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Two decades after the catastrophe: Reflections and lessons from the 2004 Indian Ocean tsunami

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ABSTRACT
The 2004 Indian Ocean tsunami was one of the deadliest natural disasters in recorded history, claiming approximately 230,000 lives across multiple countries. In two decades' time, significant advancements have been made in tsunami early warning systems, research, and disaster preparedness. This paper reviews the impact of the 2004 tsunami, analyses past and recent tsunami events, and highlights the development of global and regional tsunami mitigation strategies from the data published in research articles. Key initiatives have revolutionised tsunami detection and response, including the Indian Ocean Tsunami Warning and Mitigation System (IOTWMS), GNSS-based monitoring systems, and ocean-bottom sensors. Additionally, community-based programs, such as India's "Tsunami Ready" initiative, have enhanced coastal resilience. While technological advancements have improved early warning capabilities, further efforts are required to ensure widespread awareness, preparedness, and rapid response mechanisms. This review underscores the necessity of continuous innovation, international collaboration, and community engagement to mitigate the catastrophic effects of future tsunamis.

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1. Introduction

Catastrophic earth and atmospheric processes keep humans at risk, such as tsunamis, earthquakes, floods and other natural disasters. UN Sustainable Development Goal 11 envisions the right of human beings to live in safe, resilient, and sustainable human settlements. To achieve this goal, the formulation of effective disaster management strategies is vital. The significant impact of tsunamis on coastal environments and infrastructure makes it imperative to implement effective early warning systems in tectonically active regions on warrant. 2024 is the 20th anniversary of the catastrophic tsunami in the Indian Ocean, triggered on December 26, 2004. This study presents an overview of the initiatives taken for developing tsunami early warning systems, as well as the research and innovations carried out across the globe since 2004.

Prior to the 2004 Indian Ocean tsunami, the term "tsunami" was largely uncommon to the people in India. Tsunamis are a series of high-energy concentric ocean waves created widely by endogenic earth processes such as earthquakes (72% of the causative factors of the world's tsunamis), submarine volcanism (5%), and exogenic processes like meteoric impact (2%), submarine landslides (11%), meteorological, and other unknown factors (10%)

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Table 1. Details of the three major tsunami incidents in the last two decades.

Tsunami	Geographic distribution	Causative factor	Effects
The Indian Ocean Tsunami 2004	Affected more over 18 Countries, stretching from South east Asia to Southern Africa.	Earth quake magnitude (EQM) of 9.1-9.3. Epicenter - off the North Western coast of Sumatra Island (where Indian plate subducts beneath the Burma plate).	The most catastrophic tsunami disaster in recorded history. More than 2.30 lakh people lost their lives.
Tohoku Tsunami 2011	The Great East Japan Earthquake and Tsunami hit the Pacific Ocean of Eastern Japan.	Largest Earthquake (ever reported in Japan) EQM- 9.0	15,854 deaths, 3167 people missing and 26,992 injured.
Palu Tsunami 2018	Caused significant destruction across the coastal areas of Sulawesi, Indonesia. affected 371 locations in the city.	EQM-7.5 Epicenter: Donggala regency.	4340 people lost their lives and 10,679 people injured.

(NCEI/WDS Global Historical Tsunami Database, Gusiakov et al., 2019). It is considered one of the devastating natural disasters that impact life and the environment. It is a fact that natural disasters will impart a permanent scar in the minds of victims and on nature. The 2004 tsunami was the fatal incident that occurred on 26 December in the Indian Ocean. An earthquake of magnitude 9.1 occurred 155 miles off the coast of Sumatra, Indonesia, and had devastating effects on the coastal tracts of Asian, African, and European countries (Barnes, 2017) (Fig. 1). Indonesia, Thailand, India, Sri Lanka, and the Maldives were severely affected by the disaster.

The review of the global historical tsunami database from 1900 suggests that, on average, two tsunamis occur per year on Earth, causing disaster to the people and properties along the coast, and 72% of tsunamis were triggered by earthquakes. The Pacific Rim countries are affected largely by tsunamis (approximately 900 events happened in the 20th century) compared to Indian Ocean regions (Chandramohan et al., 2017). The Andaman-Nicobar-Sumatra Island arc and the Makran subduction zone north of the Arabian Sea (ESSO) are the significant tsunami-disturbed regions in the Indian Ocean.

