Embankment Breach Simulation and Inundation Mapping Leveraging High-Performance Computing for Enhanced Flood Risk Prediction and Assessment

Upasana Dutta[1], Yogesh Kumar Singh[1], T. S. Murugesh Prabhu[1], Girishchandra Yendargaye[1], Rohini Kale[1], Manoj Kumar Khare[1], Binay Kumar[1], Rajani Panchang[2]

[1] HPC-ESEG Group, Centre for Development of Advanced Computing, IP, Panchvati, Pashan, Pune, India
[2] Department of Environment Science, SPPU, Pune, India

Keywords: Embankment breach, flood forecasting, inundation spread, hydrodynamic modelling, high-performance computing

Abstract

Embankment breaches represent significant hazards to communities and infrastructure, precipitating catastrophic flood occurrences. The precise prediction of floods and understanding the scope of inundation stemming from embankment failures are imperative for effective disaster preparedness and response. This research delves into a case study on simulating embankment breaches to evaluate the extent of flooding. Leveraging advanced hydrodynamic models validated through high-performance computing (HPC) systems, and integrating real-time data assimilation, we aim to improve accuracy in flood forecasting. The study endeavours to bolster flood risk management by furnishing detailed inundation maps and insights into embankment breach dynamics, thereby facilitating enhanced preparedness and response strategies. Our findings reveal that simulations conducted on multicore processors offer superior performance compared to single-core setups, yielding enhanced result accuracy and providing administrators with increased lead time. It unlocks high-resolution simulations for intricate basin details, explores a wider range of flood scenarios quickly, and allows for efficient ensemble modelling to assess model uncertainty. Through HPC utilization, we can harness high-resolution digital elevation models (DEMs) for 2D-hydrodynamic modelling, enabling rapid assessment of water spread resulting from embankment breaches within a mere 20-minute timeframe, a significant improvement from the previous 3-4 hours duration.

1. Introduction

Embankments, also known as levees or dykes, are engineered structures designed to raise the level of the ground to create a barrier that provides protection against flooding and manages water flow in various landscapes. These raised constructions are primarily constructed using materials such as soil, rock, gravel, or concrete, carefully compacted to attain the desired height and stability. The importance of embankments in flood management cannot be overstated, as they serve as critical tools to mitigate the devastating impacts of flooding events. Flooding is a natural phenomenon that poses significant threats to lives, properties, and ecosystems, particularly in low-lying and flood-prone regions. Embankments play a pivotal role in flood management due to their multifaceted functions and significant benefits.

Embankment breaching, a frequent process in fluvial dynamics, and has far-reaching impacts on the physical, ecological, and socio-economic aspects of the fluvial environment, particularly in developing countries. As embankments are typically constructed using local earth materials, they are predisposed to breaches. These breaches have significant implications for various factors, including the morphology and habitat evolution of rivers and floodplains (Darby and Thorne, 1996a; Barker et al., 1997; Goodson et al., 2002), issues related to turbidity (Bull, 1997; Eaton et al., 2004).

Be it flood mitigation, channelling water flow, infrastructure protection, erosion control, risk reduction or urban planning, embankment plays a backbone role. By confining water within designated areas, embankments serve as flood barriers, preventing water from inundating nearby lands during periods of heavy rainfall, storm surges, or river overflows. It regulates water flow in rivers, canals, and reservoirs, ensuring a stable and controlled release of water during various weather conditions. By channelling water flow, embankments reduce the risk of sudden and uncontrolled flooding, offering time for flood warning and preparedness. It also plays crucial role in providing support for critical infrastructure such as roads, highways, railways, and bridges. By elevating these transportation networks above flood-prone areas, embankments safeguard them from water damage, ensuring the continuous movement of people and goods during flood events. Along coastlines and riverbanks, embankments play a pivotal role in mitigating erosion. The stable structure of embankments helps prevent soil erosion and land loss due to water currents, preserving the integrity of landforms and protecting adjacent habitats. Apart from all this, embankment significantly contribute to risk reduction and disaster resilience. By providing reliable flood protection, embankments enhance community safety and reduce economic losses associated with flooding events.

