Geospatial Analysis of Coastal Inundation in Maharashtra Using DEM and IPCC Forecasts: A Google Earth Engine Approach for Climate Resilience

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Abstract

Coastal regions are increasingly vulnerable to sea level rise (SLR) due to climate change, threatening ecosystems, infrastructure, and livelihoods. This study presents a geospatial analysis of SLR and coastal inundation in Maharashtra, India, by integrating high-resolution Cartosat DEM (2015–2019), JRC Global Surface Water (1984–2020), and IPCC AR6 projections (2020–2030) using the Google Earth Engine (GEE) cloud platform. Permanent water bodies were masked, and percentile-based inundation scenarios were generated for 2020, 2024, and 2030. The methodology also involved applying percentile-based SLR thresholds (25th, 50th, and 75th) to assess multiple risk scenarios. Resulting inundation maps provide spatial insights essential for regional planning and disaster management. With predicted inundated areas ranging from 1851 km² to 1885 km², the findings emphasize areas at critical danger of floods. The resulting spatial maps identify critically vulnerable coastal zones, enabling evidence-based climate adaptation and disaster risk planning. This study supports **sustainable coastal development**, aligns with **SDG 13 (Climate Action)**, and showcases the transformative potential of **frontier geospatial technologies** in building climate-resilient communities.

1. Introduction

Climate change-induced sea level rise (SLR) presents an urgent challenge for sustainable development in coastal regions. Driven by glacier melt, thermal expansion, and anthropogenic greenhouse gas emissions, rising sea levels exacerbate the risk of flooding, salinization, and habitat degradation. Coastal states like Maharashtra—with dense populations, vital ecosystems, and critical infrastructure—are highly susceptible to these impacts. To address this, geospatial and frontier technologies offer innovative solutions for mapping, monitoring, and mitigating coastal hazards. This study employs Google Earth Engine (GEE) and multi-source satellite data to model SLR-induced inundation, aiming to inform sustainable urban planning, ecosystem protection, and climate resilience policy at regional scales. Additional occurrences, such as cyclone-driven events and earthquakes also influence the changes in the regional/relative mean sea level (RMSL). SLR is one of the major challenges the world is now experiencing, mostly in low-lying deltaic and coastal regions.

The rising threat of sea level rise (SLR) has led to a surge in research focused on its implications for coastal environments, infrastructure, and populations. Studies worldwide have underscored the need for high-resolution elevation data and geospatial tools to monitor and model the impacts of SLR under changing climate scenarios.

The threat of rising sea levels due to anthropogenic climate change has driven a surge in research aimed at assessing, modeling, and mitigating coastal vulnerability. Numerous studies have explored the integration of geospatial data and advanced remote sensing platforms for understanding and predicting sea level rise impacts, with a growing emphasis on regional vulnerability mapping and policy implications.

Elneel et al. (2024) offered a broad overview of global SLR dynamics, emphasizing the role of glacial melt, oceanic thermal expansion, and land subsidence. Their findings underscore the need for region-specific impact models to inform mitigation efforts and adaptation policies. Similarly, Das and Swain (2024) investigated the interplay between climate change and coastal communities in India, reinforcing the urgency of localized spatial modeling for flood prediction and resilience planning.

In terms of methodology, Abdel-Aziz et al. (2020) evaluated various Digital Elevation Models (DEMs) for SLR monitoring in Egypt's Nile Delta. Their comparison highlighted the significance of DEM resolution and accuracy in reliably delineating vulnerable zones. Echoing this, Emmendorfer et al. (2024) assessed DEM performance for coastal flooding in Brazil, concluding that high-resolution elevation data, such as Cartosat DEM used in the current study, significantly enhances the precision of inundation assessments.

The application of satellite-based hydrological datasets has also proven essential in recent studies. Baby et al. (2021) developed spatial tools to identify coastal infrastructure at risk, incorporating both DEMs and land use data to guide emergency planning. Likewise, Roy et al. (2023) proposed a vulnerability framework linking SLR to coastal habitat loss, calling for the integration of remote sensing with socio-economic indicators for holistic resilience mapping.