Between 1998 and 2017, tsunamis killed more than 250,000 across the globe, including more than 227,000 who lost their lives due to the Indian Ocean tsunami that occurred in 2004 (www.who.int). During the previous 450 years, tsunamis have killed approximately 470,000 people globally (Nurendyastuti et al., 2022). After the 2004 Indian Ocean tsunami in 2011, the Tohoku tsunami and the 2018 Palu tsunami had a devastating effect on the earth's surface. Table 1 appends the details of the devastating tsunami disasters in the last two decades.

2. Tsunami inventory

Tsunami incidents have been documented in Japan since AD 869, and the archaeological evidence indicates that it traced back to 7300 BC, coinciding with the volcanic eruption of the Kikai Caldera during 14,000–400 BC (Barnes, 2017). Since 1900, Japan, Peru, Chile, New Guinea, and the Solomon Islands have reported devastating tsunamis worldwide. Tsunamis occurred in 1792, 1960, 1972 and 2011 and were disastrous (Barnes, 2017). Remote-source tsunamis affecting the entire Pacific basin are generated in the regions of the Kamchatka Peninsula, the Aleutian Islands, the Gulf of Alaska, and the coast of South America (NCEI).

The first tsunami recorded along the Indian coast was reported on 31st December 1881 and was caused by an EQM 7.9 that occurred near Car Nicobar Island. The east coast of India was affected, and a 2 m tsunami was reported at Chennai on 27th August, 1883, due to the eruption of Krakatoa volcano (Sunda Strait), Indonesia. Under the influence of EQM 8.1 in Andaman, the East Coast of India was affected by a tsunami on 26th June, 1941. The west coast of India was affected by a tsunami on 27th November, 1945, due to an earthquake at the Makran subduction zone, Baluchistan, Pakistan, of EQM 8.1 (www.incois.gov.in). The study of the global inventory data of tsunamis since 1762 suggests that 82 tsunami events out of the 121 incidents (Fig. 2) are caused by EQM > 7 (www.noaa.gov).

3. The Indian Ocean Tsunami (IOT) of 2004 effects in India

IOT 2004 was a challenge for the scientific community to rise and work on developing an early

