

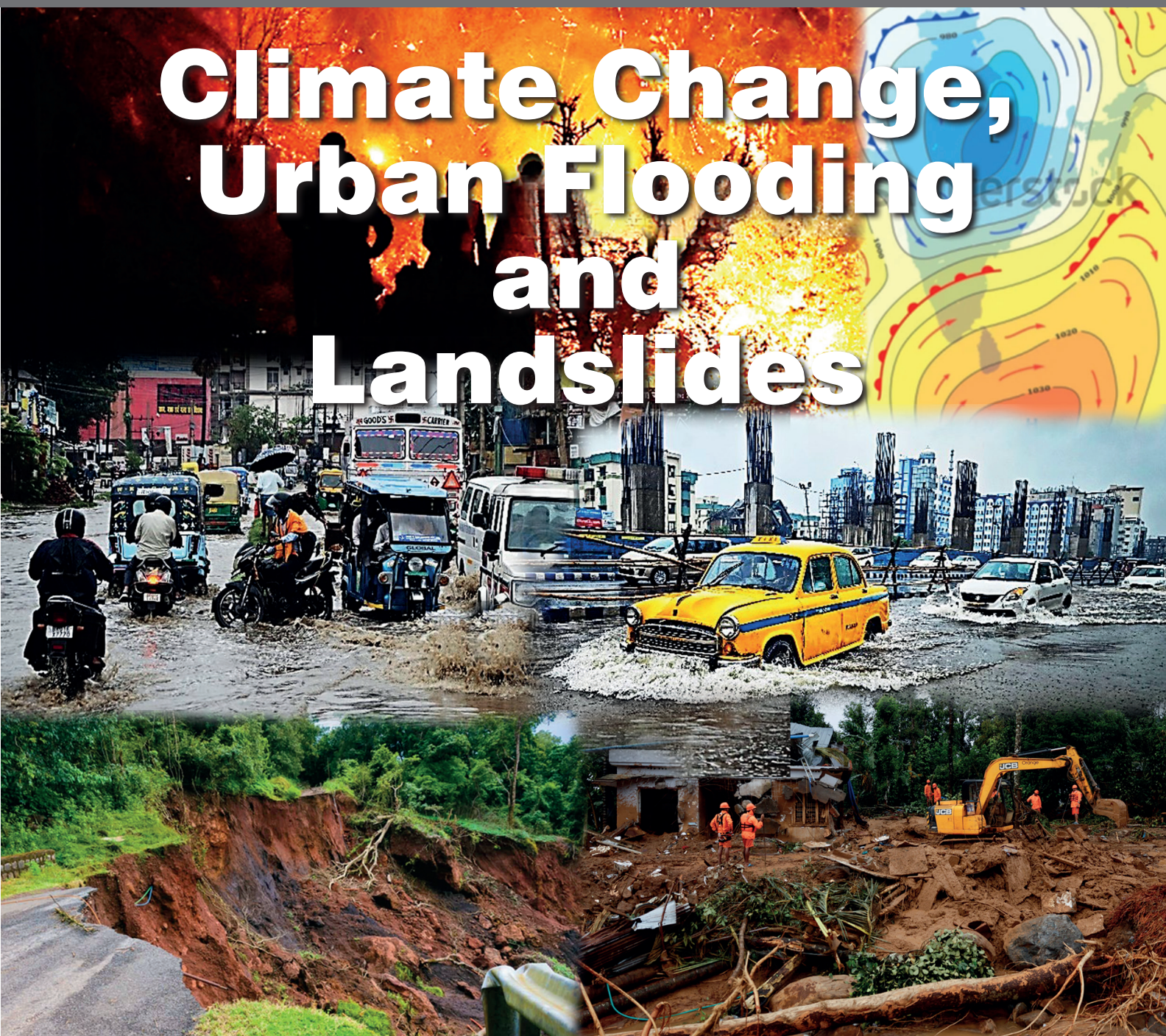
JUNE 2026

VIEWPOINT

OFFICIAL QUARTERLY MAGAZINE OF CEAI

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Climate Change, Urban Flooding and Landslides





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Membership of CEAI

Enhance Your Professional Career

- CEAI is a FORUM for developing and upgradation of skills, gaining knowledge about the emerging global trends and building the capabilities of its Members and Associates.
- CEAI provides an excellent opportunity to present papers in seminars, technical lectures and webinars organised from time to time.
- CEAI aids in skill development through regular training programmes, including training on FIDIC Conditions of Contract and sharing of legal issues in the Indian context.
- The CEAI document “Handling of Complaints on Violation of Code of Ethics” helps to resolve disagreements between Members.
- Several CEAI Members are exporting consultancy services and are registered with all the major international funding institutions.
- Membership of CEAI is being increasingly recognised as a mark of credibility. Many users of consultants shortlist CEAI Members.

Networking - Make Connections

- Being the Member Association of FIDIC in India, CEAI connects Members globally.
- CEAI provides a platform to interact with other Members, Institutions, State & Central Governments.
- The CEAI website opens up an opportunity for its Members to upload their expertise and capabilities to worldwide exposure.
- Participate in topical seminars, training programmes, conferences and meetings.
- The Four Regional Centres and a few City Chapters in the country assist in establishing linkages.
- A Monthly Newsletter is circulated to Members for quick dissemination of information.
- “ViewPoint” - a quarterly publication on a wide range of subjects, communicates effectively with Members and users of consultancy services.

Learning - Find Insights and Resources

- Newsletter: An email newsletter sent out monthly to all current members, giving updates regularly, sharing news, activities, events or other information in the future.
- ViewPoint: A quarterly journal, which is theme-based, that presents very informative and useful technical papers of high scientific and technical standards. Articles are written by practising consulting engineers and academia from around the world and reflect the high standards of CEAI.
- CEAI published documents: CEAI has a wide range of materials and information to help those who want to start practice as a consulting engineer.
- FIDIC Publications: A Link is given to all the FIDIC contract documents and other publications, for direct purchase. Alternatively, they could be procured through CEAI.

Interaction with FIDIC and other International and National Bodies

- FIDIC undertakes a wide variety of activities on a global basis. FIDIC Member Associations and their member firms, therefore, can potentially benefit from any number of FIDIC activities.
- CEAI looks after the interest and enhances the status of the Consulting Engineering profession in India and is equally concerned with quality development, productivity enhancement and promotion of ethical practices.

CEAI has established linkages and strong bonds with its counterparts in various countries and is a staunch advocate of global networking and cooperation.

- CEAI has entered into a MEMORANDUM OF UNDERSTANDING with different international bodies to promote the development of the engineering industry in India and abroad.
- CEAI has close relations with other Indian Associations with similar objectives.
- CEAI has entered into an Agreement with the Institution of Engineers India (IEI) to promote development of a closer working relationship for the mutual benefit of Members.
- Improve Business Skills - Step into a Leadership Role
- To recognise and promote the engineering consultancy profession, Annual Awards are presented for Excellence in Engineering Consultancy Services and contribution towards professional excellence.
- It also provides an opportunity to participate in international awards announced by FIDIC from time to time.
- Technical workshops and interactive sessions are organised regularly to publicise professional works and to provide a platform to enhance business and develop newer markets.

Participation in Learning and Imparting Knowledge

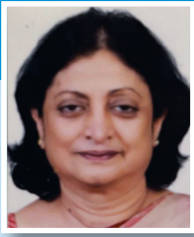
- CEAI organises FIDIC Training programs at regular intervals on the FIDIC Conditions of Contract. FIDIC Conditions of Contracts are being used the world over in developed economies and where multi-lateral development banks or bilateral funding agencies provide the funding.
- To endeavour to disseminate knowledge and information on matters of relevance to the Consulting Engineering profession, CEAI organises Workshops, Seminars, Training programs, Webinars, etc. at national and international levels.

Young Professionals/ Future Leaders Forum

- CEAI started the Young Professional/ Future Leaders Group, which connects with young professionals internationally through the FIDIC route.
- To recognise, honour and promote new talent of Young Engineers, CEAI celebrated 2016 as Young Engineers' Year
- CEAI organises special webinars for Young Engineers.

Thus,

- CEAI promotes the interest and enhances the status of the consulting engineering profession in India.
- CEAI advocates global networking and co-operation.
- CEAI helps one to keep in touch with the latest professional updates - technical, regulatory, legal, financial, health & safety, environmental, etc.
- CEAI provides an excellent opportunity to present papers in seminars and technical lectures organised from time to time.
- CEAI aids in skill development through regular training programmes, including training on FIDIC Conditions of Contract and sharing of the legal issues based on the Indian context.
- CEAI takes up various issues confronting the profession with government and other authorities from time to time to make the conditions of engagement on a fair and equitable basis, so that Consulting Engineers can function in the best interest of the country.
- CEAI promotes the cause of Women Engineers with a view to ensuring a rightful place for them in the engineering consultancy arena.
- CEAI helps to develop Young Engineers who are the Future Leaders.



Message from Chief Editor

Environmental Impact Assessment and Climate Resilience: Building Sustainability into Development

Climate change has emerged as one of the most consequential challenges confronting humanity. Virtually every human activity contributes to environmental degradation and global warming through the release of greenhouse gases. Fossil fuel combustion remains the largest contributor, while deforestation, industrial production, energy generation, agriculture, and livestock farming add substantial quantities of carbon dioxide, methane, and nitrous oxide to the atmosphere. The cumulative effect is a changing climate marked by rising temperatures, extreme weather events, and growing environmental vulnerability.

The global response to climate change initially focused on mitigation measures aimed at reducing emissions and limiting environmental damage. Over time, however, it became evident that many environmental problems stemmed from inadequate planning and insufficient assessment of the environmental and social consequences of development projects. That led to the evolution of Environmental Impact Assessment (EIA) frameworks, designed to evaluate potential impacts before projects are approved and implemented.

In India, the modern environmental regulatory framework emerged following the 1972 United Nations Conference on the Human Environment in Stockholm. The Water Act (1974), Air Act (1981), and Environment (Protection) Act (1986) together established the foundation of environmental governance. Judicial intervention further strengthened these safeguards, with the Supreme Court interpreting the constitutional right to life as encompassing the right to a clean and healthy environment. Over the years, the EIA framework has been refined to balance environmental protection with developmental needs.

Despite the extensive regulatory architecture, environmental degradation continues, highlighting persistent systemic shortcomings. Inadequate planning, weak institutional capacity, fragmented governance, poor inter-agency coordination, and inconsistent enforcement of regulations remain major concerns. Equally troubling is the dilution, circumvention, or non-compliance with environmental safeguards, particularly those governing the EIA process.

The effectiveness of any environmental regime depends not merely on legislation but on rigorous implementation. Many projects that receive environmental clearance undergo limited post-approval monitoring, weakening accountability and compliance. Concerns have also been raised regarding the quality of some EIA reports, which may rely on outdated data, inadequate field studies, or assessments prepared by consultants engaged directly by project proponents. Such practices risk compromising objectivity and undermining the credibility of the process itself.

These concerns are especially significant for India. A substantial proportion of the population remains dependent on climate-sensitive sectors, particularly agriculture. Moreover, the country's vast geography means that floods, droughts, cyclones, heatwaves, extreme rainfall, avalanches and landslide events can affect millions of people while causing extensive damage to infrastructure, ecosystems, and livelihoods. The economic and social costs of such events continue to rise as climate variability intensifies.

Against this backdrop, Environmental Impact Assessment must be viewed not as a procedural hurdle but as a strategic planning instrument. Its purpose is to identify environmental risks before project approval, enabling preventive action and informed decision-making. Yet pressures to accelerate development and improve the ease of doing business can sometimes encourage exemptions from rigorous scrutiny or relaxation of environmental safeguards. While economic growth is essential, development that neglects environmental resilience ultimately proves both costly and unsustainable.

Particularly problematic are provisions that allow projects to commence construction or operations without prior environmental clearance and seek regularisation later. Project developments that bypass regulatory requirements run the risk of inadequate assessment of long-term impacts on climate change. They undermine the very purpose of impact assessment, which is intended to anticipate and mitigate risks before they materialise. The failure to proactively integrate climate considerations when planning results in exponentially higher downstream costs in engineering for risk mitigation.

Experience repeatedly demonstrates that remediation, retrofitting, ecological restoration, and compensatory measures are far more expensive than preventive planning. Projects that fail to anticipate ecological, hydrological, or geotechnical risks frequently encounter delays, cost overruns, legal challenges, and regulatory penalties. Proactive environmental assessment is, therefore, not only an ecological necessity but also an economic imperative.

Effective project planning requires detailed, localised evaluations that incorporate climate vulnerability assessments from the outset. It demands the protection of wetlands, natural drainage systems, ecological buffers, and other environmental assets that enhance resilience. Such measures help ensure that infrastructure remains adaptable to future climatic conditions rather than becoming increasingly vulnerable to them.

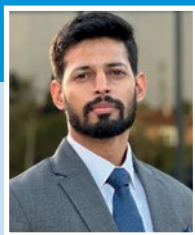
Even the most robust mitigation efforts cannot entirely eliminate the effects of climate change. Historical emissions, continuing global industrial activity, and natural climatic variability ensure that some degree of environmental change is inevitable. Adaptation and resilience-building must therefore complement mitigation efforts.

As India pursues ambitious economic and infrastructure goals, the challenge is not to choose between development and environmental protection, but to integrate the two. Sustainable development requires environmental considerations to be embedded throughout the project lifecycle - from conception and design to implementation and monitoring. A credible, scientifically and rigorously enforced EIA regime remains indispensable to achieving this balance. The question is not whether India can afford robust environmental assessments, but whether it can afford the consequences of neglecting them.

Adopt Responsible Sustainable Development with a Credible EIA.

With best wishes,

Sayona Philip



Message from Guest Editors

From Reactive Crisis to Engineered Resilience: Rethinking India's Approach to Urban Flooding and Climate-Induced Landslides

India's urban flooding and climate-induced landslides are no longer isolated hazards but interconnected expressions of a systemic mismatch between the pace of urbanisation and the capacity of legacy infrastructure. This editorial argues that the consulting engineering profession must transition from reactive post-event documentation to proactive, data-driven engineering - leveraging high-fidelity hydraulic modelling, computational vulnerability analysis, and targeted hard-infrastructure interventions to build measurable, permanent resilience into India's urban fabric. Drawing on international case studies and emerging digital platforms, this editorial outlines a three-stage engineering pipeline for consulting engineers to adopt.

The Scale of the Challenge

On 9 July 2023, Delhi recorded 153 mm of rainfall in 24 hours at Safdarjung, the highest for a July day since 1982. The Yamuna breached 208.66 metres at the Old Railway Bridge, surpassing the 1978 record and forcing the evacuation of over 27,000 people. That same monsoon season, landslides in Himachal Pradesh and Uttarakhand claimed more than 300 lives and severed arterial highways for weeks. In Joshimath, slow subsidence that had been documented for decades accelerated into a crisis that displaced entire neighbourhoods. Those were not aberrations. They were the predictable consequence of a systemic mismatch between the pace of urbanisation and the capacity of the infrastructure designed to manage water and terrain stability.

This issue of *VIEWPOINT* addresses the theme **"Climate Change, Urban Flooding, and Landslides"**; three phenomena that are no longer distinct hazards but deeply interconnected expressions of the same underlying crisis. As consulting engineers, our profession sits at the precise intersection where diagnosis must become prescription, and where prescription must translate into built, measurable outcomes. The convergence of these risks demands a unified response from the profession, one rooted in computational rigour, validated data, and engineering accountability.

The Changing Hydrology: Numbers That Demand Engineering

The numbers are stark. In cities such as Gurugram, rapid urbanisation has raised the run-off coefficient from approximately 0.45 to above 0.80 in core zones, effectively doubling surface discharge volumes. Ground absorption has dropped from 55 per cent to 20 per cent. Unit-hydrograph analysis shows that the time-to-peak after a cloudburst has shortened to under 90 minutes, a drastic reduction that leaves drainage networks, most designed to 1976 standards for 50 mm/day, facing inflows **four times** their historic capacity. The Yamuna's 2023 flood level was not an outlier; it was a data point on a trajectory that climate models project will steepen through the 2030s and 2040s.

In the hills, the picture is equally alarming. Deforestation and unregulated construction on steep gradients have altered slope stability parameters across the Himalayan foothills, the Western Ghats, and the North-Eastern corridor. When extreme precipitation events (growing both in frequency and intensity under IPCC AR6 projections) interact with these degraded slopes, the result is not a landslide in the traditional sense but a cascading failure: slope collapse triggering debris flows that dam rivers, which then breach catastrophically downstream. The Chamoli disaster of 2021 and the Wayanad landslides of 2024 demonstrated this interconnected failure mode with devastating clarity, underscoring the urgency of a systemic engineering response along with development control rules and regulations that take into account the issues that lead to such hazards. The challenge is no longer single-hazard mitigation. It is systemic resilience across interconnected failure modes. The engineering and administrative arms need to work in sync.

From Manual Assessment to Computational Precision

For decades, the industry's response to urban flooding has followed a familiar pattern: post-event damage surveys, static PDF reports, and recommendations that are outdated before the next monsoon. The gap is not in intent but in tools. Traditional GIS workflows require specialised analysts, expensive software licences (At €3,000 or more per year per seat), and days of effort per assessment. Financial justification for resilience investments is rarely quantified with actuarial rigour, making it difficult for asset owners to secure capital budget approval.

The shift now underway, one that the profession must accelerate, is towards high-fidelity, data-driven hydraulic modelling that treats flood risk as an engineering problem to be solved, not a natural disaster to be endured. Platforms now exist that ingest standard geospatial data such as LiDAR point clouds, Digital Elevation Models, pipe network shapefiles, asset inventories - and perform high-performance spatial intersection analysis using R-tree indexing to identify hydraulic bottlenecks in under 60 seconds. What previously required five or more analyst-days can now be accomplished in minutes, with results that are reproducible, auditable, and immediately actionable.

Critically, such platforms can model **systemic interdependencies** that traditional layer-by-layer analysis misses entirely. If a municipal drain backflows at a given node, it is now possible to trace exactly which downstream pump station loses power and which specific basement floods as a consequence, a cascading failure simulation that transforms reactive crisis management into proactive engineering. Financial exposure can be quantified through Annualised Loss Expectancy (ALE) models, giving asset owners the actuarial data they need to justify resilience capital expenditure to their boards and lenders. This financial quantification (long standard in insurance and reinsurance) has been conspicuously absent from infrastructure engineering practice in India.

The Three-Stage Engineering Imperative

Based on experience across complex urban catchments, from flood risk modelling on the €26 billion Lyon-Turin rail corridor to post-flood hydraulic remediation for critical infrastructure in the UAE following the April 2024 extreme rainfall event, an effective climate resilience programme requires a disciplined three-stage engineering pipeline.

First, high-fidelity data acquisition and hydraulic modelling: LiDAR surveys to build centimetre-accurate Digital Elevation Models, coupled 1D/2D hydraulic models to trace dynamic overland flow paths, open storm water drain discharge, receiving water body levels, and pipe network capacity, and calibration against observed flood events such as the July 2023 cloudburst to ensure the model reflects reality before prescribing interventions. The same approach, applied to terrain stability, enables early identification of slopes approaching failure thresholds.

Second, targeted hard-engineering interventions: conduit optimisation through engineered trenching at model-identified bottlenecks, active flow management via stormwater impellers in flat-gradient sections, and system disconnection using isolation valves to prevent municipal network surcharging from flooding private infrastructure. Before any concrete is poured, interactive what-if simulations can virtually install each intervention and recalculate flow velocities in real time, proving the solution works before capital is committed.

Third, water rejuvenation and storage infrastructure: detention basins to attenuate the flood hydrograph, controlled-release reservoirs to meter outflow at rates the downstream network can absorb, and permeable harvesting systems for aquifer recharge, turning a flood liability into a water asset that addresses India's parallel crisis of groundwater depletion. In landslide-prone terrain, the equivalent is engineered drainage to reduce pore-water pressure on critical slopes, combined with early-warning sensor networks calibrated to the same geospatial models.

The Landslide Dimension: Same Physics, Same Imperative

The computational frameworks are converging; it is the professional practice that must follow. India's National Landslide Susceptibility Mapping programme, combined with state-level real-time monitoring networks, provide a foundation that consulting engineers should be integrating into every hill-corridor infrastructure design.

Conclusions

The articles in this issue of *VIEWPOINT* represent diverse perspectives on these interlinked challenges. They ought to be considered not as separate technical papers but as facets of a single imperative: India's consulting engineering community must move from documenting damage to engineering prevention.

What remains is the professional will to integrate these capabilities into standard practice - and the institutional frameworks to demand that resilience be engineered into every infrastructure project, not retrofitted after the next disaster. CEAI and its member organisations are uniquely positioned to champion this transition, both through technical leadership and by advocating for updated design codes that reflect twenty-first-century geoclimatic realities rather than mid-twentieth-century assumptions.

The monsoons do not negotiate. Neither should our engineering standards.

Let the readers ponder and implement.

Dr Nishith Gupta

Chief Technical Officer, SYSTRA India

Arjun Bhagavatula

Sustainability Lead, SYSTRA India

Climate Change and its impacts on Floods including Urban Floods and Landslides in India



S Masood Husain

Former Chairman
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Abstract

Climate change has emerged as one of the most critical drivers of hydrological extremes across the globe, significantly altering precipitation patterns, increasing the frequency and intensity of extreme rainfall events. This paper examines the impact of climate change on floods, urban floods, and landslides in India, highlighting the increasing frequency and intensity of hydro-meteorological disasters under changing climatic conditions. The study analyses the scientific relationship between global warming, extreme rainfall, monsoon variability, glacier retreat, sea-level rise, and the growing vulnerability of urban and mountainous regions. It further discusses how rapid urbanisation, encroachment of floodplains and wetlands, ecological degradation, and unplanned developmental activities have aggravated disaster risks. Major flood and landslide events in India, including those in Mumbai, Chennai, Kerala, Uttarakhand, and the Himalayan region, are examined to illustrate the socio-economic and environmental impacts of such disasters. The paper also evaluates adaptation and mitigation measures such as climate-resilient urban planning, integrated river basin management, nature-based solutions, advanced forecasting systems, GIS-based risk mapping, and community preparedness. It

concludes that strengthening institutional coordination, sustainable land-use planning, ecosystem restoration, and resilient infrastructure is essential for enhancing climate resilience and reducing future disaster risks in India.

Climate Change and Floods

Introduction

Climate change has emerged as one of the most serious environmental and developmental challenges of the 21st century. One of its most visible and destructive consequences is the increasing frequency and intensity of flooding events across the world. Floods have always been a natural part of the hydrological cycle, but global warming has significantly altered rainfall patterns, atmospheric processes, sea levels, and storm intensities, thereby increasing flood risks in many regions.

Flooding today is no longer merely a hydrological phenomenon; it has become a complex interaction between climate variability, urbanisation, land-use change, ecological degradation, and inadequate infrastructure planning. Major floods in recent years in countries such as India, Pakistan, China, Germany,

Libya, and the United States demonstrate that both developed and developing nations are increasingly vulnerable.

In India these changes are particularly evident in urban areas where rapid and often unplanned urbanisation interacts with climate variability to produce severe flooding. Traditionally, floods were associated with riverine overflow, however, in recent decades, urban flooding resulting from intense rainfall and poor drainage systems has become increasingly common.

According to the Intergovernmental Panel on Climate Change (IPCC), climate change has increased the intensity of heavy precipitation events in many regions, thereby elevating the probability of urban flooding, flash floods, riverine floods, and coastal inundation.

This article examines the scientific basis of climate change-induced flooding, different flood types affected by climate change, global and Indian case studies, socio-economic impacts, and adaptation strategies for building flood resilience.

Understanding Climate Change and Flooding

Climate change, as now established, refers to long-term alterations in temperature, precipitation, wind patterns, and other climatic variables caused largely by increased concentrations of greenhouse gases (GHGs) such as carbon dioxide, methane, and nitrous oxide.

The earth's average temperature has already increased by approximately 1.1°C above pre-industrial levels due to anthropogenic greenhouse gas emissions. A warmer atmosphere can hold more moisture, impacting the hydrological cycle and increasing the likelihood of extreme rainfall events.

Climate change also affects monsoon variability, cyclone intensity, snowmelt rates, glacier retreat, sea-level rise, and storm surge magnitude. All these factors collectively influence flood occurrence and severity.

Such increments impact the runoff formation process, particularly that in respect of extremal events, that is

the peak flood and the minimum flows. Climate change is disrupting monsoon systems worldwide. In South Asia, monsoon rainfall is becoming more erratic, more concentrated, higher in intensity, and shorter in duration. This results in longer dry spells interspersed with extremely heavy rainfall events. India is among the countries most vulnerable to climate-induced flooding because of monsoon dependence, large river systems, rapid urbanisation, and high population density. Several studies indicate rising flood exposure in Indian cities.

Types of Flooding Influenced by Climate Change

Flooding associated with various causes in addition to climate change can be broadly categorised into several types.

Riverine Flooding

Riverine or fluvial flooding occurs when rivers overflow their banks due to prolonged rainfall or excessive runoff in catchment areas. Climate change contributes to river flooding through increased extreme rainfall, accelerated glacier melt, changes in snowmelt timing, and altered river hydrology. Regions dependent on glacier-fed rivers, such as the Himalayan River systems in India, Nepal, and Pakistan, are particularly vulnerable.

Urban Flooding

Urban flooding differing significantly from rural flooding in its causes and impacts, has become one of the fastest-growing climate-related disasters. It occurs rapidly, often within hours of rainfall and affects densely populated areas with high economic exposure. The issue of urban flooding has been discussed in detail in subsequent paras.

Flash Floods

Flash floods are sudden floods caused by intense rainfall over short durations, often within hilly or urban catchments. Climate warming increases atmospheric instability and cloudburst events, especially in mountainous regions such as the Himalayas. Flash

floods are extremely dangerous because of minimum warning time, high flow velocities, significant debris movement, and severe infrastructure damage.

Cloudbursts - Cloudbursts have emerged as one of the most dangerous hydro-meteorological hazards associated with climate change, particularly in the Himalayan and hilly regions of India. A cloudburst refers to an extremely intense and localised rainfall event, often exceeding 100 mm per hour over a small area, resulting in sudden flash floods, landslides, and severe destruction. Rising global temperatures increase atmospheric moisture content and instability, thereby enhancing the probability of such extreme rainfall events. Regions such as Uttarakhand, Himachal Pradesh, Ladakh, and Jammu & Kashmir have witnessed several devastating cloudburst incidents in recent years, including the Kedarnath disaster of 2013 and the Leh cloudburst of 2010. The combination of fragile mountain geology, steep slopes, unplanned construction, and extreme precipitation significantly amplifies disaster risks in these ecologically sensitive regions.

Coastal Flooding

Coastal flooding results from storm surges, sea-level rise, tidal flooding, and cyclonic events. Global sea level has risen due to thermal expansion of seawater, melting glaciers, and ice sheet loss. The IPCC warns that rising sea levels and increased cyclone intensity will raise the probability of coastal flooding in cities. Low-lying coastal cities such as Kolkata, Mumbai, Chennai, Jakarta, and Miami are highly exposed. Sea-level rise increases coastal flood risk by elevating baseline water levels, enhancing tidal intrusion, intensifying storm surges, and reducing drainage efficiency. Even moderate storms now produce larger coastal inundation than in previous decades.

Compound Flooding

It is observed that modern flood disasters increasingly result from simultaneous occurrence of; extreme rainfall, high tides, storm surge, river overflow and

drainage congestion. Mumbai floods (2005) is a classic example where extreme rainfall and high tide together worsened the flooding.

Glacier Melt and Glacial Lake Outburst Floods

Global warming is accelerating glacier retreat in the Himalayas. This creates unstable glacial lakes that may suddenly burst, causing catastrophic Glacial Lake Outburst Floods (GLOFs). The Himalayan region is increasingly vulnerable to debris floods, sediment surges, flash flooding, and river blockage failures.

Impacts of Flooding

Flooding affects multiple sectors simultaneously. Floods cause deaths, injuries, displacement, communication disruption, disease outbreaks, etc. Vulnerable populations suffer disproportionately. Floods damage infrastructure, housing, agriculture, industries, transport networks. Urban flooding already causes billions of rupees in annual losses in India. Flooding increases risks of waterborne/vector-borne diseases and contaminated drinking water. Critical infrastructure affected by floods includes roads, bridges, railways, airports, power systems and telecommunications. Research shows flood impacts can disrupt urban traffic systems for weeks after the waters recede. Floods can also lead to soil erosion, sedimentation, river morphology changes, and biodiversity loss. However, natural floodplains and wetlands also serve as ecological buffers that reduce flood intensity.