The use of Google Earth Engine (GEE) as a frontier geospatial platform has gained prominence in coastal hazard research. Putri et al. (2024) employed satellite fusion with DEM-based modeling to monitor SLR on island ecosystems using a nearest-neighbor approach. Their findings validate the efficiency of cloud-based platforms in handling large-scale temporal-spatial data, aligning with this paper's use of GEE for DEM mosaicking, water masking, and percentile-based SLR simulation.

On the Indian front, Sudipta et al. (2021) analyzed SLR impacts on Mumbai's coastline and emphasized the need for integration of real-time data and participatory planning. Ramesh and Iqbal (2022) further demonstrated the use of GIS-based probabilistic models for flood susceptibility mapping in urban Maharashtra, revealing the importance of combining DEMs with historical flood patterns for robust prediction models.

In summary, the existing body of literature reinforces the value of combining high-resolution geospatial datasets, DEMs, and IPCC projections for regional SLR modeling. However, there remains a research gap in operationalizing such analyses using scalable cloud platforms like GEE, particularly in the Indian context. This study fills that gap by offering a reproducible, percentile-based modeling framework for evaluating future flood risks, tailored to support sustainable development and coastal climate resilience in Maharashtra.

This study evaluates coastal inundation in Maharashtra using IPCC AR6 sea level rise forecasts and Cartosat DEM. JRC data was used to hide permanent water features, and DEM tiles were mosaicked and clipped to the research region. Inundation masks spanning various risk quantiles were created using projected sea levels for 2020, 2024, and 2030. For accuracy and efficiency, Google Earth Engine was used for all processing and analysis.

Furthermore, the results of this study are expected to contribute meaningfully to regional adaptation strategies by identifying critical coastal hotspots and infrastructure zones most susceptible to inundation. The outputs can support local disaster management authorities, coastal zone planners, and policymakers in prioritizing investments in protective barriers, green infrastructure, and early warning systems. The inclusion of time-series projections allows for scenario-based decision-making, aligning with the United Nations Sustainable Development Goals (SDGs) 11 (Sustainable Cities and Communities) and 13 (Climate Action). By leveraging GEE's scalable computation and visualization capabilities, this framework not only facilitates rapid assessments across large coastal extents but also encourages reproducibility for other vulnerable coastal states in India. Ultimately, the study underlines the pivotal role of geospatial intelligence in transforming climate data into actionable insights for resilience, mitigation, and long-term sustainability of coastal ecosystems and human settlements.

1.1 Study Area

The state of Maharashtra is situated in the western peninsula of India, between latitudes 15°36′ and 22°02′ north and longitudes 72°36′ and 80°54′ east. It is the third-largest state in India in terms of land, with over 307,713 square kilometers, bordered to the west by the Arabian Sea. Figure 1 shows the state layout of Maharashtra state.

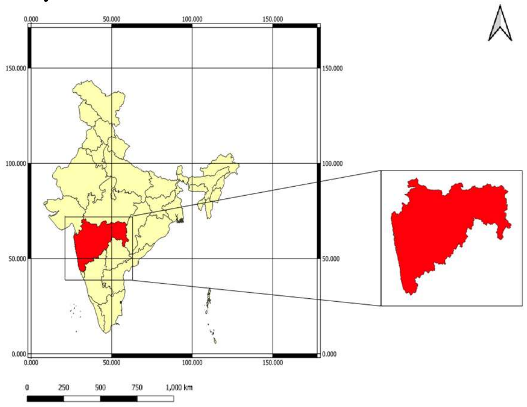

Figure. 1 Maharashtra Region

Coastal plains, plateaus, river basins, and the Western Ghats are among the varied landscapes that make up the state's physiography. Significant river basins that drain the area include the Godavari, Krishna, Bhima, and Tapi, which add to the hydrological complexity of the state. While the Deccan plateau in the interior undergoes seasonal fluctuations in water levels driven by the monsoon, the low-lying Konkan coastline region is particularly susceptible to sea level rise. Maharashtra's climate is dominated by the Southwest monsoon, bringing heavy rainfall between June and September. This seasonal precipitation significantly affects river discharge, surface water dynamics, and flood potential, especially in urbanized and low-elevation areas.