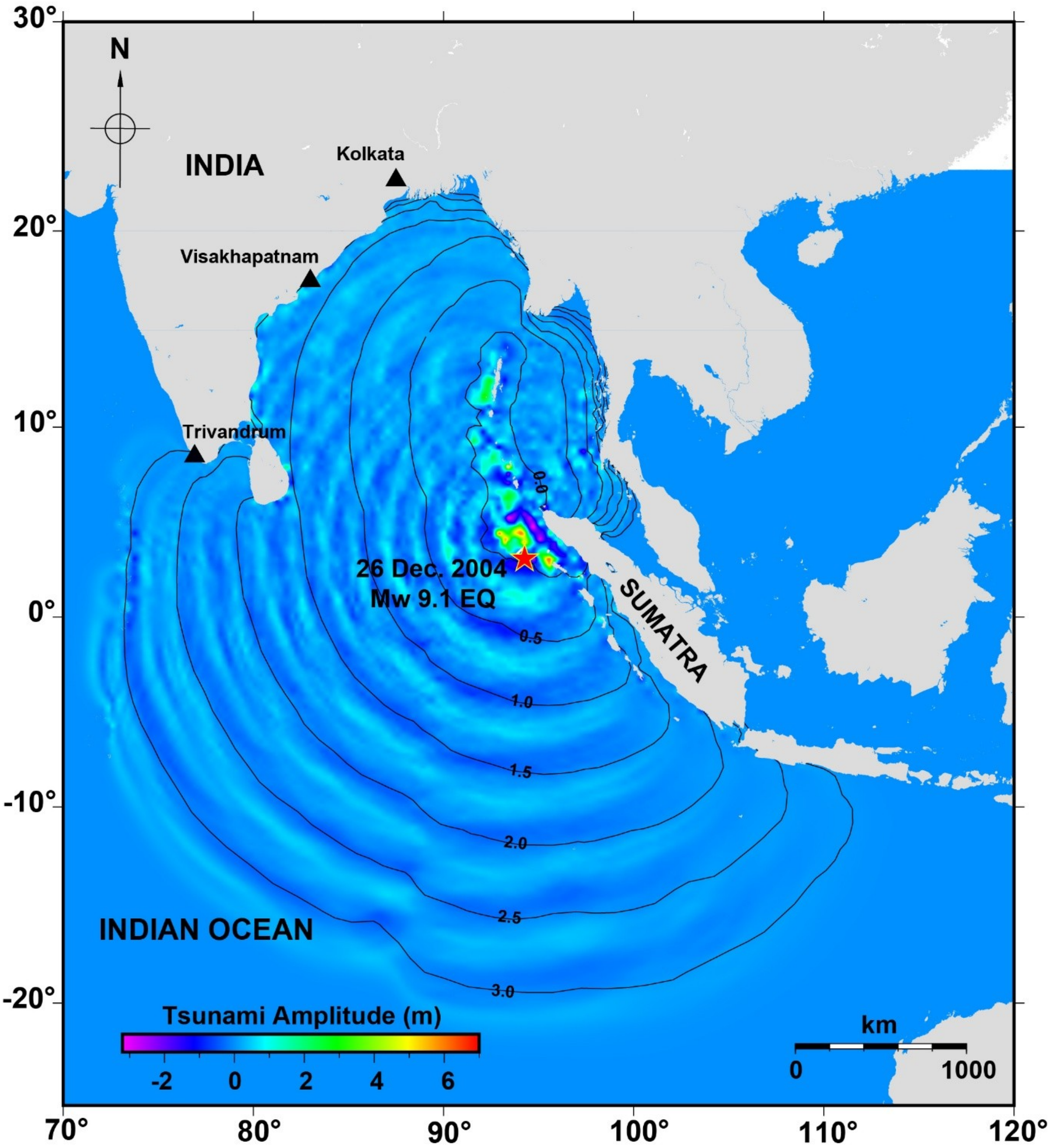

Fig. 1. Sumatra tsunami Travel-Time Diagram (TTD) with amplitude shown by contours in 30 minutes time interval with earthquake event in red star and rupture model in white grids (modified after Sladen and Hébert, 2008 and Bagiya et al., 2017).

warning system for protecting the people residing on the Indian coast from disastrous sea waves. Triggered at Banda Aceh, North Sumatra, at 6.28 am IST, the disastrous sea wave, 51 m in height, hit the east coast and southern tip of peninsular India in 90 minutes (Fig. 1). Due to the lack of early warning systems, the effect was more devastating. This catastrophic event severely affected Andhra Pradesh, Puducherry, Tamil Nadu, Kerala, and the Andaman Nicobar Islands. In Andhra Pradesh, Visakhapatnam, with a population of 1.96 lakh, and East and West Godavari, Krishna, Guntur, Prakasam, and Nellore were affected; 107 people lost their lives. Thiruvallur, Kancheepuram, Villupuram, Nagapattanam, Thiruvarur, and Thoothukudi, Tirunelveli and Kanyakumari regions of Tamil Nadu were severely damaged in this incident. The data indicates that the incident claimed the lives of 8009 people and affected 8.97 lakh others. The disaster affected about 43000 people in Karaikkal and the adjacent regions of Puducherry,

