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Mapping Flood Hazard and Resilience under Riverine Sand and Gravel Mining Conditions in a Coastal Flood Catchment: Case Study of Jagatsinghpur, India

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ABSTRACT

Floods are among the most devastating natural disasters worldwide, with their frequency and intensity increasingly amplified by climate change and anthropogenic activities. The Intergovernmental Panel on Climate Change (IPCC), in its Sixth Assessment Report (AR6), emphasises the urgent need to enhance flood resilience to mitigate escalating risks. In the Global South, particularly in India, rapid urbanisation and infrastructure expansion have driven unprecedented demand for construction materials, making riverine sand (and gravel) mining (RSM) a critical environmental concern. Although RSM is known to modify river morphology, sediment transport, and flow hydraulics, its influence on flood resilience remains largely unexplored, especially in coastal fluvial systems. This study investigates the impacts of RSM on flood *hazard* and *resilience* along a reach of the Devi River in Jagatsinghpur district, Odisha, India - an area characterised by extensive instream sand mining, high sediment availability, and recurrent fluvial flooding influenced by coastal processes. An integrated framework combining 1D–2D coupled hydrodynamic modelling and geospatial analysis is employed to assess flood *hazard* and *resilience* for varying return levels under two scenarios: (i) pre-sand mining (natural channel conditions) and (ii) post-sand mining (altered riverbed conditions due to channel incision). The results reveal that upstream reaches experience localized reductions in flood hazard due to enhanced channel conveyance, whereas downstream sections exhibit a convergence of higher flood hazard and lower resilience. Under extreme conditions, high-hazard classes expand to nearly 50% of the study area, while low-resilience classes increase to 55–60%. Concentrated upstream sand mining along the Devi River amplifies downstream flood risk, particularly affecting settlements and agricultural lands in the Naugaon and Balikuda talukas. Overall, RSM emerges as a longitudinal flood risk amplifier, underscoring the need to integrate resilience metrics into flood risk assessments. The proposed framework offers the first transferable insights to support sustainable flood management and informed policy formulation in sand-mining-affected river basins.

KEYWORDS: Flood Hazard, Flood Resilience, Hydrodynamic modelling, River Sand Mining

1 INTRODUCTION

Flood hazards constitute a paramount global challenge, with their increasing frequency, magnitude, and socio-economic devastation widely attributed to anthropogenic climate change and direct human modifications of hydrological systems *(IPCC, 2022).* The Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change explicitly identifies intensification of the hydrological cycle and increased flood risk in many regions as key consequences of global warming *(IPCC, 2022)*. In response, the paradigm of flood risk management has progressively shifted from traditional defencecentric approaches towards the concept of resilience that focuses on *"living with floods" and is* defined as the capacity of a system to absorb disturbance and recover quickly from the flooding event *(Folke, 2006; Schelfaut et al., 2011; Linkov et al., 2014).* However, the accurate mapping and assessment of resilience is critically undermined when significant anthropogenic geomorphic alterations are omitted from analytical frameworks. Among these alterations, River sand and gravel mining (RSM) has escalated into a global environmental crisis, driven by the insatiable demand for construction aggregates from rapid urbanisation and infrastructure development *(Torres et al., 2017; Bendixen et al., 2019).* The impacts of RSM on riverine systems are profound and well-documented in the geomorphological literature *(Singh et al., 2025).* Unscientific and unregulated extraction leads to channel incision and head cut propagation, bank destabilisation, alteration of bed topography, and disruption of sediment mass balance *(Kondolf, 1997; Rinaldi et al., 2005; Hackney et al., 2020).* These morphological changes directly modify hydraulic parameters, including flow velocity, stage-discharge relationships, and flow resistance, ultimately influencing flood wave propagation and inundation dynamics *(Martin-Vide et al., 2010; Bhuiyan et al., 2017).* Despite robust evidence of RSM's hydro-geomorphic impacts, a significant research gap exists at the critical intersection of RSM activity and quantification of flood resilience. Most resilience assessments focus on climatic variables, land-use/land-cover change, impacts of adaptive measures and socio-economic factors *(de Moel et al., 2015; Tellman et al., 2021; Meerow & Newell, 2019),* while treating RSM as a localised disturbance rather than a catchment-scale driver of flood regime alteration.