River embankments, however, often use local soils without filters, making them flood-prone and subject to erosion. Influencing factors include soil erodibility (Sherard et al., 1967), earth structure geometry, homogeneity/anisotropy, and compaction during construction. Crucial hydraulic characteristics include material conductivity, upstream water energy, and gradient. Internal erosion involves stages like initiation, continuation, progression, and breach failure,

https://doi.org/10.5194/isprs-annals-X-3-2024-117-2024 | © Author(s) 2024. CC BY 4.0 License.

spanning hours to days (Fell et al., 2003). Manifesting in the embankment, foundation, embankment-foundation interface, and structure-embankment junction, these processes are collectively termed 'piping.' Soils are "internally unstable" if the coarser fraction fails to filter finer particles (Sherard, 1979). Suffusion conditions involve geometric, stress, and hydraulic aspects, requiring finer particles smaller than constrictions, insufficient fines to fill voids, and flow velocity-induced stress for particle movement (Wan and Fell, 2008; Garner and Fanin, 2010).

Embankment breaches are a significant concern across the world specially in India as it is home to several flood-prone regions, and a large population residing in them. The densely populated Ganges-Brahmaputra-Meghna (GBM) delta region and other river basins experience recurrent floods, making embankment breaches a frequent occurrence. The Indian subcontinent experiences heavy monsoon rainfall during the southwest and northeast monsoons. Intense rainfall during the monsoon season leads to rapid river water-level rise, putting immense pressure on embankments. Embankment breaches can lead to mass displacement, loss of lives, and damage to properties, affecting a substantial number of people. Not just that, many embankments in India are aging and require regular maintenance. Inadequate maintenance can lead to embankment failures, increasing the risk of flooding during monsoon seasons.

To simulate embankment breach, hydrological modelling has to be carried out, which is a complex and challenging task due to numerous parameters involved and the extensive areas that require computation. To address this difficulty, parallel computing technology offers an effective computational approach for constructing high-resolution flood warning systems at the river basin level [Shang et al., 2016, Liu et al., 2017]. High-Performance Computing (HPC) techniques and resources enable simulations with higher spatial and temporal resolutions over larger areas, utilizing computing power in the order of teraflops and petaflops [La Loggia and Freni, 2018].

Flood modelling tools come in both Commercial-Off-The-Shelf (COTS) and Free and Open Source (FOSS) options. This paper focuses on the use of open-source software and tools due to their flexibility in handling parameters compared to COTS. The model presented in this paper is customised for testing the embankment breach scenarios in the Delta region of the Mahanadi River Basin. The simulations were conducted using an open-source hydrodynamic model called ANUGA Hydro, coupled with freely available GIS tools for visualization and analysis.

2. Study Area

The main river, Mahanadi in the eastern part of India, contributes around 59.16 billion m^3 of annual flows. To protect the flood plains, levees and embankments are constructed along the main rivers, with sluices strategically placed. These embankments are classified as river or saline embankments. Rapid growth in this practice necessitates assessing embankment performance. In the coastal delta, irrigation covers 4,46,616 hectares through prismatic main canals running parallel to river embankments. During the monsoon, canal water levels exceed normal river stages, while rivers experience higher flood levels. Sluices close during high flood. Embankments may also separate local water bodies from rivers, leading to reversible hydraulic conditions and erosion processes. Saline embankments in Puri, Jagatsinghpur, Kendrapara, Bhadrak, Jajpur, and Balasore safeguard vast agricultural areas from saline overland flooding. These embankments close sluice gates during high tide, allowing rainwater accumulation before tide recession. Seepage from the countryside to the seaside can occur, affecting ionic concentrations and causing internal erosion. Artificially created creeks enhance seepage, occasionally leading to control structure failures. Such occurrences are not uncommon in the state.

