Official Journal of the World Water Council
Water Policy

Water Policy Vol 25 No 12, 1175 doi: 10.2166/wp.2023.185

Progression of flood risk assessment in India at a decadal scale: a critical review

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ABSTRACT

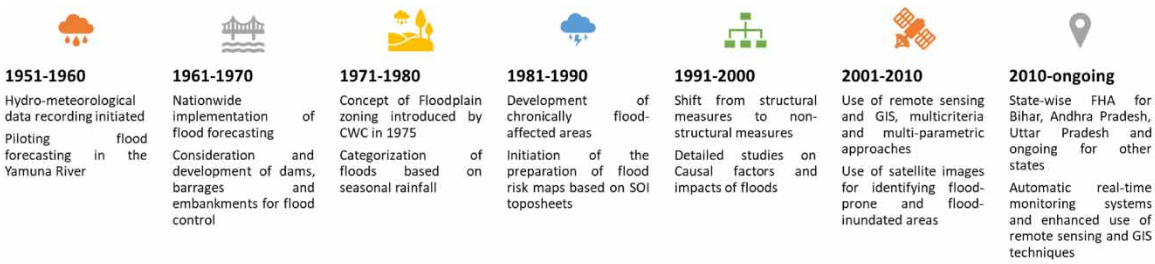
Floods are a recurrent natural phenomenon in India, including perennial occurrences in some parts of the country. Progressively, floods are transformed into flood hazards because of the anthropogenic activities in the flood plains and adjoining catchments, causing injuries, loss of lives, and property damage. Flood hazards, when considered in relation to vulnerability and exposure limits, describe the associated flood risk. This article aims to discuss the progression in flood risk assessment through several government policies and actions in India at a decadal scale from 1951 to 2020. While doing this, some important extreme flood events witnessed in those decades that shaped the perspectives, measures, action plans, and policies in the subsequent years are discussed. The review confirms that with the changing patterns of floods, associated hazards, and risks over the years, improvements in risk assessment approaches are noticeable on dual fronts. Technical advancements in flood risk assessment have corroborated the policy reforms. Albeit these developments, the issues related to the scale of study, data sources and resolutions, climatic variability, urban development, complex population dynamics, and their interrelationships in the context of flood risk need to be resolved with serious efforts. Addressing these issues through multidimensional strategies is imperative to aver robust flood risk assessment.

Key words: Decade scale, Flood risk assessment, Historical flood events

HIGHLIGHTS

- Historical floods and their impact on the development of a science of flood risk assessments in India.
- Decadal progression in flood risk assessment in India.

GRAPHICAL ABSTRACT



INTRODUCTION

A flood occurs when an excess volume of water enters an area where it cannot be drained effectively. Based on their causes, floods are categorized as fluvial, flash, urban drainage, dam break, snow melt, coastal, and erosion (WMO, 2011). Fluvial floods mainly occur in river flood plains as the flow exceeds the channel capacity and spills over the banks while adjoining catchments get inundated occasionally. Urban flooding occurs when intense rainfall in urban settlements generates rapid runoff and exceeds the capacity of storm drainage systems. A flash flood is associated with ferocious convection storms of a short duration falling over a small area. These floods are more frequent in mountainous areas due to frequent thunderstorms (Ali *et al.*, 2016). Coastal floods occur when storm surges and high winds coincide with high tides. Major deltas, such as the Mississippi and Ganges–Brahmaputra–Meghna, are prone to this type of flooding when affected by cyclones. In exceptional cases, tsunamis resulting from earthquakes can cause severe coastal flooding. In mountainous areas, snowmelts from glaciers due to temperature rise in summer may result in snowmelt floods. This flood worsens when accompanied by heavy rainfall and frozen soil acting as a catalyst. While most of the floods are generally triggered by natural processes, few result from anthropogenic activities. Human activities also turn these flood events into catastrophes (Jain *et al.*, 2016).