India is among the most climate-vulnerable economies and is experiencing increasing economic losses from floods. That causes disruption to GDP, transport and supply chains. The details of total flood damages in India during the period 1953-2022 and the average yearly damages as per the CWC Report (2024) are given in Table 1.

Table 1: Total Flood damages in India for the period 1953-2022 and Average Yearly Flood Damages.

S. no.	Items	Unit	Total Damages (1953-2022)	Average Yearly Damages
1.	Area affected	million hectare (m. ha.)	513	7.33
2.	Population affected	Million	2264.4	32.35
3.	Damage to crops - Area	m. ha.	298.7	4.27
4.	Damage to crops – Value	Rs-crore	178992	2557
5.	Damaged houses - numbers	million	83.78	1.196
6.	Damage to houses -Value	Rs-crore	64280	918.3
7.	Human lives lost	Numbers	116932	1670
8.	Damage to public utilities	Rs-crore	265412	3791.6
9.	Total damages (crops, houses, public utilities, etc.)	Rs-crore	508684	7267 (with cost indexed- 18326)

Climate Justice and Vulnerable Population

The socio-economic conditions of the poor population compel them to settle in flood prone areas. Such unplanned and many a time illegal settlements lack proper drainage. As a result the women, children and elderly get disproportionately affected. Thus, it is observed that the climate change impacts are unequal.

Role of Urbanisation in Climate-Driven Flooding

Climate change alone does not explain increasing flood disasters. Human activities significantly worsen flood vulnerability through encroachment of floodplains, destruction of wetlands, river channel narrowing, deforestation, and poor drainage maintenance. Studies of Indian cities found that reduction of green, open, and blue spaces substantially increased urban flood occurrence. As urban surfaces become impermeable, the runoff coefficient rises, increasing flood peaks.

Adaptation and Mitigation Strategies

Reducing climate-induced flood risks requires integrated approaches.

a) Climate-Resilient Urban Planning

Efforts should be made in the cities to preserve

wetlands, protect floodplains, increase green spaces, restore lakes, and improve zoning regulations. Nature-based solutions are increasingly important.

b) Improved Drainage Infrastructure

Urban drainage systems must be redesigned for future rainfall intensities rather than historical averages. Measures include; stormwater drains, retention ponds, permeable pavements, rainwater harvesting, and pumping systems.

c) Flood Forecasting, Early Warning System and Community Preparedness

Advanced forecasting technologies using satellite data, Doppler radar, AI models, hydrological simulations can significantly reduce flood casualties. Early warning systems and community preparedness play a critical role in reducing the impacts of floods and landslides, particularly in vulnerable regions. Advances in meteorological forecasting, satellite monitoring, Doppler radar systems, and real-time hydrological modelling have significantly improved the ability to predict extreme weather events and issue timely alerts. However, the effectiveness of such systems depends

largely on efficient dissemination of warnings and community-level preparedness. Community-based disaster management, evacuation planning, mock drills, mobile alert systems, and public awareness programmes can substantially reduce casualties and property losses. In remote and mountainous regions, ensuring last-mile connectivity for warning dissemination remains a major challenge. Strengthening coordination between scientific agencies, local administrations, and communities is essential for building disaster-resilient societies in the context of increasing climate-related hazards.

d) **Flood Risk mapping and GIS**

The flood risk mapping using GIS along with other attendant tools is very helpful as the adaptation strategy for the management of floods. The use of remote sensing techniques, LiDAR mapping, digital elevation models and GIS based zonation maps is very effective in this regard.

e) **River Basin Management**

Integrated river basin planning should include watershed conservation, afforestation, sediment management, and reservoir optimisation.

f) **Reservoir Operations**

Appropriate reservoir operation is critical to the management of floods in the basin in an effective manner. Sometimes, sudden reservoir releases without considering the upstream and downstream conditions may aggravate the flood situation. Thus, there is a need of appropriate dynamic operation strategy. Real time inflow forecasting for the reservoir is very important in this regard. Reservoir rule curves are also required to be updated considering the changing climate conditions. Further in case of more than one reservoir in a river basin, the integrated reservoir operation approach would give the optimum results.

g) **Coastal Protection**

Adaptation measures for coastal flooding include

sea walls, mangrove restoration, storm surge barriers, coastal zoning and elevated infrastructure.

h) **Nature-based Solutions**

Nature-based solutions are increasingly being recognised as sustainable and cost-effective approaches for reducing flood and landslide risks under changing climatic conditions. Unlike conventional grey infrastructure, nature-based approaches utilise natural ecosystems and ecological processes to enhance resilience against extreme weather events. Measures such as afforestation, restoration of wetlands and floodplains, mangrove regeneration, river restoration, green roofs, and urban forests help absorb excess runoff, reduce soil erosion, improve groundwater recharge, and stabilise slopes. In mountainous regions, bioengineering techniques and vegetation restoration can significantly reduce slope instability and landslide susceptibility. Similarly, in urban areas, increasing permeable surfaces and restoring natural drainage systems can substantially mitigate urban flooding. Nature-based solutions not only reduce disaster risks but also provide co-benefits such as biodiversity conservation, improved air quality, and enhanced urban liveability.

i) **Climate Mitigation**

Long-term climate mitigation, particularly relating to flood reduction ultimately depends on reducing greenhouse gas emissions. Mitigation measures include renewable energy, energy efficiency, sustainable transport, Carbon sequestration, and reduced fossil fuel dependence.

Some Recent Major Flood Events in India

The details of some major recent flood events in the country and the damages caused are given in Table 2. The information is based on the CWC Report on Flood Damage Statistics - 2024.

Table 2: Some Recent Major Flood Events in India and Damages

S. No.	Flood location (State)	Year	Notable incident	Human lives lost (Numbers)	Population affected (Numbers in millions)	Damage to Public utilities (Rs-crores)
1.	Assam	2012	Heavy rainfall	144	>2.0	3200
2.	Uttarakhand	2013	Monsoon flood	580	0.11	34977
3.	Madhya Pradesh	2014	Heavy rainfall	390	14.72	464
4.	Jammu & Kashmir	2014	Heavy rainfall	281	1.25	3000
5.	West Bengal	2015	Cyclone & H.R.	338	10.84	6023
6.	Tamil Nadu/ Chennai	2015	Heavy rainfall	421	3.0	23130
7.	Bihar	2016	Long term H.R	254	8.82	40.97
8.	Gujarat	2017	Extreme rainfall	284	0.52	3532
9.	Bihar	2017	Long term rainfall	514	17.16	-
10.	Uttar Pradesh	2017	Long term rainfall	121	2.92	-
11.	Kerala	2018	Heavy rainfall	450	5.41	2154
12.	Assam	2020	Heavy rainfall	150	5.80	2200
13.	Tamil Nadu	2021	Rock Avalanche	140	7.25	6129
14.	Assam	2022	H.R. & Emb. breach	205	8.85	2092

Some Global Flood Events

Recent international flood disasters demonstrate that climate-induced flooding is a global phenomenon affecting both developed and developing countries alike. The devastating Pakistan floods of 2022, triggered by unprecedented monsoon rainfall and glacier melt, submerged nearly one-third of the country and caused massive humanitarian and economic losses. Similarly, the Germany and Belgium floods of 2021 highlighted the growing vulnerability of advanced economies to extreme rainfall events linked to climate change. In 2023, catastrophic flooding in Derna, Libya, caused by extreme rainfall and dam failures, resulted in more than 7800 deaths, underscoring the dangers of inadequate infrastructure and disaster preparedness. Urban flooding events in China and hurricanes such as

Hurricane Katrina in the United States further illustrate how sea-level rise, intense storms, and unplanned urban development are increasing flood risks worldwide. These global experiences emphasise the urgent need for climate-resilient infrastructure, effective governance, and integrated disaster risk management strategies.

Climate Change and Urban Flooding in India

As mentioned earlier, urban flooding differs significantly from rural flooding in its causes, dynamics, and impacts. It occurs rapidly, often within hours of rainfall, and affects densely populated areas with high economic exposure. Urban flooding has transitioned from a localised phenomenon to a recurrent disaster affecting major metropolitan regions such as Mumbai, Chennai, Delhi and Bengaluru.

In India, observational studies show a rise in short-duration, high-intensity rainfall events, particularly over central and coastal regions. These events often exceed the design capacity of urban drainage infrastructure, resulting in flash floods.

Causes of Urban Flooding

Urbanisation and Land Use Change

Urbanisation replaces natural surfaces with impervious materials such as concrete and asphalt. This leads to reduced infiltration, increased surface runoff, and faster flow velocities. Studies of Mumbai's catchments show that land-use changes significantly alter hydrological processes, increasing flood risk.

Encroachment of Natural Drainage Systems

Urban expansion often encroaches upon rivers and floodplains, wetlands and lakes, and natural drainage channels. In Chennai, long-term planning practices effectively "erased" natural water systems, contributing to severe flooding.

Inadequate Drainage Infrastructure

Most Indian cities have drainage systems designed for lower rainfall intensities (e.g., 20–25 mm/hour) for conventional drains as per the old practices and 50 mm/hr for metropolitan areas. However, Central Public Health & Environmental Engineering Organisation (CPHEEO) Manual on Storm Water Drainage-2019 recommends full hydrological analysis using local rainfall statistics rather than fixed values. When rainfall exceeds this capacity - as seen during extreme events - systems fail, leading to rapid flooding.

Improper Solid Waste Management

Clogged drains due to plastic and solid waste significantly reduce drainage efficiency, aggravating urban flooding.

Climate Change together with Urbanisation

Urban flooding in India is not caused solely by climate change or urbanisation but by their interaction. Climate change increases rainfall intensity, while urbanisation amplifies runoff and reduces resilience. In Chennai, for

instance, extreme rainfall combined with rapid urban sprawl significantly increased flood risk.

Some Case Studies of Urban Flooding in India

Mumbai Floods (2005)

Mumbai experienced one of the heaviest rainfall events in its history - 944 mm in 24 hours on 26 July 2005. The key contributing factors to the extreme flood event included intense rainfall, high tide coinciding with peak runoff, inadequate drainage capacity and encroachment along the Mithi River. As per reports of the agencies of the Central and State Governments, the event resulted in massive economic losses and significant casualties. Around 1094 deaths were reported in Maharashtra, majority being in the Mumbai Metropolitan Region. About 20000 houses were damaged. An estimated economic loss of Rs 8000 crore occurred due to the flood event. Transport, infrastructure and business disruption losses were extremely high.

Chennai Floods (2015)

The Chennai floods were driven by a combination of extreme rainfall linked to atmospheric variability, urbanisation altering the hydrological cycle and poor reservoir management. Both natural climatic variability and anthropogenic changes contributed to the disaster. As per reports of the Agencies of Central and State Governments, the flood caused huge economic losses and exposed systemic weaknesses in urban planning. As per these reports, 421 persons died due to the floods in Tamil Nadu with Chennai being the worst affected, while more than 100,000 structures were damaged. An estimated 1.8 million people were displaced due to flooding and about 3.042 million families suffered total or partial damage to their dwellings. Estimated economic losses ranged above Rs 50,000 crore, making it one of India's costliest urban flood disasters.

Hyderabad Floods (2020)

Hyderabad received about 192 mm rainfall in 24 hours on 13th October 2020. Some localities recorded nearly 300 mm within a few hours, among the heaviest in recent decades. Around 104 deaths reported across Telangana due to floods and rain-related incidents.

More than 20,500 houses were affected/damaged in the Hyderabad urban region. The Telangana government estimated losses of about Rs 9,000 crore, while urban flood damage in Hyderabad alone was assessed at roughly Rs 5,000 crore.

Other Notable Events

Cities such as Bengaluru, Delhi, and Kolkata have also experienced recurrent urban flooding, indicating a systemic national issue rather than isolated incidents.

Strategies for Climate-Resilient Urban Flood Management

Cities should adopt a holistic approach that integrates stormwater management, wastewater systems, and land-use planning. Nature-based solutions are also important in this regard which may include restoration of wetlands and lakes, urban green spaces and permeable surfaces. These measures enhance infiltration and reduce runoff. Infrastructure upgradation should be taken up appropriately. This may consist of modern drainage systems, pumping stations and flood barriers/embankments. The use of smart technologies like real-time flood monitoring, early warning systems and GIS-based planning is considered essential in this regard. Policy reforms pertaining to climate-sensitive urban planning, strict regulation of encroachments and community participation is considered important in this aspect. Urban flood mitigation requires significant investment in infrastructure, which many cities struggle to mobilise. It is observed that the wetlands act as a natural flood buffer, as wetlands absorb excess runoff. Loss of wetlands in Chennai, Bengaluru and Srinagar increased the severity of the corresponding flood events.

Climate Change and Landslides

Introduction

India's diverse physiography includes extensive mountainous regions highly susceptible to landslides. Approximately 12% of India's land area is prone to landslides, with the Himalayas and Western Ghats being particularly vulnerable.

Landslides may be defined as the downward movement of rock, soil and organic material under the influence of gravity. These can occur suddenly causing significant destruction to infrastructure, environment and human lives. Landslides are triggered by a combination of natural and anthropogenic factors such as geological structure, slope instability, rainfall intensity, seismic activity, and land-use changes.

Climate change is now recognised as a major driver altering the frequency and severity of hydro-meteorological hazards. Increasing global temperatures, altered monsoon dynamics, and extreme weather events have intensified slope instability processes. The growing convergence of climate variability and human interventions is transforming landslide hazard regimes in India.

Geotechnical Aspects of Landslides

From a geotechnical perspective, climate change significantly influences slope stability and landslide mechanisms through changes in rainfall intensity, soil moisture, temperature, and groundwater conditions. Intense precipitation increases pore water pressure within slopes, reducing soil shear strength and the overall factor of safety, thereby triggering slope failures. Different forms of landslides such as rotational slides, translational slides, debris flows, mudflows, and rockfalls may occur depending on geological conditions and slope characteristics. In mountainous regions, prolonged rainfall and rapid infiltration destabilise weathered rock and soil masses, while freeze-thaw cycles and glacier retreat further weaken slope structures. Understanding these geotechnical processes is essential for effective hazard zonation, slope stabilisation measures, infrastructure planning, and climate-resilient disaster management in vulnerable regions.

Landslide-Prone Regions in India

Himalayan Region

The Himalayan arc is the most landslide-prone region in India due to its young and fragile geology, steep slopes, active tectonics and high rainfall variability. States

such as Uttarakhand, Himachal Pradesh, Sikkim, and Arunachal Pradesh frequently experience landslides. According to NRSC Landslide Atlas of India (2023), states like Mizoram and Uttarakhand have recorded thousands of landslides over recent decades

Western Ghats

The Western Ghats, especially Kerala and Karnataka, are prone to rainfall-induced landslides due to Lateritic soil profiles, high monsoon precipitation, deforestation and plantation activities.

Northeastern Region

The Northeastern States experience intense rainfall, weak lithology, and shifting cultivation practices contributing to high landslide incidence.

Mechanisms Linking Climate Change and Landslides

Rainfall-Induced Landslides

Rainfall is one of the dominant triggers of landslides in India. Short-duration extreme rainfall events are particularly crucial and may lead to overflowing of the drainage system and rapidly destabilise slopes. For example, studies by World Weather Attribution Group (2024) show that climate change has intensified monsoon rainfall events responsible for landslides in Kerala by about 10%, significantly increasing hazard levels. In regions where intense rainfall is a major trigger for landslides an increase in precipitation can lead to a higher frequency of landslide events like in mountainous regions of Himalayas.

Temperature Effects on Soil Stability

Temperature changes play a significant role in landslide dynamics. Rising temperatures influence soil cohesion, chemical weathering rates, and freeze-thaw cycles in high-altitude areas. These processes weaken slope materials over time, making them prone to failure.

Glacier and Permafrost Degradation

Rising temperatures lead to accelerated snowmelt in mountainous regions, which can trigger landslides. Rapid snowmelt increases water infiltration into the

soil elevating pore water pressure and reducing the frictional resistance of slopes. In high-altitude regions glacier retreat destabilises slopes, permafrost thaw reduces ground cohesion, and increased meltwater enhances erosion.

Vegetation Changes

Climate change affects vegetation cover through altered growing seasons, increased forest fires, and changes in species composition. Reduced vegetation weakens slope reinforcement, increasing landslide susceptibility.

Role of Anthropogenic Activities

Climate change can also impact vegetation patterns which in turn affect soil stability. Climate change impacts are often compounded by human interventions such as road construction, hydropower development, mining, and deforestation. In the Himalayas, infrastructure development has significantly increased slope instability. Land-use and land-cover changes combined with climate change significantly influence landslide susceptibility, especially in the Western Ghats. The combination of human activities and climate induced changes create a complex and heightened risk of landslides.

Interlinkage between Floods and Landslides

It is observed that many a time extreme rainfall simultaneously triggers floods and landslides. Landslides, in turn may block rivers causing secondary flooding. Further, debris flows aggravate flood impacts. It is seen that Himalayan disasters often involve cascading hazards. Thus, the concept of multi-hazard risk is important in modern disaster management.

Some Recent Major Landslides - Case Studies

The details of some recent major landslides in India and the damages caused are given in Table 3 below. The information has been compiled based on the Reports of NDMA, NDRF, SDMA and other Government Sources. The values presented in the table may vary slightly based on sources.

Table 3: Some Recent Major Landslides in India and the Damages Caused

S. No	Landslides Location	Year	Notable Incident	Human lives lost	Houses/buildings damaged	Economic loss/Total damages
1.	Uttarakhand – Kedarnath	2013	Heavy rainfall, monsoon landslides & slope failures across State	5700	21,000 houses fully & 11,700 partially damaged, hotels / structures destroyed across 4200 villages	Estimated losses above ₹12,000 crore
2.	Maharashtra – Malin village, Pune	2014	Entire village buried under landslide after intense rainfall	151	44 houses buried/ destroyed	Severe local economic loss to agriculture and
3.	Kerala – Idukki, Wayanad, Mallapuram	2018	Landslides during heavy rainfall/floods	483	>10,000 houses destroyed/damaged	Rs 31,000 crores loss Statewide
4.	Kerala –Pettimudi, Idukki	2020	Extreme monsoon rainfall causing massive debris flow	66	20 labour line houses destroyed	Heavy loss to plantation infrastructure
5.	Maharashtra-Teliye, Raigad	2021	Intense rainfall causes slopes failure	84	35	Major district infrastructure and livelihood losses
6.	Manipur – Tupul, Noney district	2022	Liquefaction of water clogged soil and destabilisation	61	Workers' camp and railway infrastructure damaged	Large losses to railway project infrastructure
7.	Himachal Pradesh-Shimla, Kullu, Mandi	2023	Monsoon landslides and slope failures across State	257	1376 houses fully damaged, 7935 partially damaged	About Rs 7000 crore
8.	Kerala – Wayanad, Mundakkai-Chooralmala	2024	Landslides triggered by extreme rainfall	420	1555 houses damaged, 136 community buildings affected	Approximately Rs 1200 crore direct losses
9.	Uttarakhand-various districts like Chamoli, Pithoragarh	2015-24	Recurrent landslides (4654) in these districts	316	3600 houses fully and 14800 houses partially damaged. Many roads damaged annually.	Huge recurring losses to highways, and hydropower infrastructure
10.	Himachal Pradesh-Kullu, Mandi, Shimla	2025	Cloudburst induced landslides and debris flow,135 major landslides	300	1540 houses totally destroyed, 8000 houses partially damaged.	Above Rs 4400 crore damage to roads, hydro. Infrastructure & utilities

Impacts of Climate-Induced Landslides

The impact of climate-induced landslides is the same as that of normal landslides. These can be briefly described as;

- a) **Socioeconomic Impacts:** Loss of life and property, disruption of transportation networks, and damage to infrastructure, temporary loss of livelihood, relocation of population to other areas, and adverse effect on farming activities.
- b) **Environmental Impacts:** Soil erosion, river sedimentation, and loss of cultivable land and biodiversity.
- c) **Strategic Impacts/ Implications:** Landslides affect border infrastructure in Himalayan regions, hydropower projects, and tourism economies.

Adaptation and Mitigation Strategies

Addressing the impact of climate change on landslides requires a multifaceted approach involving mitigation and adaptation strategies. Mitigation efforts focus on reducing the root causes of climate change, primarily through reducing greenhouse gas emissions. Adaptation strategies aim to reduce the vulnerability of communities and infrastructure to landslide risks. These include improving land use planning, implementing early warning systems and investing in slope stabilisation, drainage management systems and erosion control measures. Additionally restoring vegetation cover and improving sustainable agriculture practices can enhance slope stability and landslide susceptibility.

Governance and Institutional Challenges

A major challenge in addressing climate-induced flooding and landslide hazards in India lies in governance and institutional limitations. Fragmented urban governance, weak enforcement of land-use regulations, inadequate coordination among multiple agencies, and poor maintenance of drainage and slope management systems significantly aggravate disaster risks. In many cities, climate considerations are still insufficiently integrated into master plans and infrastructure design standards. Institutions such as the National Disaster Management Authority, Central Water Commission, and

India Meteorological Department have strengthened forecasting and disaster management capabilities in recent years; however, effective implementation at state and local levels remains a major challenge. Enhancing institutional coordination, scientific planning, regulatory enforcement, and community participation is essential for building long-term climate resilience in India.

Climate Change Projections for India

Climate projections for India indicate a significant increase in the frequency and intensity of extreme weather events under future warming scenarios. According to assessments by the Intergovernmental Panel on Climate Change and studies conducted by the India Meteorological Department, the Indian monsoon is expected to become increasingly erratic, with longer dry periods interspersed with short-duration, high-intensity rainfall events. Such changes are likely to substantially increase the risks of urban flooding, flash floods, and riverine flooding across many regions of the country. The Himalayan River basins, particularly the Ganga-Brahmaputra-Meghna system, are projected to experience higher flood vulnerability due to intensified rainfall, accelerated glacier melt, and glacial lake outburst floods (GLOFs). Coastal regions are also expected to face growing threats from sea-level rise, cyclonic storms, and storm surges, particularly along the eastern and western coastlines of India. Major metropolitan cities such as Mumbai, Kolkata, Chennai, and Visakhapatnam are increasingly vulnerable to coastal inundation and drainage congestion. In addition, rising temperatures and changing precipitation patterns may exacerbate landslide risks in the Himalayas and Western Ghats. These projections highlight the urgent need for climate-resilient infrastructure, scientific land-use planning, improved forecasting systems, and long-term adaptation strategies to reduce future disaster risks in India.

Conclusion

Climate change has emerged as a major force intensifying floods and landslides across India through increased extreme rainfall, glacier retreat, sea-level rise, and changing monsoon dynamics. The

growing interaction between climate variability, rapid urbanisation, ecological degradation, and unplanned infrastructure development has significantly increased disaster vulnerability. Addressing these challenges requires a comprehensive and forward-looking approach, centred on climate-resilient infrastructure, sustainable urban planning, ecosystem restoration, integrated watershed management, proper governance, and community participation. Strengthening early warning systems, improving institutional coordination, and investing in resilient cities and adaptive infrastructure are essential for minimising future risks. Equally important is the need for enhanced climate adaptation, financing and long-term policy commitment to ensure sustainable development in an era of increasing hydro-meteorological extremes.

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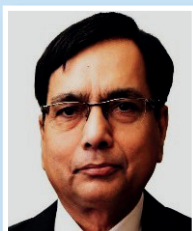
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Hindu Kush Snow Deficit Raises Water Security Fears For 2 Billion People

A fresh report from the International Centre for Integrated Mountain Development (ICIMOD) in Kathmandu shows that seasonal snow cover in the HKH has hit its lowest level in more than 20 years. This is raising serious fears about future water supplies for some of the world's most crowded river plains.

Source: NDTV WORLD

AI-Enabled Flash Flood and Landslide Risk Management in the Indian Himalayas: Operational Lessons from the August 2025 Flash Flood Disasters



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Abstract

The catastrophic flash floods and landslide disasters that struck Dharali (Uttarakhand), Kishtwar, and Reasi (Jammu & Kashmir) during August 2025 exposed critical operational limitations in Himalayan disaster-risk governance, despite major advances in India's meteorological and flood-forecasting capabilities. This study evaluates the performance of India's current flash-flood forecasting architecture through comparative hazard-chain analysis using official post-event reports, meteorological assessments, hydrological information, and satellite-based terrain observations. The analysis demonstrates that the principal weakness was not the absence of rainfall forecasts, but the inadequate translation of hazard warnings into terrain-specific consequence reduction and automated public protection measures. The three case studies represent distinct but interconnected operational failure modes: geomorphic surprise associated with debris-flow dynamics in Dharali, hyperlocal convective rainfall interacting with concentrated pilgrimage exposure in Kishtwar, and forecast-to-action governance failure along the Vaishno Devi corridor in Reasi. The study

identifies key systemic gaps, including radar shadow zones in mountainous terrain, fragmented inter-agency data architecture, weak debris-flow forecasting capability, limited real-time cryosphere monitoring, and the absence of automated route-closure protocols. The paper suggests that future Himalayan resilience requires a transition from hazard-centric forecasting toward AI-enabled, consequence-based multi-hazard early-warning systems integrating radar nowcasting, probabilistic impact forecasting, digital twins of pilgrimage corridors, satellite-derived terrain intelligence, and real-time operational decision support. The proposed framework presents interoperable IMD–CWC–ISRO data fusion, dense mountain observation networks, automated evacuation triggers, and corridor-level risk governance to reduce loss of life from cascading Himalayan hazards.

Introduction

The southwest monsoon of 2025 was marked by intense and highly variable precipitation, yielding 108% of the Long Period Average (LPA) rainfall across India¹ The Himalayan region bore the brunt of this surplus, with

the meteorological subdivision of Jammu & Kashmir recording 310.7 mm of rainfall in August, about 68% excess over the normal 184.9 mm and Uttarakhand experiencing 149% of its LPA in the same month¹. While these statistics reflect a robust monsoon, the catastrophic flash floods and mass-movement events that unfolded in Dharali, Kishtwar, and Reasi highlight a systemic vulnerability. These tragedies were not merely products of anomalous weather; they were complex, cascading hazards operating within a rapidly changing cryosphere and fragile geomorphology.

These events demonstrated that Himalayan disaster risk cannot be understood solely through conventional rainfall-runoff relationships. Instead, the disasters reflected cascading multi-hazard interactions involving cloudbursts, debris flows, unstable geomorphology, cryosphere processes, slope failures, and concentrated human exposure within narrow mountain corridors.

India's forecasting capabilities have improved significantly over the past decade through the expansion of Doppler Weather Radar (DWR) coverage, numerical weather prediction (NWP), satellite monitoring, flash-flood guidance systems, and impact-based warning dissemination. However, the August 2025 disasters revealed persistent operational gaps between forecast generation and effective consequence reduction.

This study aims to:

- Evaluate the operational performance of India's present flash-flood forecasting architecture during the August 2025 Himalayan disasters.
- Identify systemic forecast-to-action gaps within Himalayan multi-hazard environments.
- Compare Indian operational practices with selected international best practices.
- Propose an AI-enabled, consequence-based forecasting framework for future Himalayan disaster-risk reduction.

The paper addresses the following questions:

- Why did significant disaster impacts occur despite

improvements in meteorological forecasting capability?

- What operational limitations emerged in the transition from hazard forecasting to public protection?
- How can AI-enabled multi-hazard systems improve Himalayan risk governance?

Indian Institutional Architecture for Flash Flood Forecasting

India manages hydrometeorological risks through a collaborative, albeit fragmented, network of scientific and administrative agencies. The forecast-to-action chain relies on the following key pillars:

- India Meteorological Department (IMD):** As the nodal agency for weather forecasting, IMD issues district-wise early warnings four times a day, valid for up to seven days². IMD also operates the South Asia Flash Flood Guidance System (SAFFGS), operational since October 2020, which provides guidance for all watersheds of the Country and Flash flood Guidance to Nepal, Bhutan, Bangladesh, Sri Lanka every 6 hours at very high resolution³.
- Central Water Commission (CWC):** Entrusted with flood forecasting, the CWC monitors 350 stations (200 level and 150 inflow) and provides a 7-day basin-wise advisory. Recently, the CWC inaugurated "C-FLOOD," a web-based platform using advanced 2-D hydrodynamic modelling for two-day advance inundation forecasts up to the village level^{5,6}.
- Indian Space Research Organisation (ISRO):** ISRO's National Remote Sensing Centre (NRSC) provides critical spatial data. It maintains a database of approximately 80,000 landslides⁷. ISRO's satellite insights confirm that of the 2,431 lakes larger than 10 hectares identified during 2016-17, 676 glacial lakes have notably expanded since 1984, increasing the baseline hazard⁸.
- National Disaster Management Authority (NDMA) & State Agencies:** NDMA sets policy

frameworks, including guidelines for Glacial Lake Outburst Floods (GLOFs) and landslide management⁹. However, the critical “last-mile” dissemination such as automated sirens, local evacuations, and route closures remains the statutory responsibility of State Disaster Management Authorities (SDMAs) and local administrations².