However, no prior studies have explicitly attempted to quantify flood *hazard* and flood *resilience* under RSM scenarios on a multi-hazard coastal flood-prone catchment with a comprehensive flood simulation exercise. This gap is particularly acute in the Global South, where regulatory enforcement is often weak, and the pressure on riverine resources is extreme *(Meredith, 2020).* India presents a critical and compelling context for this investigation. As one of the world's largest consumers of sand *(UNEP, 2019),* its river networks are under severe stress from indiscriminate mining. This coincides with high exposure to flooding, especially in populous coastal-deltaic regions where fluvial and coastal processes interact to compound risk *(Guhathakurta et al., 2020).* The Mahanadi River basin in Odisha is a quintessential example. It is frequently ravaged by monsoonal floods while its distributaries, such as the Devi River, are hotspots for extensive sand mining due to favourable sedimentology and proximity to urban markets *(Padhan, 2021).* The Jagatsinghpur district, situated within this coastal catchment, thus embodies a complex socio-hydrological system where the imperative for flood *hazard* and *resilience* is directly challenged by the pervasive practice of RSM.

This study posits that RSM is a first-order control on contemporary flood dynamics around fluvial systems and that omitting its effects leads to a significant underestimation of flood *resilience* and *hazard* patterns in modern-day flooding events influenced by anthropogenic influence. To test this, we integrate high-resolution geospatial analysis with advanced hydrodynamic modelling to map and quantify flood resilience under pre- and post-RSM scenarios at a very fine grid scale. Our present research is guided by two primary objectives: (1) to set up a 1D-2D coupled flood model to generate flood inundation extent, depth, and hydraulic parameters under pre-mining (baseline) and post-mining (future) conditions, and (2) to develop and apply a spatially explicit multi-dimensional flood resilience assessment framework that can be applied to any mined catchments. By bridging the disciplines of fluvial geomorphology, flood modelling, and risk science, this work aims to provide empirical evidence and a transferable methodology for assessing flood *hazard* and *resilience* in mined river catchments. The findings are intended to inform targeted policy and management interventions that reconcile resource extraction with sustainable flood management in dynamic coastal environments, particularly in areas with growing RSM activities.

2 MATERIALS

2.1 Study Area

Our Study was conducted on a reach of the Devi River in Jagatsinghpur district, Odisha, Eastern Coastal India *(Figure 1).* According to sources *(Web-1, Web-2, Web-3, and Web-4),* unchecked sand mining activities have triggered severe environmental consequences across 18 sand ghats (quarries) spanning over several tehsils (administrative sub-district units, locally also referred to as talukas), within the district. Heavy vehicles, such as cranes and trucks, are the primary method for excavating sand from riverbeds on the study reach. This unchecked mining has accelerated soil erosion along the Devi River, posing significant risks to villages settled nearby. As reported in *Web-1* and *Web-3*, deep digging and drilling have led to the formation of ponds, which have increased the risk of the river changing its course during floods over the past years. Flanked by the coast and marked by evidence of problems caused by active sand mining along the sandbars of the Devi River, it serves as an ideal study reach for our research.

