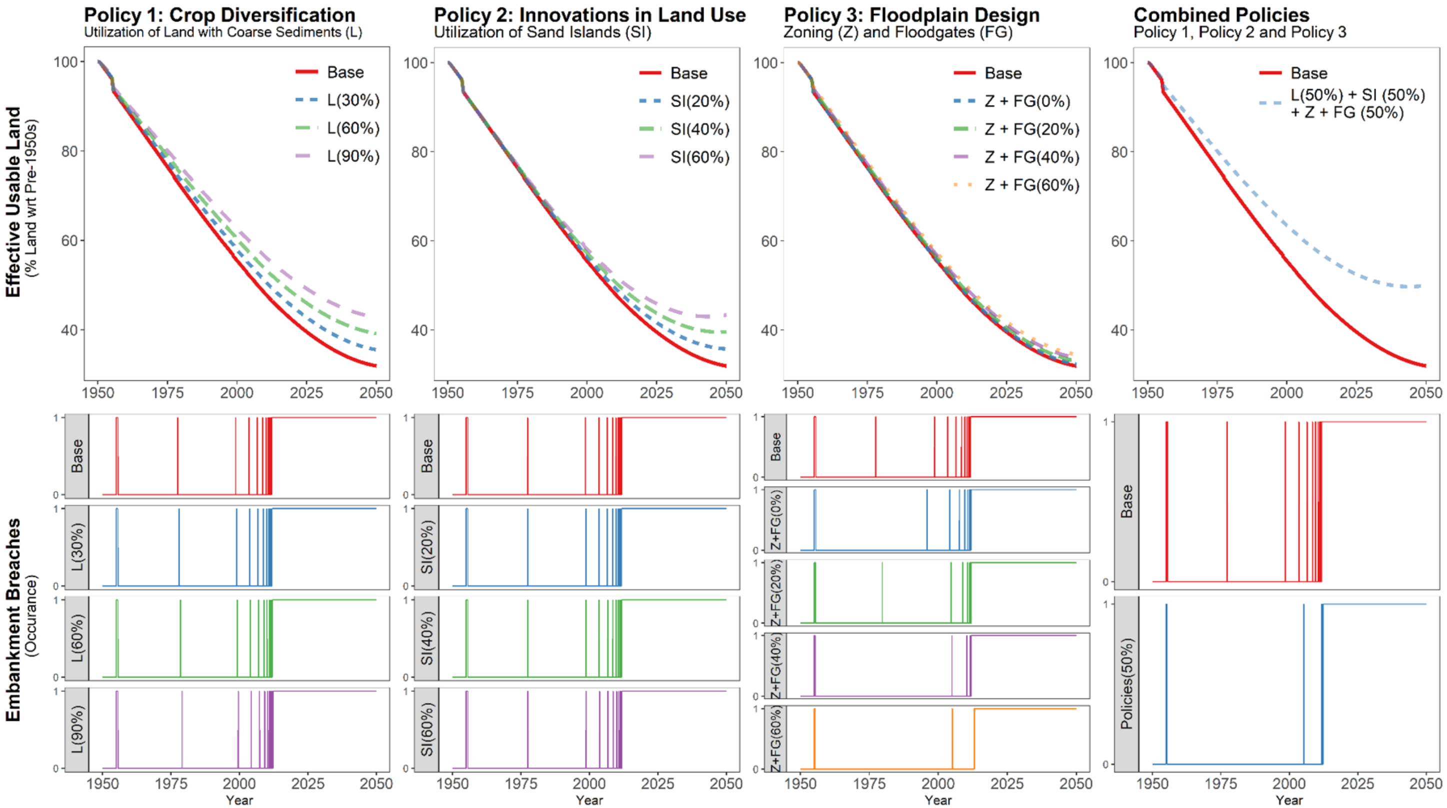


**Figure 6.** The model is tested with four policy alternatives to examine the changes in 'effective usable land' in villages and 'embankment breaches.

## 4. Discussion and conclusion

The findings of this study highlight the need for a paradigm shift towards AM and point to the limitations of conventional flood control measures in the Brahmaputra Basin. The scenario experiments illustrate the exacerbation of vulnerability of the riparian community to flood and bank erosion due to the reinforcing loop between the embankment breaches and the village level protests. This dynamic aligns with research by Varma and Mishra (2017), which points to the unintended consequences of embankments, including people settling in high-risk areas due to a false sense of security. STSDM effectively reveals these cross-scale interactions, offering a more nuanced understanding of the interdependencies between river morphology, flood control infrastructure, and socio-economi c conditions.