While fluvial floods are most common, all types of floods are frequently witnessed in India due to the physiographical diversity and varied climate and rainfall patterns across the country. To study these diverse flood issues, river systems in India are categorized into four regions (INCID, 1993) (Figure 1).

Understanding flood risk is a critical public safety concern for a highly populous country like India. Flood risk is a function and product of hazard and vulnerability (Ologunorisa, 2004). Risk is minimal when one of these components is absent and increases and decreases according to the increase and decrease in these components (Kelman & Spence, 2003). In other words, it is a combination of the impact of a particular event with the chance (probability) of its occurrence (Sayers *et al.*, 2006). UNISDR (2009) has defined hazard and vulnerability. A hazard is a dangerous phenomenon, substance, human activity, or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage. Vulnerability is the characteristic and circumstance of a community, system, or asset that make it susceptible to the damaging effects of a hazard. The assessment of flood risk is based on several parameters. These parameters can also be categorized as hazard-defining

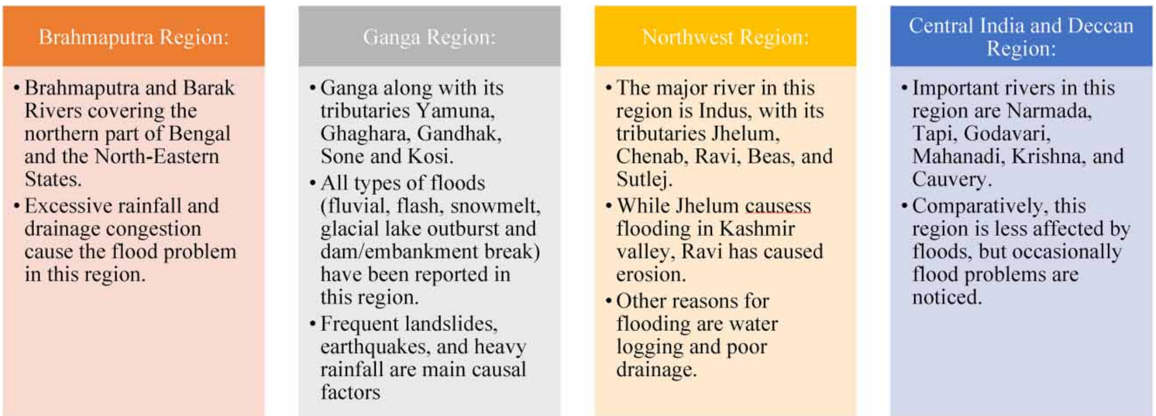


Fig. 1 | Classification of river systems in India for flood studies (INCID, 1993).

parameters and vulnerability-defining parameters. Meteorological, hydrological, and hydraulic parameters define the hazard of a flood event individually or in combination, while socioeconomic parameters define the area's vulnerability.

The history of reporting flood events in India goes back to 1770 (Ramdas, 1976), whereas the recording of rainfall data started in 1784 at Calcutta (Kolkata) (Rakhecha & Singh, 2009). Though the development was initiated in the 18th century and progressed steadily in the 19th century, a significant breakthrough was observed after the independence when river discharge measurement was initiated (Ramdas, 1976). While preliminary flood risk assessment (1951–1980) was limited to these meteorological and hydrological observations, integrating hydrometeorological data with vulnerability and exposure information enhanced the risk assessment in forthcoming decades (1971–1990). Thereafter, advances in remote sensing (RS) and geographic information systems (GIS), including improved estimates of hydrometeorological parameters and spatially distributed socioeconomic characteristics, resulted in the improved assessment of flood risk (1990 onward).