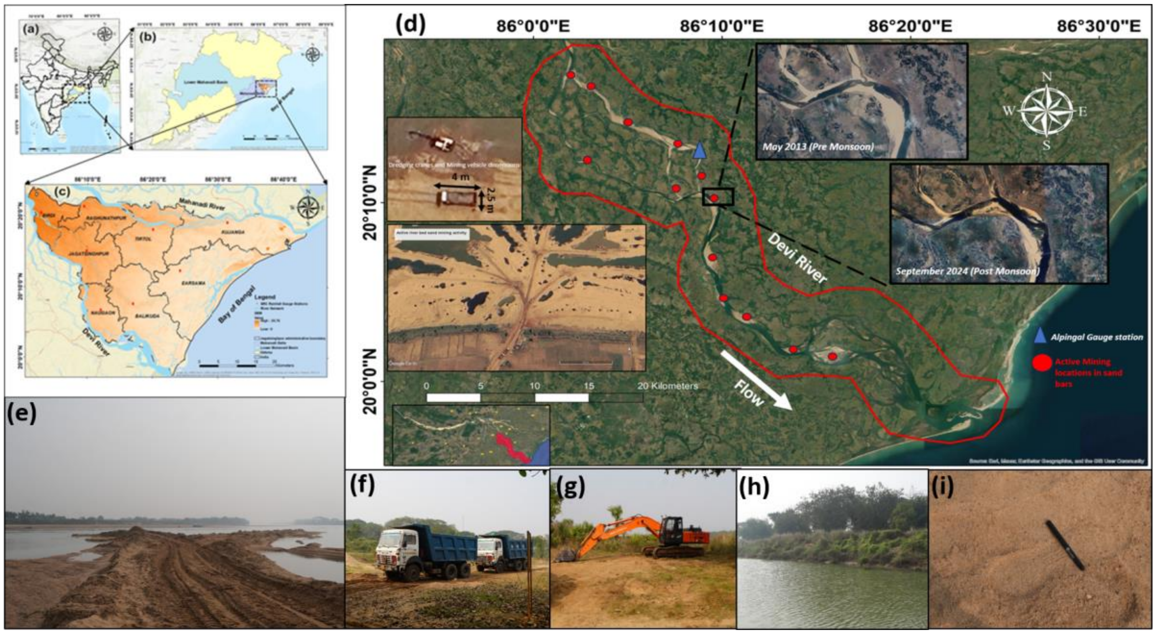

Figure 1: Details of the study area: (a) Map of India representing the administrative boundaries of all states; (b) Geographical location of Jagatsinghpur district, Odisha, India, illustrated in Mahanadi delta of Lower Mahanadi Basin; (c) High resolution Digital Elevation model (DEM) of Jagatsinghpur along with taluka names and river network in the catchment, mainly Mahanadi and Devi river along with its tributaries. (d) Sand mining study reach of the Devi River in Jagatsinghpur district. The zoomed images from Google Earth show sand mining on a sidebar in the pre-monsoon period (May 2013) and post-monsoon period (September 2024). Circles in red are the active mining locations along the stretch of the Devi River in the side bars, while triangle in blue show the location of the gauge station at the study reach (Alpingal). Field Photographs in the bottom panel (from e to i) illustrate the incision of the river bed at the sand bar due to in-stream sand mining, mining trucks, sand dredging cranes, natural habitat along the bank of the Devi River and sediment matrix of the river bed.

2.2 Data Inventory

This study utilises a multi-source dataset assembled to represent compound flood drivers in the deltaic study reach. A combination of hydrometeorological and spatial datasets was used to set up, calibrate, and validate the MIKE hydrodynamic model *(Web 5)* used in this study. Hydrometeorological datasets include daily taluka-level rainfall *(1993–2024)* from *Odisha's Special Relief Commissioner*, daily discharge *(1980–2024)* from Mundali station *(source: Department of Water Resource, Odisha, Government of India)* for upstream boundaries, daily water level records (1980–2024) from Naraj and Alipingal station *(Central Water Commission of India)* for 1D model calibration and validation, next astronomical *(1900–2010)* and observed storm tides *(2011–2015)* from Paradip *(INCOIS)* for downstream boundary. Whereas, spatial datasets include soil Infiltration data at a taluka level *(source: Central Water Board of India and OUAT, Odisha, 2024)* for infiltration inputs in the 2D model, along with high-resolution DEM for bathymetry and cross-sections, *10 m* Dynamic World LULC *(Brown et al., 2022)* for

Manning's coefficients and built-up data sourced from *OpenStreetMap*. Altogether, these integrated datasets enable a detailed representation of hydrologic, tidal, and terrain controls on flooding in the study reach.