A key insight from the study is the need to explore alternative land-use strategies that align with river dynamics rather than resisting them. The simulation demonstrates the potential for an increase in sand islands and char formations that can be interpreted as an increase in total land area through reconnection of such islands with floodplain, a phenomenon observed in the study area. However, the continued decline of productive agricultural land in villages underscores the urgency of exploring innovative land-use solutions. This finding is particularly relevant given the historical lack of systematic land studies in Assam since 1964 (Anand 2017), which limits policymakers' ability to design informed interventions.

The policy experiments further illustrate the effectiveness of an integrated approach. A combination of three strategies—utilization of land covered with coarse sediment, innovations in land use, and floodplain redesign—emerged as the most viable approach for mitigating land loss and embankment failures. Policy 4 (the combination of these three elements) resulted in significantly more usable land and fewer embankment breaches. This suggests that future flood management strategies should focus on multi-level interventions rather than isolated engineering solutions. The integration of climate resilient interventions that benefit the lives and livelihoods of riparian communities— like crop diversification, sandbar cropping, and hybrid renewable energy systems (Maibangsa *et al* 2015, Chowdhury 2016, Zhou *et al* 2024) together with wetland restoration, and zoning for intentional flooding, could provide a more sustainable approach to managing flood risks in the basin. However, this calls for a transformation from a control paradigm to alternative concepts such as 'making room for the river,' 'living with water,' 'river restoration,' and 'floodplain design' which will include planned resettlement initiatives (Muhar *et al* 2018, Pew Charitable Trusts 2019, Bogdan *et al* 2022, Nardini 2022).

The study also points to the socio-political barriers to such transformation. The reluctance of tribal communities to relocate due to cultural and economic constraints presents a significant challenge to planned resettlement initiatives. Similar resettlement efforts in Odisha in India, Bangladesh, and Indonesia provide valuable lessons, but they must be carefully adapted to the local context, different land availability and political sensitivities (Baruah 2023, Dash and Roul 2024, Meshkani 2024). The dearth of formal land ownership among riparian communities, stemming from colonial influence on land policies and historical perceptions of riverbank areas as 'waste lands' (Varma and Mishra 2017), complicates compensation and adaptation efforts. Addressing these governance issues will be critical for the success of any new flood management strategy.

This study, along with previous fieldwork elsewhere in Brahmaputra Valley (Tortajada *et al* 2024), points to the repercussions of miscommunication and lack of communication and coordination. Ongoing ambiguity regarding the causes of flooding, particularly concerning dam releases and embankment breaches, and uncertainty regarding the disaster status of riverbank erosion, have led to problems of coordination and trust between street level bureaucrats, policymakers, and local communities, exacerbating vulnerability to flood hazards. Strengthening participatory governance through incorporating problem-solving and co-design of solutions using boundary objects like models could help address such wicked problems (Markowska *et al* 2020).

Our findings also underscore the need for continuous learning and policy adaptation. Our simulations follow the LAP (Nanson and Huang 2018), which suggests that river morphology may be stabilizing, but uncertainties remain related to future climate change and seismic activity. Thus, policies must remain flexible and responsive to emerging risks such as STSDM support scenario planning and experimentation, enabling policymakers to test alternative strategies and assess their long-term implications. By treating policies as hypotheses that must be tested and refined over time, AM provides a framework for more resilient and adaptive flood management.

This study has several limitations. The SD model relies on calibrated estimates for parameter values and does not explicitly account for forestry dynamics or climate change projections. Also, the model treats time as continuous, whereas hydrogeomorphological changes occur over centuries, and socio-economic dynamics can shift within months or years. Future research should refine the model by incorporating climate projections, expanding empirical data collection on sediment quality and land use, and engaging with local stakeholders to validate findings and explore implementation pathways.

In conclusion, this study highlights the limitations of conventional flood control measures in the Brahmaputra Basin and presents a compelling case for shifting towards an AM approach. By integrating systems thinking, participatory governance, and multi-level interventions, policymakers can develop more sustainable and resilient flood management strategies. The findings call for a reorientation of flood policies away from rigid infrastructure towards more flexible and adaptive solutions that account for social-hydro-geomorphological dynamics, socio-political constraints, and community needs. Translating these insights into pilot projects and scaling up successful interventions will be critical to achieving long-term resilience in the Brahmaputra Valley.

While we do not claim that the *results* of this analysis can be applied to other riparian nations of the river system- China, Bhutan or Bangladesh, this *method* could certainly be used there. A similar boundary object could be developed to encourage transboundary analysis to address the current tensions between the four riparian countries—China, Bhutan India, and Bangladesh—over water resources and flood management, while also considering geopolitical factors. However, such an analysis would differ significantly from the one presented here.