The study focuses on part of the Mahanadi River Basin's delta region in Odisha, covering 618 sq. km. The nearest town to the breach location is Pubansa in Kendrapara district. The threat of embankment breaches in the Pubansa area of the Mahanadi River Basin holds immense relevance and urgency (Figure 1). Situated in a region susceptible to seasonal flooding, embankments serve as vital defence against inundation. A breach in these embankments could unleash swift and extensive flooding, endangering the lives and livelihoods of the local population. Given the likely high population density in this area, the risk of displacement and loss of life is a grave concern. Moreover, the fertile agricultural lands of the Mahanadi Basin are a critical source of livelihood for the community, and flooding resulting from an embankment breach could lead to substantial crop damage, threatening food security and economic stability. Additionally, the vulnerability of infrastructure, such as roads, bridges, and buildings, further underscores the significance of addressing this threat promptly. With the impending monsoon season characterized by heavy rainfall, embankment integrity becomes increasingly critical.

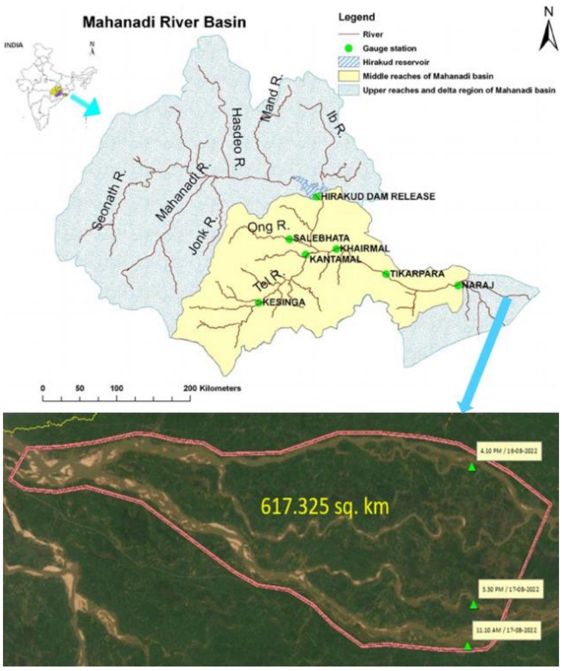

Figure 1. Study Area Map along with embankment breach locations [Tiwari, et. al (2012)].

3. Methodology

The simulation of embankment breaches using hydrological modelling can be significantly enhanced through the

https://doi.org/10.5194/isprs-annals-X-3-2024-117-2024 | © Author(s) 2024. CC BY 4.0 License.

utilization of High-Performance Computing (HPC) systems. Such simulations entail intricate calculations, necessitating a formidable computational capacity that HPC systems provide. This intricate process involves the precise representation of the interplay between water flow, sediment transport, and the structural integrity of the embankment.

The process of conducting a hydrological modelling simulation for embankment breaches on HPC systems typically encompasses several key phases. Initially, relevant data, including topographical details, soil characteristics, hydrological data, and initial conditions, were compiled and made ready for use. Subsequently, ANUGA Hydro, a free and open-source hydrological model was selected—one capable of accurately emulating water flow, erosion, sediment movement, and breach development. This model was then configured with inputs like boundary conditions, initial water levels, and precipitation patterns. The computational core of the process lies in numerical solvers designed to address the partial differential equations governing fluid dynamics and sediment transport. The parallel processing capabilities of HPC systems were harnessed during the simulation execution, as the computational workload is divided into smaller segments that can be processed concurrently across multiple processors. This division accelerated the simulation substantially.

Following the simulation's execution, post-processing enters the scene. This stage involved a meticulous analysis of the simulation outputs to decipher breach formation, water flow characteristics, erosion rates, and potential ramifications. Visualization tools were used for the comprehension comparison of complex data sets. To ensure the reliability of the outcomes, validation against real-world observations or historical data is paramount, and adjustments to model parameters were made as needed.

The following steps were followed for the simulation runs:

1. **Data Collection and Preparation:** Topographic data (LIDAR DEM from CWC), river network information (Satellite data), real-time rainfall data (IMD- WRF model data), surface roughness (Landuse-Landcover map – 2019 Sentinel data) and discharge data (CWC) were gathered to develop the hydrodynamic model. IMD WRF data is mainly used due to its several advantages. Firstly, its high resolution captures the complexities of India's diverse terrain, leading to more accurate simulations. Secondly, the data is specifically tailored for the Indian subcontinent, incorporating regional weather patterns for improved forecasts compared to global models. Finally, its accessibility and consistent formatting from the IMD streamline integration with flood models and facilitate research collaboration within India. This data is crucial for creating an accurate simulation model. OSDMA, Bhubaneshwar provided the actual breach location data from the Mahanadi Delta region for the year 2022 (Figure 2);