3 METHODS

A detailed graphical overview of the adopted methodology in this study is shown in *Figure 2*. As already shown in *Figure 1*, identifying the study reach and collecting datasets during the field visit were the initial steps in setting up the flood model for the two scenarios defined in this research. *Scenario I- pre-sand mining activity* and *Scenario II- post-sand mining activity*.

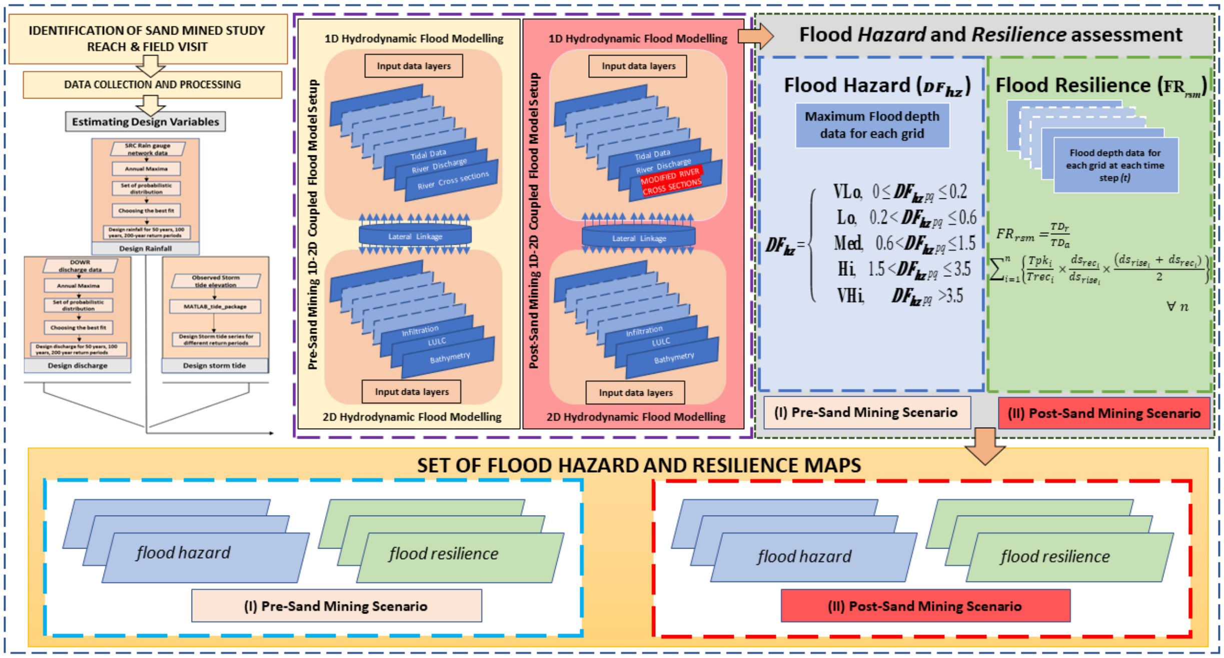

Figure 2: A graphical overview of the methodology used in the study.

3.1 Flood Model Setup

In this study, we utilised a commercially available, sophisticated MIKE flood model to simulate a 24-hour flood event at 50- and 200-year return levels. The initial process involves designing rainfall, discharge, and tidal inputs into the flood model. A set of 9 widely used parametric distributions was used for estimating the boundary inputs. For our study, we set up our flood model for the post-sand mining scenario as well, using modified river cross sections as the primary input. Our assumption of providing modified river cross-sections as input to the 1D model was largely based on the method of RSM activity used in our study reach. The evidence of instream sand mining in our study reach leads to the deepening of riverbeds and modifications in river geometry. An extensive calibration and validation procedure is then performed, using performance metrics, before establishing the model for further simulations and assessing flood hazard-resilience patterns at varying return periods.