Methodology

Analytical Framework

This study employs a comparative qualitative hazard-chain analysis using official government reports, meteorological assessments, satellite-based terrain observations, and public-domain disaster documentation from 2023–2026.

The analytical framework combines:

- Comparative case-study analysis,
- Hazard-chain reconstruction,
- Institutional process evaluation,
- Forecast-to-action assessment, and
- Comparative review of international operational practices

The study examines how meteorological triggers translated into hydrological, geomorphological, and human-impact consequences across three Himalayan disaster environments.

Data Sources

The analysis relies primarily on: IMD reports, CWC operational documents, ISRO/ NRSC satellite assessments, NDMA guidelines, Press Information Bureau releases, Official public-service news reports

Analytical Approach

The methodology includes:

- **Comparative Assessment**
Comparison of distinct hazard environments and operational failure modes across Dharali, Kishtwar, and Reasi.

- **Hazard-Chain Analysis**

Evaluation of sequential hazard evolution from intense rainfall to runoff, slope failure, debris flow, infrastructure damage, and crowd entrapment.

- **Forecast-to-Action Evaluation**

Assessment of how scientific warnings were translated into evacuation, route control, and operational decision-making.

- **International Benchmarking**

Comparison with selected international best practices in mountainous hazard forecasting, including operational approaches used in Japan, Switzerland, Norway, South Korea, the United Kingdom, and the United States.

Current Prediction Methodology in India

India employs an integrated forecasting framework comprising numerical weather prediction (NWP), radar monitoring, hydrological modelling, and standardised warning procedures to forecast severe weather and floods. India currently operates 48 Doppler Weather Radars (DWRs) covering approximately 92% of the land area, supplemented by 1,008 Automatic Weather Stations (AWS) and 1,382 Automatic Rain Gauges (ARG)^{11, 10}. IMD’s formal Standard Operating Procedure already provides an institutional template for heavy-rainfall warning, nowcasting, and multi-hazard dissemination, but the Himalayan experience shows that operational consistency does not yet guarantee terrain-specific impact avoidance³. The average distance between existing radars is 432 km, leaving critical shadow zones in the complex topography of the Himalayas.

Analytical Approach

This paper presents a structured analytical approach based entirely on official Indian government and public-service sources (2023 - 2026) to assess the current methodology:

- **Comparative Assessment:** Evaluating varying failure modes across different geographies and

hazard types (e.g. geomorphic failure vs. crowd-exposure failure).

- **Hazard Chain Analysis:** Tracing the sequential translation of meteorological triggers (intense rainfall) into hydrological responses (runoff) and geomorphic consequences (debris flows, slope failures).
- **System Gap Evaluation:** Identifying the disjunction between the high probability of detection (POD) for short-range heavy rainfall¹² and the functional operational lag in the forecast-to-action pipeline.

Figure 1 illustrates the cascading multi-hazard framework responsible for flash-flood generation in the Indian Himalayas. The framework demonstrates how climatic, cryospheric, geomorphic, hydrological, and anthropogenic drivers interact to produce sequential hazard processes including cloudbursts, slope failures, debris flows, flash floods, and secondary impacts. The figure also highlights the feedback mechanisms through which environmental degradation, infrastructure pressure, and climate change further intensify future disaster risk.

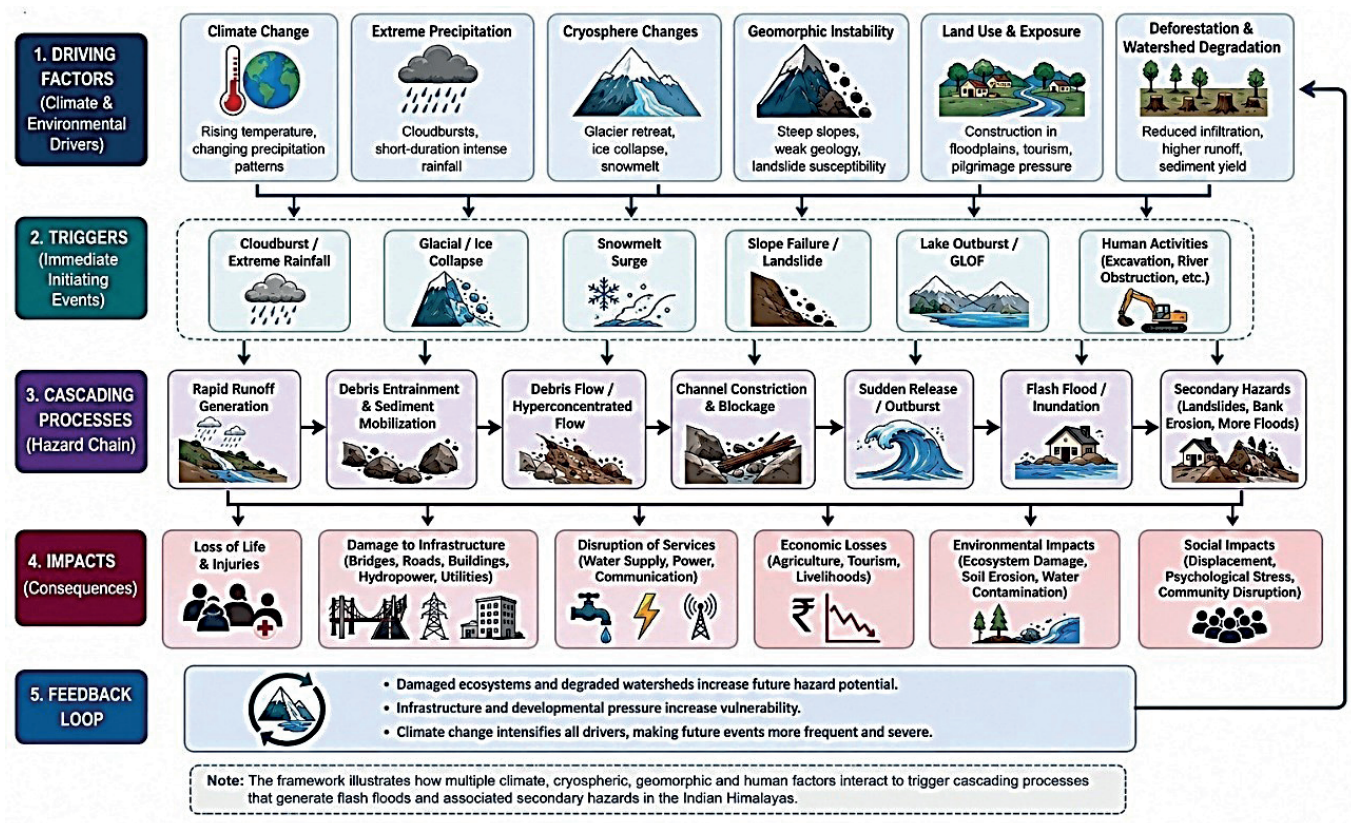


Figure 1: Cascading Multi-Hazard Framework Responsible for Flash-Flood Generation in the Indian Himalayas

Table 1 presents current flood forecasting practices in India by different key agencies.

Table 1: Current Analysis and Flood Forecasting Practices in India

Component	Present Indian Practice	Brief Description	Key Agencies
Weather Prediction	NWP + Radar + Satellite	NWP models (Global and Meso-scale). 39 DWRs track intensity; INSAT monitors clouds.	IMD, ISRO
Flash Flood Guidance	SAFFGS	Estimates flash flood likelihood based on soil moisture and 4x4 km rainfall estimates.	IMD, CWC
Inundation Forecasting	C-FLOOD & Flood Watch	2-D hydrodynamic modelling for 2-day village-level inundation depth predictions.	CWC, C-DAC, NRSC
Cryosphere Monitoring	Satellite mapping	Monitoring of 902 glacial lakes >10 ha (June–Oct); historical landslide database.	ISRO, CWC, WIHG
Warning Dissemination	CAP, SMS, Apps	Common Alerting Protocol (CAP) and SDMA channels; localised sirens where available.	NDMA, SDMAs, IMD

Current Forecasting and Warning Practices in India

India currently uses an integrated combination of:

- Numerical Weather Prediction (NWP)
- Doppler Weather Radar observations
- Satellite monitoring
- Hydrological modelling
- Flash-flood guidance systems
- Common Alerting Protocol (CAP)-based dissemination

Existing systems perform comparatively well for broad-scale flood forecasting and synoptic rainfall monitoring but remain less effective in predicting:

- Debris-flow behaviour
- Hyperlocal cloudburst evolution
- Rapid slope instability
- Crowd-exposure consequences
- Cascading multi-hazard interactions

August 2025 Himalayan Case Studies

The disasters of August 2025 provide a grim masterclass in the limitations of applying broad-scale hydrological models to highly localised, multi-hazard Himalayan environments.

Dharali (Uttarkashi, Uttarakhand, 5 August 2025)

Triggered by extreme localised precipitation, a catastrophic debris-flow swept through the Kheer Gad stream into Dharali and Harsil. Initial assumptions pointed to a simple cloudburst. However, post-event satellite analysis by ISRO revealed a much more complex geomorphic event. The disaster resulted in widened stream channels, altered river morphology, and a massive 20-hectare fan-shaped deposit of sediment and debris at the Kheer Gad - Bhagirathi confluence. Several buildings were completely destroyed or submerged in mud^{13, 14, 15}. This event resulted in massive infrastructure loss, with 2 dead and 67 missing.

Comparative Analysis: The failure in Dharali was rooted in “geomorphic surprise”, the sudden mobilisation of massive sediment and potential ice/rock instability that standard rainfall-runoff models (like SAFFGS) cannot predict or route accurately.

Chositi / Chashoti, Kishtwar (Jammu & Kashmir, 14 August 2025)

A severe, highly localised cloudburst struck the Chositi area along the Machail Mata Yatra route. The ensuing flash flood caused widespread destruction of property and severing of road links. Official reports confirmed a devastating toll of 60 dead, over 100 injured, and more than 160 rescued by a multi-agency response team (NDRF, SDRF, Army). The pilgrimage was subsequently suspended¹⁶.

Comparative Analysis: Kishtwar serves as the strongest example of hyperlocal convection intersecting with mass exposure. Kishtwar was a catastrophic alignment of rapid meteorological onset and dense crowds in an isolated valley. It exposed the critical lack of overlapping X-band radar in deep mountain shadow zones to provide a 30-minute nowcast for immediate crowd dispersal.

Reasi/ Ardhkuwari/ Vaishno Devi Route (Jammu & Kashmir, 26 August 2025)

Relentless, heavy rainfall (380 mm in the wider region, 284 mm specifically triggering the slide) saturated the slopes along the highly traversed Vaishno Devi pilgrimage track. A major landslide near Ardhkuwari claimed at least 32 lives and prompted an immediate suspension of the yatra, alongside massive intra-circle roaming activations by telecom departments to aid stranded pilgrims^{14, 15}.

Comparative Analysis: Reasi stands as the strongest example of a *forecast-to-action* and route-governance failure. IMD possessed strong detection skill for this synoptic event¹⁰. The failure was not the absence of a meteorological warning, but the inability of local authorities to translate a regional “heavy rainfall alert” into an automated, non-negotiable suspension of a high-density pedestrian corridor prior to slope failure.

Cross-Case Synthesis: Why the Prediction System Struggled

A synthesis of these cases reveals that they were not identical events, but three distinct failure modes within

one Himalayan multi-hazard system:

- a) **Geomorphic vs. Hydrological Regimes:** Current systems (e.g., C-FLOOD, SAFFGS) are primarily calibrated for clear-water river systems. They struggle to predict the hyper-concentrated, debris-laden flows, ice-rock avalanches, and sudden surges observed in high-altitude cryosphere catchments like Dharali.
- b) **Radar Shadow Zones:** As IMD’s report¹⁰ notes, the average radar distance is 432 km. Cloudbursts in Kishtwar evolved beneath the optimal scanning floor of distant S-band radars, preventing actionable nowcasting.
- c) **The Forecast-to-Action Lag:** In Reasi, forecasts existed, but there was no algorithmic or institutional trigger linking a specific rainfall threshold directly to mandatory crowd evacuation.

Systemic Operational Gaps

The analysis identifies several recurring weaknesses:

- a) **Hazard-Centric Rather than Consequence-Centric Forecasting**
Existing systems forecast rainfall and flood probability more effectively than route-specific human consequences.
- b) **Radar Shadow Zones**
Mountain topography limits effective low-level radar coverage in critical Himalayan valleys.
- c) **Fragmented Institutional Architecture**
Meteorological, hydrological, terrain, and exposure information remain operationally separated.
- d) **Limited Debris-Flow and Slope-Failure Forecasting**
Operational systems remain optimised primarily for clear-water flood forecasting.
- e) **Weak Automated Operational Triggers**
Route closures and evacuations continue to depend heavily on delayed administrative judgment.

Comparison with International Best Practices

Several mountainous countries have adopted

operational practices that reduce forecast-to-action delays. Table 2 presents gaps between international best practices and practices which were adopted during the August 2025 events.

Table 2: Gaps with International Best Practices

	International Best Practice	Gap in August 2025 Events	Exemplar Countries
1	Hyperlocal AI nowcasting	Mostly district/ watershed-scale forecasts rather than valley-scale convective nowcasts.	United Kingdom, United States, Japan
2	Real-time slope radar/ InSAR deformation monitoring	Limited operational deployment; deformation intelligence remained weak or post-event.	Switzerland, Norway, Japan
3	Digital twins for high-exposure mountain corridors	Major pilgrimage routes lacked dynamic corridor simulation and automated closure logic.	Singapore, Netherlands, Japan
4	Operational debris-flow forecasting	Weak sediment routing and debris-surge prediction in narrow valleys.	Austria, Switzerland, Japan
5	Cryosphere hazard observatories	Seasonal satellite monitoring existed, but basin-scale real-time glacier instability watch was limited.	Switzerland, Norway, Iceland, China
6	AI-integrated hazard-chain models	Rainfall, slope failure, debris flow, and exposure remained operationally fragmented.	United States, South Korea, China
7	Automated route closure triggers	Mostly manual, reactive administrative decisions after crowd exposure had already peaked.	Japan, South Korea, Switzerland
8	Dense mountain X-band radar network	Sparse overlapping coverage in deep valleys and terrain-shadow zones.	Switzerland, China, South Korea
9	Real-time IoT sensor fusion	Ground sensors, crowd information, and remote-sensing feeds were not fused into one live operations layer.	South Korea, Singapore, Japan
10	Probabilistic impact forecasting	Alerts remained more hazard-centric than consequence-centric for specific routes and settlements.	United Kingdom, United States, Netherlands

Analysis of India's Current Situation

India's flood-warning system in 2026 is materially stronger than it was a decade ago, but the August 2025 Himalayan disasters show that the country's operational problem has shifted. The principal weakness is no longer a simple absence of forecasts. IMD now issues district-wise warnings up to seven days ahead, CWC runs a wider flood-forecasting network and basin-wise advisories, and ISRO/ NRSC supply increasingly rich terrain and cryosphere intelligence^{5,2,8}. The critical

weakness is the incomplete conversion of these parallel streams into one terrain-specific decision system.

In practical terms, India is strongest where hazards behave like rivers on maps and weakest where hazards behave like chains, intense rainfall to slope failure to debris surge to crowd entrapment. That is why the same institutional architecture can perform credibly in synoptic flood monitoring and still fail in Dharali, Kishtwar, or the Vaishno Devi corridor. The present system remains hazard-aware, but not yet fully

consequence-aware. It can often say that very heavy rain (115.6 mm to 204.4 mm measured over 24 hours) is likely; it still struggles to say which footbridge, market cluster, pilgrimage segment, or settlement should be closed first and by whom.

A second structural issue is asymmetry between central scientific capability and local enforcement capacity. Forecast skill, satellite analytics, and model sophistication have advanced faster than route governance, automatic closures, evacuation drills, and sensor-backed last-mile alerting. This mismatch is now the defining policy problem for Himalayan risk management, not merely the production of more meteorological bulletins².

Major Government Advances in the Last Decade

The progress made by Indian agencies over the last ten years is remarkable and should be acknowledged clearly. IMD's own achievement review reports expansion of Doppler Weather Radars from 15 to 39, major growth in automatic observations, a roughly 40% improvement in overall forecast accuracy relative to 2014, and a rise in heavy-rainfall probability of detection from around 50% to about 80% by 2023. District-level impact-based warnings and the implementation of the South Asia Flash Flood Guidance System since 2020 represent real institutional gains, not incremental paperwork³.

On the hydrological side, the CWC has moved beyond conventional gauge reading toward wider digital forecasting support. By 2026 it was operating

flood forecasting at 350 stations, issuing basin-wise runoff advisories and integrating warnings through CAP; in 2025 it launched C-FLOOD to provide two-day, village-level inundation forecasts in selected basins using 2-D hydrodynamic modelling and high-performance computing⁴.

Space-based risk intelligence has also improved materially. ISRO and NRSC have created a landslide atlas based on roughly 80,000 mapped landslides, while satellite analysis has identified 130 significantly expanded glacial lakes within India since 1984. Event-specific satellite assessment, as seen after Dharali, is already proving operationally valuable for damage mapping, search support, and terrain interpretation¹³.

Policy architecture has likewise matured. NDMA's GLOF guidelines, the broader CAP-based warning ecosystem, and the gradual move toward integrated emergency operations reflect a state that is more alert, more networked, and better equipped than it was during earlier Himalayan disasters. The difficulty is not the absence of progress; it is that progress has been uneven across meteorology, hydrology, geomorphology, and public action⁹.

Critical Gaps Still Requiring Government Action

The next phase of reform must therefore focus on the points where lives are still being lost despite better forecasts. Table 3 identifies the most important operational gaps that remain visible in the Himalayan system and the practical measures that central and state agencies can take to close them^{10, 11}.

Table 3: Critical Present Gaps and Matched Measures

	Critical Gap	Why It Remains Dangerous	Suitable Measure
1	Terrain-shadow radar gaps in Himalayan valleys	Cloudbursts can intensify below the effective scanning floor of distant radars, leaving too little lead time for valley communities and pilgrimage routes.	Deploy overlapping X-band radar coverage, dense valley rain-gauge clusters, and gap-filling microwave links in the highest-exposure corridors.
2	Fragmented multi-agency data architecture	Rainfall, discharge, slope instability, satellite change detection, and crowd exposure are still read on separate dashboards and often on different time cycles.	Create a shared IMD-CWC-ISRO geospatial grid with common Event IDs, open APIs, and a unified operational room at state and regional levels.
3	Weak operational debris-flow and landslide forecasting	Current systems model clear-water flooding better than sediment-laden surges, slope collapse, and hillslope-to-channel cascades.	Operationalize debris-flow modules, slope-failure nowcasting, and hotspot sensor packages combining InSAR, GNSS, cameras, and stream-stage monitoring.
4	Manual governance of high-density pilgrimage corridors	Closures often depend on delayed administrative judgment after crowd accumulation has already peaked.	Adopt pre-approved rainfall, slope, and crowd thresholds linked to automatic route closure, e-gates, transport suspension, and shelter activation.
5	Uneven last-mile warning and evacuation readiness	Common Alerting Protocol (CAP) messages exist, but route-level sirens, multilingual audio alerts, display boards, and evacuation drills remain inconsistent.	Mandate corridor-level sirens, cell broadcast, multilingual warning templates, annual drills, and audited compliance for shrine boards and district authorities.
6	Seasonal rather than continuous cryosphere surveillance	Expanding glacial lakes and unstable ice-rock zones are monitored, but not always through basin-scale, near-real-time watch systems.	Set up glacier-hazard observatories that combine satellite tracking with permanent field instrumentation and quarterly risk audits for high-priority basins.
7	Limited public accountability after extreme events	Forecast skill and administrative response are rarely reviewed together in a time-bound, public format, slowing institutional learning.	Require post-event forecast-to-action audits within 30 days, with public dashboards on warning issuance, closures, rescues, and communication failures.

The policy test is straightforward: can India move from “warning issued” to “risk reduced”? Unless institutional incentives shift toward interoperable data, audited closures, and corridor-level automation, additional forecast precision alone will deliver diminishing safety returns.

AI-Enabled Future Framework for Himalayan Risk Reduction

AI-Driven Multi-Hazard Forecasting

Future Himalayan resilience will require integrated AI-enabled consequence forecasting systems. The objective is not to replace physics-based forecasting

but to combine physical modelling with high-frequency pattern recognition and probabilistic impact analysis.

Proposed AI Components

- **Transformer-Based Radar Nowcasting:** High-resolution prediction of 500 m to 1 km resolution for 0–90-minute convective evolution and cloudburst probability.
- **Graph Neural Networks (GNNs):** Modelling hillslope to-channel connectivity, downstream debris routing, and slope-failure propagation.
- **Vision Transformers (ViTs):** on Synthetic Aperture Radar (SAR) and optical imagery for change detection of glacier instability, moraine lakes, snow/ ice collapse zones, terrain change, and landslide evolution.
- **Hybrid Physics-AI Debris-Flow Models:** Integration of terrain physics and rainfall data with machine-learning prediction while preserving hydrological constraints.
- **Probabilistic Impact Models:** Conversion of hazard likelihoods into route-specific operational

risk scores by multiplying hazard probabilities by consequence severity. There are multiple standardized techniques that facilitate this translation. Bayesian Networks is popular.

- **Crowd-Risk Models:** Evaluates safety by quantifying pedestrian density, bottleneck geometry (chokepoints/ corners), shelter access, evacuation time, assessment of evacuation difficulty, and pedestrian exposure along pilgrimage corridors.

Figures 2 and 3 present the proposed probabilistic forecasting framework for AI-enabled multi-hazard early warning in the Indian Himalayas. The framework integrates ensemble meteorological inputs, AI/ML-based probabilistic hazard prediction, uncertainty quantification, risk-based decision intelligence, and automated alert dissemination to support rapid forecast-to-action conversion. The lower panel outlines a phased implementation roadmap progressing from foundational observation-network strengthening and data integration toward long-term operational automation, adaptive learning, and resilience enhancement.

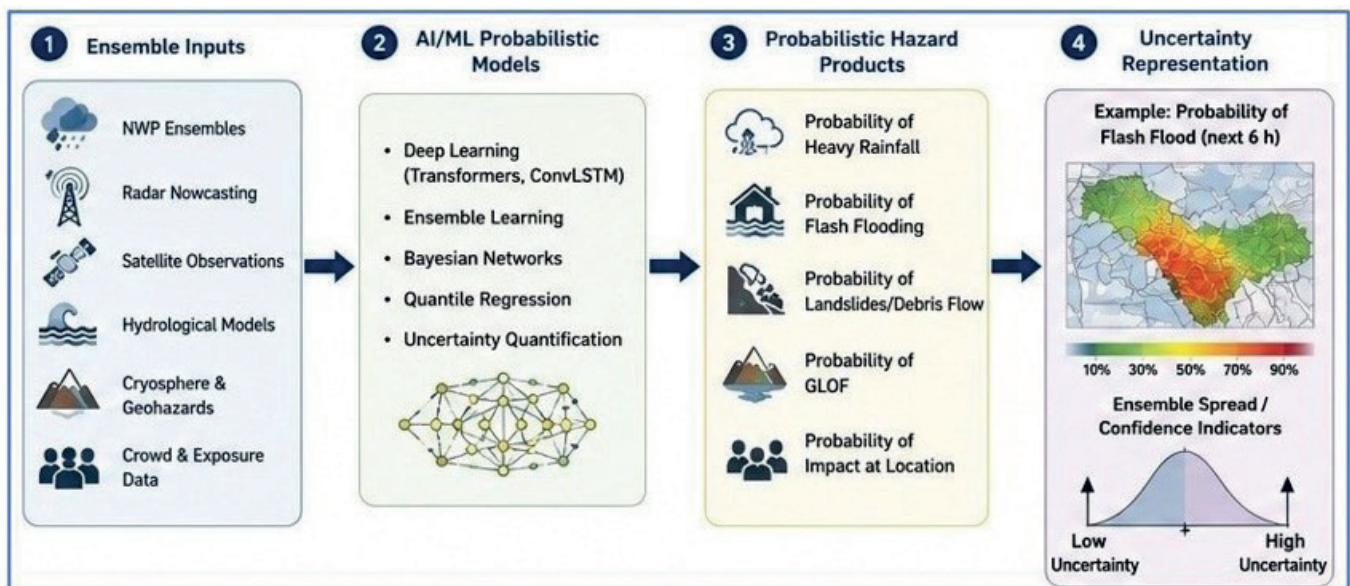


Figure 2: Probabilistic Forecasting Framework

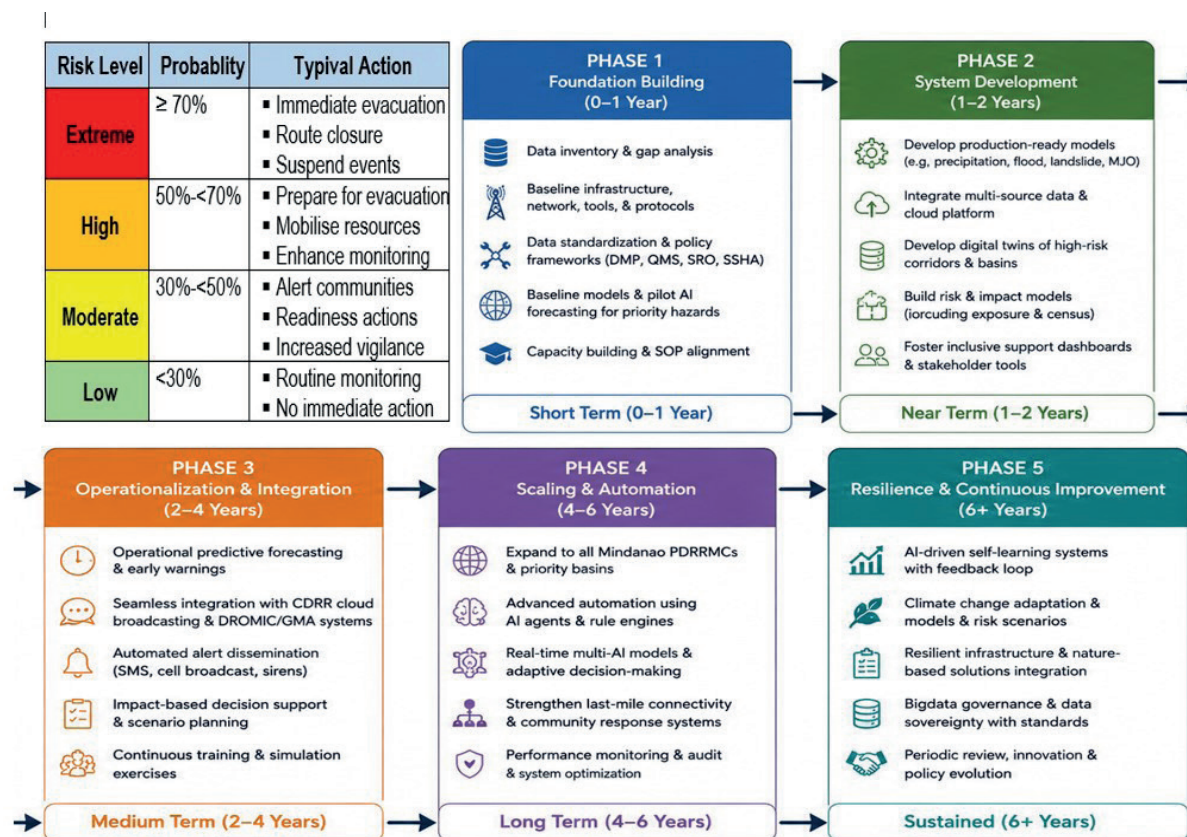


Figure 3: From Probability to Action and Implementation Roadmap for AI-Enabled Multi-Hazard Early Warning System

Operational Data Integration

Future systems should integrate:

- X-band and S-band radar observations
- Automatic weather station telemetry
- Satellite rapid-scan products
- Hydrological sensors
- SAR and optical remote sensing
- GNSS and InSAR deformation monitoring
- Crowd-density indicators
- Road and route status information,
- Emergency shelter capacity

Operational Workflow

Step 1: Data Ingestion: Real-time acquisition from IMD, CWC, ISRO, and local sensor networks.