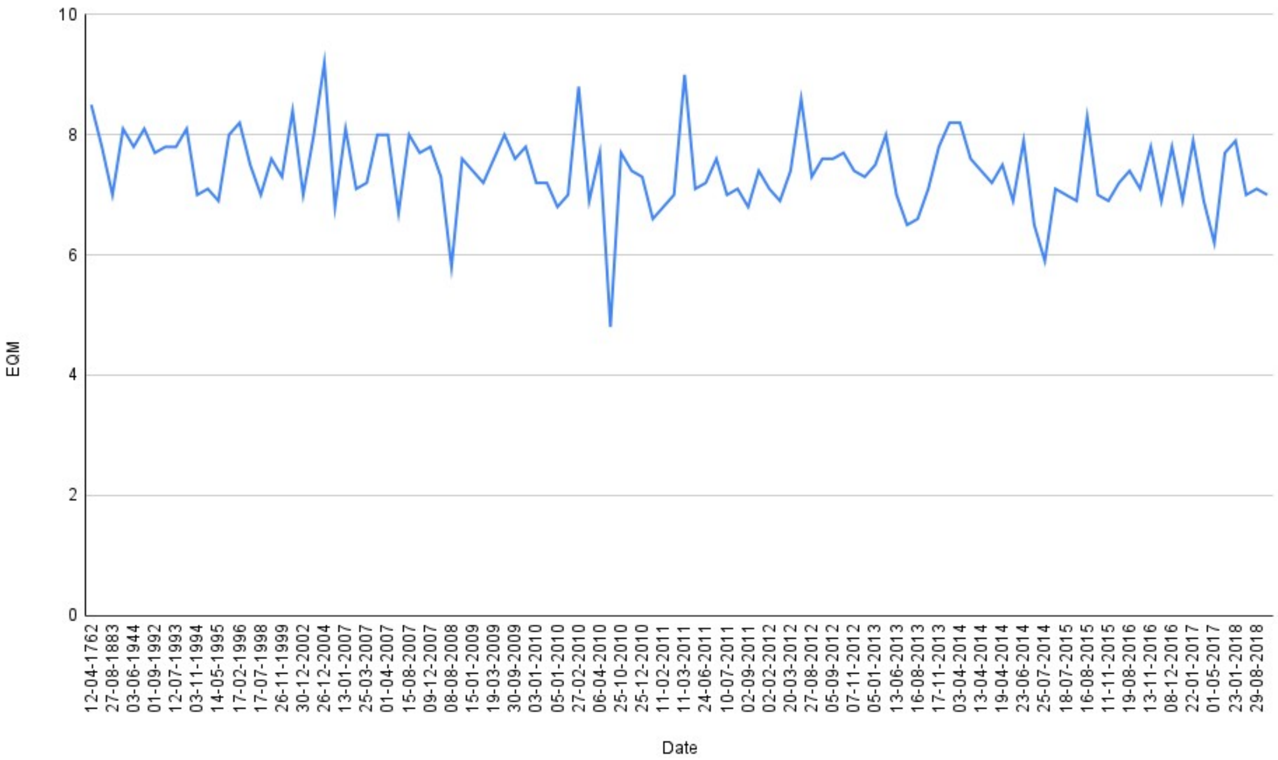

Fig. 2. Major tsunami incidents around the world since 1762. From date 12-04-1762 to 29-08-2018 plotted in the X axis and earthquake magnitude (EQM) on Y axis.

resulting in a recorded death toll of 599. The disaster severely affected Kerala, marking the first tsunami incident in the region. The giant waves shattered the coastal districts of Kollam, Alappuzha, and Ernakulam. The waves affected approximately 30 lakh people, resulting in a death toll of 177. The Alappad village of Kollam district was severely affected, and 132 people died. In the Andaman Nicobar Islands, 3.56 lakh people were affected, and 3513 people died (www.undp.org).

3.1. Tsunami preparedness after IOT 2004

The quote of Benjamin Franklin (20th century), ‘Failing to prepare is preparing to fail,’ is true for managing the disaster without the preparedness phase. Improved tsunami preparedness, prompt warning, and efficient reaction can reduce the devastating effects, and effective early warning systems serve as useful instruments for minimising casualties, and they are the primary step in disaster management. Cutting-edge technology, communication and community compassionate leadership will help to reduce the disastrous effects of a disaster to an extent. Aware of these facts, the affected countries, initiated capacity augmentation for tsunami disaster management. Safe island program in Maldives, development of Early Warning System (EWS) and legal and institutional framework, including mobile phone siren/ringtone alert system, and mock drills were implemented in Sri Lanka at community level; these are such initiatives.