Figure 2: Breach locations in the study area

2. **Model Selection:** ANUGA Hydro is a powerful open-source software designed for hydrological modelling and floodplain inundation simulations. By employing finite-volume methods to solve the shallow-water equations, ANUGA Hydro accurately captures complex water flow dynamics during flooding events and embankment breaches. Notable for its adaptive meshing, parallel processing capabilities, and diverse boundary condition handling, the software excels in simulating a range of hydrological scenarios. ANUGA Hydro's visualization tools aid in comprehending simulation outputs, while its open-source nature encourages collaboration and customization within the hydrological research and disaster management communities, making it a versatile and valuable tool for studying water flow behaviours and flood inundation patterns.

3. **Model Setup:** First the area's geometry and topography were defined, incorporating the embankment's shape and breach location. It is followed by the generation of an adaptive mesh that accurately represents the topography and flow changes, focusing on finer resolution near the breach site. Initial water levels were defined, considering upstream and downstream conditions. Boundary conditions were defined by detailing water levels upstream and downstream. It was followed up with defining embankment properties, such as its height and width. Configuration of simulation parameters like time step size and total duration was done. Finally, the simulation results were visualized and analysed to understand breach progression, flow dynamics, and inundation extent.

4. **Numerical Solver:** Built upon the finite-volume method, this numerical solver tackles the complex equations governing shallow-water flow dynamics. By discretizing the domain into a mesh of cells, the solver calculates fluxes of water and sediment between neighbouring cells, capturing intricate variations in flow patterns and elevation changes. This approach accommodates adaptive meshing, where cells dynamically adjust their size based on flow conditions, enhancing accuracy where gradients are steep. Utilizing parallel processing capabilities, the solver distributes computations across multiple processors, optimizing simulation performance and enabling the modelling of extensive areas with high detail.

https://doi.org/10.5194/isprs-annals-X-3-2024-117-2024 | © Author(s) 2024. CC BY 4.0 License.

5. **HPC Implementation:** The integration of High-Performance Computing (HPC) technology with ANUGA Hydro marks a significant advancement in the realm of hydrological modelling and simulation. Leveraging the parallel processing capabilities inherent in HPC systems, ANUGA Hydro achieves accelerated execution of complex simulations involving flood inundation and embankment breaches. The software's adaptive meshing capability synergizes effectively with HPC, as simulations can be divided into smaller tasks that are concurrently processed by multiple cores or nodes. This results in substantially reduced computation time, enabling the simulation of vast geographical areas and intricate scenarios that were previously computationally impractical.

6. **Results visualization:** The results are obtained as *.sww* files which can be opened in the ANUGA Hydro visualization tool or QGIS using the Crayfish plugin. Visualization tools were very useful in presenting the data in a comprehensible manner.

7. **Post-Processing:** During this stage, data analysis techniques were applied to interpret the outputs. It revealed patterns, trends, and significant features of the simulation. It also included the visualization of water levels, flow velocities, and inundation extents over time and space. By generating graphical representations and maps, these tools unveil the dynamic behaviour of water, aiding in the identification of flood-prone regions, the assessment of vulnerability, and the validation of the simulation against real-world observations. In addition, during post-processing, quantitative metrics, such as maximum water depths or flood duration, were derived.

8. **Validation:** The validation of results allows for gauging the accuracy and reliability of the model's predictions. This crucial phase involves comparing the simulation outputs with real-world observations, and historical data, wherever available. By quantitatively and qualitatively comparing the simulation results with empirical evidence, the model's performance was critically evaluated. The model is calibrated and validated using historical flood events and real-time data to ensure accuracy. Validation of the breach inundation is done using optical and SAR satellite imagery. Extracting flood inundation from both optical and SAR data involved a two-pronged approach. Optical imagery, with its strength in capturing spectral information, was used to identify inundated areas based on spectral indices that differentiate water from land. The Normalized Difference Water Index (NDWI) effectively distinguishes water bodies due to water's strong absorption in the near-infrared region. SAR data, on the other hand, excels in penetrating cloud cover and offers sensitivity to water surfaces regardless of illumination conditions. Here, thresholding techniques were employed, where pixels exceeding a specific backscatter threshold were classified as flooded. The list of freely available data is given below (Table 1);