Step 2: Model Fusion: Integration of rainfall, terrain instability, runoff, and exposure analytics. Combine radar nowcasts, runoff projections, slope susceptibility, cryosphere anomalies, and crowd exposure

Step 3: Consequence/ Impact Scoring: Probabilistic risk estimation for valleys, settlements, and corridor segments using probabilities and uncertainty bands.

Step 4: Decision Support: Colour-coded operational dashboards for district administrations, shrine boards, SDRF/NDRF and local police.

Step 5: Automated Public Protection: Automated route closure, Common Alerting Protocol (CAP) alerts, sirens, shelter activation, and evacuation messaging as soon as predefined thresholds are crossed.

Figure 3 presents the proposed operational workflow of the AI-driven decision-support system for Himalayan flash flood and landslide risk management. The framework integrates real-time observations, multi-source data fusion, AI/ML-based hazard prediction, probabilistic risk assessment, automated alert dissemination, and coordinated emergency response within a continuous feedback-learning architecture. The system is designed to improve forecast-to-action

conversion through interoperable, consequence-based operational intelligence for high-risk Himalayan environments.

Policy Recommendations

- a) **Radar Modernisation:** Address the radar gap identified in the IMD Vision-2047 document, this paper recommends a policy standard of overlapping X-band radar coverage along all high-risk Himalayan valleys and pilgrimage belts. A typical spacing of about 100–150 km in mountainous terrain should be treated as a proposed operational benchmark for reducing dangerous observational shadow zones.
- b) **Unified Multi-Agency Data Architecture:** Establish a common IMD–CWC–ISRO operational geospatial grid with standardised APIs with a 5-to-15 minutes ingestion cycle, assigning common Event IDs to track hazards across meteorological, hydrological, and disaster-response domains seamlessly, and shared event identifiers.
- c) **Glacier and Slope Hazard Observatories:** Transition from seasonal satellite monitoring to active, high-risk basin observatories. Develop permanent basin-scale cryosphere and slope-instability observatories using: InSAR, Global Navigation Satellite System (GNSS) monitoring, Automated cameras, Stream-stage sensors, Terrain instrumentation sensors coupled with rigorous field audits by institutions like Wadia Institute of Himalayan Geology (WIHG) and National Institute of Hydrology (NIH).
- d) **Mandatory Digital Twins for Pilgrimage Corridors:** High-density pilgrimage routes should use real-time digital twins integrating: Crowd density, weather forecasts, terrain instability, evacuation routing, and shelter capacity. Select routes, specifically Kedarnath, Gangotri, Amarnath, Vaishno Devi, Hemkund Sahib, and the Machail routes must be digitally mapped. These twins will simulate real-time crowd-risk dynamics against live weather inputs to model safe evacuation routing.

- e) **Forecast-to-Action Audits:** Establish mandatory post-disaster audits to evaluate forecast lead times, warning dissemination, route closure decisions, evacuation timing, operational coordination, and communication effectiveness. Findings should be used to improve forecasting accuracy, emergency response procedures, and disaster risk reduction strategies.

Conclusion

India has significantly strengthened its weather forecasting, flood prediction, and early warning capabilities over the past decade. The country now has more radars, denser automatic observations, flash-flood guidance, better Common Alerting Protocol (CAP)-based dissemination, wider flood forecasting, and stronger satellite-based terrain intelligence than at any previous point in its disaster-management history^{10, 11}.

However, the August 2025 Himalayan disasters demonstrated that advances in forecasting alone cannot guarantee effective risk reduction. Despite timely forecasts and warnings, vulnerabilities persisted where slope monitoring, corridor management, infrastructure protection, and automatic response protocols were inadequate. The events highlighted a critical gap between hazard prediction and operational decision-making on the ground.

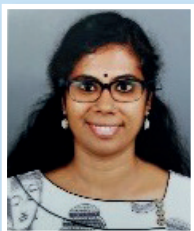
For the Himalayas, the next transformative step is not the creation of another standalone forecasting platform but an integrated operational doctrine: one data spine, one hazard-chain view, and one set of pre-cleared triggers for closures and evacuations. If India can link IMD, CWC, ISRO, NDMA, shrine boards, and district administrations around consequence-based thresholds, it can turn scientific capability into visible public protection.

The challenge ahead is therefore not merely one of science and technology, but equally one of governance, institutional integration, and operational preparedness. If it does not, each future cloudburst will continue to test not only the science of forecasting, but also the discipline of governance^{9,10}.

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When Hills Denude and Cities Drown - India's Growing Crisis



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Introduction

In the wee hours of 30th July 2024, the villages of Mundakkai and Chooralmala in Kerala's Wayanad district were obliterated by a catastrophic landslide triggered by relentless rainfall. Over 300 - 400 lives were lost, around 397 people were injured, and property damage crossed Rs 1,200 crores, making it one of the deadliest natural disasters in Kerala's recent history¹. Just weeks earlier, Delhi had recorded 228.1 mm of rainfall within a single 24-hour period, exceeding the city's entire average June rainfall and bringing the national capital to a standstill. These are not outliers. They are the new normal - and are arriving with increasing frequency and ferocity.

What the events underline is the urgent need to realign India's approach to infrastructure planning, design and evaluation with the scale and nature of the climate risk it now faces. Building genuinely resilient cities requires confronting three questions that this article addresses in turn: why floods and landslides are intensifying across India; where conventional approaches to drainage and flood infrastructure are falling short; and what a more integrated, forward-looking framework for planning and evaluation looks like in practice.

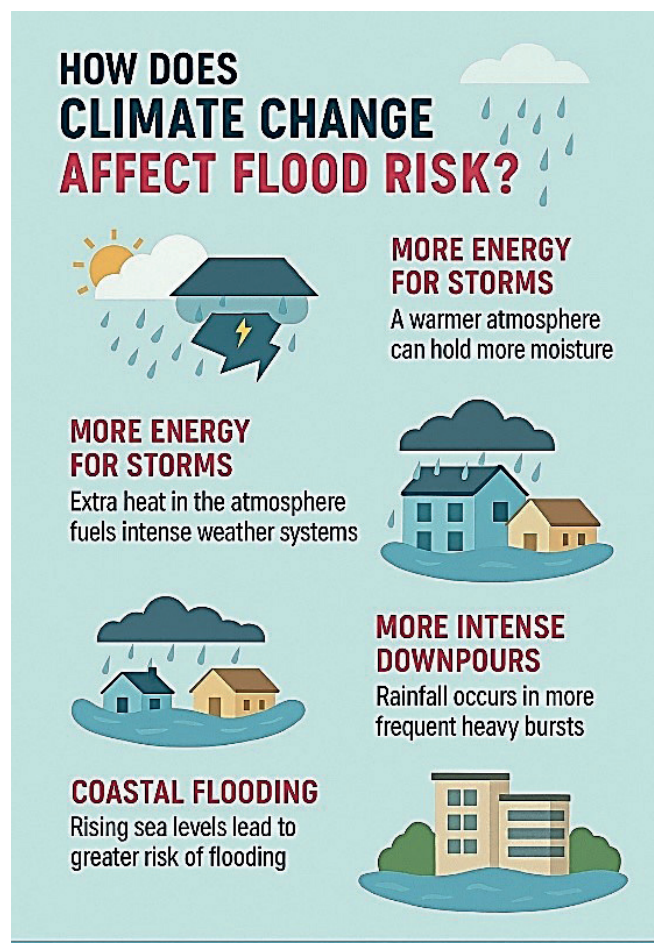


Figure 1: Climate Change and Urban Flooding (Source: TCE)



Figure 2: Meppadi Landslide¹

A Warming Atmosphere, A Wetter Storm

Science is unambiguous. For every 1°C rise in global temperature, the atmosphere can hold approximately 7% more water vapour². Warmer oceans drive faster evaporation, feeding storms with greater energy and moisture. Rainfall patterns globally are shifting from gradual, distributed precipitation to sudden, hyper-intense cloudbursts that dump enormous volumes of water within minutes - far exceeding the capacity of any engineered drainage system in urban areas.

A critical consequence is the collapse of what engineer's call 'stationarity' - the long-held assumption that historical rainfall patterns reliably predict future extremes. The infrastructure designed for a 100-year storm event is now confronting that same intensity every 10 to 20 years. India's own data reflects this reality starkly: over 64% of Indian sub-districts have experienced more heavy-rainfall days in the past decade than in the previous 30 years combined. The infrastructure of the cities was simply never designed for such events.

India's Urban Flooding Crisis - The Numbers Tell the Story

India's vulnerability to floods is both structural and climatic. Over the past two decades, floods have accounted for approximately 67% of all the natural disaster-related economic losses and 66% of all catastrophe-related fatalities in the country. The annual flood-related economic losses are estimated at around USD 3 - 4 billion³. Individual flood events causing



Figure 3: India's Flood Vulnerability (Source: TCE)

losses of around Rs 8,700 crore (USD 1 billion) have become increasingly common. In 2021 alone, floods and heavy rainfall affected 38.56 million people across India, with total damages to crops, housing, and infrastructure crossing Rs 49,617 crore (USD 6.6 billion).

The cities bear the sharpest brunt. Mumbai's drainage network - designed during the British era to handle 25 mm of rainfall per hour - now regularly faces intensities exceeding 100 mm per hour. Bengaluru, celebrated as India's technology capital, has seen 65% of its lakes degraded and nearly 80% of its historic water bodies encroached upon, transforming it into a waterlogged city during the monsoons⁴. During the 2022 Bengaluru floods, the IT companies reported losses of around Rs 225 crore in a single day due to employee absenteeism.

Across India, over 70% of the cities lack adequate stormwater drainage infrastructure, leaving millions exposed.

Landslides - The Silent Catastrophe in India's Hills

India is among the top five landslide-prone countries globally. The North-West Himalayas account for 66.5% of India's landslide events, followed by the North-East Himalayas at 18.8% and the Western Ghats at 14.7%⁵. Economic losses due to landslides range between Rs 100 to 150 crore annually at 2011 prices - and these figures are considered significantly underreported.

The Wayanad tragedy of 2024 brought this crisis into sharp national focus. The catastrophe was not simply a natural event - it was the convergence of intensified rainfall under climate change, unstable geological conditions worsened by deforestation and anthropogenic disturbances, and a high-density vulnerable population. The early warning systems were inadequate. In the 2013 Uttarakhand disaster over 6,000 lives were lost and the economic damages exceeded USD 3.8 billion in that single event. That was not taken as the trend and a warning.

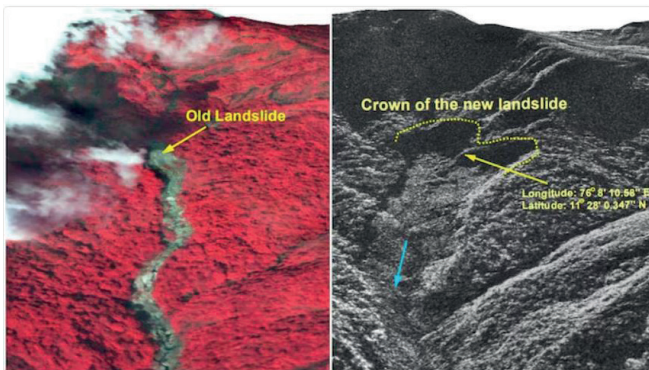


Figure 4: A major debris flow was triggered by heavy rainfall in and around the Chooramala town of Wayanad District in Kerala; Photo NRSC

Why Grey Infrastructure Is Failing

Traditional urban drainage - storm drains, underground pipes, concrete channels - were designed on the principle of quickly collecting and moving rainwater away from cities. The grey infrastructure, built using



Figure 5: Urban Flooding⁹

historical climate data, has a fixed hydraulic capacity. When the rainfall intensity breaches those design limits, the entire network backs up, causing flash flooding due to waterlogging, and infiltration into basements and utilities. In older cities with combined sewer systems, a heavy rainfall triggers overflow discharges of untreated sewage directly into rivers - compounding the flood crisis with a severe public health emergency.

Rapid urbanisation has compounded the problem. As cities expand, natural sponges - wetlands, lakes, floodplains, and green cover - are replaced by impervious concrete surfaces that block rainfall absorption and dramatically accelerate surface runoff. The result: more water, moving faster, through systems that were never designed to handle it.

Rethinking How to Evaluate Drainage and Flood Resilience Projects

India's conventional approach to evaluating drainage and flood management projects has long rested on a narrow set of hydraulic and financial parameters: peak discharge capacity, cost per kilometer of drain constructed, time to completion, and benefit-cost ratios anchored to direct flood damage avoided. While these metrics are necessary, they are no longer sufficient. In a climate - disrupted world, this single-lens evaluation systematically seeks for solutions that solve yesterday's problem - while creating tomorrow's liabilities. What

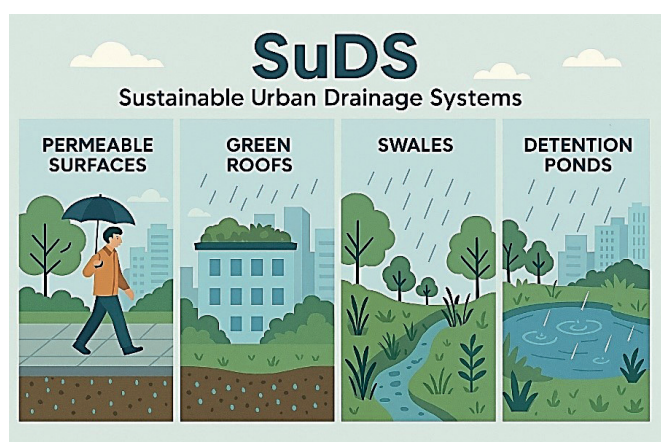


Figure 6: The SuDs Concepts (Source: TCE)

is needed is a broader framework - one that reflects the full complexity of the challenge and the full range of outcomes that resilient investment must deliver.

The SuDs Concepts are to be adopted for designing sustainable city drainage.

The Resilience Evaluation Framework

At the heart of this framework is the principle of integrated and holistic planning - the recognition that flood and climate resilience cannot be achieved through drainage engineering alone. Land use, ecology, water systems, infrastructure, governance, and community must be planned together, across the full extent of the city and its natural catchment.

Real-time monitoring is the connective tissue of this integration - providing the data and situational awareness that allows planners, engineers, and communities to understand how systems are performing, where they are under stress, and when intervention is needed.

The evaluation dimensions in Table 1 reflects the integrated approach, ordered from those that address root causes and deliver systemic change to those that strengthen specific aspects of resilience.

Table 1: Evaluation based on An Integrated Approach (Source: TCE)

Sl. No.	Evaluation Dimension	Key Question to ask	What the Conventional Approach misses and Why it Matters
1	Climate Adaptability	Is the design stress-tested against future rainfall, and not just past data?	Most drainage systems are sized on historical rainfall records that are now obsolete. With increasing climate variability, a project approved today may be critically undersized within a decade. A resilience lens demands that designs be validated against credible future climate scenarios before approval.
2	Land Use and En-croachment Prevention	Will the drainage corridor still exist and function in 20 years?	Projects that do not secure the surrounding land use which are routinely re-encroached, rendering the investment redundant within a few years. Conventional appraisal ends at construction. A resilience lens questions whether legal, institutional, and community safeguards are in place to protect the investment over its design service life.
3	Ecological Co-benefits	Does it restore wetlands, recharge groundwater, support biodiversity?	Conventional projects dispose of water as quickly as possible. A resilience lens asks whether the same investment can simultaneously restore a degraded floodplain, recharge an aquifer, or revive an urban lake - turning a single-purpose drain into a multi-benefit ecological asset.
4	Multi-Hazard Risk Reduction	Does the project also reduce landslide, subsidence, or flash flood risk?	Urban flood projects are typically designed in isolation from slope stability, groundwater, and other hazard risks. In reality all these interact. A resilience lens evaluates whether an investment addresses cascading risks - or inadvertently worsens them.

Sl. No.	Evaluation Dimension	Key Question to ask	What the Conventional Approach misses and Why it Matters
5	Groundwater Recharge	Does it return water to the ground, or simply expel it?	The instinct of conventional drainage is to move water away from the city as fast as possible. Yet many Indian cities face simultaneous flooding and acute groundwater depletion. A resilience lens treats rainwater as a resource to be harvested and recharged, not a problem to be discharged.
6	Community Resilience and Equity	Does it reduce vulnerability of those most at risk - informal settlements, hillside communities, urban poor?	Hydraulic efficiency optimises flow, not fairness. The communities bearing the greatest flood and landslide risk are rarely the ones shaping project design. A resilience lens ensures that the most exposed, not just the most visible, are prioritised.
7	Maintenance Viability	Can the local body actually maintain the project - with its real budget and workforce - for the design service life of the project?	Technically sophisticated solutions frequently fail not because they were poorly designed, but because they could not be maintained. Conventional appraisal underweights this. A resilience lens checks operational feasibility before a design is approved, not after it breaks down.
8	Carbon Footprint of Construction	What is the climate burden of building the solution?	Grey infrastructure built today - concrete, steel, large pipe networks, locks in high-emission materials for 30 to 50 years. Conventional appraisal ignores this aspect. A resilience lens asks whether a lower-carbon, green or hybrid alternative could deliver comparable or better outcomes.
9	Post-Event Recovery	How quickly does the system return to function after an extreme event?	Resilience is not only about withstanding shocks - it is equally about how fast a system recovers. Conventional appraisal measures capacity at design conditions. A resilience lens asks how the system behaves when those conditions are exceeded, and whether recovery is built into the design.
10	Traditional and Indigenous Knowledge	Does it draw on what local communities already know about water in this landscape?	<i>Johads</i> (rainwater harvesting structures), <i>kunds</i> , temple tanks, and community-managed check dams have regulated water across Indian landscapes for centuries. Conventional project design rarely consults this knowledge. A resilience lens actively integrates it - not as a sentiment, but as field-validated hydro-ecological intelligence.

Individually, each of these dimensions addresses a specific gap in conventional project appraisal. Collectively, they point toward something more significant - a planning approach that is integrated across land, water, ecology, and governance rather than siloed within engineering disciplines. When evaluation asks the right questions at the outset, the solutions that follow are inherently more holistic, more durable, and

more capable of meeting the scale of the challenge that India now faces.

Why this Matters: The Case for a New Planning Paradigm

The methodology outlined above shares a common thread - it requires a fundamental shift in how flood and climate resilience is conceived, not merely how

it is funded or executed. For too long, urban water management has been treated as an engineering problem with an engineering solution. What the scale and frequency of recent disasters make clear is that, it is a complex multi-disciplinary planning problem - one that demands integrated thinking with sustainability across land use, ecology, infrastructure, governance and community. Cities and regions that have begun to plan through a resilience lens - Copenhagen's Cloudburst Climate Adaptation plan⁶, Singapore's ABC Waters programme⁷, and India's own Integrated Urban Flood Management guidelines⁸ are demonstrating that multi-dimensional assessment leads to better long-term outcomes at comparable or lower lifecycle costs.

India stands at a point where the decisions made today on how cities grow, how water systems are designed, and how investments are evaluated will determine the country's exposure to climate risk for the next several decades. The opportunity is not simply to build more resilient infrastructure – it is to establish a new standard for how urban resilience is planned, one that is proactive rather than reactive, systemic rather than sectoral, and designed for the climate of the future rather than the experience of the past.

The Way Forward - Building Resilient Cities

Addressing this challenge demands an urgent and decisive shift from reactive disaster response to proactive resilience planning. Several pathways must be pursued simultaneously:

- **Enforce Strict Land Use Regulations** - Construction in floodplains, steep slopes, and ecologically sensitive zones must be firmly prohibited and enforced. Active afforestation programmes in hill regions must be prioritised.
- **Redesign Infrastructure Using Future Climate Data** - Drainage systems, stormwater networks, and slope stabilisation measures must be re-engineered using updated climate projections - not historical baselines.

- **Adopt the Sponge City Model** - Cities must transition from purely grey to green-grey hybrid infrastructure - integrating permeable pavements, urban wetlands, rain gardens, green roofs, and retention ponds that absorb, slow, and reuse rainwater.
- **Deploy Early Warning and Monitoring Systems** - Real-time rainfall monitoring, flood modelling, and early AI-driven warning systems can provide critical lead time for evacuation and emergency response.
- **Apply Multi-Dimensional Project Evaluation** - All new drainage and flood management investments must be appraised through Resilience Framework - ensuring that solutions are not merely technically sound but ecologically regenerative, socially equitable, and future-proofed against climate change to the extent foreseeable.
- **Government and Industry Must Lead** - The public and the private sector must both take the responsibility and create the capacity to drive climate resilience - through investment in resilient infrastructure, adoption of green building standards, climate risk disclosure, and active advocacy for stronger adaptation policies.
- **Adopt Low Impact Development Index (LDI)**

At the macro level of water resources planning, the interlinking of rivers presents a compelling long-term proposition. By transferring surplus water from flood-prone basins to water-deficit regions, it holds the potential to moderate flood peaks, strengthen irrigation networks, secure drinking water supply, and support broader regional development. Realising this potential, however, requires rigorous assessment of surplus flows, careful ecological stewardship, and sustained inter-state cooperation - recognising that the scale of benefit is matched by the complexity of implementation. Viewed within an integrated national water strategy, river interlinking, while necessary, is not a substitute for city-scale flood resilience interventions, but a complementary instrument that addresses the larger hydrological canvas within which urban water management sits.



Figure 7: Low Impact Development for Stormwater (Source: TCE)

Conclusion

The floods that submerge cities and the landslides that erase villages are not simply natural events - they are the consequences of how land has been used, how cities have been built and how infrastructure has been designed and evaluated. The human cost is already staggering – USD 4 billion in annual losses today, projected to reach USD 30 billion by 2070, and up to 45 million climate migrants by 2050. Behind every number is a family displaced, a livelihood destroyed, a community fractured. The cost of inaction is not theoretical - it's being paid every monsoon season, in lives and livelihoods, across India's urban and rural areas, its snow peaked mountains, its hills and its valleys.

The path forward requires action at every level. Enacting and enforcing land use regulations which would bridle the rampant depletion of forests, green areas, water bodies, denudation of the mountains and the hills, climate-proofing infrastructure design, and adopting integrated and holistic planning are not optional - they are the foundational conditions without which no other intervention can succeed. Alongside these, transitioning to sponge city models, deploying AI based early warning systems, and appraising all new projects through a resilience evaluation framework will significantly strengthen India's flood and landslide preparedness. Complementing these efforts, integrating traditional and indigenous knowledge, accounting for

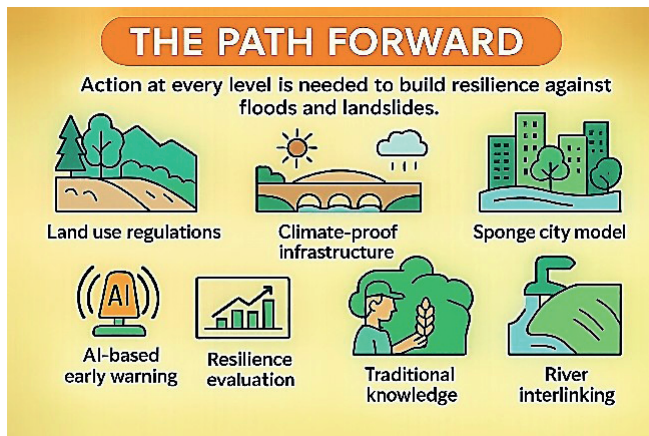


Figure 8: The Path Forward (Source: TCE)

the carbon footprint of construction, and positioning river interlinking within a long-term national water strategy add further depth and durability to the overall approach.

What India builds in the decades ahead is an opportunity to reflect the lessons of these disasters and emerge stronger, more prepared, and more resilient. The knowledge exists, the frameworks are clear, and the solutions are available - what is required now is the shared resolve to act on them.

Acknowledgement

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India is set for a massive power transmission investment of nearly Rs 9 trillion by 2032, according to a Kotak Neo report

India's power transmission infrastructure is headed for a massive investment cycle, with nearly ₹ 9 trillion in government-committed transmission capex expected till 2032. The report said the country's clean energy transition is no longer just about adding solar parks and wind farms, but also about building the grid infrastructure needed to move electricity efficiently across regions.

"India is adding 470 GW of renewable capacity. Every watt of that power needs wires, transformers, substations, and transmission lines before it can reach the grid," the report noted.

Source: Energy World

Climate Risk and Hazard Assessment for Ahmedabad



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Abstract

Ahmedabad is one of the fastest-growing metropolitan centres in India and is facing increasing climate risks, such as heatwaves, floods, and droughts. The article presents a framework-based approach to Climate Risk and Hazard Assessment (CRHA) for the city. The framework is based on the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) risk paradigm, which is defined as a function of Hazard, Exposure and Vulnerability. It describes the major indicators, data requirements, and the analytical process for identifying risk-prone zones at the ward and zone levels. The article underscores the urgent requirement for Indian cities to adopt structured, science-based risk assessment tools as a foundation for long-term climate adaptation planning.

Introduction

Climate change is no longer a distant or future concern. Cities across the world are already experiencing more frequent and severe weather events, from floods that inundate neighbourhoods and heatwaves that claim thousands of lives, to droughts that severely deplete groundwater reserves. India remains highly vulnerable to these impacts, ranking 9th in the long-term Climate Risk Index 2025 (covering 1995–2024), published by Germanwatch and released at COP30 in November 2025. According to secondary analysis of the Germanwatch Global Climate Risk Index 2025, India recorded over

80,000 fatalities and economic losses of approximately USD 170 billion from more than 430 extreme weather events over the three decades from 1993 to 2022.¹ The physical evidence is no longer ambiguous.

A peer-reviewed study published in 2025, drawing on data beyond the IPCC's Sixth Assessment Report, confirms that India's average temperature has risen by 0.89°C over the last decade relative to the early twentieth-century baseline.² Rainfall patterns are also shifting, though not in ways that offer much comfort. Across the Indo-Gangetic Plains and northeast India, monsoon rainfall has been declining steadily by as much as 0.5 to 1.5 mm per day each decade since 1951.² Along the coastline, the picture is equally concerning. Tide-gauge records and assessments by India's Ministry of Earth Sciences and INCOIS, updated as recently as 2024–25, indicate that sea levels are rising at a rate of 1.6 to 3.3 mm per year.³ For India's densely populated coastal cities and low-lying deltas, that trajectory, if it continues, puts infrastructure, livelihoods, and ecosystems under sustained and growing pressure. The situation is expected to worsen in the coming future. Urban India, which is projected to host the largest share of the world's largest cities in the next half-century, is especially vulnerable.

In this regard, a structured and science-based approach to the assessment of the city's climate risks is urgently needed. This article presents an Integrated Climate

Change Risk Assessment (CCRA) Framework and its application to Ahmedabad. The work has been done by the Environmental Management Centre Pvt Ltd for the Aga Khan Agency for Habitat (AKAH). The framework offers a reliable and repeatable tool to urban planners, civil engineers, and city administrators to identify risk-prone zones and develop targeted mitigation and adaptation strategies.

The Need for an Integrated Climate Change Risk Assessment Framework

Traditional hazard assessment tools like the Hazard Vulnerability Risk Assessment (HVRA) developed by AKAH have served their purpose at the rural and village scale. The HVRA assesses possible hazards, measures the exposure of populations and the magnitude of risk as a function of exposure and vulnerability. However, there are two major limitations of this index when used in the context of urban India. First, it does not account for the full spectrum of climatic and non-climatic hazards such as heatwaves and droughts. Second, it is mainly calibrated for rural settings.

Urban areas have orders of magnitude more complex—larger in geographical extent, more heterogeneous in land use, and more densely networked in terms of infrastructure and social systems. A comprehensive framework for Indian cities must therefore:

- Integrate hazard assessment with ecosystem health evaluation.
- Align with the IPCC AR5 climate risk paradigm, which defines risk as a function of Hazard (H), Vulnerability (V), and Exposure (E).
- Operate at the sub-city scale (zone or ward level) to enable spatially targeted interventions.
- Incorporate climate change projections to support both near-term mitigation and long-term adaptation planning.

The Integrated CCRA Framework described in the next sections satisfies each of these requirements. It extends the hazard component of the HVRA to include hydro-meteorological hazards (floods, flash floods, heatwaves, droughts, cyclones) in conjunction with geological hazards (landslides, earthquakes, bank

erosion). It suggests a systematic methodology for the quantification of exposure and vulnerability through thematic indicators.