Following the 2004 Indian Ocean tsunami, the United Nations conference in Kobe, Japan, in January 2005, resolved to set up the Indian Ocean Tsunami Warning and Mitigation System (IOTWMS) as a first step towards developing an International Early Warning Program (Lauterjung et al., 2010; Hiroyuki et al., 2022). Indonesia and other impacted regions developed warning systems. However, due to the non-operation of the detecting buoys, Indonesia’s system was shut down in 2012.

The INCOIS (Indian National Centre for Ocean Information Services), which was established in 1999 by the Ministry of Earth Sciences (MoES) formerly the Department of Ocean Development (DOD), Government of India, receives data from over 35 sea level tidal gauges, Bottom Pressure Recordings (BPR) and a network of seismographs installed in the Indian

Ocean regions. It operates as a network using the advanced Global Seismic Network (GSN) technology. The INCOIS established the Indian Tsunami Early Warning Centre (ITEWS) in 2007. The warning systems collect information from approximately 17 seismic stations of the India Meteorological Department (IMD) and more than 300 international stations along with the INDOFOS (Indian Ocean Forecasting System) and Oceansat-2.

4. Research and development

Bibliometric analysis is carried out with the aid of the Web of Science (WOS) platform. A literature search carried out using the keywords 'Tsunami' and 'Tsunami Disaster Management' reveals that 16296 and 1356 research outputs have been published, respectively, during the past 20 years since IOT 2004. The top ten countries involved in tsunami academic research are the USA (research articles (RA) 4025), Japan (3604), China (1408), England (1228), Germany (1004), France (982), India (976), Australia (926), Italy (866), and Canada (684).

4.1. Post-tsunami Environmental and Biodiversity Impact Assessment

Post-tsunami environmental recovery requires comprehensive research and continuous monitoring, particularly to assess the extent of damage and guide the restoration of affected ecosystems. Coastal habitats, including macro-benthic and meiofaunal communities, often experience immediate and severe impacts due to such events. Investigative methods typically involve the collection and analysis of sediment and meiofauna samples across various tidal zones, grain size assessments, and standard decantation and sieving techniques. These approaches help in evaluating disruptions to ecosystem services and estimating the recovery timelines of benthic macroinvertebrate assemblages. Additionally, tsunami-induced soil salinisation is a significant concern, with its effects commonly assessed through ion chromatography for water-leachable anions and inductively coupled plasma atomic emission spectroscopy (ICP-AES) for cations using time-series sampling to track changes. Landscape alterations, such as those occurring in ria coastal regions, are studied through Digital Elevation Models (DEMs) to monitor erosional changes and bare rock exposures (Kontar et al., 2014).

In parallel, the assessment and modelling of contamination through Submarine Groundwater Discharge (SGD) is essential, as SGD serves as a critical pathway for the transport of nutrients and pollutants into coastal waters, particularly in tsunami-impacted zones (Kontar et al., 2014). Field and laboratory-based methodologies are employed to quantify these fluxes and their ecological effects. Radon-222 (^{222}Rn) is used as a tracer to determine SGD rates, while manual and electromagnetic seepage meters measure direct discharge. Chemical assessments include nutrient concentrations analyzed via flow injection autoanalyzer and trace metal content determined by inductively coupled plasma mass spectrometry (ICP-MS), along with evaluations of basic water quality parameters such as temperature, salinity, pH, and dissolved oxygen (Kontar et al., 2014).

Metrics such as benthic metabolism, oxygen demand, sedimentary organic carbon, and aquatic community structure, including diatom populations, examine biological responses. Geophysical techniques, such as transient electromagnetic (TEM) sounding, radon surveys, and piezometer installations, aid in spatial mapping and preliminary screening of SGD. Remote sensing technologies are increasingly utilized for monitoring SGD and associated ecological changes. Numerical modelling, incorporating 3D ocean circulation and particle-tracking systems, is instrumental in predicting pollutant dispersal and understanding long-term impacts. These models also integrate hydrological, geological, and chemical data to simulate fluid, nutrient, and energy migration. Future research aims to enhance the accuracy and affordability of in situ and remote sensing technologies and refine modelling approaches to improve the protection and sustainable management of coastal water resources in tsunami-affected environments (Kontar et al., 2014).