This paper reviews the progress of the science of flood risk assessment in India on a decadal scale from 1951 onward. This review includes listing significant floods in different regions of the country according to their types, impacts in terms of loss of lives and property, and their significance in defining the milestones in the risk assessment process. Various critical approaches are used, and studies carried out for flood risk assessment in the last seven decades have been analyzed along with their interlinkages with modern techniques and tools that became available over time. The next important focus of this paper is to review the progress and updates in decision-making evident through the development of strategies, policies, and guidelines regarding the country's robust and widescale flood risk assessment. It is essential to understand that in earlier times, flood risk management focused on post-event damage control; however, the importance of reducing the flood risk by prior risk assessment was not explicitly targeted. In fact, in earlier times, the terms flood risk assessment and flood risk management were sometimes observed to be used to substitute each other. While significant progress has also been made in flood risk management, this paper focuses on the progress of the scientific process of flood risk assessment over the years.

EVOLUTION OF FLOOD RISK ASSESSMENT IN INDIA

In this section, decadal development in India's flood risk assessment approach is analyzed from 1951 onward.

1951–1960

During this era, flood risk assessment was in a rudimentary phase focusing on identifying the flood or drought events based on rainfall. Ramdas (1949) gave an insight into rainfall patterns in India, which were linked with floods and droughts. Bagchi (1955) highlighted floods in West Bengal Rivers, but the scope of these studies was limited to excess rainfall in the physiographic region. In October 1955, northern India experienced one of the most devastating floods, with an estimated death toll of 1,500 (De *et al.*, 2005) due to rising water levels in Ravi, Sutlej, Beas, and Yamuna Rivers. Uppal & Sehgal (1956) attributed these unprecedented floods to hefty and continuous rains. In this timeframe, the risk associated with the flood was given very scant attention, with an ambiguous estimation of losses. Under initial 5-year plans (1951–1956 and 1956–1961), several water resource projects were initiated in addition to enhancing the capabilities for recording the hydrometeorological data to assist in flood forecasting and early warning systems.

In India, flood forecasting was initiated by the Central Water Commission. A flood forecasting unit was established in 1958 in Delhi for flood forecasting on the Yamuna River. The overall increase in awareness about increasing flood issues led to a transformation of this site-specific unit into a flood forecasting system (1969) to cover almost all the flood-prone interstate river basins. Later, studies related to flood warnings and forecasting were reported (Flood Forecast Monitoring Directorate, 2012).

1961–1970

India experienced major floods in the 1960s. According to news reports, floods across the state of Bihar in 1961 killed about 800 persons (Chicago Tribune, 1961), and in 1967, floods in the Yamuna River due to monsoon rains exposed several cities like Agra and Etawah to a catastrophe (Chicago Tribune, 1967). The news highlighted the inundation of the Taj Mahal from three sides, the bridge collapse near Etawah. Along with the breach of Nanak Sagar Dam and floods in Shahjahanpur, a total death count of approximately 500 was reported in North India. In 1968, Gujarat experienced devastating floods in the first week of August, caused by hefty rains in southern parts of the state (Mavalankar & Srivastava, 2008). Floods were also reported in other parts of the country in 1968; several states were affected, including Kerala, Haryana, Uttar Pradesh, Bihar, Rajasthan (Daly & Feener, 2016), West Bengal, and Sikkim (Government of West Bengal, 1968).

Damage due to these events was quantified in the form of loss of agricultural produce and loss of human and animal lives. Accordingly, compensation was provided to victims. However, most of these activities were related to post-event damage control. A few measures for flood protection and planning for disaster management were reported in this decade in the form of the development of barrages and embankments (Mazumder, 2011). However, breaching incidences in 1965 and 1966 raised suspicions about these structures' design aspects and constructions (UN-HABITAT & UNEP, 2002). Between 1969 and 1970, the Government of India created a Central Flood Forecasting Directorate: six flood forecasting divisions were set up, and 41 forecasting sites were added on interstate river basins (Singh, 2005).

1971–1980

The flood of 11 August 1979 on the Machhu River in Gujarat was a record-breaking event worldwide, leading to a death toll of 1,500 and causing damage worth millions of US dollars (Rakhecha, 2002). The Machhu-2 dam on the Machhu River, which was situated upstream of Morbi town in the Rajkot district of Gujarat, was destroyed by excessive rain and massive flooding leading to the disintegration of the dam's earthen walls. Other noticeable flood events recorded in this decade include Mahi (1977), Sabarmati (1973), Sone and Tons (1971), Godavari (1976), and Mahanadi (1977) rivers and their tributaries.