The study area is ecologically and socio-economically significant due to its mix of urban megacities like Mumbai and large agricultural zones. The region faces increasing threats from sea level rise, changing water levels, and flood risks, necessitating a scientific approach for monitoring and assessment. Thus, the integration of Cartosat DEM, JRC Global Surface Water, and IPCC AR6 sea level projections using Google Earth Engine (GEE) is essential for detailed flood mapping, vulnerability analysis, and sustainable water management planning across Maharashtra.

2. Methodology

This study integrates high-resolution Cartosat Digital Elevation Model (DEM) data and IPCC AR6-projected sea level rise datasets within the Google Earth Engine (GEE) cloud platform to assess future coastal inundation scenarios in Maharashtra. The adopted methodology as shown in figure 2 comprises five major stages:

2.1 Dataset Acquisition and Preprocessing

2.1.1. Digital Elevation Data

A total of 44 Cartosat DEM tiles covering the coastal stretch of Maharashtra were acquired and mosaicked into a single elevation raster. The mosaic was reprojected to EPSG:4326 with a spatial resolution of 40 meters and clipped to the administrative boundary of Maharashtra obtained from FAO GAUL Level 1 data.

2.1.2 Permanent Water Mask

To eliminate interference from existing water bodies, the JRC Global Surface Water occurrence layer was used. Pixels with more than 50% water occurrence were identified as permanent water and masked out from inundation zones.

2.1.3 Sea Level Rise (SLR) Data

Projected sea level rise data was sourced from the IPCC AR6 Sea Level Projections Image Collection. Three quantiles 25th, 50th, and 75th percentiles—were extracted for the years 2020 and 2030. To estimate SLR values for 2024, linear extrapolation between 2020 and 2030 was performed:

$$SLR2024 = SLR2020 + 0.4 \times (SLR2030 - SLR2020)$$

2.2 Inundation Mapping

An inundation mask was generated by comparing the elevation layer with the projected SLR values. Areas where the DEM elevation was less than or equal to the SLR were marked as inundated, excluding regions already masked as permanent water.

$$Inundation(x, y) = \begin{cases} 1, & \text{if } Elevation(x, y) \le SLRq(x, y) \text{ and } Watermask(x, y) = 0 \\ & 0, otherwise \end{cases}$$

2.3 Inundation Area Calculation

A number of geospatial processing methods were used to produce useful outputs for inundation study and sea level rise (SLR). By following these procedures, spatial resolution consistency and research area relevance were guaranteed:

- Cartosat DEM was mosaicked, reprojected (40m), and clipped to Maharashtra's boundary.
- SLR quantiles (25th, 50th, 75th) for 2020, 2024, and 2030 were retrieved from IPCC AR6 data.
- Permanent water bodies were excluded using the JRC Global Surface Water mask.

2.4 Evaluation of Inundated Areas

The area of inundated land was calculated using pixel area summation:

$$Area_{inundated} = \sum(InundationMask \times PixelArea)$$

Each mask was visualized on the GEE map interface using distinct color codes per quantile.

2.5 Export to CSV

For each year and quantile, a summary Feature Collection was constructed capturing:

- Mean sea level rise (m)
- Inundated area (km²)

These summary statistics were exported as CSV files for analysis.