3.2 Flood Hazard Assessment

After the successful setup of the flood model, flood depth rasters derived from simulations were used for flood hazard assessment. Flood hazard is classified into five ordinal hazard levels as represented in *Equation 1*. The colour codes assigned to each classified hazard level are blue, green, yellow, orange and red from very low to very high classes, respectively.

Discretisation of Flood hazard depth (in metres)

Let $\mathbb{d}_{mx}$ constitute a matrix of maximum flood depth of each grid cell simulated from a 1D-2D coupled hydrodynamic flood model set up in (I) Pre and (II) Post Sand mining scenarios, where $\mathbb{d}_{mx} \in R^{+\,y\times z}$ and R^{+} is a set of positive real numbers.

The matrix elements are denoted as $\mathbb{d}_{mx\,pq}$, where $1\le p \le y$, $1 \le q \le z$. These elements are also real numbers (R^{+}).

The matrix $\mathbb{d}_{mx}$ is discretised into five classes: Very Low (VL_o), Low (L_o), Medium (M_{ed}), High (H_i), and Very High (VH_i). We define a new matrix $\mathbf{D}_{\hat{h}pq}$ belonging to $\{VL_o, L_o, M_{ed}, H_i, VH_i\}^{y\times z}$, where $\mathbf{D}_{\hat{h}pq}$ represents the discretised depth class of cell (p, q).

$$\mathbf{D}_{\hat{h}} = \begin{cases} VL_o, & 0 \le \mathbf{D}_{\hat{h}_{pq}} \le 0.2 \\ L_o, & 0.2 < \mathbf{D}_{\hat{h}_{pq}} \le 0.6 \\ M_{ed}, & 0.6 < \mathbf{D}_{\hat{h}_{pq}} \le 1.5 \\ H_i, & 1.5 < \mathbf{D}_{\hat{h}_{pq}} \le 3.5 \\ VH_i, & \mathbf{D}_{\hat{h}_{pq}} > 3.5 \end{cases} \tag{1}$$

3.3 Flood Resilience Assessment

In this current study, flood resilience is quantified by building upon water retention depth and inundation duration at a specific location in the study reach. Flood damage is primarily controlled by the depth, duration, and frequency of inundation, with impacts intensifying when floodwaters persist for longer periods, reach greater depths, or repeatedly affect the same area. In particular, the duration of waterlogging and the depth of accumulated water are critical determinants of flood severity. Areas where floodwaters drain rapidly and remain shallow typically experience limited damage and a faster recovery, whereas locations that retain deeper water for extended durations are more vulnerable to severe impacts.

Flood resilience (FR_{rsm}) was computed at the grid level by simulating 24-hour water depth time series extracted for the study reach under 50-year and 200-year return period flood scenarios. For each grid, depth–time curves are generated from the corresponding water depth time series, enabling visualisation of floodwater accumulation and recession dynamics. This metric integrates both the magnitude and persistence of inundation over the flood duration, effectively capturing how much water accumulates and how quickly it drains from a given area. Grids exhibiting low FR_{rsm} values correspond to areas with prolonged water retention and significant waterlogging that persists beyond 24 hours, indicating higher flood susceptibility. In contrast, grids with high FR_{rsm} values demonstrate rapid and complete drainage within the event duration, reflecting greater flood resilience. The formulation adopted here follows *Mondal et al. (2025)* and is presented from *Equations (2) to (4).*

$$FR_{rsm} = \frac{TD_r}{TD_a} \sum_{i=1}^{n} \left\{ \frac{Tpk_i}{Trec_i} \times \frac{ds_{rec_i}}{ds_{rise_i}} \times \frac{(ds_{rise_i} + ds_{rec_i})}{2} \right\} \qquad \forall n \tag{2}$$

$$TD_r = \sum_{i=1}^{n} ds_{rec_i} \tag{3}$$

$$TD_a = \sum_{i=1}^{n} ds_{rise_i} \tag{4}$$

where, FR_{rsm} is *Flood Resilience* for the nth grid cell; TD_r is total depth reduction over all segments; TD_a is total depth accumulation over all segments**;** T_{pk} is the segmental time of peak; T_{rec} is the segmental recession duration; ds_{rec} is depth reduction during segmental recession; ds_{rise} is depth accumulation during segmental rising; T_{sim} is simulation time; TD_r is $\sum_{i=1}^{n} ds_{rec_i}$, and TD_a is $\sum_{i=1}^{n} ds_{rise_i}$.