Satellite Type	Sensor	Spatial Resolution	Imagery Date/ Time
Optical	Landsat 9	30 m x 30 m	17 Aug2022 / 10:00
Optical	Landsat 8	30 m x 30 m	16 Aug 2022 / 10:00
Optical	Sentinel 2	10 m x 10 m	17 Aug 2022 / 10:00
Optical	Sentinel 2	10 m x 10 m	18 Aug 2022 / 10:00
SAR	Sentinel 1	25 m x 10 m	16 Aug 2022 / 18:00
SAR	Sentinel 1	25 m x 10 m	18 Aug 2022 / 18:00

Table 1: Details of satellite data used for validation

4. Results

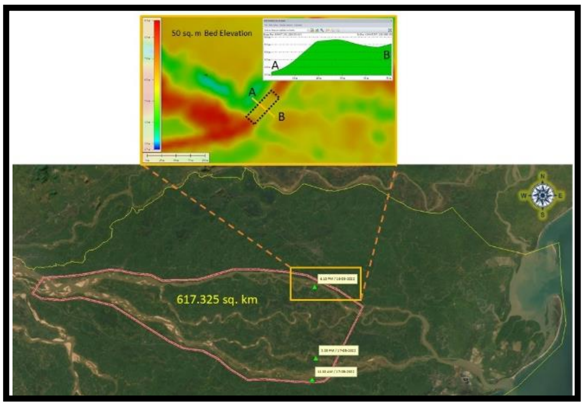

Figure 3: Area where simulation was run (Pubansa) in Mahanadi Delta Region along with the edited DEM of the one breach site for which simulation was run.

Figure 3 shows the section of the Pubansa area where the breach occurred on the 17th of Aug 2022 along with the river cross-section. Points A and B show the points from where the breach has occurred. For modelling purposes, the DEM from A to B was edited to remove the embankment from the data. The simulation was run on 50 m^2 mesh. The total simulation area was roughly 618 km^2

For the current simulation, a breach of width 22 m that occurred at 15:30 hours on 17-08-2022 near Gobardhanpur under the Mahanadi South division was used. Mahanadi barrage discharge for the period from 17-08-2022 06:00 hours to 19-08-2022 06:00 hours was used as inflow to the river, shown in the table below (Table 2); the roughness coefficient was calculated using a landuse/ landcover map of the year 2022. Since no rainfall was recorded on that day, zero rainfall input was taken for the simulation.

Date	Time	Mahanadi Discharge (m^3/s)
17-08-2022	06:00	16468.59
17-08-2022	09:00	16468.59
17-08-2022	12:00	16468.59
17-08-2022	15:00	16468.59
17-08-2022	18:00	16468.59
17-08-2022	21:00	16468.59
18-08-2022	00:00	14555.73
18-08-2022	03:00	14555.73
18-08-2022	06:00	14555.73
18-08-2022	09:00	14555.73
18-08-2022	12:00	14555.73
18-08-2022	15:00	14555.73
18-08-2022	18:00	14555.73

Table 2: River discharge data from Mahanadi barrage

The simulated inundation at 18:00 hours on 18-08-2022 is shown below in Figure 4;