## Data availability statement

No new data were created or analysed in this study.

## ORCID iDs

Navarun Varma https://orcid.org/0009-0003-2296-1160
Ryan Tan https://orcid.org/0000-0003-2376-3919
Robert J Wasson https://orcid.org/0000-0003-4318-1182
Cecilia Tortajada https://orcid.org/0000-0001-6308-4924
Raghupratim Rakshit https://orcid.org/0000-0002-2922-7255
Abhinandan Saikia https://orcid.org/0000-0001-8648-0567

## References

Anand M 2017 No land study in Assam since 1964: report *The Asian Age*

Barlas Y 1996 Formal aspects of model validity and validation in system dynamics *Syst. Dyn. Rev.* **12** 183–210

Baruah M 2023 The political ecology of an environmental crisis in the Brahmaputra Valley, Assam *Ecol. Econ. Soc. INSEE J.* **6** 121–45

Baruah S 2012 Whose river is it anyway? Political economy of hydropower in the Eastern-Himalayas *Econ. Polit. Wkly.* **47** 41–52

Best J, Ashmore P and Darby S E 2022 Beyond just floodwater *Nat. Sustain.* **5** 811–3

Biggs R, De Vos A, Preiser R, Clements H, Maciejewski K and Schlüter M 2021 *The Routledge Handbook of Research Methods for Social-Ecological Systems* (https://doi.org/10.4324/9781003021339)

Bogdan E A, Beckie M A and Caine K J 2022 Making room for nature? Applying the Dutch Room for the River approach to flood risk management in Alberta, Canada *Int. J. River Basin Manage.* **20** 153–65

Buurman J J G and Wasson R J 2018 The levee effect: an analysis on the Brahmaputra River *IWA World Water Congress and Exhibition* (*Tokyo, Japan*)

Byatt G 2023 Managing flooding risk in Bangladesh: key points (available at: https://disastersavoided.com/floods-bangladesh)

Caccamo M, Pittino D and Tell F 2023 Boundary objects, knowledge integration, and innovation management: a systematic review of the literature *Technovation* **122** 102645

Cash D W, Adger N W, Berkes F, Garden P, Lebel L, Olsson P, Pritchard L and Young O 2006 Scale and cross-scale dynamics: governance and information in a multilevel world *Ecol. Soc.* **11** 8

Checkland P 2000 Soft systems methodology: a thirty-year retrospective *Syst. Res. Behav. Sci.* **17** S11–S58

Chowdhury N I 2016 Sandbar cropping in Bangladesh, an innovative technology solution for millions (available at: https://peoplefoodandnature.org/blog/sandbar-cropping-in-bangladesh-an-innovative-technology-solution-for-millions/)

Das P J, Chutiya D and Hazarik N 2009 Adjusting to floods on the Brahmaputra plains, Assam, India (International Centre for Integrated Mountain Development) (available at: https://lib.icimod.org/record/8025)

Das T K, Haldar S K, Gupta I D and Sen S 2014 River bank erosion induced human displacement and its consequences *Living Rev. Landsc. Res.* **8** 1–35

Dash B and Roul A 2024 Cyclone Dana exposes climate-resilient resettlement processes in Odisha Down To Earth (available at: https://www.downtoearth.org.in/climate-change/cyclone-dana-exposes-climate-resilient-resettlement-processes-in-odisha) (Accessed 5 May 2025)

Dekaraja D and Mahanta R 2021 Riverbank erosion and migration inter-linkage: with special focus on Assam, India *Environ. Syst. Res.* **10** 2–10

Di Baldassarre G, Viglione A, Carr G, Kuil L, Yan K, Brandimarte L and Bloschl B 2015 Debates-Perspectives on socio-hydrology: capturing feedbacks between physical and social processes *Water Resour. Res.* **51** 4770–81

Dunham J B, Angermeier P L, Crausbay S D, Cravens A E, Gosnell H, McEvoy J, Moritz M A, Raheem N and Sanford T 2018 Rivers are social–ecological systems: time to integrate human dimensions into riverscape ecology and management *WIREs Water* **5** e1291

Fusinato E, Han S, Kobiyama M and de Brito M M 2024 Safe development paradox: evidence and methodological insights from a systematic review *Nat. Hazards* **120** 13693–714

Gamble R, Tan G G, Xu H, Beavis S, Maurer P, Pittock J, Powers J and Wasson R J 2024 *Rivers of the Asian Highlands: From Deep Time to the Climate Crisis* (Routledge)

Gohain H 2008 Big dams, big floods: on predatory development *Econ. Polit. Wkly.* **43** 19–21 (available at: www.jstor.org/stable/40277761)