4.2. Innovations in tsunami early warning systems

Technology evolved over time, and limitations in the early warning systems led to the development of innovative real-time data integration and analytical systems (Srinivasa Kumar and Manneela, 2021). Recently, to estimate tsunami hazards, machine learning and numerical modelling have been employed for analysing rupture characteristics from acoustic data (Gomez and Kadri, 2023). The chronologic evolution of the Tsunami Early Warning System is summarised in Fig. 3.

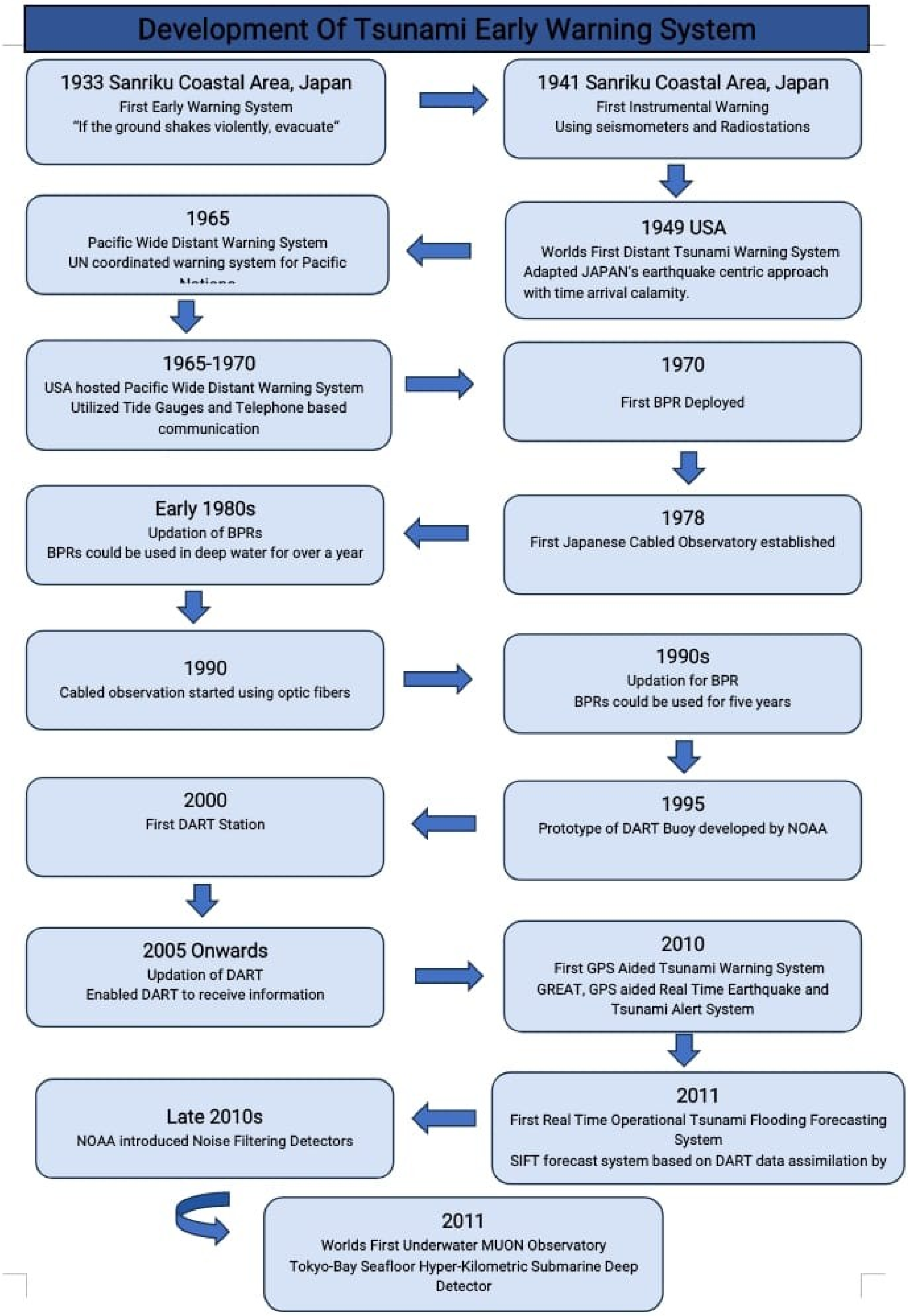

Fig. 3. Chronological progression of the evolution of Tsunami Early Warning Systems.