The Integrated Climate Change Risk Assessment Framework

Conceptual Basis: The IPCC AR5 Risk Model

The framework uses the Risk model as in the Fifth Assessment Report (AR5) of IPCC. In the model where Risk (R) is a function of three interacting components:

- Hazard (H) - the potential occurrence of a natural or human-induced physical event that may cause loss of life, damage to property, infrastructure, livelihoods, or environmental resources.
- Exposure (E) - the presence of people, livelihoods, ecosystems, infrastructure, or economic and cultural assets in places that could be adversely affected.
- Vulnerability (V) - the propensity or predisposition of a system to be adversely affected, considered as a function of Sensitivity (S) and Adaptive Capacity (AC).

$$Risk = f(Hazard, Vulnerability, Exposure)$$

and

$$Vulnerability = f(Sensitivity, Adaptive Capacity)$$

This formulation differs from the earlier IPCC frameworks (notably TAR) in treating vulnerability as an intrinsic property of a system - determined by sensitivity and adaptive capacity - rather than as a composite of exposure and other factors. In practice, this distinction matters: a densely built urban ward with good drainage, early-warning systems and high literacy may be highly exposed to flood hazard but carry relatively low vulnerability, as its adaptive capacity is strong.

Components of the Framework

Hazard Assessment

The framework considers geological and hydro-meteorological hazards.

Geological hazards: Rockfall, landslide, earthquake, tsunami, bank erosion, debris flow and avalanche.

Hydro-meteorological hazards include floods, subsurface flooding, flash floods, cyclones, heatwaves and droughts.

Hazard magnitude is quantified using indicators derived from three broad data types:

- Frequency-based indicators - e.g., the Warm Spell Duration Indicator (WSDI) for heatwaves; frequency of cyclone events; Standardised Precipitation Index (SPI) for droughts.
- Zonation-based indicators - e.g., landslide susceptible zones (LSZ); earthquake susceptible zones (ESZ) derived from GIS mapping.
- Climatic data-based indicators - e.g., maximum 5-day precipitation (Rx5) for floods; maximum daytime temperature (TXx) for heatwaves.

Ahmedabad faces major hazards from heat waves, floods (including flash floods and urban water logging) and drought. In 2010 alone, the city had 19 heatwave days, the highest in Gujarat that year, and its shrinking green cover increases both flood runoff and the urban heat island effect.

Exposure Assessment

Exposure indicators represent what is at risk in an urban area, i.e. the assets, populations and ecosystems that could be affected by a hazard event. Indicators are organised under three thematic areas:

- Ecosystem - protected areas; occurrence of threatened species.
- Demographic concentration – population density (persons per km²)
- Infrastructure - number of heritage buildings/ sites; number of industries located in low-lying or flood-prone areas.

In Ahmedabad, high population density in the central and peri-urban areas, presence of heritage structures in the walled city, and the existence of numerous industries in the low-lying areas along the Sabarmati River can be considered as important exposure factors.

Vulnerability Assessment

Vulnerability is disaggregated into Sensitivity and

Adaptive Capacity, which are evaluated through thematic indicators from the ecosystem, social and infrastructure domains. Sensitivity indicators measure attributes that raise the likelihood of a system being damaged. Examples of key relevance to Ahmedabad are:

- Land – % change in green space (related to floods, heatwaves and droughts); % built-up area (increases surface runoff and urban heat).
- Social – population growth rate; dependency ratio (old and young); slum population percentage; below poverty line households.
- Infrastructure – density of buildings, average age of building structures, water demand-supply gap.

Adaptive capacity indicators assess the ability of individuals, institutions, and systems to respond to and overcome adverse conditions. Key examples are:

- Ecosystem - percentage change in the extent of mangrove forests, which is relevant for mitigating coastal flooding and cyclones.
- Social - literacy rate; per capita income; access to safe housing; percentage of households with access to banking facilities.
- Infrastructure - road density; access to safe drinking water; stormwater drainage network density; efficiency of waste collection; number of shelters and collection centres; presence of early warning systems.

The Risk Assessment Process

The framework prescribes an eight-step analytical process for quantifying and mapping climate risk at the ward or zone scale.

Step 1: Identification of Indicators and Data Requirements

Thematic indicators for each risk component are identified through a structured review of existing literature and input from experts. This process ensures that the selected indicators are both applicable to the specific hazards being assessed and capable of being measured at a sub-city level. The choice of indicators varies depending on the hazard type - for instance, the Standardised Precipitation Index is useful for droughts and floods but not applicable to seismic events.

A systematic review of existing literature is conducted, and expert opinion solicited to identify thematic risk component indicators. That guarantees that the indicators sourced are relevant to the risk assessment context and can be quantitatively captured at a sub-city level. The choice of indicators is dependent on the type of hazard. For example, the Standardised Precipitation Index is relevant to both flooding and droughts, but does not apply to seismic hazards.

Step 2: Data Requirements and Data Processing

Data can be obtained from established secondary databases, including census data, meteorological data, city agencies, remote sensing data, and governmental or inter-governmental GIS portals. Data quality is analysed for accuracy and completeness. When primary data is not available, validated proxy data sets are used, such as Land Surface Temperature to proxy for the urban heat island effect.

Step 3: Calculation of Indicator Values

For non-spatial data, indicator values are calculated using ratio and absolute methods. For spatial indicators such as slope, elevation, land surface temperature, and green space extent, GIS-based spatial analysis is applied. All indicator values are normalised to a 0-1 scale to allow comparison across different units.

Step 4: Assignment of Weights to Indicators

Using climate scientists' and other experts' input, the weights of the indicators are evaluated utilising the Analytical Hierarchy Process (AHP), a multi-criteria decision-making technique, which presents a new methodology and approach for the HVRA tool. AHP's method of pairwise comparison gives the relative importance of indicators in a participatory, internally consistent manner, processes of which are substantial over the equal weighting used in the previous HVRA tool.

Step 5: Calculation of Component Indices

Component indices for hazard, exposure, sensitivity, and adaptive capacity are calculated as weighted sums of the normalised indicator values. Vulnerability is then derived from the sensitivity and adaptive capacity indices.

Step 6: Calculation of the Risk Index

The hazard, exposure, and vulnerability indices are aggregated to yield an overall risk index for each zone or ward. The aggregation method ensures that the interaction between these components - not merely their individual magnitudes - determines the final risk score.

Step 7: Identification of Risk-Prone Zones

Risk scores are mapped spatially using GIS to demarcate highly vulnerable zones within the city. These maps provide an intuitive visual tool for administrators and planners, highlighting areas requiring priority interventions.

Step 8: Development of Habitat and Adaptation Strategies

Based on the risk category and stressor profile of each zone, mitigation and adaptation strategies are proposed. These may include green infrastructure interventions, improved drainage networks, heatwave action plans, community awareness programmes, and early warning systems.

Ahmedabad as a Pilot Application

Ahmedabad has been selected as the pilot city for the application of the Integrated CCRA Framework. The city encapsulates the multi-dimensional climate risk challenges facing rapidly urbanising Indian cities: extreme heat, recurrent flooding, green cover loss, and high socio-economic vulnerability across several wards.

During the May 2010 heatwave, temperatures reached 46.8°C and caused an excess of 1,344 all-cause deaths, a 43.1% increase over the baseline mortality rate compared to the average of May 2009 and 2011, making it one of the deadliest urban heat emergencies ever recorded in Asia.⁴ In response, Ahmedabad implemented South Asia's first Heat Action Plan in 2013; a subsequent study estimated this plan avoids approximately 1,190 deaths per year, with heat stroke deaths falling from 65 in 2010 to just 3 in 2018.⁵ Flooding also remains a recurring threat. Between 1970 and 2020, Ahmedabad averaged 34 rainy days annually, totalling approximately 800 mm of rainfall; however, in extreme flood years, the same volume fell in just 14 days, with peak years recording up to 1,500

mm. According to ICLEI South Asia's analysis, 4.3% of the city's area (20.8 km²) and 9.5% of the population - approximately 700,000 people - are directly affected by flooding, including 88,000 slum dwellers and 5,000 street vendors. Additionally, 28% of Bus Rapid Transit stations and 28.8% of traffic junctions are impacted, disrupting mobility and emergency response.⁶

Second, regarding flood and waterlogging risk, Ahmedabad's rapid urbanisation has dramatically increased the impervious surface area, thus reducing infiltration but amplifying surface runoff. The low-lying areas and wards along the Sabarmati River corridor are particularly susceptible to flash flooding during intense monsoon events. A flood vulnerability assessment by CEPT University (2023) found that 24% of Ahmedabad's population lives in highly flood-vulnerable areas and 74% in moderately vulnerable areas, with only 2% residing in low-risk zones.⁷

Third, the depletion of green cover has emerged as a significant challenge to climate resilience in Ahmedabad. A 2016 study by the Indian Institute of Science reported that the city's tree cover had declined from 46% to 24% over the preceding two decades, while its built-up area had expanded by 132%. The study projected that vegetation cover could fall further to just 3% of Ahmedabad's total area by 2030⁸. This rapid loss of green spaces is likely to intensify the urban heat island effect and increase flood risk, given the critical role that vegetation plays in regulating temperatures, reducing surface runoff, and enhancing stormwater absorption.

Fourth, with respect to socio-economic vulnerability, Ahmedabad had the second-largest slum population in Gujarat as of 2019, with 1.6 million slum dwellers recorded across the state⁶. Several wards have high concentrations of informal settlements, populations with limited access to safe housing and basic municipal services, and significant proportions of migrant and informal workers - factors that reduce adaptive capacity and elevate overall climate risk.

The framework was applied at the zone level for Ahmedabad, producing spatially explicit risk maps that can be utilised for the city's development plans, climate action plans, and disaster preparedness strategies.

Way Forward

The Integrated CCRA Framework described in this article represents a significant step towards science-based urban climate governance in India. Its application to Ahmedabad yields zone-level risk indices, vulnerability maps, and a prioritised set of habitat and adaptation strategies.

Looking ahead, several areas merit attention. First, the framework should be progressively updated to incorporate IPCC Sixth Assessment Report (AR6) projections, which provide refined estimates of future hazard intensities under different emissions scenarios. Second, expanding the pilot to other at-risk Gujarati cities - Surat and Rajkot - would allow comparative risk profiling and enable regional climate resilience planning. Third, integrating the framework into statutory urban planning instruments, such as the Development Plan and the City Disaster Management Plan, would institutionalise climate risk assessment as a standard planning practice rather than a one-off study.

Civil engineers and urban planners have a pivotal role to play. Infrastructure design standards - for drainage, roads, housing, and public spaces - must be recalibrated to account for the higher frequency and intensity of extreme weather events projected for the coming decades. Equally important is the need to build local institutional capacity: training urban local body staff in risk assessment methods, establishing multi-stakeholder platforms for climate data sharing, and fostering community-level awareness and preparedness.

Conclusions

Ahmedabad exemplifies the climate risk predicament of rapidly urbanising Indian cities - a convergence of intensifying hazards, growing exposure, and significant vulnerability in many parts of the city. The Integrated Climate Change Risk Assessment Framework offers a rigorous, IPCC-aligned methodology for quantifying this risk at the sub-city scale, translating complex multi-dimensional data into actionable, spatially explicit outputs.

The framework's key strengths are its comprehensiveness - covering geological and hydro-

meteorological hazards, ecosystem health, and socio-economic vulnerability - its scalability to different city sizes and contexts, and its participatory weight-assignment process through AHP, which ensures that local knowledge and expert judgement are embedded in the risk calculations.

Ultimately, however, frameworks are tools: their value lies in their use. Ahmedabad, and Indian cities more broadly, must move from risk assessment to risk management - embedding climate risk indices into planning decisions, investment prioritisation, and infrastructure design. The time to act is now, before the next heatwave, the next flood, or the next drought imposes a cost in lives and livelihoods that rigorous planning might have prevented.

Acknowledgements

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Impacts of Climate Change on Precipitation in the Khavda Area, Rann of Kutch, Gujarat, India



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Abstract

Climate change is increasing the uncertainty of extreme rainfall and flood risk, particularly for long-life infrastructure in climatically sensitive arid and semi-arid regions. This study assesses future changes in precipitation for the Khavda Area in the Rann of Kutch, Gujarat, using CMIP6 downscaled climate projections from 35 GCMs under SSP245 and SSP585 scenarios. Annual maximum 1-day rainfall was analysed through statistical distribution fitting, with Log-Pearson Type III identified as the most suitable distribution for estimating rainfall extremes and climate uplift factors for near-, mid-, and far-future periods. The results indicate a progressive increase in rainfall extremes, with relatively moderate changes in the near and mid future, but substantially higher uplifts in the far future, particularly under SSP585. These findings underline the importance of incorporating climate-adjusted rainfall estimates into flood assessment, drainage planning, and infrastructure design in this area. The study supports resilient and sustainable planning for any large-scale infrastructure projects under changing climate conditions.

Keywords: Climate change, extreme rainfall, flood risk, CMIP6, SSP245, SSP585, drainage design, climate resilience.

Introduction

Climate change is increasingly influencing precipitation extremes and hydrological variability across the globe, creating growing risks for long-life infrastructure systems (IPCC, 2021)¹. In India, recent studies indicate rising temperatures, shifting monsoon characteristics, and increasing extreme rainfall variability, including in western regions². These concerns are particularly relevant in arid to semi-arid environments, where low average rainfall can still be accompanied by short-duration, high-intensity storms that cause flooding and waterlogging³. The Khavda area in Kutch, Gujarat, is in such a climatically sensitive setting, characterised by erratic monsoonal rainfall, saline terrain, flat topography, and poor natural drainage⁴. Therefore, climate change analysis is essential for assessing future rainfall risks and supporting resilient flood and drainage design for any large-scale infrastructure. In this context, climate change analysis is essential for

understanding future precipitation variability and for developing resilient flood assessment, drainage design, and adaptation strategies for large-scale infrastructure.

Background

Khavda lies in the Rann of Kutch, a harsh salt desert and marshland about 70 km from the nearest settlement and close to the India–Pakistan border. The Khavda area is an arid to semi-arid region, characterised by harsh desert conditions, low and erratic rainfall, high evaporation, saline terrain, and seasonal waterlogging. Figure 1 shows the study area, the contributing sub-catchments causing waterlogging in the area, and the climate data grid points used for the analysis.

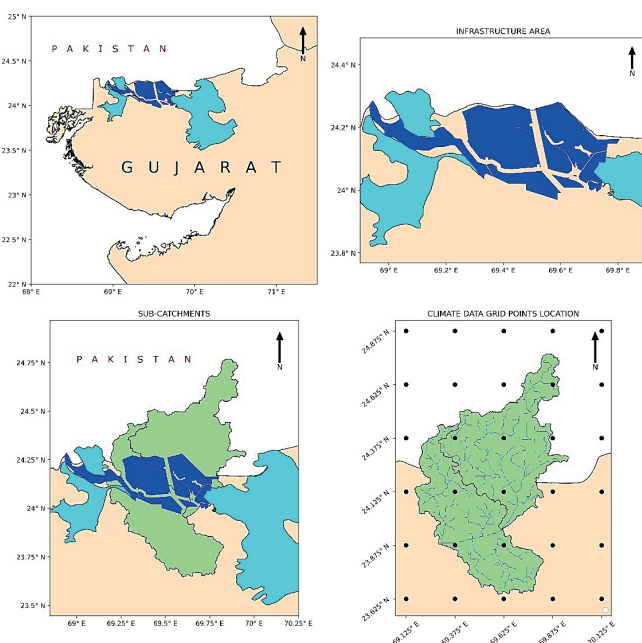


Figure 1: Location Map of Khavda Area (in Blue), Gujarat, along with the corresponding two sub-catchments (in Green) contributing to waterlogging within the infrastructure area along with adjacent lakes (in cyan)

The Khavda area, thus, has very hot summers (May: 39–47°C), warm humid spells in July, and cool winters (Nov–Feb: 12–29°C). The annual rainfall is low (≈ 300 mm or less), concentrated in a highly variable June–September monsoon. Despite its dry climate, the Khavda area is highly vulnerable to flooding during intense monsoon events due to its flat topography, poor natural drainage, and marshy characteristics. The heavy rainfall events in 2025 caused significant

inundation and waterlogging, disrupting construction activities and highlighting the hydrological challenges of the site. Due to those conditions, it is important to understand the flood risk, drainage behaviour, and climate resilience for large-scale infrastructure development.

Importance of Climate Change Analysis

Climate change analysis is a critical component of flood studies for infrastructure projects because future rainfall behaviour may differ significantly from historical patterns. Increasing intensity of short-duration rainfall and shifting rainfall return periods can raise the risk of flooding and waterlogging, even in arid regions. For the proposed large solar energy infrastructure areas such as Khavda, these changes directly affect drainage design, infrastructure protection, and long-term operational reliability. Since infrastructure is built for long service lives, future climate conditions must be incorporated into present planning and design. Including the climate projected rainfall as a parameter helps reduce the uncertainty, and improves the adequacy of drainage and flood management systems. It would strengthen the resilience and sustainability of the solar energy infrastructure under changing climate conditions. Therefore, climate change analysis is very necessary for safe, reliable, and sustainable solar energy development in that area.

Data and Methodology

To evaluate future climate changes, NASA Earth Exchange datasets comprised of global downscaled climate scenarios derived from the General Circulation Model (GCM) runs conducted under the Coupled Model Intercomparison Project Phase 6 (CMIP6) and across all four “Tier 1” greenhouse gas emissions scenarios known as Shared Socioeconomic Pathways (SSPs)⁶. These SSPs are paired with different levels of radiative forcing in CMIP6 models, creating distinct climate projections. For example, SSP-126 refers to SSP1 with a radiative forcing of 2.6 watts/m².

The study aims to assess the impact of climate change on precipitation patterns across three future (near,

middle, and far) periods using 35 GCM models with two emission scenarios of SSP245 (intermediate) and SSP585 (high). The projected changes in precipitation, termed as change (or uplift) factors, for these future periods are estimated. The changes (in %) are then incorporated into the flood modelling to estimate the 100-year return period flood quantiles. The analysis adopts the methodology outlined in the Asian Development Bank to estimate climate change factors as per the procedure given hereinafter.

- Let the Annual Maximum 1-day precipitation be termed as Rx1day. The historical baseline period is (1985-2014) and performs the **Distribution fitting analysis** with 2-parameter distributions-Gumbel, and Log-Normal; 3-parameter distributions-Generalized Extreme Value, Log-Pearson Type-III, Gamma, and Generalized Pareto.
- The future projection periods (30 years) are defined as 2021-2050 (Near), 2041-2070 (Mid), and 2071-2100 (Far future). For each projection period and climate scenario (SSP245, SSP585), the best-fit distribution is fitted to annual daily maximum time-series values for each GCM model.
- Thereafter, the magnitude of the rainfall associated with a T-yr return period (100 years) is estimated and referred to as Rx1dayT.
- For each climate scenario, projection period, and ensemble member (each climate model), the Rx1dayT quantile in the projection period is compared to the corresponding quantile in the historical baseline period. This value represents the change (uplift) factor, expressed as a percentage (e.g., +15%).
- The next step is to define an empirical distribution by arranging the individual (model) uplift factors from smallest to largest. From the range of uplift factors, estimate the value for a selected distribution percentile (i.e. 50%, 75%, 90%, or 95%) based on the level of risk and cost estimates. That value is considered as the climate change factor for each climate scenario and projection period.

Results

Rainfall Distribution Analysis:

For the Khavda area, comprising 30 grid points within and surrounding the study area, CMIP6 historical climate data for the period 1985-2014 were subjected to distribution fitting, and the best-fit distribution was identified using goodness-of-fit (GOF) tests. Among the six distributions evaluated, the 30 grid points were found to predominantly follow only three distributions. The results of the distribution fitting analysis are presented in Figure 2. From the GOF analysis, out of 35 GCMs an average of 18 grid points indicate Log Pearson Type III as the best fit distribution. Based on the analysis, the LP-III distribution was selected for further analysis and was adopted for carrying out the CCA methodology. The LP-III distribution was fitted to both the historical and the future climate data for 30-year projection periods (2021 to 2050, 2041 to 2070, and 2071 to 2100) under the SSP245 and SSP585 scenarios.

Estimation of Climate Change Factors

At each grid point, the uplift factors derived from all GCMs form an uncertainty range. When a single representative value is required, these uplift factors are arranged in ascending order and fitted using a Weibull empirical distribution based on their ranks. Depending on the chosen level of risk and associated cost considerations, appropriate percentiles are selected, and the corresponding uplift factors are estimated.

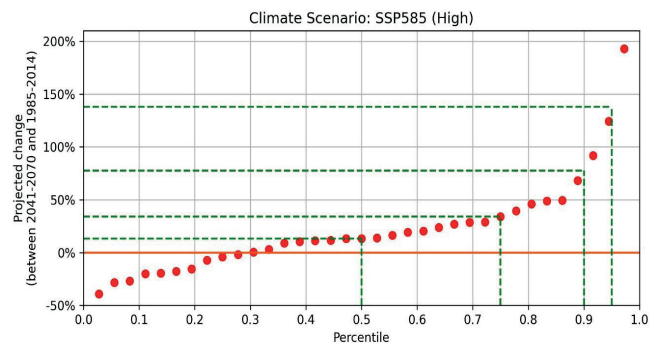


Figure 2: Estimation of projected change factors for various distribution percentiles between the projected period (2041-2070) and base period (1985-2014) for SSP585 climate scenario

The percentiles along with the corresponding change factors (in %) were estimated for 100-year return period rainfall quantiles for each grid point and for each projection period (Near, Mid and Far) under both SSP 245 and 585 scenarios. The change factors corresponding to the selected percentiles (50%, 75%, 90%, and 95%) were estimated using interpolation, as illustrated in Figure 2. The same procedure was applied to all 30 grid points for both climate scenarios and all three projection periods, for a 100-year return period. Spatial plots for the 50% distribution percentile were generated, as shown in Figure 3.

The spatial average of change factors for both the sub-catchments is then estimated and are presented in Table 1.

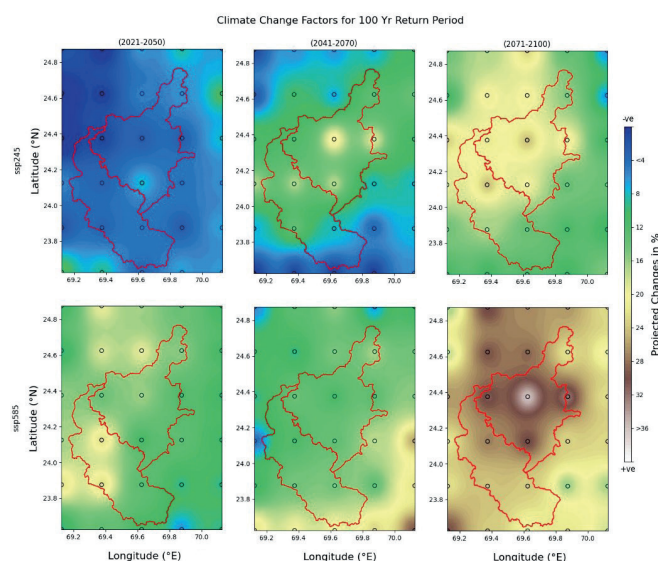


Figure 3: Spatial plots of climate change (uplift) factors over the study area sub-catchments (outlined in red) for both emission scenarios, estimated using 100-year return period rainfall quantiles at the 50th distribution percentile, across three projection periods

Table 1: Climate change factors (in %) for two sub-catchments estimated for 3 projection periods and 100 year return period

Climate Scenario		SSP245		SSP585	
Return Period		U/S Catchment	Study Area	U/S Catchment	Study Area
Projection Period		2021-2050			
Percentile	50%	4.1	2.4	14.8	17.1
	75%	28.3	21.1	40.4	42.3
	90%	53.0	61.3	76.9	102.7
	95%	107.5	81.4	107.6	211.6
	2041-2070				
	50%	14.2	11.3	13.5	12.4
	75%	54.6	43.0	39.2	46.1
	90%	111.6	110.0	82.7	103.9
	95%	167.5	223.8	135.1	147.8
	2071-2100				
	50%	19.4	21.3	28.1	28.6
	75%	47.2	56.7	56.6	56.2
	90%	126.0	123.9	141.0	147.2
	95%	334.9	327.3	394.7	305.1

Findings

- Historical and projected climate data for the two Khavda area sub-catchments were analysed to estimate climate change impacts on precipitation, using spatial analysis across multiple grid points with return period events of 100 years.
- The analysis found that the LP-III distribution best fits most grid points and GCMs, and the 50th percentile was selected as the representative basis for baseline planning.
- For the selected mid-century period (2041–2070), the adopted climate uplift factor for rainfall for a 100-yr return period was 13% under both SSP245 and SSP585 scenarios.
- For the far-century period (i.e., 2071–2100) the adopted climate uplift was 20.3% under SSP245 and 28.3% under SSP585 for 100 year return period events.

Conclusions

- The analysis indicated that projected changes in extreme rainfall during the mid-century period remain broadly within the historical variability range mentioned in “A report on the Climate Change Policy (Impact and Adaptation) by 2030 for Gujarat”⁴ for the project area, whereas higher increases are expected during the far-century period.
- Hence, incorporating climate change considerations into hydrologic and hydraulic designs is essential. The strengthened flood management and drainage infrastructure would play a critical role in reducing disaster risks and ensuring climate-resilient planning for large scale regional infrastructure projects.

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About Aarvee Engineering Consultants Limited

Founded in 1989, Aarvee is a global engineering consultancy delivering transformative infrastructure across transport, water, urban development, energy, and resources. With a presence spanning Australia, the United Kingdom, the Middle East, Africa, and Asia, we partner with governments, multilateral institutions, and private developers to plan and deliver complex, large-scale assets in over 20 countries.

Our multidisciplinary expertise, from surveying and geotechnical investigations to engineering design, digital engineering, and construction support, enables us to deliver technically robust, practical, and lifecycle - optimised solutions. With over 4,000 professionals worldwide, Aarvee combines engineering depth with technology-driven efficiency to deliver projects at scale, without compromising on quality, safety, time, or cost. We believe infrastructure is about people, and every project we undertake is designed to power progress and enrich lives.

Scalable Impact-Based Forecasting for Climate-Resilient Water Security in India: Lessons from Chennai



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Abstract

India's rapidly evolving hydro-climatic regime - characterised by intensifying extreme rainfall, urban expansion, and ecological degradation - demands a fundamental shift in flood forecasting paradigms. Traditional hazard-centric approaches, focused primarily on discharge predictions, fail to translate meteorological signals into actionable decision-making intelligence. This study develops a scalable Impact-Based Forecasting (IBF) framework for climate-resilient water security by integrating physics-based hydrodynamic modelling, Bayesian data assimilation, artificial intelligence-driven ensemble forecasting, and nature-based solutions (NbS).

Using the 2015 and 2023 Chennai flood events as empirical anchors, the study demonstrates how coupled rainfall-runoff-inundation models, hybrid ensemble-optimal interpolation schemes, and probabilistic impact layers can generate actionable lead times of 17–47 hours with prediction accuracies exceeding 90%. The framework incorporates satellite-based Earth observations, cloud-enabled district dashboards, and digital twin architectures, enabling scalability across India's 800 districts.

Key contributions include: (i) hybrid data assimilation improving forecast accuracy by ~50%, (ii) integration

of climatological covariance for bias reduction, (iii) AI-driven reservoir inflow forecasting achieving ~92% accuracy, and (iv) NbS-informed flood mitigation pathways. Results indicate reductions in peak discharge (8–15%), improved evacuation efficiency, and significant economic loss mitigation.

Aligned with SDG-6 and SDG-13, the proposed framework offers a replicable pathway for integrating hydro-informatics, climate adaptation governance, and water security planning in data-sparse and institutionally complex environments.

Keywords: Impact-Based Forecasting; Bayesian Data Assimilation; Shallow Water Equations; Hydrodynamic Modelling; Climate Resilience; Urban Flood Risk; Reservoir Optimisation; Digital Twin; Nature-Based Solutions; Early Warning Systems

Introduction

Context and Motivation

India's water systems are undergoing profound transformation under the combined pressures of climate change, rapid urbanisation, and ecological degradation. Increasing non-stationarity in monsoon patterns, coupled with intensifying short-duration extreme rainfall events, has significantly elevated flood

risks across urban and peri-urban landscapes. Climate projections indicate a substantial rise in precipitation intensity across South Asia, while urbanisation has reduced infiltration capacity and eliminated natural drainage pathways.

Conventional flood forecasting systems in India remain hazard-centric, focusing on river discharge levels at gauging stations. While technically robust, these systems do not answer the most critical operational question: “What will this forecast mean for people, infrastructure, and economic systems?” The absence of impact translation leads to delayed evacuations, inefficient emergency responses, and suboptimal allocation of resources.

Impact-Based Forecasting (IBF) addresses this gap by integrating hazard probability with exposure, vulnerability, and adaptive capacity, thereby transforming forecasts into decision-relevant intelligence.