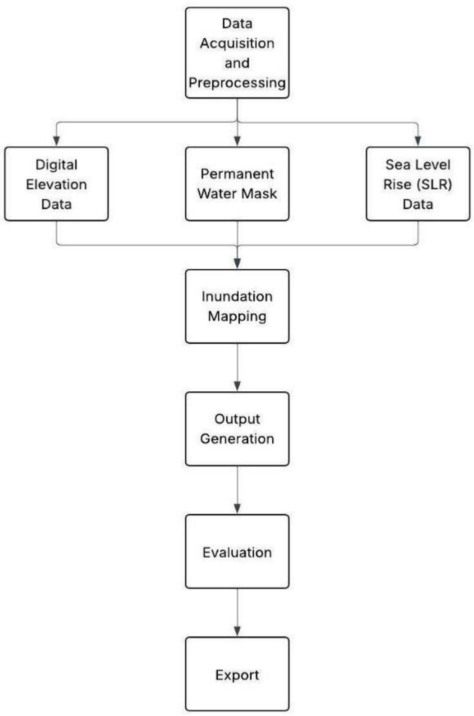

Figure. 2 Methodological Framework for SLR-based Inundation Assessment

This methodological framework ensures an end-to-end, automated, and reproducible workflow for sea level rise assessment using cloud-based geospatial tools. By leveraging the computational power of Google Earth Engine (GEE), the study eliminates the limitations associated with desktop-based processing, such as hardware dependency and storage constraints, while ensuring near-real-time data accessibility. The workflow integrates high-resolution elevation data, hydrological information, and climate projections within a unified analytical environment, enabling large-scale spatial analyses with exceptional efficiency and transparency.

The use of percentile-based projections (25th, 50th, and 75th quantiles) provides a comprehensive understanding of uncertainty in climate model outputs and allows decision-makers to evaluate potential risks under both moderate and extreme scenarios. Moreover, the integration of IPCC AR6 datasets ensures global consistency and scientific credibility, while the Cartosat DEM contributes local precision essential for accurately capturing subtle topographic variations along the Konkan coastline.

Beyond technical soundness, this workflow is scalable and adaptable for application in other coastal states such as Gujarat, Tamil Nadu, and Odisha, with minimal modifications. The use of open-access datasets and cloud-based computation democratizes the analytical process, allowing academic institutions, government agencies, and research centers to replicate and expand upon the model for disaster risk reduction and coastal planning.

Finally, the output CSV files generated from the GEE platform serve as crucial inputs for statistical analysis, visualization, and temporal trend evaluation in Python or R environments. These datasets form the foundation for generating vulnerability indices, hotspot identification, and temporal change detection, facilitating data-driven decision-making for sustainable coastal management. This integrated methodology not only enhances scientific reproducibility but also bridges the gap between geospatial research and practical policy implementation.

3. Results and discussions

The analysis focuses on projected sea level rise (SLR) and associated inundated areas across the Konkan coastal region of Maharashtra for the years 2020, 2024, and 2030. The projections are based on IPCC AR6 quantile data and are visualized using a digital elevation model (DEM) after masking permanent water bodies using the JRC Global Surface Water Dataset.

Sea level rise (SLR) projections (in meters) and associated flooded areas (in square kilometers) for 2020, 2024, and 2030 are summarized in Table 1 using the 25th (low), 50th (median), and 75th (high) percentiles of sea level rise estimates from the IPCC AR6 dataset. This tabular depiction illustrates the possible escalation in flood-prone zones under several future scenarios and aids in quantifying the spatial impact of different sea level rise levels on the Maharashtra region.

Using the 25th, 50th, and 75th percentile SLR scenarios, Figure 3 SLR Inundated Areas for 2020 illustrates the extent of low-lying and coastal areas that will be inundated in the base year 2020. The image compares observed flood extents with projected projections to validate the model and show historical inundation patterns.

system:index	SLR_mean_25th_m	SLR_mean_50th_m	SLR_mean_75th_m	inundated_area_25th_sqkm	inundated_area_50th_sqkm	inundated_area_75th_sqkm	year
0	0.916	2.116	3.7	1851.501	1866.804	1883.767	20

							20
1	0.899	2.129	3.407	1851.03	1867.272	1884.005	2024
2	0.873	2.149	3.462	1851.03	1867.509	1885.418	2030

Table 1 Sea Level Rise Scenarios (2020-2030)