Collaboration of countries for data sharing, research and development of technology for mitigating tsunami disasters had been developed over the past 20 years. Some of the global technological approaches employed for tsunami detection are

4.2.1. Real time GNSS arrays (GNSS-SHIELD)

Stations orientated perpendicularly and close to the trench collect both horizontal and vertical displacement using continuous geodetic Global Navigation Satellite System (GNSS). From those data, synthetic observations and rupture models and curves are obtained depending on the resolution of the synthetic array (tsunami in Sumatra and Java). The GNSS shield arrays placed along the trench will be able to estimate the seismic moment (magnitude) of the corresponding sections of a rupture zone (partial magnitude) within just a few minutes of an earthquake. The shield is able to capture relatively slow post-slip at the fault, which is undetectable using seismic methods.

4.2.2. Ocean-bottom Sensors S-Net System

For a sustainable future, after the 2011 Tohoku tsunami and earthquake, the Japan Meteorological Agency proposed ocean bottom sensors and S–net wave data (Mulia and Satake, 2021). After simulating a sizable collection of artificial earthquake source models, wave profiles for offshore and certain coastal locations can be obtained by analysing governing equations based on physics that account for both temporal and spatial resolution. By using the right exposure and fragility models, we can simulate coastal tsunami flooding and calculate the potential damage to buildings, which helps in developing an early warning system for common hazard measures.

Nevertheless, every tsunami early warning system has its limitations. Indonesia's current tsunami early warning system (Ina-TEWS) faces several operational challenges, including high maintenance demands, vulnerability to damage, and delays in information dissemination. Between 2012 and 2018, 22 buoys were reported lost or damaged, underscoring the fragility of buoy-dependent detection (Adityawan et al., 2023). Moreover, the 5-minute delay in alert transmission and the time-consuming nature of hierarchical coordination reduce the system's effectiveness in fast-response scenarios.

To address these limitations, a maritime wireless communication system using Very High Frequency (VHF) radio has been proposed as a complementary or alternative solution. This system promises quicker warnings and reduced maintenance but is constrained by factors such as limited communication hop counts, basic service capabilities, dependency on ship availability, and the impact of ship positioning on signal transmission efficiency.

4.3. Enhanced Tsunami Early Warning Capabilities in India

India's Tsunami Early Warning Centre (ITEWC) has significantly strengthened its monitoring and response systems through a multi-faceted approach combining seismic, geodetic, oceanographic, and modelling technologies. Seismic monitoring has been enhanced via a dense network comprising approximately 350 global stations, 17 national stations, and the Indian Seismic and GNSS Network (ISGN), which now includes 100 seismic and 30 GNSS stations. This expansion has reduced earthquake detection times to 3–8 minutes and improved the accuracy of source parameter estimation (Manneela et al., 2016).

To enable rapid detection near subduction zones such as the Andaman and Nicobar Islands, INCOIS is integrating GNSS and strong motion sensors. A network of 35 such instruments is being deployed, allowing for near-instantaneous estimation of moment magnitude (Mw) based on ground displacement, providing crucial early warning where seismic data alone may be delayed. Sea level monitoring has also improved, with the addition of four new tsunami buoys and ten tide gauges, enhancing the confirmation of tsunami occurrence and wave assessment. Advanced modelling using pre-computed simulations (TUNAMI N2) and a decision support system enables rapid scenario selection based on seismic input, with refined advisories targeting only threatened regions. The ITEWC meets international standards, achieving high performance indicators for detection and bulletin issuance, and has been recognized as a Tsunami Service Provider (TSP) by IOC/UNESCO (IOC, 2015) since 2012. Ongoing collaborations and drills ensure operational readiness. Lessons from past events, such as the 2011 Japan tsunami, have driven improvements in real-time modelling, GNSS data integration, and focal mechanism estimation. Despite these advancements, challenges remain in real-time tsunami height forecasting and providing sufficient lead time for near-field events. The ITEWC continues to prioritize last-mile communication, stakeholder engagement, and public awareness to enhance overall tsunami preparedness.