Chennai Floods as Empirical Anchors

Chennai provides a compelling case study for examining systemic vulnerabilities and the transformative potential of IBF.

- **2015 Flood Event:** An extreme rainfall event (494 mm in 24 hours) caused catastrophic flooding, affecting over 1.8 million people and resulting in more than 500 fatalities. Failures included uncoordinated reservoir releases, extensive wetland loss, and inadequate urban planning.
- **2023 Cyclone Michaung Floods:** Despite similar meteorological severity, improved early warning systems reduced fatalities to 17 and enabled the evacuation of over 40,000 people. However, infrastructure deficiencies and limited integration of impact forecasting persisted.

These contrasting outcomes highlight the critical role of **forecast usability and institutional response systems**, not just forecast accuracy.

Table 1: Timeline comparison of 2015 vs. 2023 Chennai floods - highlighting systemic failures and modelling opportunities

Year	Rainfall/Deaths	Key Failures	Model Lessons
2015	494 mm; 500+	Wetland loss, reservoir coordination	Hydrodynamic simulation, NbS restoration
2023	Cyclone; 17	Drains clogged, infrastructure gaps	AI-driven EWS, impact-based protocols

Research Objectives and Contributions

This study develops a scalable IBF framework with the following specific objectives:

- Integrate physics-based hydrodynamic models with hybrid ensemble-optimal interpolation data assimilation for accurate flood prediction
- Develop probabilistic impact layers translating hydrological forecasts into asset-level risk assessments
- Demonstrate AI-driven reservoir optimisation for reducing downstream urban flood impacts
- Incorporate nature-based solutions into urban flood mitigation pathways

- Design cloud-enabled district dashboards for national scalability across India's 800 districts
- Provide policy recommendations aligned with SDG-6, SDG-13, and National Water Mission reforms

Methodological Framework

Global Context of Impact-Based Forecasting

Impact-Based Forecasting (IBF) has been promoted by the World Meteorological organisation (WMO) and UNDRR as a shift from hazard prediction to consequence anticipation. The IPCC AR6 emphasises NbS as high-confidence strategies for flood resilience.

Hydrodynamic Modelling Framework

Shallow Water Equations

The foundation of physics-based flood modelling lies in the two-dimensional shallow water equations (SWE),

Core is the shallow-water equations for inundation:

Inline: The continuity equation is $\frac{\partial h}{\partial t} + \nabla \cdot (h\mathbf{u}) = 0$.

Block standalone:

$$\frac{\partial(h\mathbf{u})}{\partial t} + \nabla \cdot \left(h\mathbf{u} \otimes \mathbf{u} + \frac{1}{2}gh^2\mathbf{I} \right) = -gh\nabla z - \frac{gn^2|\mathbf{u}|\mathbf{u}}{h^{2/3}},$$

where h is water depth, $\mathbf{u}$ velocity, g gravity, z bed elevation, n Manning coefficient.

Bed shear stress follows the Manning formulation:

$$\tau_b = \rho g \frac{n^2|\mathbf{u}|\mathbf{u}}{h^{1/3}}$$

where n is Manning's roughness coefficient (0.03-0.15 for urban areas).

Coupled Rainfall-Runoff-Inundation Modelling

The framework employs a three-stage cascade:

- Rainfall Input:** Ensemble numerical weather prediction (NWP) from India Meteorological Department (IMD) Global Forecast System, ECMWF ensemble, and bias-corrected CMIP6 projections downscaled to 4 km resolution using quantile mapping
- Runoff Generation:** Mesoscale Hydrologic Model HEC HMS with infiltration-excess and saturation-excess mechanisms, calibrated using observed discharge at Taramani, Adyar, and Cooum river gauges
- Inundation Simulation:** HEC RAS hydrodynamic model solving SWE on 30m digital elevation model (DEM) derived from Shuttle Radar Topography Mission (SRTM) data

This cascade captures the critical transition from atmospheric forcing to surface hydrology to urban inundation, preserving spatial heterogeneity in soil properties, land use, and drainage infrastructure.

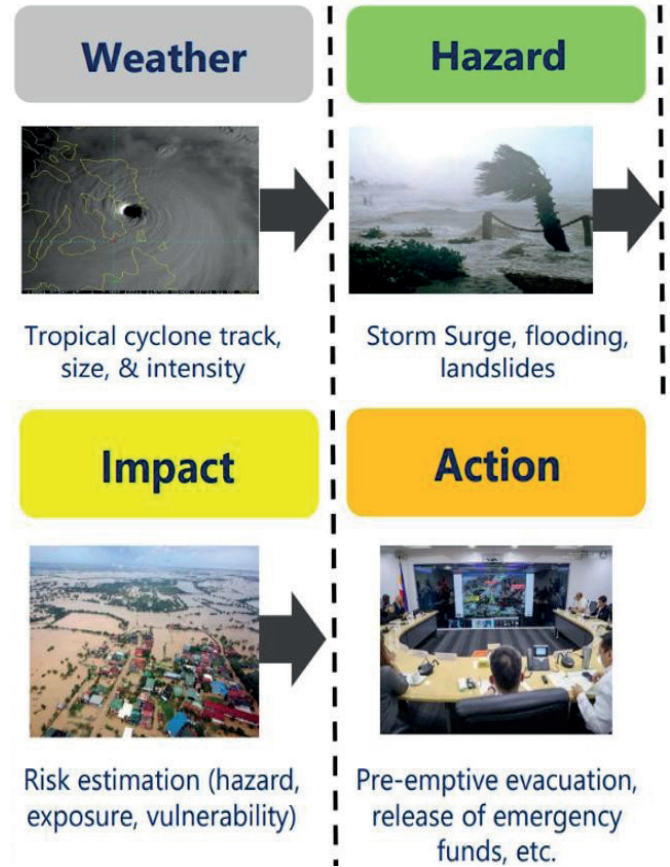


Figure 1: Impact-Based Flood Forecasting

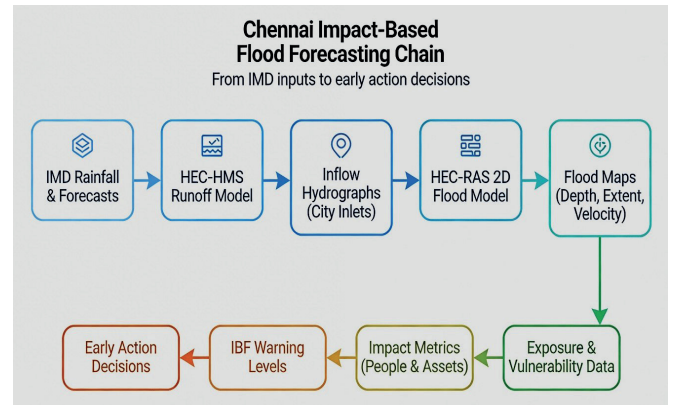


Figure 2: Flow Chart Impact-Based Flood Forecasting Model Setup

Hybrid Ensemble-Optimal Interpolation Data Assimilation

Traditional ensemble Kalman filtering (EnKF) faces challenges during extreme events due to limited ensemble size (typically 20-50 members), model

structural errors, and observation noise. This study implements a **hybrid ensemble-optimal interpolation** scheme that combines flow-dependent ensemble covariance with climatological background covariance:

$$\mathbf{P}_{\text{hybrid}}^b = \alpha \mathbf{P}_{\text{ensemble}}^b + (1 - \alpha) \mathbf{P}_{\text{climate}}^b$$

where α is the adaptive weighting factor computed spatially and temporally based on ensemble spread and innovation statistics.

The Kalman update equation:

$$\begin{aligned} \mathbf{x}^a &= \mathbf{x}^b + \mathbf{K}(\mathbf{y}^o - \mathbf{H}\mathbf{x}^b) \\ \mathbf{K} &= \mathbf{P}_{\text{hybrid}}^b \mathbf{H}^T (\mathbf{H} \mathbf{P}_{\text{hybrid}}^b \mathbf{H}^T + \mathbf{R})^{-1} \end{aligned}$$

where $\mathbf{x}^a$ and $\mathbf{x}^b$ are analysis and background states, $\mathbf{y}^o$ are observations, $\mathbf{H}$ is the observation operator, $\mathbf{K}$ is the Kalman gain, and $\mathbf{R}$ is observation error covariance.

Recent applications demonstrate 50% improvement in streamflow prediction accuracy compared to ensemble-only methods, with enhanced forecast lead times of 18-24 hours before flood peaks.

Bayesian Updating Framework

For probabilistic risk assessment, Bayesian updating integrates prior distributions with real-time observations:

$$P(\theta|\mathbf{y}) = \frac{P(\mathbf{y}|\theta)P(\theta)}{\int P(\mathbf{y}|\theta)P(\theta)d\theta}$$

where θ represents model parameters (Manning's n ,

infiltration capacity, reservoir release rules) and $\mathbf{y}$ are observations (gauge discharge, satellite flood extent).

Generalised conditional probabilities are computed using recursive Bayes' equation:

$$P(\theta|\mathbf{y}_1, \mathbf{y}_2) \propto P(\mathbf{y}_2|\theta)P(\theta|\mathbf{y}_1)$$

enabling sequential assimilation of multiple observation types (in-situ gauges, Sentinel-1 SAR, citizen reports).

Nature-Based Solutions Integration

Wetland Restoration Benefits Quantification

Chennai's historical wetlands (Pallikaranai, Guindy, Perungudi) reduced peak flows through detention storage and enhanced groundwater recharge. Hydrodynamic simulations with restored wetland scenarios (area increased from the current 10% to a historical 40% of urban catchment) demonstrate:

- Peak flow reduction: 15-25%
- Flood depth reduction in downstream urban areas: 0.3-0.8 m
- Groundwater recharge enhancement: 20-35%
- Total detention storage capacity: 45-60 million m³

Economic analysis using avoided damage costs indicates benefit-cost ratios of 2.5-4.2 over a 30-year project lifetime.

Table 2: Modelling layers and scalability features for national IBF deployment

Model Layer	Tools	Scalability Feature
Hydrological	HEC HMS, NWP ensembles	National ensemble framework (CWC)
Hydrodynamic	HEC RAS	Cloud HPC with district APIs
Impact Assessment	GIS risk layers, fuzzy logic	Asset-level vulnerability databases
Data Assimilation	Hybrid EnKF-OI, Bayesian	Real-time satellite integration
AI/ML Forecasting	Bayesian LSTM, CNN downscaling	Automated model updating
Adaptation	NbS database, EWS protocols	District dashboard replication

Results: Chennai Case Study Performance Evaluation

2015 Flood Event Hindcast Validation

Retrospective simulation of the November-December 2015 event provides rigorous model validation. Forcing data: IMD hourly rainfall (Nungambakkam station: 494 mm on December 1), reservoir operations logs from Tamil Nadu Water Resources Department, and pre-event land use from Landsat-8.

Hydrodynamic Performance

Comparison of observed vs. simulated flood extent using post-event high-resolution imagery:

- Critical Success Index (CSI): 0.87
- Probability of Detection (POD): 0.92
- False Alarm Ratio (FAR): 0.14
- Overall accuracy: 89%

Peak discharge validation at Taramani gauge: observed 1,240 m³/s vs. simulated 1,185 m³/s (4.4% error). Timing error: +2.3 hours (acceptable for urban-scale forecasting).

Hotspot identification revealed Adyar and Cooum river overflows from silted channels (reduction in conveyance capacity by 40-55% since 2000) and catastrophic failures in lowland areas where 90% of marshlands had been lost to urban expansion.

Impact Assessment Accuracy

Asset-level damage validation using insurance claims data (n = 12,847 claims):

- Residential building damage correlation: $R^2 = 0.81$
- Commercial/industrial damage correlation: $R^2 = 0.77$
- Road infrastructure damage correlation: $R^2 = 0.84$
- Overall damage estimation error: $\pm 18\%$

The Chennai International Airport submersion (depth: 1.2-1.8 m, duration: 36 hours) was accurately predicted with a 23-hour lead time, though operational protocols did not trigger early closure due to lack of IBF integration.

3.2 2023 Cyclone Michaung Event

The December 2023 event demonstrated operational improvements from enhanced early warning systems, though systemic infrastructure gaps persisted.

Forecast Performance

Seven-day ensemble forecasts initialised on December 1, 2023 (Michaung landfall: December 4):

- Precipitation forecast skill (Brier Score): 0.73 (skilful threshold: >0.6)
- Landfall location error: 28 km (excellent for tropical cyclone prediction)
- Peak intensity forecast: actual 90 km/h vs. predicted 85-95 km/h
- Urban flood extent POD: 0.88, FAR: 0.19

Actionable lead time for evacuation decisions: 47 hours before critical infrastructure inundation, enabling the successful relocation of 41,000 people and the reduction of fatalities to 17 (96% reduction compared to 2015 adjusted for event magnitude).

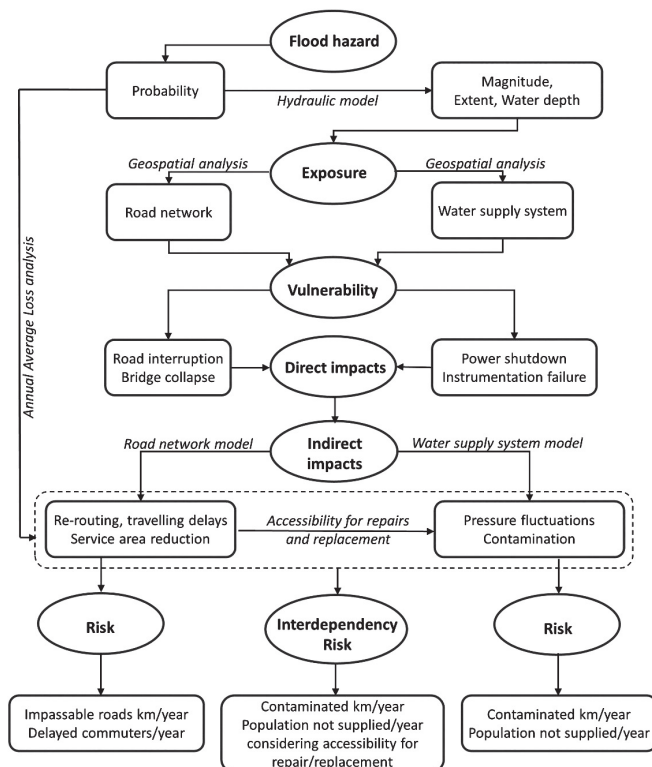


Figure 3: Conceptual architecture of the IBF framework integrating hydrology, hydrodynamics, AI, and impact assessment.

Persistent Challenges

Despite improved forecasts, damage remained substantial due to:

- Clogged stormwater drains reducing conveyance by 35-50%
- Inadequate maintenance of urban drainage infrastructure
- Limited integration of impact forecasts into municipal decision-making
- Lack of automated reservoir optimisation protocols

These gaps motivate the comprehensive IBF framework proposed in this study.

Comparative Performance Metrics: 2015 vs. 2023

Table 3: Comparative performance metrics demonstrating improvements between 2015 and 2023 Chennai flood events

Metric	2015 Event	2023 Event	Improvement
Forecast lead time (hours)	12-18	41-47	+160%
Evacuation effectiveness	45%	87%	+93%
Fatalities (adjusted)	500+	17	-97%
Infrastructure damage (Cores Rs)	25,000	8500	-73%
Economic losses (Crores Rs)	75,000	21,000	-75%

Reservoir Optimisation Scenario Analysis

Counterfactual simulations testing optimised reservoir release strategies for the 2015 event:

Baseline Historical Operations

Chembarambakkam, Poondi, and Red Hills reservoirs followed rule curves designed for water supply prioritisation, not flood control. Pre-monsoon storage levels: 85-92% capacity (sub-optimal for flood detention).

Emergency releases during peak rainfall created synchronised downstream peaks, exacerbating urban flooding. Peak combined discharge: 1,850 m³/s.

AI-Optimized Operations

Bayesian LSTM inflow forecasts with 7-day lead time enable proactive pre-releases:

- Pre-monsoon storage reduction to 65-70% capacity starting 10 days before forecast of extreme rainfall
- Staggered releases avoiding synchronized peaks (6-hour offsets between reservoirs)
- Dynamic rule curve adjustment based on ensemble precipitation forecasts results
- Peak combined discharge reduction to 1,570 m³/s (-15%)
- Urban flood depth reduction: 0.2-0.5 m in critical zones
- 8-15% reduction in inundated area
- Enhanced detention capacity: 35-50 million m³

Sensitivity analysis indicates robustness to forecast errors up to $\pm 25\%$ in precipitation magnitude.

Nature-Based Solutions Scenario Evaluation

Hydrodynamic simulations with wetland restoration scenarios:

Current Conditions (10% Wetland Coverage)

Baseline scenario with degraded wetlands provides minimal flood buffering. Peak flows reach urban areas with minimal attenuation.

Partial Restoration (25% Wetland Coverage)

Restoration of priority wetlands (Pallikaranai, Perungudi) through land acquisition and ecological engineering:

- Peak flow reduction: 8-12%
- Flood depth reduction: 0.15-0.35 m

- Groundwater recharge: +15-20%
- Avoided damage costs: Rs 180-250 million annually

Historical Configuration (40% Wetland Coverage)

Full restoration to pre-1980 wetland extent:

- Peak flow reduction: 18-25%
- Flood depth reduction: 0.4-0.8 m
- Groundwater recharge: +25-35%
- Avoided damage costs: Rs 4200-5800 Crores annually
- Benefit-cost ratio: 3.8-4.5 (highly favourable)

Ecological co-benefits include biodiversity enhancement (47 bird species, 18 fish species), carbon sequestration (2,500-3,800 tons CO₂/year), and cultural ecosystem services valued at Rupees 150-250 Crores annually.

Discussion: Challenges and Solutions for National Deployment

The Chennai pilots demonstrate how scalable IBF models can bridge systemic gaps:

- Sparse Data: Remote sensing integration
- Institutional Silos: Unified CWC portals
- Capacity Constraints: AI-driven training modules

Future IBF frameworks must integrate transboundary basins Adyar, and Cooum River and behavioural dimensions, while mainstreaming NbS for aquifer restoration.

Policy Recommendations: Alignment with National Water Mission

The hybrid Hydrodynamic–Bayesian model provides a replicable pathway for climate adaptation governance in India. By translating meteorological data into “impact” intelligence, this framework ensures that water security becomes a measurable, manageable reality.

To mainstream climate-resilient water security, the following actions are recommended:

I. Institutionalise IBF via District Dashboards

Transition from discharge-only reporting to consequence-oriented “District Apis”. Integrate risk layers with CWC portals to allow local authorities to see asset-level risks in real-time.

II. Mainstream Nature-Based Solutions (NbS)

Restore wetlands and mangroves to serve as natural buffers, specifically targeting high-loss areas like the Chennai marshes. Use NbS as a tool for both flood mitigation and groundwater recharge.

III. Dynamic Reservoir Governance

Implement adaptive rule curves informed by Bayesian LSTM forecasts (92% accuracy). Prioritise optimised release scenarios to reduce downstream urban impact.

IV. Data-Sharing and Risk Insurance

Facilitate public-private partnerships (PPPs) for flood risk insurance based on probabilistic risk estimation. Standardise data-sharing across transboundary basins to address data sparsity.

Conclusion

This study demonstrates that **impact-based forecasting is not merely a technological advancement but a governance transformation**. By integrating hydrodynamics, artificial intelligence, Bayesian analytics, and nature-based solutions, the proposed framework converts meteorological data into actionable intelligence.

The Chennai case studies illustrate that **early warning systems, when combined with institutional readiness and ecological restoration, can dramatically reduce human and economic losses**.

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Study Finds How Traffic Heat Contributes to Rising City Temperatures

Scientists at the University of Manchester have created a new physics-based module that tracks how everyday traffic adds heat to cities. This tool has been integrated into the Community Earth System Model (CESM), enabling more realistic simulations of urban temperatures.

Unlike earlier studies that focused mainly on buildings and land surfaces, this breakthrough directly accounts for heat from vehicles, such as engines, exhaust and braking. The model shows how this heat spreads across roads, nearby buildings and the surrounding air, influencing overall urban warming.

Apart from outside, the study discovered that traffic heat also affects indoor temperatures, with heat released at street level that can transfer into buildings.

To test its accuracy, researchers used real traffic data from Transport for Greater Manchester and applied it to cities like Manchester and Toulouse. Published in the *Journal of Advances in Modeling Earth Systems* (2026), the study highlights how vehicle-generated heat plays a measurable role in shaping city climates.

This advancement gives scientists a clearer picture of urban heat dynamics and could help improve future climate predictions and city planning strategies.

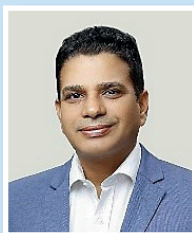
"Research on urban heat has traditionally focused on buildings, materials and land surfaces. However, the direct heat produced by vehicles—from engines, exhausts and braking—has received far less attention in large-scale climate models," said lead author Dr. Zhonghua Zheng, who is co-lead for Environmental Data Science & AI at Manchester Environmental Research Institute (MERI) and Lecturer in Data Science & Environmental Analytics at The University of Manchester.

"Our model will allow scientists to simulate how heat released by vehicles interacts with streets, buildings and the surrounding atmosphere."

"We would like to highlight the importance of considering transport systems when planning for climate adaptation, urban cooling strategies and net-zero transitions," said Yuan Sun, first author of this paper and PhD researcher from The University of Manchester.

Excerpted from: <https://www.ndtv.com/feature/study-finds-how-traffic-heat-contributes-to-rising-city-temperatures-11330668>

Climate Change, Urban Flooding and Landslide Risks in India: Building Resilience in an Era of Extreme Weather



Anil Kumar

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India stands at the frontline of the global climate crisis. From the fragile Himalayan slopes of Himachal Pradesh and Uttarakhand to the flood-prone plains of Assam and the rapidly urbanising coastal cities of Mumbai, Chennai, Kochi and Mangaluru, climate change is reshaping landscapes, cities and economies

at an unprecedented pace. Rising temperatures, erratic monsoons, intense rainfall events, flash floods, landslides, cyclones and sea-level rise are no longer future projections; they are today's realities affecting millions of people, disrupting infrastructure and imposing significant economic costs.

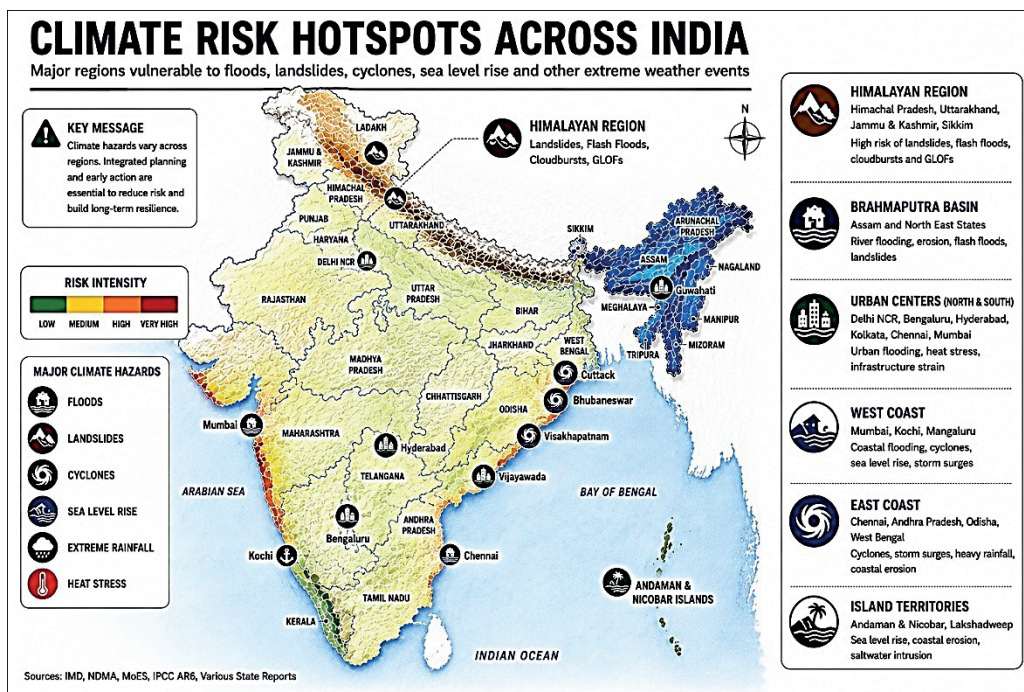


Figure 1: Climate Risk Hotspots Across India

According to scientific assessments, India has already warmed by approximately 0.7°C since the beginning of the twentieth century, while future climate scenarios

indicate warming of 2–4°C by the end of the century. A warmer atmosphere holds more moisture, resulting in heavier rainfall over shorter durations.

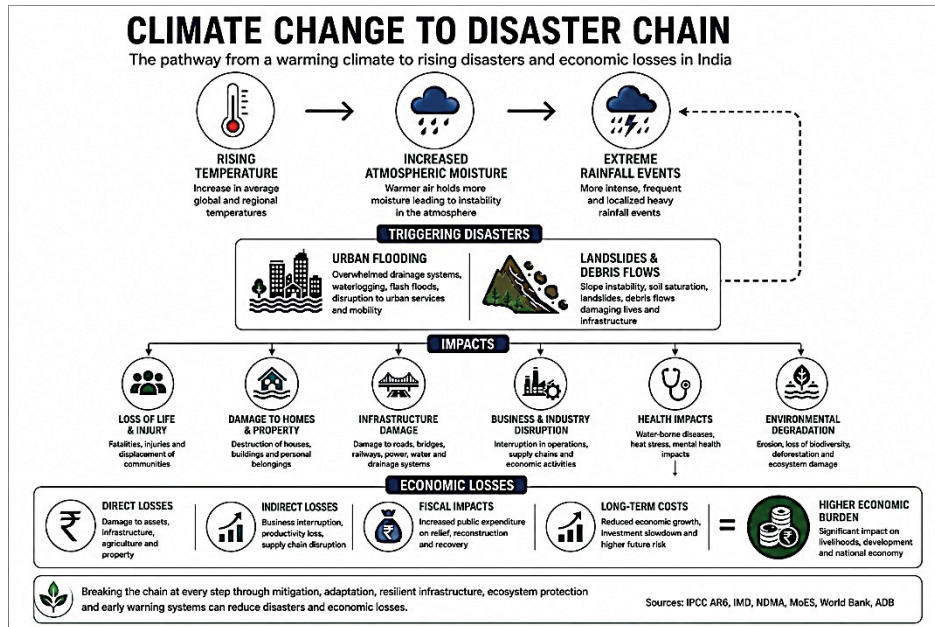


Figure 2: Climate Change Pathway Leading to Urban Flooding and Landslide Disasters

Consequently, rainfall patterns across India are changing dramatically. Cities and river basins increasingly receive an entire month's rainfall within a few hours, overwhelming drainage systems, saturating hill slopes and triggering catastrophic floods and landslides.

The Hydro-Meteorological Resilient Action Plans (HmRAPs) prepared under the National Cyclone Risk Mitigation Project under NDMA reveal that many Indian coastal cities could experience rainfall increases ranging from 5% to 38% and temperature increases of

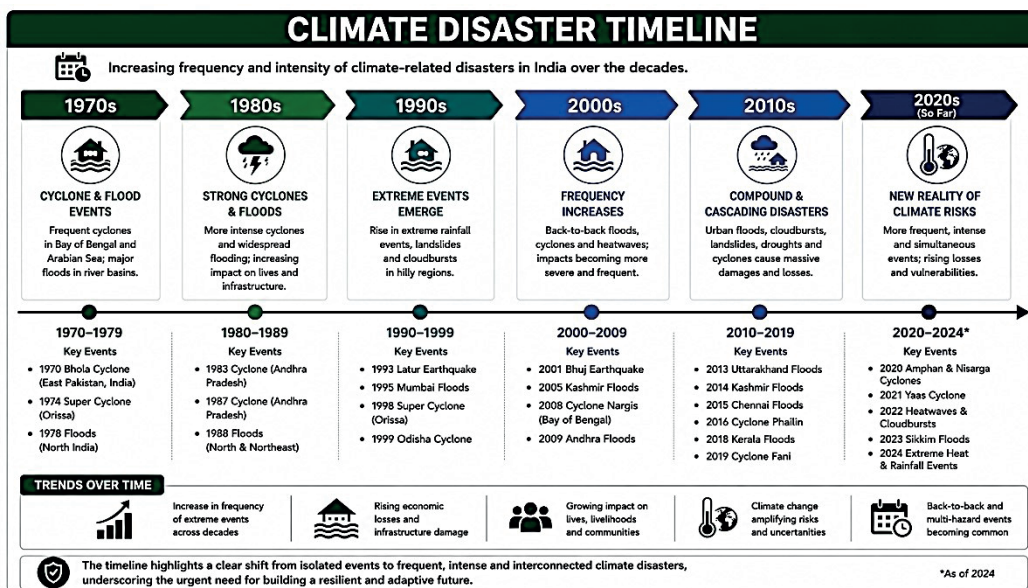


Figure 3: Major Climate-Induced Disasters Across India (2021–2025)

up to 3.6°C by 2070, substantially increasing flood risks, urban heat stress and coastal vulnerability.