4 RESULT AND DISCUSSION

The spatial comparison of pre- and post-sand mining *flood hazard* and *resilience* maps for the 50-year *(Figure 3)* and 200-year *(Figure 4)* return periods reveals a systematic redistribution of flood risk along the river floodplain. The results demonstrate that sand mining alters not only flood hazard but also the capacity of the river–floodplain system to absorb and recover from flood events, with impacts intensifying under extreme flood conditions.

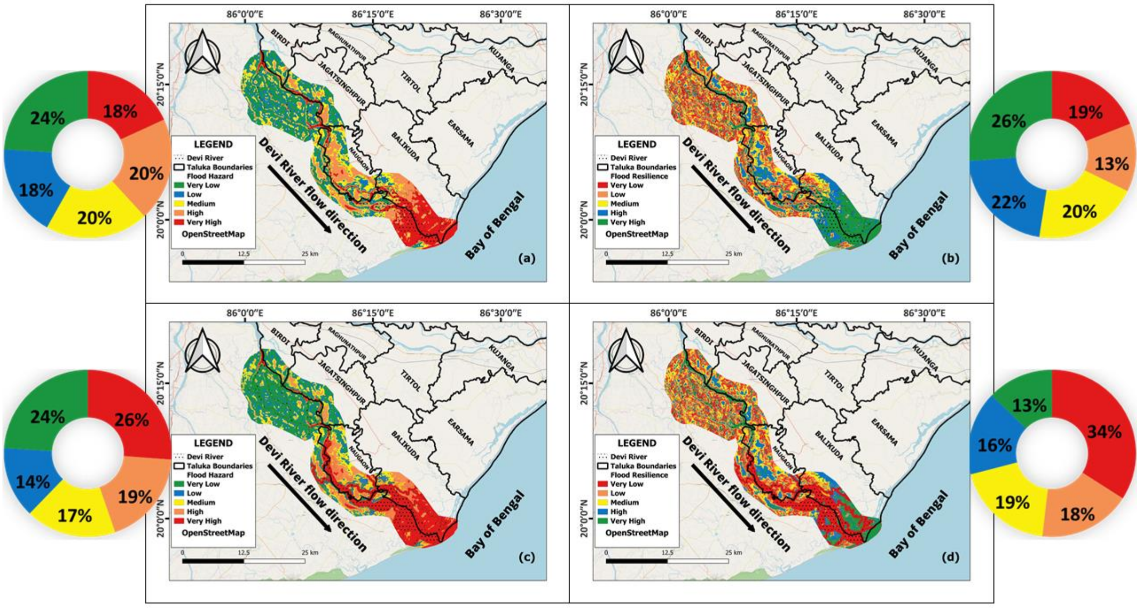

Figure 3: (a,c) Flood Hazard (in terms of depth) and (b,d) Flood resilience maps during Pre-Sand mining scenario and Post -Sand mining scenario respectively for 50-year return period. The Inset donut chart shows the percentage of grids in each hazard and resilience classes during each scenario in the study reach for 50-year return period.