Despite notable advancements in tsunami early warning systems, several critical challenges and gaps remain in achieving comprehensive preparedness and response (Bernard and Titov, 2015). A key limitation lies in the continued reliance on earthquake-centric warning models, which fail to accurately predict coastal flooding—the true hazard during a tsunami—due to the weak correlation between earthquake magnitude and tsunami impact. This has led to over- or under-warnings, inappropriate public responses, and reduced trust in warning systems. Furthermore, the lack of standardized, specific warning products—such as real-time flooding maps, tsunami energy estimates, and harbour current forecasts—hampers effective evacuation and port operation planning, especially as most large ports still lack tailored tsunami response protocols. Technological constraints also persist, including high costs, system vulnerabilities, and limited global data sharing, particularly from GNSS buoys and cabled observatories. To address these issues, there is a pressing need for internationally standardized procedures, interoperable systems, and web-based forecasting tools like Tsunami web that can be adopted by nations with varying technical capacities. Additionally, community-level preparedness remains insufficient, with limited investment in risk education, land-use planning, drills, and infrastructure, all of which are essential—especially for near-field tsunamis where response times are minimal. Compounding these challenges is the growing exposure of coastal populations and infrastructure due to urbanization, climate change, and economic concentration in port areas, necessitating a more integrated, people-focused approach to tsunami risk reduction.

4.4. New initiatives

Japan with the aid of cutting-edge technology, developing an innovative system aimed at attaining zero causality during Tsunami events. With active EWS the Tohoku Tsunami 2011 affected only 3% of the population. Aiming at zero causality goal, they are improving techniques in horizontal and vertical evacuation methods. 'Shelter in place' is such an initiative from the Japanese researchers to create water tight containers that can hold 10–12 persons safely within it during a Tsunami event (Bernard, 2023). They are developing survival capsules that accommodate 2-3 persons in it.

In India, Odisha Government has implemented 'Tsunami Ready Community Resilience' programme by empowering and equipping people by conducting mock drills, constructing safe relief camps, creating safe route maps etc. The village of Noliasahi in the Jagatsingpur District, Odisha, on August 7, 2020, received recognition as Tsunami Ready under the Pilot Community Performance Based Tsunami Recognition Programme being implemented by the UNESCO/IOC (Inter Governmental Oceanographic Commission) (IOC, 2015). In the 2nd Global Tsunami Symposium in Indonesia, the National Tsunami Ready Recognition Board (NTRB) verified that the 24 coastal villages in Odisha were Tsunami Ready. In Kerala, the training is given to 9 coastal communities in the Alappad village, Kollam district transforming them Tsunami Ready. INCOIS also has been collaborating with the Kerala State Disaster Management Authority (KSDMA) to train communities in several villages, including those in Ernakulam district.

Over the past twenty years, although tsunami detection systems in India have significantly improved, the Tsunami Ready programs implemented in states like Odisha and Kerala need to be expanded to other states. Efforts are required to create awareness among the coastal communities about tsunami disaster preparedness and to develop technologies comparable to tsunami disaster management systems in other countries and to implement effective disaster preparedness programs. The coastal villages in India will become 'Tsunami Ready' villages capable of managing tsunamis, and to mitigate the disaster in India in the future.

Conflict of Interest Statement

The authors A.U. Anish, Sreenandana Venu, A.B. Krishnaprabha, Mekha Santhosh, S. Anandu and P.S. Sunil declare that they have no known competing financial interests or personal relationships that could influence the work reported in this paper.

Credit statement

AUA, SV: Conceptualization, Investigation, Methodology, Formal analysis, Writing – original draft. **ABK, MS, SA**: Data curation, Formal analysis. **PSS**: Supervision, review & editing.

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