With an increase in flood frequency and magnitude over the years in the Indian peninsula (Kale, 1999, 2012), Central Water Commission, (CWC) India prepared guidelines for floodplain zoning in 1975 in which flood plains were to be categorized into three zones: prohibitive, restrictive, and warning zones based on the concept of design flood. Guidelines were circulated to the states to assess flood risk (INCID, 1993). However, the participation of states in implementation was not encouraging, as only the state of Manipur acted on it.

In this decade, the Indian Meteorological Department (IMD) and the Government of India proposed flood assessments based on rainfall in excess of normal rainfall over a meteorological subdivision. The seasonal rainfall of 26–50% over the normal is considered moderate flood, an excess of more than 50% of the normal as a severe flood, and the rainfall between 0 and 26% of normal was regarded as a less severe flood (Indian Meteorological Department, 1971; Government of India, 1976). This was the first imprint of flood risk assessment in India. Though flood risk assessment was initiated, linking meteorological data related to storms and rainfall with hydrological data of flows and water levels for understanding flood risk was sporadic.

1981–1990

In the 20th century, the frequency of extreme floods was highest in this decade (Kale, 2012). The 1987 Bihar flood, caused by a landslide that blocked the main route of the Bhote Kosi River and triggered high levels of water in the Kosi River, was one of the worst floods in India in this decade. Government reports list damage to crops at an estimated 68 billion Indian rupees and damage to public property at 68 million rupees. In 1989, North Indian Ocean Cyclone caused flash floods in Uttar Pradesh, Orissa, and Andhra Pradesh. Other major flood events observed in this decade are the Indus floods (1988) and the Mahanadi flood (1982, 1985, and 1986) (Rakhecha, 2002).

In this decade, development on several fronts took place, which resulted in profound evolution of the science of flood risk assessment at the policy level. In 1981, a report on the 'development of chronically flood-affected areas' by the planning commission in India sets the guidelines for identifying chronically flood-affected areas and strategy toward their development (Government of India, 1981). Here, chronically flood-affected regions were referred to as backward areas affected by natural havoc and lying in the flood plains without embankments. The guidelines were based on the available knowledge of nearby hydrological observations. The following criteria were suggested for the identification of chronically flood-prone areas:

a. Flood frequency of at least once in 3 years,
b. Flood duration of at least a 7-day period at a stretch,
c. Flood depth of more than the standing paddy at that time, and
d. Flash floods with strong currents can uproot plants even if the duration is less than 7 days.

CWC also initiated the preparation of flood risk maps through the Survey of India (1985–1990) and completed about 50,000 km^2 area by 1990 (INCID, 1993). Overall progress in this decade indicates the analysis of flood risk assessment based on hydrological observations and integrating those with exposure and vulnerability information in the background. The use of information about the command area, roads, infrastructure, etc., from toposheets, along with observed hydrological data, ensued flood risk estimation from spatial and socioeconomic perspectives. Accordingly, flood protection measures were planned and implemented, such as constructing dams, reservoirs, and embankments.

1991–2000

Several flood events have been reported in this decade, and the associated risk is also analyzed. On 13 November 1992, torrential rains triggered by a cyclone in the Bay of Bengal hit the southern districts of Tamil Nadu and Kerala, caused flash floods and landslides, and killed 179 people. Between 9 and 12 July 1993, heavy rainfall in the northwest Indian region of Gujarat, Punjab, and Haryana caused widespread flooding (Kulkarni *et al.*, 1996). Flash floods, landslides, and overflow of rivers and irrigation canals inflicted a high death toll and severe damage to housing, agriculture, and infrastructure (UN-DHA, 1993). In 1994, 147 people died in Kerala, and a death toll of 138 was reported in Gujarat during monsoon floods. In 1995, Uttar Pradesh, Haryana, and Arunachal Pradesh experienced flash floods with an estimated death toll of 214. Floods continued in 1996 and 1997, distressing people in one or other parts of the country. In 1998, floods in the northeastern part of India caused severe damage in the Kaziranga Wildlife Sanctuary, dipping its population to half (Nandy, 2006).