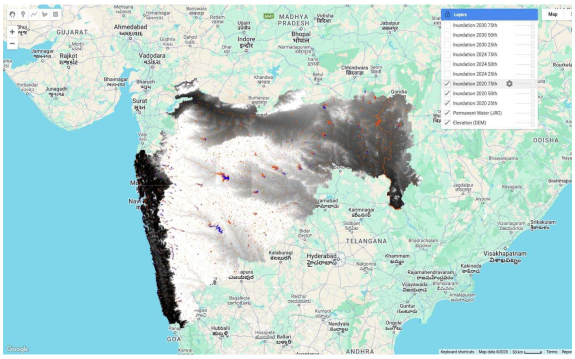

Figure 3 SLR Inundated Areas for 2020

The anticipated flooded areas for 2024 under the same percentile scenarios are shown in Figure 4 Inundated Areas from 2020 to 2024. It illustrates how coastal communities, infrastructure, and agricultural areas can be greatly impacted by even slight rises in sea level (25th percentile). The visual comparison of the maps from 2020 and 2024 highlights the necessity of planning for climate resilience and offers insights into the rate of expansion of at-risk locations.

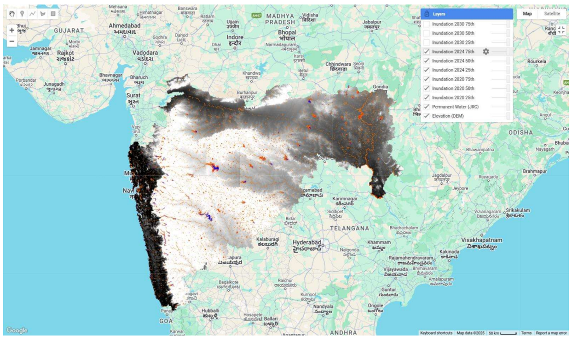

Figure 4 SLR Inundated Areas from 2020 to 2024

The future forecast for 2030 is depicted in Figure 5 SLR Inundated Areas from 2020 to 2030, where it is anticipated that the extent of flooding will increase under all three percentiles, but especially under the 75th percentile scenario, which denotes a high-risk perspective. The cumulative effect of sea level rise is highlighted by the increasing trend throughout all numbers, which also emphasizes how crucial it is to combine elevation data with climatic estimates in order to support coastal zone management decision-making.

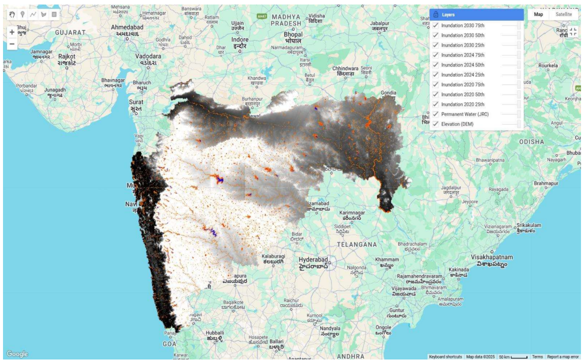

Figure 5 SLR Inundated Areas from 2020 to 2030

3.1 Sea Level Rise Trends:

- In 2020, the SLR for the 25th, 50th, and 75th percentiles were approximately 0.92 m, 2.12 m, and 3.37 m, respectively.
- By 2024, a slight decrease in the 25th percentile SLR (0.899 m) was observed, while the 50th and 75th percentiles continued to rise to 2.13 m and 3.41 m, respectively.
- The 2030 projections indicate a continued rise in SLR across all percentiles, with the 75th percentile reaching approximately 3.46 m.

This trend reflects the increasing uncertainty in future projections, with higher SLR values more probable under high-emission scenarios. Coastal vulnerability is rising in tandem with sea level rise, particularly in low-lying, heavily populated places. Planning adaptive infrastructure and disaster risk reduction measures in coastal areas that are susceptible to disasters requires the use of these percentile-based predictions.

3.2 Inundated Area Trends

- In 2020, the inundated area ranged from 1851.50 sq. km (25th percentile) to 1883.77 sq. km (75th percentile).
- For 2024, inundation was nearly the same for the 25th percentile (*1851.03 sq. km), while the 50th and 75th percentiles slightly increased to 1867.27 sq. km and 1884.00 sq. km, respectively.
- By 2030, inundated areas continued to expand, especially for the 75th percentile which reached 1885.42 sq. km.