Hazarika S 2000 *Strangers of the Mist: Tales of War And Peace From India's Northeast* (Penguin India)

Herrera de Leon H J and Kopainsky B 2020 Do you bend or break? System dynamics in resilience planning for food security *Syst. Dyn. Rev.* 35

Herrfahrdt-Pähle E 2014 Applying the concept of fit to water governance reforms in South Africa *Ecol. Soc.* **19** 25

Hoekstra A Y, Bredenhoff-Bijlsma R and Krol M S 2018 The control versus resilience rationale for managing systems under uncertainty *Environ. Res. Lett.* **13** 103002

Holling C S, Allen C R, Angeler D G, Garmestani A S and Gunderson L H 2014 Panarchy: theory and application *Ecosystems* **17** 578–89

Hugo J and Kopainsky B 2019 Do you bend or break? System dynamics in resilience planning for food security *Syst. Dyn. Rev.* **35** 287–309

Ibrahim A, Kadir A, Asmawaty T, MacDonald R and Daniyal H 2023 Hand calibration with limited data as the initial step towards system dynamics model validation for COVID-19 case In Malaysia *In: IEEE 8th Int. Conf. On Software Engineering and Computer Systems (ICSECS)* (*Penang, Malaysia, 25–27 August*) pp 200–4

Kotir J H, Smith C, Brown G, Marshall N and Johnstone R 2016 A system dynamics simulation model for sustainable water resources management and agricultural development in the Volta River Basin, Ghana *Sci. Total Environ.* **573** 444–57

Lahiri S K and Borgohain J 2011 Rohmoria's challenge: natural disasters, popular protests and state apathy *Econ. Polit. Wkly.* **46** 31–35 (available at: www.jstor.org/stable/27918011)

Lane D C 2024 Engaging with diverse worldviews using system dynamics *Syst. Res. Behav. Sci.* **41** 1–6

Lazurko A, Schweizer V and Armitage D 2023 Exploring "big picture" scenarios for resilience in social–ecological systems: transdisciplinary cross-impact balances modeling in the Red River Basin *Sustain. Sci.* **18** 1773–94

Lyneis J M and Pugh A L 1996 Automated vs. "hand" calibration of system dynamics models: an experiment with a simple project model *Proc. 1996 Int. System Dynamics Conf., System Dynamics Society* (*Cambridge, MA*) ed G P Richardson and J D Sterman pp 317–20

Maibangsa S, Borah N, Maibangsa M, Sharma K and Chowdhury D 2015 Characterization of sand-silt deposition in agricultural land of Dhemaji and Lakhimpur districts of Assam, India, and evaluation for crop suitability *J. Sci. Environ. Today* **1** 33–41

Mao F, Clark J, Karpouzoglou T, Dewulf A, Buytaert W and Hannah D 2017 HESS opinions: a conceptual framework for assessing socio-hydrological resilience under change *Hydrol. Earth Syst. Sci.* **21** 3655–70

Markowska J, Szalińska W, Dąbrowska J and Brząkała M 2020 The concept of a participatory approach to water management on a reservoir in response to wicked problems *J. Environ. Manage.* **259** 109626

Meshkani T 2024 Climate change and flooding: governmental responses to displacement and relocation in Jakarta's informal neighborhoods *Int. J. Disaster Resil. Built Environ.* **15** 551–70

Muhar S, Sendzimir J, Jungwirth M and Hohensinner S 2018 Restoration in integrated river basin management *Riverine Ecosystem Management* (*Aquatic Ecology Series*) vol 8, ed S Schmutz and J Sendzimir (Springer) (https://doi.org/10.1007/978-3-319-73250-3_15)

Nanson G C and Huang H Q 2018 A philosophy of rivers: equilibrium states, channel evolution, teleomatic change and least action principle *Geomorphology* **302** 3–19

Nardini A G C 2022 Making room for our forthcoming rivers *Water* **14** 1220

Naugle A, Langarudi S and Clancy T 2024 What is (quantitative) system dynamics modeling? Defining characteristics and the opportunities they create *Syst. Dyn. Rev.* **40** e1762

Oliva R 2003 Model calibration as a testing strategy for system dynamics models *Eur. J. Oper. Res.* **151** 552–68

Pahl-Wostl C 2007 Transitions towards adaptive management of water facing climate and global change *Water Resour. Manage.* **21** 49–62

Pandey A, Prakash A, Barua A, Syed A and Nepal S 2020 Upstream-downstream linkages in Ganges-Brahmaputra-Meghna basin: the hydro-social imperatives *Water Policy* **22** 1082–97