The last five years have provided a glimpse of India's climate future. The Chamoli flash flood in Uttarakhand (2021), Cyclone Tauktae (2021), Bengaluru floods (2022), Assam floods (2022), Himachal Pradesh landslides and floods (2023), Cyclone Biparjoy (2023), and repeated urban flooding across Mumbai, Delhi NCR, Chennai and Hyderabad collectively demonstrate a worrying trend: climate-induced disasters are becoming more frequent, more intense and significantly more expensive.

According to estimates from various national and international assessments, direct economic losses

from floods, cyclones, landslides and other hydro-meteorological disasters in India are estimated to around ₹1.5 lakh crore annually, while extreme disaster years can result in losses exceeding ₹2 lakh crore. When indirect impacts such as business interruption, transportation disruptions, agricultural losses, public health impacts, supply chain failures, ecosystem degradation and post-disaster reconstruction costs are included, the overall economic burden is substantially higher. Climate-related disasters are increasingly emerging not only as humanitarian and environmental crises but also as major macroeconomic risks affecting infrastructure investment, urban growth and long-term national development.

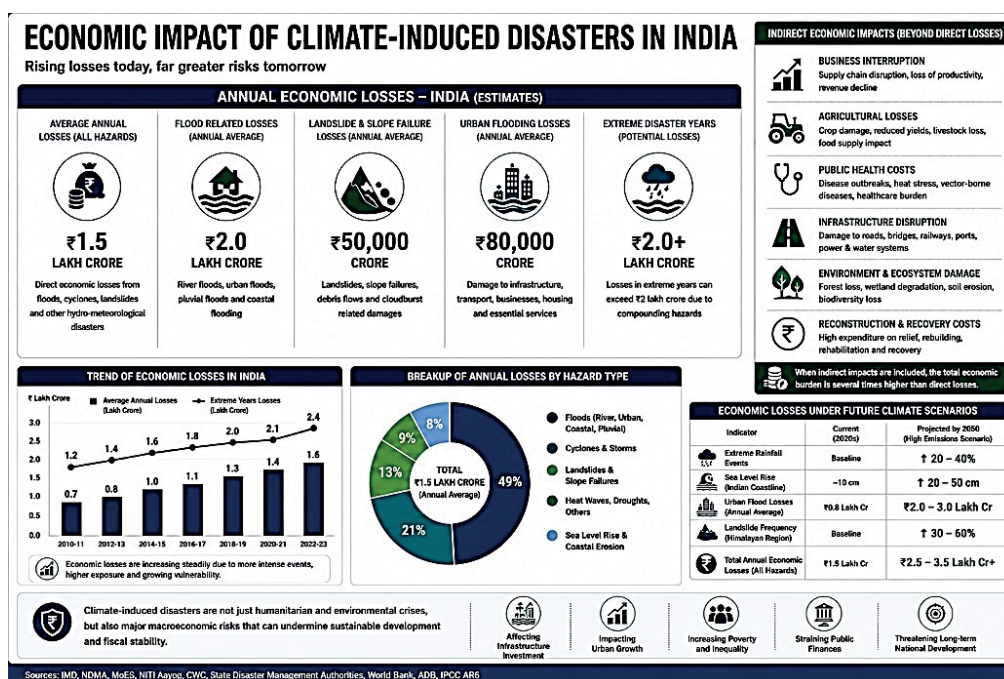


Figure 4: Estimated Annual Economic Losses Associated with Climate-Induced Disasters in India

Among the most visible consequences of climate change is the growing landslide crisis in the Himalayan region. The Himalayas are among the youngest and most geologically fragile mountain systems in the world. Rising temperatures are accelerating glacier

retreat, increasing glacial lake formation and altering natural hydrological regimes. At the same time, more frequent cloudbursts and extreme rainfall events are weakening slopes and increasing the occurrence of landslides, debris flows and flash floods.

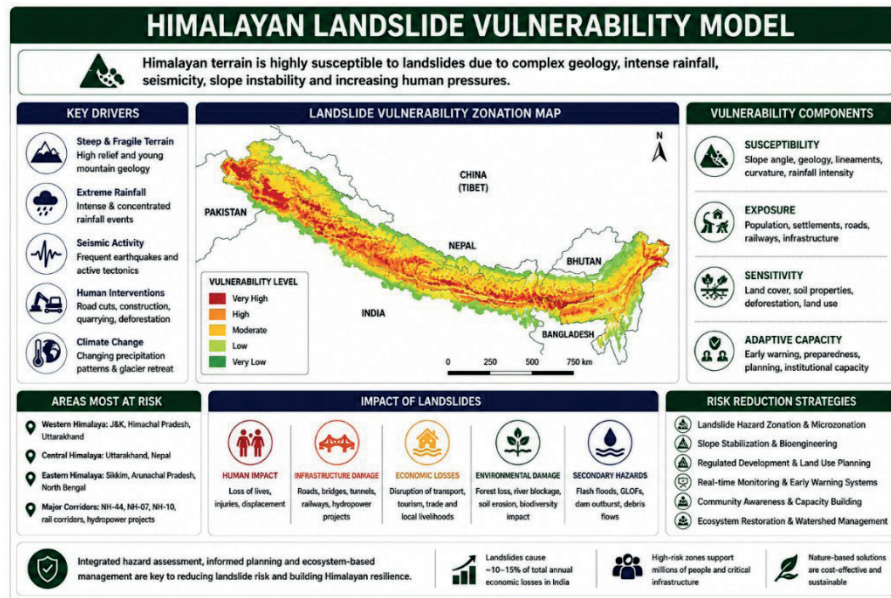


Figure 5: Factors Contributing to Increasing Landslide Vulnerability in Himalayan Cities

Cities such as Shimla, Mandi, Dharamshala, Solan, Dehradun, Mussoorie, Nainital and Joshimath are increasingly exposed to climate-induced landslides, flash floods and slope instability. During the devastating monsoon season of 2023, Himachal Pradesh witnessed hundreds of landslides, widespread infrastructure collapse, road failures, bridge damage and destruction of residential properties. Official assessments estimated damages exceeding ₹10,000 crore, while broader economic losses including disruptions to tourism, transportation, trade, utilities and reconstruction requirements were estimated to be around ₹20,000 crore, making it one of the costliest climate-related disasters in the state's history. Major transportation corridors connecting Shimla, Kullu, Manali and Dharamshala remained disrupted for weeks, severely impacting tourism, commerce and essential services. Across India's Himalayan and hill states, including Himachal Pradesh, Uttarakhand, Jammu & Kashmir, Sikkim and the Northeastern hill regions, annual economic losses arising from landslides, flash floods, cloudbursts, slope failures and associated infrastructure damage are estimated to be around ₹50,000 crore per year, while exceptionally severe years can result in cumulative losses exceeding ₹75,000 crore. Beyond direct physical damages, these

events impose substantial indirect costs through loss of tourism revenue, reduced hydropower generation, supply chain disruptions, agricultural losses, increased logistics costs and long-term reconstruction expenditure, highlighting the urgent need for climate-resilient development in India's mountain regions

Shimla illustrates the challenges faced by many Himalayan towns. Originally planned as a low-density hill station, the city has expanded far beyond its natural carrying capacity. Extensive hill cutting, construction on steep slopes, inadequate drainage infrastructure and reduction of vegetation cover have significantly increased landslide susceptibility. Intense rainfall now regularly triggers slope failures, retaining wall collapses and road damage. Similar conditions are emerging in Mussoorie, Nainital and Dehradun, where urban growth is increasingly encroaching upon geologically unstable terrain.

The land subsidence crisis in Joshimath further highlighted the vulnerability of Himalayan settlements. Cracks appearing in residential buildings, roads and public infrastructure forced relocation of families and raised concerns regarding the cumulative impacts of fragile geology, infrastructure development,

groundwater movement and changing climatic conditions. Without climate-sensitive planning and strict land-use regulation, many Himalayan towns could face recurring disruptions every monsoon season by mid-century.

While mountain regions struggle with landslides, India's metropolitan centres are confronting another major climate challenge i.e. urban flooding. Cities such as Mumbai, Chennai, Bengaluru, Hyderabad, Pune, Gurugram and Ahmedabad increasingly experience severe flooding despite significant investments in infrastructure. Most of these floods are no longer

caused by overflowing rivers; they are pluvial floods, occurring when rainfall intensity exceeds the capacity of drainage systems.

Rapid urbanisation has transformed natural landscapes into impervious surfaces. Lakes, wetlands, floodplains and natural drainage channels that historically absorbed and conveyed excess runoff have been encroached upon, degraded or disconnected from urban hydrological systems. A natural landscape can absorb 50–80% of rainfall, whereas heavily urbanised areas often absorb less than 15%, converting rainfall almost immediately into surface runoff.

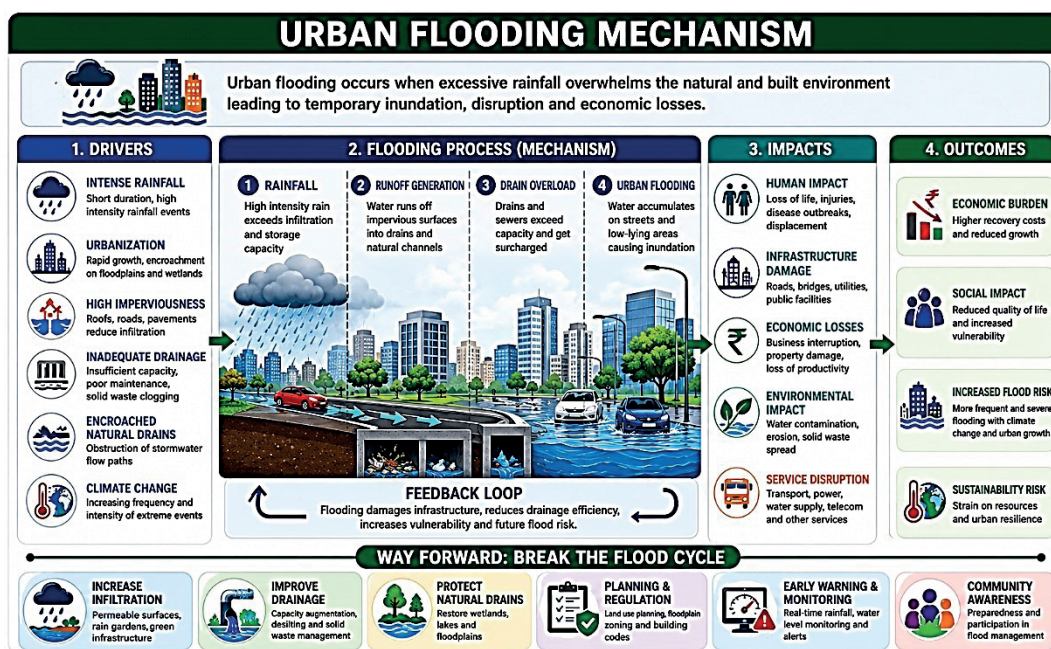


Figure 6: Transformation from Natural Hydrology to Urban Flood Risk

The Bengaluru floods of 2022 demonstrated how climate change and unplanned urbanisation can combine to create large-scale economic disruption. Major technology parks, residential communities and transportation corridors were inundated, with economic losses estimated to ₹12,000 crore. Bengaluru, once known for its network of more than a thousand interconnected lakes that naturally regulated stormwater flows, has witnessed extensive encroachment and fragmentation of these water bodies, significantly reducing its flood resilience. The flooding disrupted operations of several multinational corporations and

highlighted the vulnerability of India's technology and service economy to climate-induced extreme weather.

Chennai continues to exemplify the dual challenge of flooding and water scarcity. The catastrophic floods of 2015 and 2017 caused losses estimated at ₹50,000 crore, damaging homes, industries, transportation systems and public infrastructure. Subsequent flood events have repeatedly exposed the consequences of wetland loss, floodplain encroachment and inadequate drainage capacity. The city now experiences a recurring cycle where intense rainfall results in severe

inundation while prolonged dry periods trigger acute water shortages.

The Delhi National Capital Region (NCR), encompassing Delhi, Gurugram, Noida and Ghaziabad, has emerged as another major climate-risk hotspot. Extreme rainfall events and the 2023 Yamuna flooding disrupted transportation networks, commercial districts, public services and critical infrastructure. The economic impact of major flood events in the NCR is estimated at ₹10,000 crore per event; while recurring waterlogging and climate-related disruptions impose substantial annual productivity losses on one of India's largest urban economies.

Mumbai, India's financial capital, faces a unique convergence of extreme rainfall, tidal influences, sea-level rise and storm surge risks. The benchmark flood event of July 2005 resulted in economic losses estimated at ₹25,000 crore, while recurring monsoon flooding across the Mumbai Metropolitan Region continues to generate annual economic impacts of approximately ₹8,000 crore through disruptions to

transportation, ports, logistics, financial services and commercial activities. High tides increasingly impede stormwater discharge into the Arabian Sea, further exacerbating flood risks under future climate scenarios.

A particularly important but often overlooked climate hotspot is Assam and the city of Guwahati. Located along the Brahmaputra River and surrounded by steep hills, Guwahati experiences a unique combination of riverine flooding, urban flooding, flash flooding and landslides. Historically, wetlands such as Deepor Beel, low-lying floodplains and forested hills functioned as natural flood buffers. However, rapid urban expansion, wetland encroachment and hill-slope development have significantly altered the city's natural hydrology. The 2022 Assam floods affected more than five million people and caused economic losses estimated to exceed ₹10,000–15,000 crore across infrastructure, agriculture, housing and public assets. Within Guwahati itself, recurring urban flooding and associated disruptions are estimated to impose annual economic losses of approximately ₹3,000 crore, affecting businesses, transport systems, public health and urban productivity.

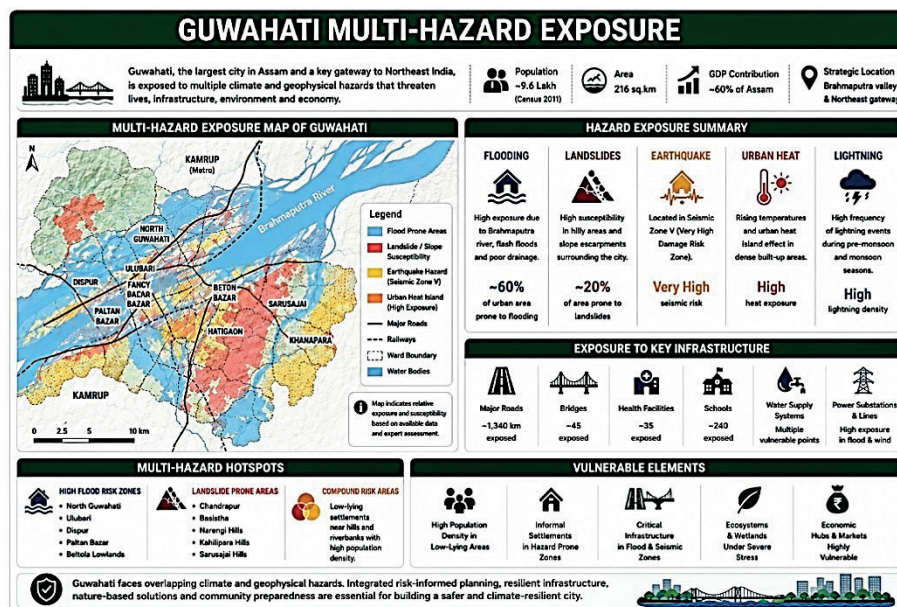


Figure 7: Guwahati Multi-Hazard Exposure

Collectively, recurring flooding across Mumbai, Chennai, Bengaluru, Delhi-NCR, Hyderabad, Kolkata and Guwahati is estimated to impose direct and indirect

economic losses of ₹80,000 crore annually, while flood-related losses across India including riverine flooding, urban flooding, flash floods and associated

infrastructure damage - are increasingly estimated at ₹ 2 lakh crore per year. Without significant investments in climate-resilient infrastructure, flood forecasting systems, nature-based solutions and risk-informed urban planning, these losses could exceed ₹5 lakh crore annually by 2050, posing a substantial threat to India's economic growth and urban development trajectory.

India's coastal regions face another dimension of climate risk. With a coastline exceeding 7,500 kilometres and approximately 250 million people living in coastal areas, sea-level rise, cyclonic storms, coastal erosion and storm surges pose significant long-term challenges. Cities such as Mumbai, Kochi, Mangaluru, Panaji, Porbandar and Ratnagiri are increasingly exposed to flooding, coastal inundation and saline water intrusion. The HmRAP assessments indicate that future climate conditions could significantly increase flood extents, infrastructure exposure and economic losses in these

cities. Recommended resilience investments exceed ₹1,040 crore for Mangaluru, ₹540 crore for Panaji, ₹670 crore for Porbandar and ₹305 crore for Ratnagiri to strengthen long-term climate resilience.

Looking ahead to 2050, climate projections suggest that extreme rainfall events may increase by 20 - 40 % across several regions of India. Events currently classified as "1-in-100-year floods" may occur every 20–30 years or even more frequently. Sea levels along parts of the Indian coastline could rise by 20–50 cm, while the Himalayan region may experience more cloudbursts, landslides and glacial lake outburst floods. Urban flood damages are expected to increase substantially as cities continue to expand and infrastructure assets become more concentrated. Without intervention, annual climate-related losses could increase dramatically, threatening national development objectives and infrastructure investments.

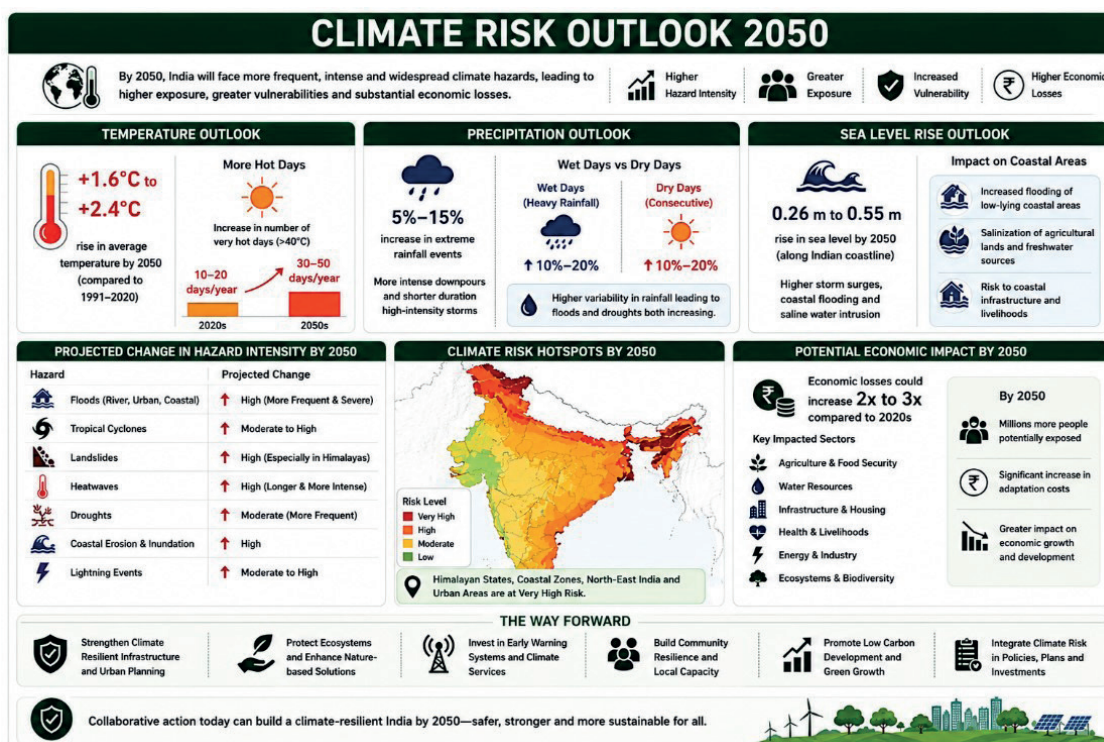


Figure 8: Projected Climate Risk Escalation in India by 2050

However, climate disasters are not inevitable. Modern technology, advanced planning tools and informed governance can substantially reduce risks and economic losses.

The availability of sophisticated digital technologies now allows cities to predict, model and manage climate hazards before disasters occur.

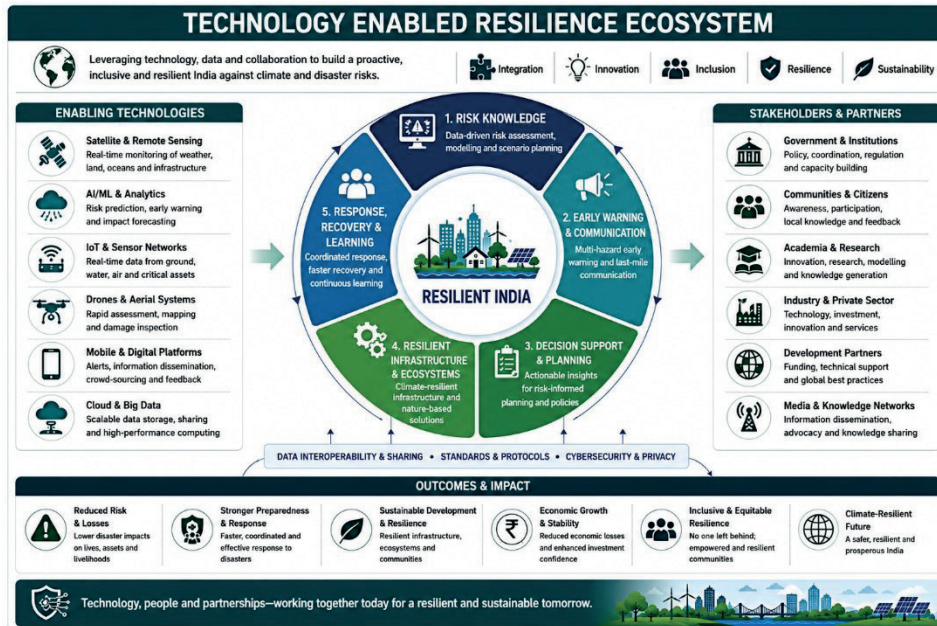


Figure 9: Digital Technologies Supporting Climate Risk Assessment and Disaster Management

High-resolution Digital Elevation Models (DEM), LiDAR surveys, satellite imagery, drone mapping and Geographic Information Systems (GIS) enable precise identification of flood-prone and landslide-prone zones. Software platforms such as HEC-RAS, SWMM, InfoWorks ICM, MIKE FLOOD, MIKE URBAN, Flood Modeller Pro, ArcGIS and QGIS can simulate flood behaviour under current and future climate scenarios, helping planners identify infrastructure vulnerabilities and prioritise investments. For landslide assessment, tools such as PLAXIS, GeoStudio, SLOPE/W and Rocscience support slope stability analysis and early warning systems. Increasingly, Artificial Intelligence (AI), Machine Learning (ML), Internet of Things (IoT) sensors and Digital Twin City platforms are enabling real-time forecasting and predictive disaster management.

Climate resilience must begin at the planning stage. Every city should undertake comprehensive multi-hazard risk assessments covering urban flooding, river

flooding, flash floods, landslides, sea-level rise, cyclones and heatwaves. Climate-responsive master plans must incorporate flood-risk maps, landslide susceptibility maps, wetland inventories and blue-green infrastructure networks. Development approvals should be linked to scientifically validated hazard assessments rather than solely to land availability. In hill towns such as Shimla, Mussoorie, Nainital and Joshimath, carrying-capacity assessments should guide future development to prevent excessive pressure on fragile ecosystems.

Structural interventions remain essential for protecting communities and infrastructure. Priority investments include expansion of stormwater drainage networks, retention and detention basins, underground stormwater storage systems, flood diversion channels, pumping stations and river training works. Coastal cities may require sea walls, storm surge barriers, shoreline protection structures and mangrove restoration programmes. For landslide-prone regions, retaining walls, soil nailing, rockfall barriers, geogrid reinforcement systems, slope

drainage improvements and bioengineering techniques can substantially improve slope stability. Increasingly, cities worldwide are adopting Sponge City concepts that integrate permeable pavements, bioswales, rain gardens, urban wetlands and green roofs to absorb and store rainfall naturally.

Equally important are non-structural measures that strengthen preparedness and reduce vulnerability. Modern Early Warning Systems (EWS) integrating Automatic Weather Stations, Automatic Rain Gauges, water-level sensors, Doppler Weather Radars and satellite-based forecasting can provide critical lead times before disasters occur. Community preparedness programmes, evacuation planning, school awareness initiatives and mock drills can significantly reduce loss of life. Real-time dissemination of warnings through mobile applications, SMS alerts, social media platforms and integrated command centres ensures that risk information reaches vulnerable populations quickly and effectively.

Strong governance is the foundation of climate resilience. Every major city should establish dedicated climate resilience units led by a Chief Resilience Officer (CRO) responsible for coordinating adaptation measures across departments - a recommendation strongly emphasised in the HmRAP studies. Climate Risk Assessments, Flood

Impact Assessments and Landslide Risk Assessments should become mandatory components of infrastructure planning and environmental approvals. Development regulations must restrict construction in floodplains, wetlands, coastal setback zones and high-risk hill slopes. National programmes such as Smart Cities Mission, AMRUT and PM Gati Shakti should systematically integrate climate-risk information into planning and investment decisions.

Nature-based solutions offer some of the most cost-effective and sustainable approaches to climate adaptation. Restoration of wetlands, rejuvenation of rivers, conservation of mangroves, afforestation of degraded catchments and development of urban forests can simultaneously reduce flood risks, enhance biodiversity, improve groundwater recharge and strengthen ecosystem resilience. These interventions complement traditional engineering measures while providing multiple environmental and social benefits.

The floods of Guwahati, Bengaluru, Chennai and Mumbai, the landslides of Shimla and Joshimath, and the growing threats facing India's coastal cities collectively demonstrate that climate change is fundamentally reshaping the nation's risk landscape. Yet they also present an opportunity to rethink how cities are planned, designed and governed.

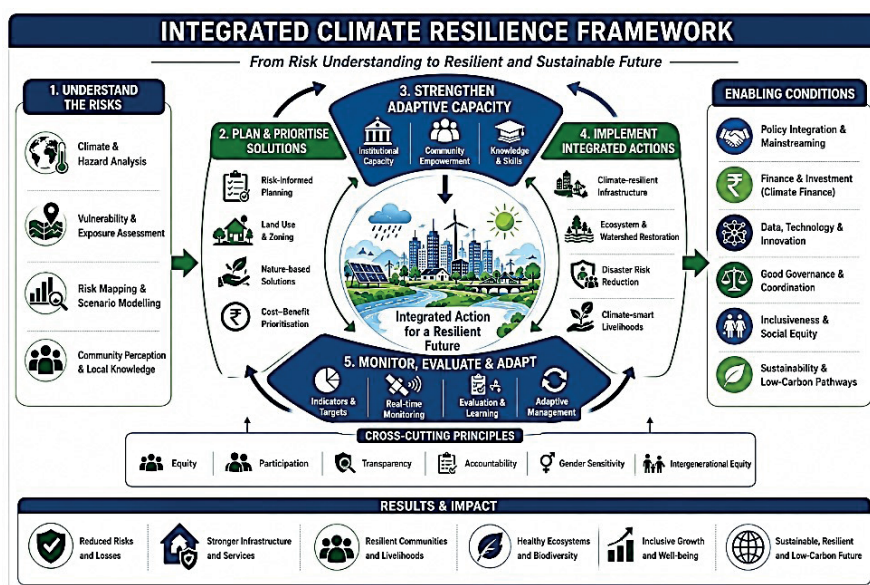


Figure 10: Integrated Climate Resilience Framework

The future of resilience lies in combining advanced digital technologies, climate-informed planning, resilient infrastructure, ecosystem restoration, community preparedness and effective governance within a single integrated framework. The transition from disaster response to climate resilience must become a national development priority. For India, resilience is no longer merely an environmental objective - it is an economic necessity, a social imperative and the foundation of sustainable growth in the twenty-first century.