Scientific and technological advancements in this decade supported a better understanding of the risk in comparison to earlier timeframes. Scientific and academic studies in this decade initiated the use of RS and GIS to explore the causal factors, risk levels, and impacts of floods on river morphology and floodplain mapping. A study by Sharma *et al.* (1996) noted that during 1988, the flooding in Punjab was mainly due to the overflowing of rivers, whereas in 1993, it was due to breaches in the embankment of rivers and canals. NIH, Roorkee, carried out floodplain mapping of the Yamuna River from Gangoh to New Delhi with the help of satellite data, and aspects of oxbow lake formations and channel meandering were discussed (National Institute of Hydrology, 1997).

With an improved understanding of the flood risk than earlier, a shift in government policy was noticed in this decade from the rudimentary risk assessment and post-damage control to a more rigorous flood risk management with an emphasis on floodplain management, flood forecasting, disaster relief, and flood insurance. After 1990, flood risk management in India shifted its focus from structural to non-structural measures for flood control. CWC suggested the need for non-structural measures for flood control, considering the limitations of embankments, reservoirs, and dams for different magnitudes of flood and the costs involved (INCID, 1993). The report further emphasized the development of floodplain zoning, regulation, and flood forecasting to enhance the applicability of structural measures for flood control.

2001–2010

This era's major floods and related issues are unique in their causal factors and effects. Climate-driven and human-induced catastrophes were observed in this period. The Tsunami, because of the 2004 Indian Ocean earthquake, hit the mainland Indian states of Andhra Pradesh, Tamil Nadu, and Kerala badly, along with Andaman and Nicobar Islands. This event is termed the 'deadliest natural disaster in recorded history' as its turmoil massively affected life in several countries in South and Southeast Asia. On 18 August 2008, a major breach occurred on the eastern embankment of Kosi at Kusaha (Nepal), 12 km upstream of the Kosi barrage (Sinha *et al.*, 2013). This resulted in the shift of the Kosi River from its current channel to paleochannels causing one of the most devastating floods in northern Bihar, India, and Sundari district in Nepal that affected more than 2.6 million people in the region and resulted in long-term socioeconomic impacts on the region caused by the destruction of houses and infrastructure, and changes in soil properties due to the deposition of coarse sediments over the area of 284,000 ha (Bhattacharyya *et al.*, 2013; Kafle *et al.*, 2017). Though heavy rains triggered this event, poor maintenance of embankments is believed to have transformed it into a horrific calamity. This decade also witnessed some of the major urban floods in the country (Chennai in 2004, Mumbai in 2005, Surat in 2006, and Kolkata in 2007).

Predominantly driven by RS and GIS techniques, flood risk assessment in the start of the 21st century focused on amalgamating geospatial techniques with reinforcing multicriteria and multiparametric approaches. Moreover, the ability of the system to improve decision-making by evaluating the alternatives (Malczewski, 2006) using satellite-based information for mapping different aspects of flood-prone or flood-inundated areas in the GIS framework is found to be effective. Apart from these, modeling approach-based studies also emerged in the flood risk assessment. Various hydrologic and hydraulic modeling tools are being tested for deriving flood peaks and their routing in the river channel to understand the inundation patterns. Geomorphic and morphometric aspects, urban flood studies, and real-time flood forecasting are advancements of the current era.