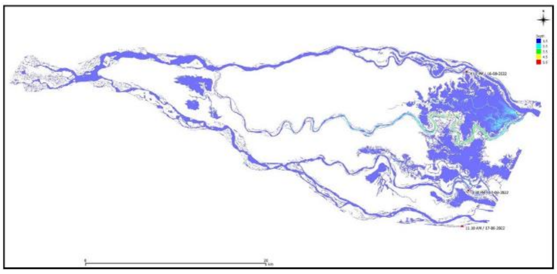

Figure 4: Simulated output of 18 Aug 2022 at 18:00 hrs

The momentum of water, coupled with depth, is critical for embankment breach simulation as it provides essential insights into the dynamics and severity of flooding events. By incorporating momentum, which encompasses flow velocity, into simulations, we gain a comprehensive understanding of the erosive forces acting on embankment structures. Higher flow velocities indicate increased erosion potential, particularly in vulnerable areas of the embankment, where breach formation may occur. Consequently, accurate predictions of water momentum enable better identification of high-risk zones and the development of targeted mitigation strategies to reinforce embankments or implement emergency measures. Moreover, considering both depth and momentum in simulations allows for a more realistic representation of flood dynamics, facilitating improved flood risk assessment, disaster preparedness, and response planning. Figure 5, below, shows the momentum of water during the breach from 16th Aug 2022 at 18:00 hours till 18th Aug 2022 at 18:00 hours.

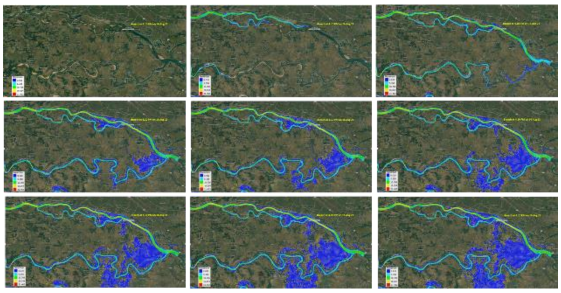

Figure 5 Momentum of water during breach from 16th Aug 2022 at 18:00 hours till 18th Aug 2022 at 18:00 hours

The validation exercise was carried out utilizing SNAP and Sentinel SAR data which involved a systematic approach to assess the accuracy of simulated inundation extents. Initially, Sentinel-1 SAR imagery acquired on August 18, 2022, was obtained and pre-processed to ensure compatibility with the simulated inundation data. SNAP's functionalities were then leveraged to co-register the SAR imagery with the simulated inundation extents, ensuring spatial alignment. Visual inspection was conducted to qualitatively compare the simulated inundation boundaries with the flooded areas identified in the SAR image. Additionally, quantitative analysis was performed using SNAP's tools to calculate statistical metrics. This comprehensive validation process facilitated a thorough evaluation of the accuracy and reliability of the simulated inundation extents against observed SAR imagery, contributing valuable insights for damage assessment. Figure 6 shows the Simulated output overlaid over the sentinel-1 SAR data acquired. The comparison was done by matching the data acquisition time along with the simulated output time.

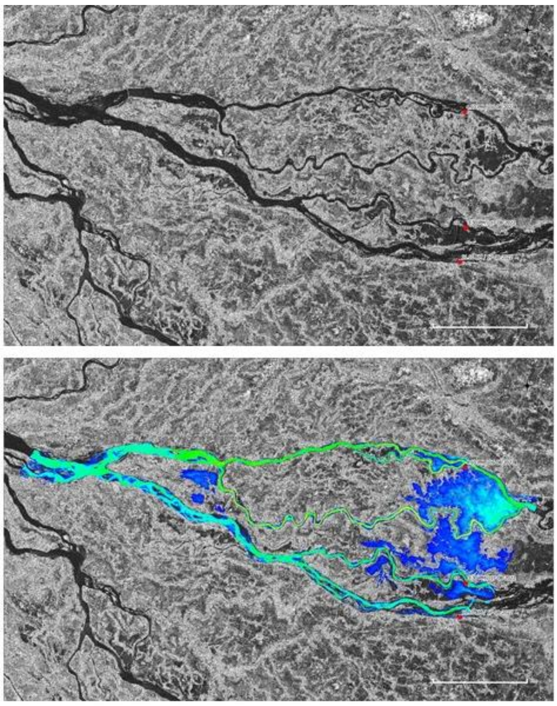

Figure 6: The inundation spread is overlaid on Sentinel-1 SAR Image acquired at 18:00 hours on 18-08-2022 to check the accuracy of simulated spread from the breaches.

https://doi.org/10.5194/isprs-annals-X-3-2024-117-2024 | © Author(s) 2024. CC BY 4.0 License.