Under pre-sand mining conditions, flood hazard is primarily distributed across *low to moderate classes*, particularly in *upstream and midstream reaches*. For the *50-year* return period, approximately *38–42%* of the study area falls within *very low to low hazard classes*, while *very high hazard* classes occupy about *18%* of the grids. Following sand mining, this balance shifts markedly: *high- and very high-hazard* grids increase to nearly *45%*, indicating a downstream amplification of inundation depth. For the *200-year* return period, the effect is more pronounced, with very high hazard alone exceeding *32%* of the total grids, compared to about *25%* under pre-mining conditions. This longitudinal increase in flood hazard can be attributed to riverbed incision and sediment depletion caused by sand extraction activities. While channel deepening may locally *increase conveyance* and *reduce flood stages upstream*, it *steepens the energy gradient* and *promotes downstream aggradation and backwater effects*, thereby *elevating flood depths in lower reaches (Kondolf, 1997; Surian & Rinaldi, 2003).* Similar downstream hazard amplification following sand mining has been reported in several alluvial river systems *(Padmalal & Maya, 2014; Hackney et al., 2020).*

Flood resilience exhibits a contrasting yet compounding response. Under pre-sand mining conditions, *moderate to high resilience* dominates much of the study reach, with *68%* of grids falling within *moderate to high resilience* classes for the 50-year flood. Post-sand mining, resilience declines substantially, with *very low resilience* increasing from about *19%* to nearly *34%* of the grids. For the 200-year return period, this degradation is more severe, as *very low resilience* alone accounts for approximately 55–59% of the study area during both pre- and post-sand mining scenarios, while high-resilience classes reduce to below *10%.*

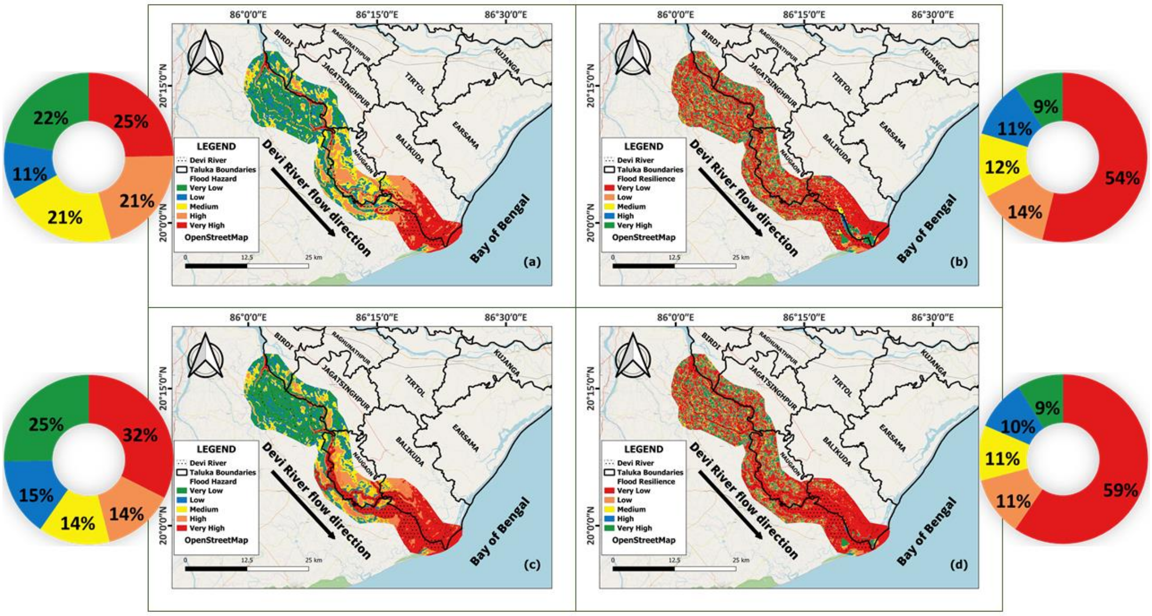

Figure 4: (a,c) Flood Hazard (in terms of depth) and (b,d) Flood resilience map during Pre-Sand mining scenario and Post -Sand mining scenario respectively for 200-year return period. The Inset donut chart shows the percentage of grids in each hazard and resilience classes during each scenario in the study reach for 200 year return period.