On the policy front, the key decisions taken in this decade are primarily covered in the 'Guidelines for flood management' by NDMA. Two critical decisions regarding flood risk assessment are as follows:

1. Establishing the Decision Support Centre at NRSC in 2002 was a key step. The center analyzed satellite images for pre- and post-event monitoring of floods. This capacity was further strengthened in the next decade for improved flood risk assessment.
2. Expansion and modernization of flood forecasting at CWC, IMD, and State departments: with increased floods and exposure, it was felt that the infrastructure available for flood forecasting is inadequate and therefore needs strengthening. Accordingly, several Automatic Weather Stations (AWS) and flow monitoring stations were installed across India.

Overall, it can be said that progress made by India on flood-associated policies is multidimensional and emphasizes the need and utility of RS and GIS technology for pre- and post-event impact assessments. Important academic or research studies incorporating RS and GIS techniques, multicriteria, and modeling approaches are summarized below.

i. Suprit *et al.* (2010) used Geographic Resources Analysis Support System-Geographic Information System (GRASS-GIS) to identify low-lying areas (using slope value) for guessing flood-prone areas along the Talpona and Galjibag rivers of South Goa. The data requirement of this study was limited in the form of hourly rainfall data from AWS and Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM). A rational method of estimating flood peaks is used, and flood-prone areas are identified based on slope and distance from the stream.
ii. Maiti (2007) integrated a community-based approach with RS and GIS to assess the flood risk in Orissa for the 2003 floods. Flood frequency analysis is done to establish the return period of 2003 floods. Using Radarsat satellite imagery, flood inundation maps are generated. Land depth and duration are noted at village levels using questionnaires, and damages are calculated. Based on these, risk contribution is defined for the 2003 floods.
iii. Bhatt *et al.* (2007) used Landsat satellite data from 1974 to 2013 for flood risk assessment in the Chamoli District of Uttarakhand, India.
iv. Sinha *et al.* (2008) used topographic data, IRS LISS III data, and census data along with observed peak discharges and inundation depth data in the Kosi River for developing the GIS-based multiparametric approach of analytical hierarchy process (AHP) for flood risk analysis.

2011 onward

The most devastating floods in recent times include the Alaknanda flood of June 2013, where cloud burst-type heavy rains together with a burst of the moraine-dammed (Chorabari) Lake caused heavy flooding in the Mandakini tributary of the Alaknanda River in Kedarnath, Uttarakhand, resulting in significant loss of life and property (Dobhal *et al.*, 2013). The Kerala floods in 2018 were also one of the major catastrophic events. From 1 June 2018 to 19 August 2018, Kerala received enormous rainfall, which was 42% above the normal rainfall, and specifically during 1–19 August, the rainfall was 164% above normal. While high-intensity rainfall was the main causal factor for these floods, reservoir operations pertaining to the hedging principle were also questioned as most reservoirs were filled to their full capacity and thus released water around the event, which might have exacerbated the overall flood situation (Mishra & Shah, 2018). This triggered multiple debates in the country about effective reservoir management, challenges about inflow forecast, emergency action plans, interstate coordination about reservoir management and utilization of rule curves during the floods, and the necessity for regular review and revision of rule curves.

A series of flood events in July–August 2019 in different rivers in southern India, mainly in Karnataka, Maharashtra, and Kerala, further highlighted the importance of effective reservoir management during the floods and review and updating of rule curves. Heavy rainfall in the Western Ghats led to concurrent flooding in multiple tributaries of the Krishna River, and it is debated that the majority of the reservoirs being 'close-to-full' had to release humongous flows, which worsened the flood situations in downstream areas.

Apart from these, important flood events of recent times include September 2014 floods in the Jhelum River that claimed 287 lives and affected over 550,000 people with severe impacts on the region's economy and ecology (Wani, 2023). Chennai flood of 2015 was among the very few examples of floods due to heavy northeastern rainfall. Depressions formed over the Bay of Bengal, believed to be triggered by El Nino, resulted in heavy rainfall events marking November 2015 as the wettest month in 100 years. Furthermore, on 2nd December, the highest daily rainfall of 319.6 mm was observed. While rainfall was the trigger, unchecked and mistaken development along riverbanks and in marshy areas is believed to have worsened the situation of floods in Chennai

(Bandyopadhyay *et al.*, 2021). In addition, a few flood events in some of the major metro cities (Delhi, Patna, and Jaipur) were recorded in 2020.