Initially, the simulation was run on PARAM Porul using 20 CPU Nodes with 46 Cores each. This is equivalent to 66 TF compute power. The 60-hour simulation was completed in 18 hours and 30 minutes at a mesh resolution of 50 sq. m. (approximately 20 million mesh elements). Since the hydrodynamic model is scalable, further using 40 nodes, the compute time was reduced to about 9 hours and with 120 nodes, the simulation could be completed in 2 hrs (roughly 10-15 minutes for every three hours' simulations). This timing includes pre- and post-processing of the data, which roughly took 22 minutes. The scaling was still nearly linear, which gives us confidence that it may further reduce, however as documented, ANUGA Hydro has some limitations with a maximum optimisation till 2000 number of mesh elements.

5. Discussion

The results of embankment breach simulations provide valuable insights into the behaviour of water flow during potential breach scenarios, aiding in our understanding of the associated risks and facilitating informed decision-making. Upon analysing the simulation outcomes, several key findings and observations become evident.

Firstly, these simulations highlight the significance of accurate topographic and hydrographic data, as they form the foundation for precise modelling. The availability of high-resolution data enables more realistic representations of embankments and surrounding terrain, ultimately leading to more reliable predictions of breach dynamics.

Secondly, the simulations underscore the importance of considering various breach scenarios. By examining different breach sizes, locations, and initiation mechanisms, we gain a comprehensive view of the potential outcomes and their associated risks. This multifaceted approach allows for a more robust assessment of vulnerabilities and helps identify critical areas where mitigation measures should be prioritized.

Thirdly, analysis of flow momentum reveals crucial information about the velocity and direction of water flow during flooding events. This analysis will help in identifying regions with high water velocities and understanding the forces exerted by the floodwaters. By combining information on water depth and momentum, a comprehensive understanding of flood flow, aids in the assessment of flood risk, infrastructure vulnerability, and emergency response planning.

Furthermore, embankment breach simulations help quantify the extent of potential inundation and the areas at risk. This information is vital for emergency response planning and resource allocation during flood events. It also aids in defining evacuation zones and determining the necessary infrastructure improvements to enhance resilience.

The utilization of an HPC system significantly enhances the accuracy and speed of processing data critical for embankment breach simulation, a task that would otherwise be impractical on single-core systems. HPC systems offer parallel processing capabilities, allowing for the simultaneous execution of numerous computational tasks, thereby expediting the simulation process. Moreover, the intricate algorithms and complex hydrodynamic models involved in embankment breach simulation demand extensive computational resources, which HPC systems provide efficiently. By distributing computational workload across multiple cores, HPC systems not only accelerate processing but also ensure accuracy by minimizing computational errors and uncertainties. Additionally, the scalability of HPC systems enables the handling of large datasets and high-resolution models, which are essential for capturing the intricacies of flood dynamics accurately.

Lastly, the insights gained from embankment breach simulations provide valuable input for developing and improving flood risk management strategies. These simulations assist authorities in making informed decisions about land use planning, emergency response protocols, and infrastructure development, ultimately contributing to more resilient and disaster-resilient communities.

6. Conclusion

Embankment breach simulation is a critical necessity for India to address the country's vulnerability to floods and associated challenges. Accurate flood forecasting and preparedness can save lives, protect infrastructure, and ensure effective response and recovery measures. By investing in advanced simulation techniques, India can build resilience against floods and minimize the devastating impacts of embankment breaches on its population, economy, and environment. HPC is indispensable for embankment breach simulations due to its ability to handle complex modelling, large datasets, and the real-time demands of such simulations. Results have shown that the HPC systems excel at performing these computations efficiently and accurately. Moreover, they offer the advantage of parallel processing, scalability, and precision, all of which are critical for predicting water flow behaviour during a breach accurately. The ability of HPC to provide rapid results is particularly vital for real-time decision-making during flood events. Furthermore, the scalability of HPC systems allows for the exploration of various breach scenarios, contributing to comprehensive risk assessment. This study demonstrates the feasibility of using advanced hydrodynamic models and HPC systems to generate detailed inundation maps, aiding disaster preparedness and response efforts.

Collaborative efforts involving experts from these domains are pivotal in delivering precise results and optimizing computational resources. Advances in both hydrological modelling software and HPC technology have opened avenues for highly detailed and accurate simulations of intricate phenomena like embankment breaches, thereby contributing substantively to improved risk assessment and disaster preparedness strategies.