The decline in resilience reflects *reduced floodplain connectivity, increased channel instability, and loss of sediment-mediated buffering capacity*. Riverbed lowering disconnects the channel from its floodplain, limiting lateral storage and delaying post-flood recovery processes *(Singh et al., 2025).* Importantly, even upstream reaches that exhibit reduced flood hazard post-mining show declining resilience, indicating increased sensitivity to extreme events despite lower inundation depths.

The coupled *hazard–resilience* analysis highlights the emergence of *high-hazard–low-resilience* zones, particularly in downstream reaches, present inside the boundary of Balikuda and Naugaun taluka. For the *200-year flood, more than half* of the study reach simultaneously experiences *very high hazard* and *very low resilience*, representing a critical risk state. These results confirm that hazard-only assessments underestimate flood risk, as similar hazard levels can correspond to vastly different resilience conditions. The category-wise percentage changes clearly demonstrate that sand mining acts as a longitudinal risk amplifier in the selected reach, transferring hazard downstream while eroding resilience throughout the river system. Overall, the results show that the impacts of sand mining, as a dominant anthropogenic intervention, are non-linear and scale-dependent, becoming disproportionately severe under extreme flood conditions. The integration of *hazard* and *resilience* metrics across return periods provides a more comprehensive understanding of flood-risk dynamics in heavily human-modified river systems.

5 CONCLUSION

The research work in this study provides an analytical understanding of the *flood hazard* and *resilience* levels at a finer resolution grid scale due to the impact of river sand and gravel mining activities in a small study reach of the Devi River, a coastal flood catchment in Jagatsinghpur, India. It helps in proposing a novel framework that integrates the use of high-resolution satellite imagery and a 1D-2D coupled hydrodynamic flood modelling simulations to generate flood *hazard* and *resilience* of a multi-hazard coastal flood-prone catchment that undergoes alteration in channel geometry due to rampant extraction of sediments. Key takeaways from the study are highlighted below:

1. Post-sand mining conditions show a clear increase in *high* and *very high hazard grids*, rising from about *one-third* to nearly *one-half* of the study reach for the *50-year* and *200-year* flood events. Flood resilience declines substantially following sand mining, with *low* and *very low resilience* classes of grids expanding to nearly *55–60%* under extreme flood conditions, indicating reduced recovery capacity of the river floodplain system.
2. Riverbed sand mining significantly alters flood *hazard* and *resilience* levels, with contrasting upstream and downstream longitudinal impacts. While upstream reaches may experience localised hazard reduction due to channel deepening, resilience consistently deteriorates, indicating an increased danger level of the river system.
3. Downstream reaches are disproportionately affected, experiencing both elevated flood hazard and reduced resilience, leading to the emergence of *high hazard–low resilience* zones, which represent critical flood hotspots.
4. The percentage shifts in *hazard* and *resilience* classes confirm that sand mining impacts are non-linear and magnified under extreme events, underscoring the limitations of hazard-only flood assessments.
5. The concentrated upstream sand mining in the Devi River has significantly increased downstream flood hazard during both 1-in-50 and 1-in-200-year floods, heightening flood risk for settlements and agricultural land in the Naugaon and Balikuda talukas.
6. The findings reveal that sand mining cannot be considered only as a localised intervention, as its impacts propagate along the river reach. The discrete *hazard-resilience* classification framework employed in this study offers a robust and transferable methodology for identifying zones with amplified hazard and lower classes of resilience.

From a management perspective, the results emphasise the need to integrate resilience assessments while framing sand mining regulation, adopt reach-scale impact assessments, and prioritise downstream flood-prone areas in monitoring and river regulatory strategies. Major limitations of our work include the unavailability of sand extraction data and incised bed level data. Future work should incorporate sediment transport dynamics, hydraulic assessments with in situ datasets, climate-informed flood scenarios, temporal planform analysis with high-resolution satellite imageries and socio-economic vulnerability to further strengthen the assessment of sand mining impacts on flood risk at different scales of fluvial mined catchments. The approach presented here offers a practical decision-support option for stakeholders and policymakers to facilitate sustainable river management and flood risk governance.

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