Noticeable work on the policy side includes the preparation of the Flood Hazard Atlas (FHA). National Remote Sensing Centre (NRSC), National Disaster Management Authority (NDMA), and the state disaster management agencies have prepared the FHA using a geospatial approach. The first version of the FHA for Bihar state was launched in 2013, and for Odisha, it was released in 2019. The FHA for Andhra Pradesh and Uttar Pradesh were released in July 2021 and April 2022, respectively; work is ongoing for other states. The FHA provides the foundation for flood risk estimation, which can be utilized to define insurance premiums. Currently, flood insurance premiums are mostly uniform in most urban settings disregarding the varying probability of the area being flooded. Therefore, the ongoing activity of FHA across India will revolutionize India's flood insurance industry. Many studies for research or commercial use (insurance/reinsurance industry) in this decade have utilized RS datasets, geospatial environments, GIS tools, automatic real-time data monitoring systems, and multicriteria analysis. A few relevant studies have been listed below.

i. Topography-driven river connectivity and its effects on flood hazards of the Kosi River are studied by Jain *et al.* (2016) and Sinha *et al.* (2013).
ii. For risk assessment of the Panchganga tributary of the Krishna River using the GIS-based multicriteria decision technique, Panhalkar & Jarag (2017) selected four layers as criteria, such as Land Use-Land Cover (LULC), infrastructure, elevation, and water level, and weighted them to generate flood risk maps of the study area.
iii. For the Ganga River Basin, RMSI (2015) used hydrometeorological data along with satellite data in the form of topography, LULC, and soil maps to set up conceptual models like the Soil Conservation Service (SCS) curve number method and the SCS unit hydrograph approach for assessing rainfall losses and generating runoff hydrographs. The Muskingum method of stream flow routing is used for routing the flow in all major reaches of the Ganga River. The Hydrologic Engineering Center's River Analysis System (HEC-RAS) hydraulic model is used to develop water surface elevations, floodplain boundaries, and depth of stream flooding. Finally, flood hazard maps for a 2- to 100-year return period are developed.
iv. Mishra (2013) used RS and GIS techniques to study the geomorphology and flood risk of the Kosi River in North India with reference to the 2008 Kosi avulsion. Satellite imageries, toposheets, rainfall data, and census data are used along with field data to prepare flood risk maps for identified blocks in the Kosi basin.
v. Saini *et al.* (2016) incorporated physiographic, hydrometeorological, and socioeconomic aspects of Ambala City into the GIS and the HEC-RAS-based study to analyze the risk of Tangri River floods for various land use types.
vi. Kumar *et al.* (2022), developed a composite urban flood risk index with three sub-indices (hazard, exposure, and vulnerability) and 20 key natural, physical, and socioeconomic influencing factors in a GIS framework for ward-wise mapping of flood risk in the city of Cuttack, India. It involved multicriteria analysis with rainfall characteristics, land use, and topographical settings at a varying spatial scale. The findings of such studies are very useful in policy and decision-making processes and support the larger narrative of integrated flood risk management.

Most studies have focused on GIS, RS, and multicriteria analysis for flood risk assessments. In recent times, Pakhale *et al.* (2023) evaluated whether flood events are really intensifying in the Krishna River Basin and concluded that 'the hypothesis that flood events are intensifying is untenable for most subsystems of KRB except K7 (Lower Krishna Basin) being the sole exception where, in sharp contrast, flood events show signs of moderation'. While the debate about increasing or decreasing floods is ongoing, two important topics, including – (i) role of reservoirs in flood control and (ii) the climate change – especially after 2018 Kerala floods, have grabbed the attention of various researchers. Mishra & Shah (2018) provided a hydrometeorological perspective and suggested that the event was not linked to long-term climate change but was instead driven by short-term natural climate variability. On the other hand, Kumar *et al*. (2021) discussed the role of dams and provided various perspectives, which are typically avoided. They provided insights into the causal factors of the flood and the storage capacities of reservoirs and addressed contentious issues such as criticism blaming dams and development for floods. Ultimately, the authors emphasized the socioeconomic and ecological benefits of large dams and pointed out that these benefits can be maximized through improved forecasting, flood routing, and inundation studies.