Acknowledgement:

We extend our sincere gratitude to the Odisha State Disaster Management Authority (OSDMA), the Ministry of Electronics and Information Technology (MeitY), and the Central Water Commission (CWC) for their invaluable support and contributions to the aforementioned work. Their assistance has been instrumental in facilitating the research and development efforts aimed at enhancing flood risk management through advanced hydrodynamic modelling and simulation of embankment breaches. We are deeply thankful for their collaboration and commitment to fostering innovation in disaster preparedness and mitigation strategies.

References

Barker, R., et al., 1997. Use of terrestrial photogrammetry for monitoring and measuring bank erosion. *Earth Surface Processes and Landforms*.

Bull, L. J. 1997. Magnitude and variation in the contribution of bank erosion to the suspended sediment load of the River Severn, UK. *Earth Surface Processes and Landforms*.

Darby, S. E., and Thorne, C. R., 1996. Numerical simulation of widening and bed deformation of straight sand-bed rivers, I, Model development. *Journal of Hydraulic Engineering*, 122, 184–193.

Eaton, B. C., et al. 2004. Rational regime model of alluvial channel morphology and response. *Earth Surface Processes and Landforms*.

Fell, R., Foster, M. A., Cyganiewicz, J., Sills, G. L., Vroman, N. D., Davidson, R. R., 2008. Risk Analysis for Dam Safety: A Unified Method for Estimating Probabilities of Failure of Embankment Dams by Internal Erosion and Piping. URS Australia, New South Wales, Sydney, Australia, *Canadian Geotechnical Journal*, Vol.22, pp. 215-225.

Fell, R., Wan, C. Fai, Cyganiewicz, J., and Foster, M., 2003. Time for Development of Internal Erosion and Piping in Embankment Dams. *Journal of Geotechnical and Geoenvironmental Engineering*, 129, 307-314.

Garner, S. J., and Fannin, R. J. 2010. Understanding internal erosion: a decade of research following a sinkhole event. *International Journal on Hydropower and Dams*, 17(3), 93-98.

Goodson, J. M., Gurnell, A. M., Angold, P. G., and Morrissey, I. P. 2002. Riparian seed banks along the lower River Dove, UK: their structure and ecological implications. *Geomorphology*, 47(1), 45-60.

La Loggia, G., and Freni, G., 2018. A Parallel Flood Forecasting and Warning Platform Based on HPC Clusters. In Proceedings of the 13th International Conference on Hydroinformatics (HIC 2018), Palermo, Italy, 1 July 2018; Puleo, V., de Marchis, M., Eds.; EPiC Series in Engineering. EasyChair Publications: Manchester, UK, 2018; Volume 3, pp. 1232–1239.

Liu, R., Wei, J., Ren, Y., Liu, Q., Wang, G., Shao, S., and Tang, S., 2017. HydroMP—A computing platform for hydrodynamic simulation based on cloud computing. *Journal of Hydroinformatics*, 19, 953–972.

Shang, Y., Guo, Y., Shang, L., Ye, Y., Liu, R., and Wang, G., 2016. Processing conversion and parallel control platform: A parallel approach to serial hydrodynamic simulators for complex hydrodynamic simulations. *Journal of Hydroinformatics*, 18, 851–866.

Sherard, J. L., Woodward, R. J., Gizienski, S. F., and Clevenger, W. A., 1967. Earth and earth-rock dams, Chapter 2. John Wiley and Sons, New York.

Sherard, J. L., 1979. Sinkholes in dams of coarse, broadly graded soils. Transactions of the 13th ICOLD Congress, International Commission on Large Dams, New Delhi, India, Vol. 2, 25-35.

Tiwari, Mukesh K and Song, Ki-Young and Chatterjee, Chandranath and Gupta, Madan, 2012. River-Flow Forecasting Using Higher-Order Neural Networks. *Journal of Hydrologic Engineering*. 17. 655-666. 10.1061/(ASCE)HE.1943-5584.0000486.

Wan, C. F., and Fell, R., 2008. Assessing the potential of internal instability and suffusion in embankment dams and their foundations. *Journal of Geotechnical and Environmental Engineering*, ASCE, 134(3), 401-407