Perry D, Praskievicz S, McManamay R, Saxena A, Grimm K, Zegre N, Bair L, Ruddell B L and Rushforth R 2024 Resilient riverine social–ecological systems: a new paradigm to meet global conservation targets *WIREs Water* **11** e1753

Pew Charitable Trusts 2019 Washington partnership fosters innovative floodplain management (available at: www.pewtrusts.org//media/assets/2019/11/washington_partnership_fosters_brief_final.pdf)

Pradhan N S, Das P J, Gupta N and Shrestha A B 2021 Sustainable management options for healthy rivers in south Asia: the case of Brahmaputra *Sustainability* **13** 1–23

Rahman K A U and Reza I 2012 Accessing and retaining access to the sandbars by the extreme poor: experiences from the practical action project *Working Paper No. 9* (*Dhaka, Bangladesh*) p 28

Sarkar M H and Thorne C R 2006 *Morphological Response of the Brahmaputra–Padma–Lower Meghna River System to the Assam Earthquake of 1950* ed G H S Smith, J L Best, C S Bristow and G E Petts ch 14 (https://doi.org/10.1002/9781444304374.ch14)

Sarker M H and Thorne C R 2009 Morphological response of the Brahmaputra-Padma-Lower Meghna river system to the Assam earthquake of 1950 *Braided Rivers: Process, Deposits, Ecology and Management* ed G H S Smith, J L Best, C S Bristow and G E Petts (Blackwell Publishing) pp 289–310

Sarma J N and Acharjee S 2018 A study on variation in channel width and braiding intensity of the Brahmaputra River in Assam, India *Geosciences* **8** 343

Sendzimir J, Magnuszewski P and Gunderson L 2018 Adaptive management of riverine socio-ecological systems *Riverine Ecosystem Management: Science for Governing Towards a Sustainable Future* ed S Schmutz and J Sendzimir (Springer) pp 301–24

Sendzimir J and Schmutz S 2018 Challenges in riverine ecosystem management *Riverine Ecosystem Management: Science for Governing Towards a Sustainable Future* ed S Schmutz and J Sendzimir (Springer) pp 1–16

Senge P M 1990 *The Fifth Discipline: The Art and Practice of the Learning Organization* (Doubleday/Currency)

Sterman J D 2000 *Business Dynamics: Systems Thinking and Modeling for a Complex World* (McGraw-Hill)

Thorne C R, Russell A P G and Alam M K 1993 Planform pattern and channel evolution of the Brahmaputra River, Bangladesh *Geol. Soc.* **75** 257–76

Tortajada C, Varma N, Rakshit R and Rahman M Z 2024 Resilience and adaptation to climatic and non-climatic factors: role of large dams in India. Centre for International Development Grants 2022 *Final Project Report* (University of Glasgow)

Tschakert P, Das P J, Pradhan N S, Machado M, Lamadrid A, Buragohain M and Hazarika A 2016 Micropolitics in collective learning spaces for adaptive decision making *Glob. Environ. Change* **40** 182–94

Varma N 2016 Disaster and governance in the Brahmaputra Basin of India: a case study of an ecological surprise within Assam *PhD Thesis* TERI University, Department of Policy Studies (available at: hdl.handle.net/10603/139534)

Varma N and Hazarika S 2019 Bridges and barriers for governance of water resources in South Asia—Insights from Brahmaputra Basin in India *Climate Change Governance and Adaptation* ed A Barua, V Narain and S Vij (CRC Press) pp 161–82

Varma N, Kelkar U, Bhardwaj S, Singh P and Mishra A 2015 Climate change, disasters and development: testing the waters for adaptive governance in India *Vision* **18** 327–38

Varma N and Mishra A 2017 Discourses, narratives and purposeful action—Unraveling the social-ecological complexity within the Brahmaputra Basin in India *Environ. Policy Governance* **27** 207–28

Vennix J A M 1996 *Group Model Building: Facilitating Team Learning Using System Dynamics* (Wiley)

Vij S, Warner J F, Biesbroek R and Groot A 2020 Non-decisions are also decisions: power interplay between Bangladesh and India over the Brahmaputra River *Water Int.* **45** 254–74

Wasson R, Saikia A, Bansal P and Joon C C 2020 Flood mitigation, climate change adaptation and technological lock-In in Assam *Ecol. Econ. Soc. INSEE J.* **3** 83–104

Zhou Y, Chaudhary S, Hutton C and Rahman T 2024 Techno-economic and sensitivity analysis of floating photovoltaics for river island communities in Bangladesh *Energy Sustain. Dev.* **83** 101539