CONCLUSION

This paper thoroughly reviewed decadal patterns in Indian floods and evolvement in flood risk assessment juxtaposed with government policies and flood management strategies. Technological and policy-related advancements in understanding and managing flood risks are chronologically studied for the post-independence period. While flood frequencies and their associated hazards and risks are increasing over time, methods of flood risk assessment and measures for flood control also advanced proportionately. Initiated with the simple identification of 'above normal rainfall events', the science of flood forecasting and risk assessment is now in its upgraded version, where technological and scientific advancements in various fields of science are being tested and verified for it. With these advancements, now a cyclic approach of risk assessment, risk management, and monitoring followed by a revision in risk assessment and management strategies is adopted in India. Figure 2 summarizes the progress seen in India's flood risk assessment process over the years, with milestones for each decade.

While significant progress has been observed in India, specifically in the last two decades, comparing the global standards, establishing and adopting a comprehensive flood risk assessment framework at a nationwide scale supported by the effective implementation of comprehensive policy reforms are urgently needed to curtail the risks of these inevitable natural calamities. Structural and non-structural measures such as (i) the adoption of floodplain zoning bill by remaining states and moving toward integrated floodplain management by allowing river and its corridor to maintain morphodynamics by keeping critical infrastructure away from the river or floodplain; (ii) the development of FHA for remaining states including flood risk assessments with scenarios for Levy/embankment breach; (iii) improved coordination among various government agencies for flood control and regular review and revision of rule curves for effective, timely, and informed decision-making about the operation of large dams; (iv) incorporation of outcomes from the relevant academic/research studies with specific focus on climate resilient flood risk management in policy-making; (v) use of high-end technologies such as like Internet of Things (IoT), Crowd Sourcing, and Artificial Intelligence (AI) for forecast and impact modeling for flood risk

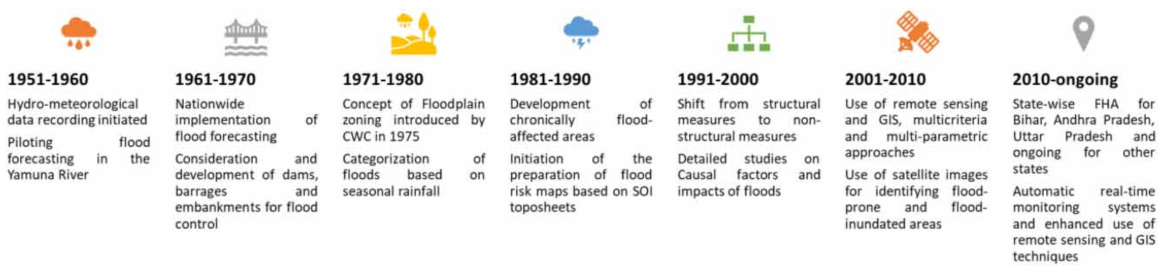


Fig. 2 | Decadal progression in flood risk assessment in India.

assessments; (vi) expansion of flood monitoring network; and (vi) multistakeholder consultations involving civil societies, NGOs, corporates, administrators, and flood insurance providers for expanding the flood insurance through a set of guidelines will add significantly to the science and management of flood risk in India. In addition, promoting and adopting concepts such as room for the river, diversion and storage of flood flows, and interlinking of rivers will help better manage the flood risk; however, these aspects need to be studied thoroughly for their technical, environmental, and socioeconomic feasibility and sustainability.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 12 August 2023; accepted in revised form 11 November 2023. Available online 22 November 2023