The increase in inundated areas closely correlates with rising SLR values, showing that even small increases in sea level can result in substantial land loss, especially in low-lying coastal regions. These results highlight how urgently vulnerable coastal areas require efficient flood risk management plans. The geographical distribution of flooding also identifies important regions that need focused adaptation and mitigation measures to reduce harm to ecosystems and infrastructure.

3.3 Key Observations

The percentile-based inundation assessment provides critical insights into the spatial and temporal dynamics of sea level rise impacts along Maharashtra's coastline.

1. Marginal Variation at Lower Percentiles: The 25th percentile scenario indicates minor fluctuations in both SLR and inundated area between years, suggesting relative stability under optimistic or moderate climate projections. This implies that lower-risk coastal regions may experience slower or negligible short-term changes,

offering a potential window for adaptive infrastructure planning and ecosystem-based interventions.

2. Rapid Growth at Higher Percentiles: In contrast, the 75th percentile values show a consistent and accelerated increase in both SLR and inundation extent across time steps. This clearly highlights the severity of flood risk under high-emission or worst-case scenarios, emphasizing the need for proactive policy actions such as managed retreat, coastal defense enhancement, and land-use restrictions in high-exposure zones.

3. Saturation Effect: Between 2024 and 2030, even as projected SLR continues to rise, the rate of inundated area expansion begins to plateau. This saturation effect indicates that certain low-lying coastal areas may have already reached their maximum potential inundation, given existing topographic and hydrological constraints. Such insights are vital for understanding nonlinear hazard progression and for distinguishing between regions of active encroachment and those of persistent submergence.

Together, these findings reinforce the need for scenario-based adaptation planning, where both gradual and abrupt inundation dynamics are considered in decision-making. The analysis underscores the capacity of Google Earth Engine to capture these subtle yet critical percentile-based variations, offering a nuanced understanding of regional vulnerability that supports evidence-based coastal governance and resilience-oriented spatial planning.

3.4 Policy Implications:

The generated inundation maps offer valuable insights for planners and policymakers to identify high-risk zones in districts like Mumbai, Ratnagiri, and Raigad. These outputs can inform **coastal zoning regulations**, prioritize **infrastructure adaptation projects**, and guide **urban resilience strategies**. Integration with socio-economic data could further help target **vulnerable populations** and support the formulation of **early warning systems** and **climate-smart land use plans**. This spatial decision support framework contributes directly to **India's National Action Plan on Climate Change (NAPCC)** and the **UN Sustainable Development Goals (SDG 11, 13, and 14)** by enhancing climate-informed governance.

This study not only addresses the technical challenge of modeling coastal inundation due to sea level rise, but also aligns with broader global development goals and policy frameworks. By focusing on the Konkan coast of Maharashtra—home to major urban hubs like Mumbai, Alibag, and Ratnagiri—the research brings attention to a region that is socio-economically vital and environmentally vulnerable. The use of Google Earth Engine, a cloud-based and open-access geospatial platform, highlights how frontier technologies can democratize environmental intelligence and enable scalable, real-time climate resilience planning. Furthermore, the paper contributes meaningfully to Sustainable Development Goals (SDGs), particularly SDG 13 (Climate Action) through climate risk modeling, SDG 11 (Sustainable Cities and Communities) via spatially targeted urban adaptation strategies, and SDG 14 (Life Below Water) by identifying zones of ecological sensitivity. The inclusion of women researchers and student contributors also reflects a commitment to SDG 5 (Gender Equality), promoting inclusive participation in frontier scientific work. The proposed methodology—combining high-resolution DEMs, water occurrence data, and percentile-based sea level rise scenarios—is transferable to other vulnerable coastal regions globally, supporting wider resilience-building efforts under the Sendai Framework and India's National Action Plan on Climate Change. This research, therefore, serves as both a technical model and a policy-relevant tool for sustainable coastal development.

The insights derived from this study hold immense potential for advancing both scientific understanding and applied coastal management in Maharashtra. The integration of multi-source datasets within a cloud-based geospatial framework represents a major step toward operationalizing climate adaptation at local and regional levels. The generated inundation models are not only analytical tools but also decision-support systems that can be integrated into smart city planning, marine spatial zoning, and disaster preparedness strategies. By translating geospatial analytics into actionable information, urban planners and district authorities can prioritize interventions such as strengthening embankments, relocating vulnerable settlements, and preserving mangrove buffers to reduce exposure to inundation risks.

Moreover, the methodology underscores the role of **open-source and cloud computing technologies** like Google Earth Engine in democratizing access to environmental intelligence. Traditionally, coastal vulnerability assessments have been limited by data scarcity and computational constraints. However, through scalable cloud-based systems, regional and municipal authorities can now conduct **real-time monitoring, scenario modeling, and visualization of flood risk** without high infrastructure costs. This democratization of technology ensures that even smaller local bodies can engage in evidence-based decision-making, aligning with the broader goals of digital governance and climate transparency.

From a sustainability standpoint, the research supports **ecosystem-based adaptation (EbA)** approaches that integrate coastal ecosystem conservation—such as mangroves, wetlands, and estuarine zones—into resilience planning. These natural buffers play a crucial role in attenuating storm surges, reducing erosion, and maintaining ecological balance. The study's outputs can therefore assist in identifying priority conservation zones and formulating adaptive land-use policies that balance developmental growth with environmental protection.

In the context of community engagement, the outcomes of this study can be extended to build **citizen-centric early warning systems** through participatory mapping and awareness programs. Local communities, particularly those dependent on fisheries and coastal agriculture, stand to benefit from spatially explicit flood forecasts and preparedness frameworks. Such participatory initiatives promote inclusive climate action, ensuring that resilience building extends beyond technology and policy to reach the most affected populations.

Finally, this work reinforces the importance of **interdisciplinary collaboration**—bridging engineering, environmental science, and policy domains—to tackle the complex challenges posed by sea level rise. Future extensions of this research can incorporate **machine learning-based flood susceptibility modeling**, integration of **tide gauge and radar altimetry data**, and **simulation of compound hazards** involving storm surges and extreme rainfall. These advancements will further refine risk assessments and contribute to Maharashtra's vision of sustainable coastal development under changing climatic regimes.

4. Conclusion

By combining high-resolution Cartosat DEM, historical water occurrence datasets, and IPCC AR6 sea level projections within the Google Earth Engine (GEE) framework, this study demonstrates a robust geospatial approach to assessing sea level rise (SLR) impacts along Maharashtra's coastline. The percentile-based inundation maps reveal both immediate and long-term flood vulnerabilities under varying climate scenarios. Importantly, this research underscores how frontier technologies like GEE can empower decision-makers with scalable, cloud-based, and real-time spatial intelligence. As sea levels continue to rise, such data-driven methods are crucial for sustainable coastal development, resilient infrastructure planning, and climate-proofing vulnerable communities.

Beyond its technical contribution, this work emphasizes the importance of integrating science, technology, and policy to create actionable insights for coastal resilience. The approach presented here not only enhances the accuracy of flood risk assessments but also supports multi-sectoral decision-making by aligning with India's National Action Plan on Climate Change (NAPCC) and the UN Sustainable Development Goals (SDGs 11, 13, and 14). By identifying high-risk coastal districts such as Mumbai, Ratnagiri, and Raigad, the study provides a valuable spatial foundation for adaptive zoning regulations, early warning systems, and infrastructure prioritization.

Moreover, the methodological framework developed in this study is transferable and replicable—enabling researchers and policymakers across other coastal regions of India and the Global South to assess SLR vulnerabilities with limited computational resources. The cloud-based and open-access nature of GEE ensures transparency, reproducibility, and inclusivity, allowing institutions and local authorities to conduct independent analyses and make informed decisions.

Looking ahead, the integration of machine learning algorithms, hydrodynamic modeling, and socio-economic vulnerability indices can further enhance predictive capability and improve the precision of coastal adaptation planning. Establishing continuous monitoring systems that combine satellite-derived observations with ground-based tide gauge data will also refine regional estimates of relative sea level change.

In essence, this research bridges the gap between advanced geospatial analytics and sustainable policy implementation. It reinforces the critical role of technology-driven environmental intelligence in achieving climate resilience and protecting the ecological and socio-economic fabric of India's coastal zones.

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