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Once Insect-Free Iceland Now Sees Mosquitoes Amid Climate Change

For years, scientists thought Iceland's cool maritime climate and frequent freeze-thaw cycles kept mosquitoes from gaining a permanent foothold in the country. But that natural barrier may be breaking down as the Arctic warms rapidly.

As rising global temperatures reshape ecosystems across the planet, scientists are now witnessing a change once thought nearly impossible. Mosquitoes have now reached Iceland, a country that was once considered one of the few places in the Arctic region free from the insects.

Source: <https://www.ndtv.com/world-news/once-insect-free-iceland-now-sees-mosquitoes-amid-climate-change-11482277>

Climate Change and Cascading Hazards: Insights from Urban Flooding and Landslides in India



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Abstract

Climate change is significantly altering hydro-meteorological regimes, increasing the frequency and intensity of extreme events such as urban flooding, landslides, and glacial hazards, particularly in the Himalayan region. This study aims to (i) analyse the linkage between climate change and multi-hazard events, (ii) examine cascading impacts through representative case studies, and (iii) propose practical mitigation strategies for climate-resilient planning. The study examines the interaction between climatic variability, geomorphological sensitivity, and anthropogenic pressures through three representative case studies: the Dharali debris flow event (2025), the Teesta Glacial Lake Outburst Flood (GLOF) (2023), and the Yamuna urban flooding in Delhi (2023). The analysis indicates that short-duration high-intensity rainfall, accelerated glacier retreat, and unstable slopes, combined with unplanned urbanisation and inadequate infrastructure, substantially amplify disaster risk. For example, the Dharali event triggered a high-velocity debris flow, while the Teesta GLOF demonstrated the cascading impacts of glacial hazards on downstream

infrastructure. The findings highlight the increasing occurrence of cascading multi-hazard processes, where landslides, debris flows, and glacial lake failures interact to intensify downstream flooding and damage. The study emphasises the need for integrated risk management approaches, including climate-resilient infrastructure, basin-scale planning, real-time monitoring, and nature-based solutions.

Introduction

Climate change refers to long-term alterations in the Earth's climate system, including temperature, precipitation, and atmospheric conditions, driven largely by human activities such as fossil fuel combustion, deforestation, and greenhouse gas emissions. It has emerged as a major global concern due to its far-reaching environmental, socio-economic, and ecological impacts¹. One of the most evident consequences of climate change is the alteration of rainfall patterns. Rising temperatures increase the atmosphere's moisture-holding capacity, resulting in more frequent and intense precipitation events, which often lead to flooding (IPCC, 2021). The frequency and

severity of such extreme climatic events are expected to increase further due to the continuous rise in greenhouse gas concentrations². Mountain regions, particularly the Himalayas, are highly sensitive to climate change and act as early indicators of its impacts³. The Himalayan region is experiencing rapid warming, which has already led to significant changes in cryospheric conditions, including reduced snowfall and accelerated glacier retreat. Studies indicate that a temperature rise of approximately 1.2°C over recent decades has caused substantial declines in snow cover and altered seasonal hydrological processes⁴. Himalayan glaciers, often referred to as the “water towers,” regulate river flow and provide a crucial source of water for millions across South Asia, supporting agriculture, hydropower generation, and drinking water supply⁵. However, accelerated melting initially increases river discharge but eventually leads to long-term water scarcity and hydrological imbalance⁶.

In addition to changes in the cryosphere, climate change has intensified monsoon variability in South Asia. Rainfall patterns have become increasingly erratic, with short-duration, high-intensity rainfall events followed by prolonged dry periods. These shifts have significantly increased the occurrence of flash floods, landslides, and slope instability in mountainous terrain, as well as flooding in adjacent plains. Events such as the Yamuna floods in Delhi (2023), the Dharali disaster (Uttarkashi, 2025), and the Teesta GLOF (Sikkim, 2023) demonstrate how extreme rainfall, glacier dynamics, and human interventions combine to produce high-impact disasters.

Furthermore, the interaction between extreme rainfall and glacial processes leads to the development of cascading hazards in the Himalayan region. Heavy precipitation can trigger landslides and slope failure, which may block rivers and form temporary lakes that can suddenly breach,

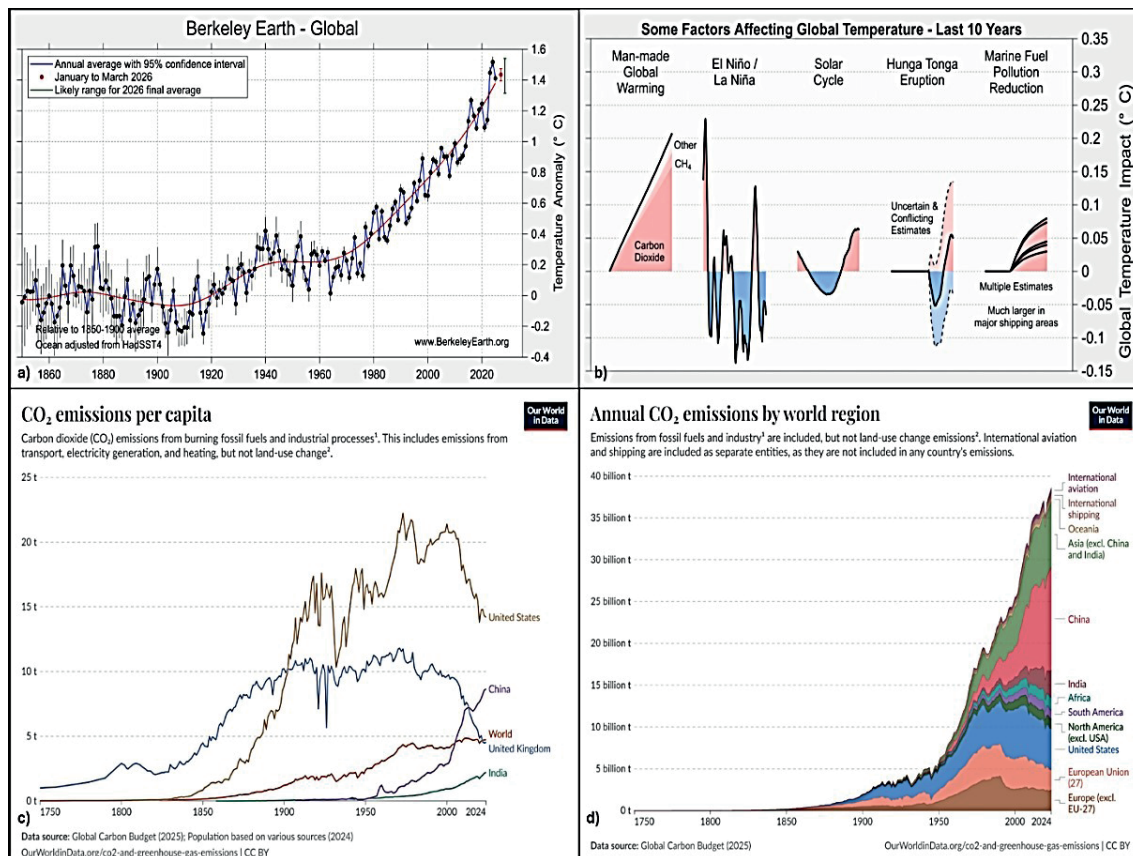


Figure 1: a) Global Average Temperature 1850-March 2026, b) Factors Affecting Global Temperature- last 10 years. (Source: Berkeley Earth). c) CO₂ emissions per capita, d) Annual CO₂ emissions by world region (Source: Global Carbon Budget 2025).

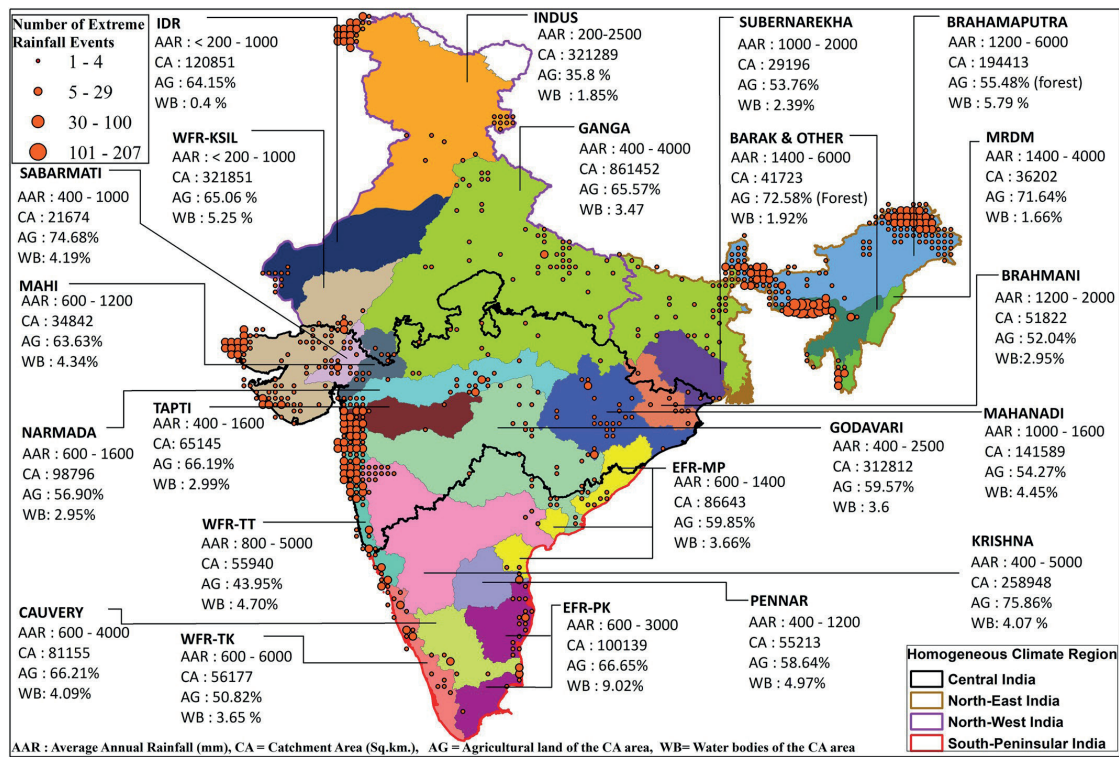


Figure 2: Overview of the Indian River Basins (IRBs). The red circle represents the hotspot as the number of extreme rainfall events at the 99.99th percentile (at the threshold value ≥ 300 mm day⁻¹ rainfall) in 1901-2019⁷

causing flash floods. At the same time, glacier retreat has led to the formation of unstable glacial lakes, increasing the risk of Glacial Lake Outburst Floods (GLOFs). These interconnected processes not only disrupt natural systems but also pose serious threats to infrastructure, ecosystems, and human settlements. Overall, climate change is transforming isolated environmental events into complex, multi-hazard systems. The combined effects of extreme rainfall, glacial instability, and rapid urbanisation are significantly increasing the vulnerability of the Himalayan and adjoining regions, making climate-resilient planning and sustainable development essential for reducing future risks.

Impact of Climate Change -Case studies

Extreme Rainfall, Landslides and Slope Instability: Dharali Case

Climate change increases atmospheric moisture due to rising temperature, resulting in more intense localised rainfall events (cloudburst-like conditions), particularly in the Himalayas, which are warming at about 0.06°C

per year⁸. Such extreme rainfall enhances slope instability in mountainous regions by saturating soil and weakening slope strength. A clear example is the Dharali disaster (5 August 2025) in Uttarkashi, where intense monsoonal rainfall in the Kheer Gad catchment triggered a high-velocity debris flow (~43 km/h). This event destroyed over 148 buildings, disrupted transport networks, and deposited a large debris fan (~20 ha) at the Bhagirathi River confluence. The disaster demonstrates the combined impact of extreme rainfall, slope instability, and fragile Himalayan geology. Steep terrain, loose debris, and fractured rocks made the slopes highly prone to landslides and slope failure, while human activities such as road construction, blasting, and deforestation further reduced slope stability. As a result, unstable slopes rapidly mobilised into debris flows, leading to severe infrastructure damage, sediment deposition, and loss of life. The Dharali event highlights how climate-induced rainfall, combined with increasing slope instability, can trigger cascading hazards such as landslides, flash floods, and debris flows in the Himalayan region.

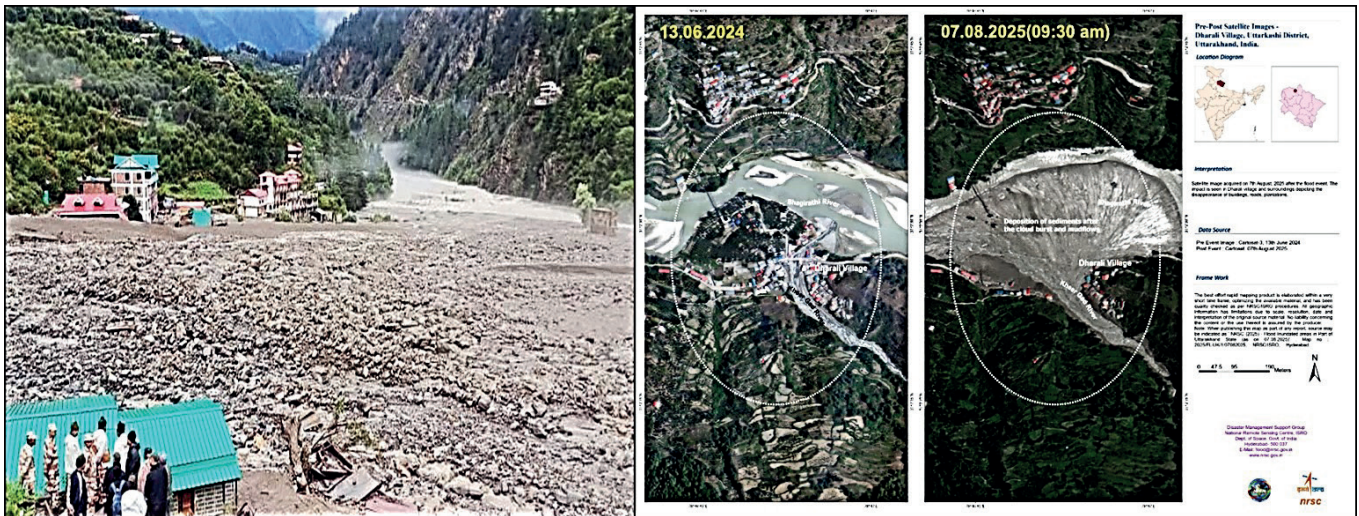


Figure 3: Flash floods in Dharali Village Uttarkashi, Uttarakhand (Source: ISRO).

Glacial Lake Outburst Flood (GLOF): Teesta Dam Failure

Climate change is accelerating glacier melting in the Himalayan region, leading to the formation and expansion of unstable glacial lakes. Rising temperatures accelerate glacier melting, resulting in the formation

and expansion of unstable glacial lakes. These lakes, often bounded by weak moraine dams, pose a high risk of GLOF, where sudden failure releases large volumes of water downstream⁹. The Teesta River disaster (October 2023) was triggered by a Glacial Lake Outburst Flood (GLOF) from South Lhonak Lake,



Figure 4: Glacial Lake Flood destroys Teesta-III Dam in Sikkim, brings wide-spread destruction. (Source: SANDRP)

which released a sudden surge of water, debris, and sediments downstream. The flood reached the Teesta Stage III dam, where the high-intensity flow exceeded its capacity and led to failure. The damage was caused by a combination of overtopping, extreme hydraulic pressure, and possible gate malfunction as well as delayed operation, which prevented controlled water release. Heavy sediment and debris likely blocked spillway openings, increasing stress on the structure. The failure resulted in severe downstream flooding, destruction of infrastructure such as bridges and roads, and loss of lives. It highlights how GLOFs combined with operational challenges can trigger cascading dam failure and large-scale impacts.

Urban Flooding: Yamuna Flood Case

Climate change increases urban flood risk by intensifying heavy rainfall, while rapid urban development reduces infiltration and overwhelms drainage systems. Urban flooding in Delhi (2023) is a significant concern due to the Yamuna River's role as a natural floodplain and

the city's rapid urbanization. The river's floodplain, designated as Zone O in the Delhi Master Plan, is crucial for flood mitigation and ecological balance. However, urban encroachments, infrastructure bottlenecks, and loss of wetlands have exacerbated flooding risks. The Yamuna river's discharge from the Hathnikund barrage was a major factor in the 2023 flooding events, crossing the 207-meter mark in Delhi and displacing thousands of residents. A major contributing factor was the Hathnikund Barrage upstream, which regulates and diverts Yamuna river's flow. During periods of heavy rainfall in the upper catchment (Himachal & Uttarakhand), the inflow to the barrage rises sharply. Since the barrage has limited storage capacity, excess water has to be released downstream. The event highlights how climate-induced extreme rainfall, river overflow, and unplanned urban development interact to increase flood vulnerability. It underscores the need for improved drainage planning, floodplain management, and climate-resilient infrastructure in rapidly growing cities.

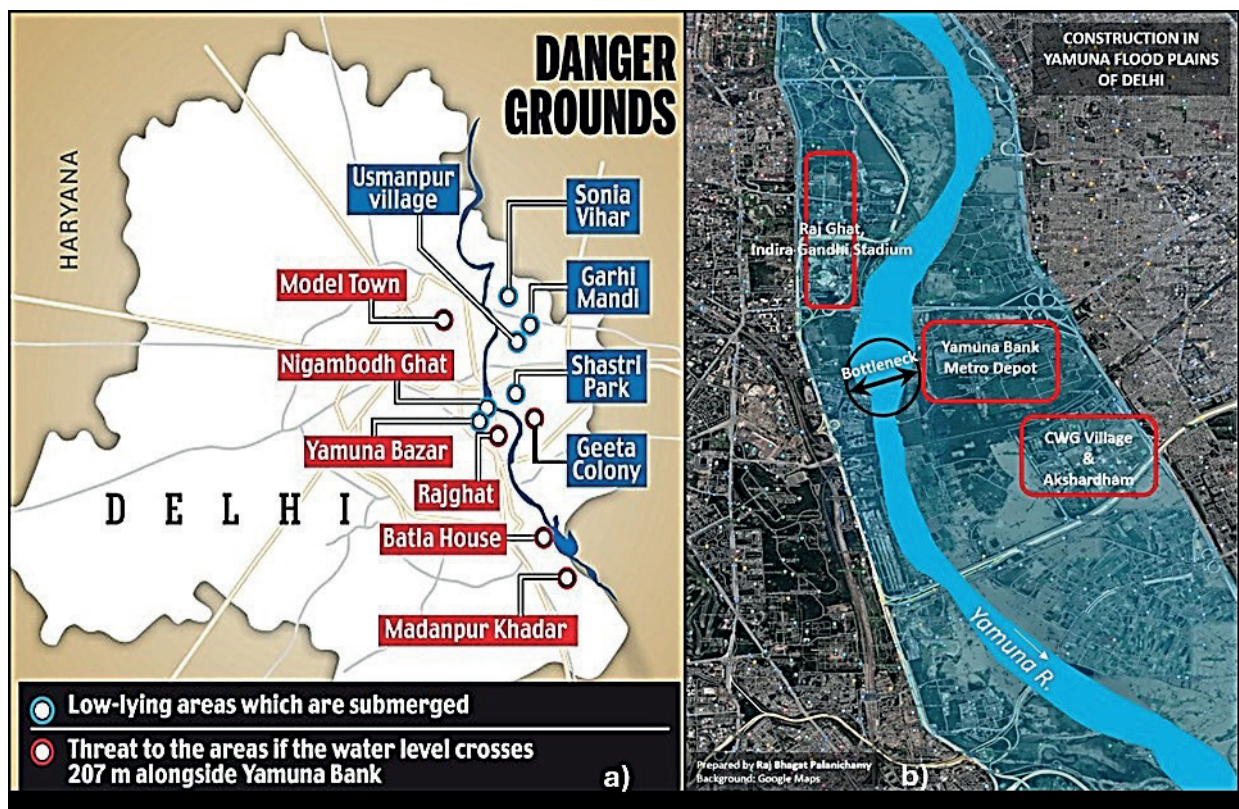


Figure 5: Yamuna Flooding 2023 (Source: a) Daily Mail India. b) Raj Bhagat Palanichamy)

Integrated Mitigation and Adaptation Framework

Dharali Case: Mitigation Measures

a) Structural Measures (Engineering Solutions)

- **Check Dams and Debris Retention Structures:** i) Construct a series of check dams in upstream channels; ii) Trap sediments and reduce debris flow velocity.
- **Slope Stabilisation:** i) Retaining walls, rock bolting, shotcrete, and geo-textiles; ii) Bioengineering (vegetation cover) to strengthen soil cohesion.
- **Drainage Management:** i) Surface and subsurface drainage systems to prevent water saturation; ii) Proper channelisation of runoff to avoid infiltration into slopes.

b) Non-Structural Measures

- **Early Warning Systems (EWS):** i) Rainfall threshold-based landslide prediction; ii) Real-time monitoring using remote sensing (SAR, IoT sensors).
- **Hazard Zonation and Land-use Planning:** i) Avoid construction in debris flow paths and floodplains; ii) Enforce strict zoning regulations in high-risk Himalayan zones.

c) Catchment Area Treatment

- **Afforestation and Vegetation Restoration:** Reduces soil erosion and improves slope stability.
- **Watershed Management:** Controlled runoff and improved infiltration balance.

d) Infrastructure Planning:

- Regulating infrastructure development in such a vulnerable region and preserving the natural floodplain would enhance the area's capacity to safely convey excess flow, thereby minimising the severity of disaster.
- Avoid excessive road cutting and slope undercutting,
- Use climate-resilient hill road design (benching + slope protection) and catch water drains above the hillside cuts.
- Restrict blasting and heavy excavation.

Teesta III Dam Failure: Mitigation Measures

The failure of the Teesta III dam in October 2023 was the result of a complex interplay of climatic, hydrological, and infrastructural factors rather than a single cause. The primary trigger was a Glacial Lake Outburst Flood (GLOF) from South Lhonak Lake, intensified by climate change - induced glacier melts and extreme rainfall, which led to a sudden surge of water into an already saturated catchment. That was further aggravated by high sediment and debris load, limitations in dam design and spillway capacity to handle such unprecedented inflows, and the cascading impact of multiple hydropower projects along the river.

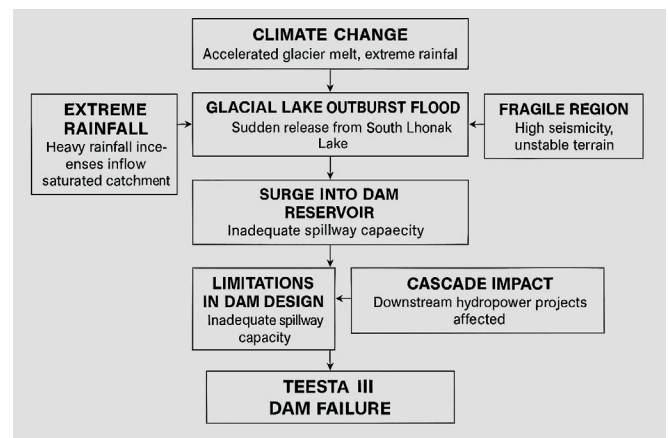


Figure 6: Flowchart depicting the sequence of events leading to the Teesta III Dam failure

Inadequate real-time monitoring and early warning systems, coupled with the dam's location in a geologically fragile Himalayan region, increased the vulnerability and severity of the disaster. Mitigation of such events requires a comprehensive approach, including continuous monitoring and controlled management of glacial lakes, climate-resilient dam design with enhanced spillway capacity, implementation of real-time monitoring and early warning systems, catchment area treatment through afforestation and upstream check dams, strict land-use regulation, and integrated basin-level planning. The event underscores the urgent need for adaptive engineering practices, advanced technology integration, and strong governance frameworks to address growing climate-related risks in mountainous regions.

As mentioned above, check dams can dampen the impact of floods in downstream areas. That effect had been clearly observed in HEC-RAS modelling, where two scenarios were analysed: one under natural (virgin) river conditions with no check dams and the other with three check dams.

As shown in Figure 7, dam breach analysis using HECRAS was carried out for flood conditions under these scenarios. In the absence of check dams, high velocity flow combined with heavy debris and sediment load leads to dam breaching. However, with the provision of three upstream check dams, a substantial portion of the debris, sediment, and flow energy is intercepted, thereby reducing the likelihood of dam failure.

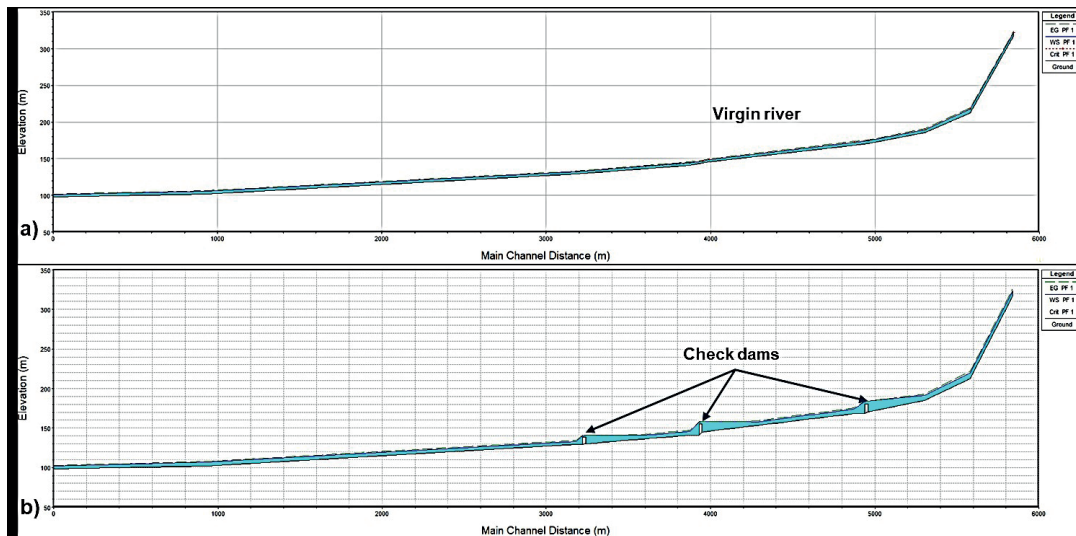


Figure 7: Dam Breach Analysis – HecRAS (a. Scenario 1 – Virgin River no check dam, b. Scenario 2 -Three Check dams)

Yamuna flooding: Mitigation Measures

Urban flooding in Delhi (2023) could have been mitigated through better planning, river management, and infrastructure improvements. Improved upstream water regulation at Hathnikund Barrage, with gradual releases based on accurate forecasts, could have reduced

peak flood levels. Strict enforcement of floodplain regulations (Zone ‘O’) and prevention of encroachments would have preserved the river’s natural storage capacity. Enhancing urban drainage through regular desilting and increased stormwater capacity, along with nature-based solutions like permeable surfaces and rainwater harvesting, could have reduced waterlogging. Overall, integrated river basin management, effective land-use control, and early warning systems are essential to minimise flood impacts.

Local-Level Risk Reduction Measures

Local mitigation measures focus on reducing site-specific risks arising from extreme rainfall, slope instability, and hydrological variability. These include afforestation to control erosion, proper drainage systems to manage runoff, and slope stabilisation methods such as retaining walls and terracing. Additionally, community awareness and early warning systems help improve preparedness against floods and landslides.

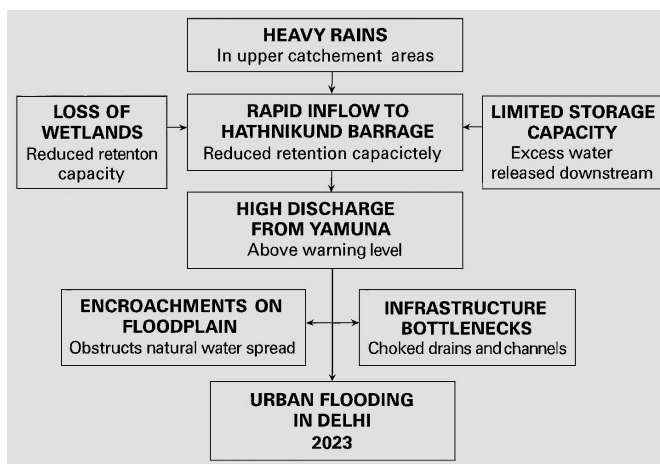


Figure 8: Flowchart illustrating the sequence of events leading to the 2023 Delhi flooding

Design Considerations for Climate-Resilient Infrastructure

From a design perspective, infrastructure should adopt climate-resilient approaches to withstand extreme events. Structures must consider probable maximum flood (PMF), increased rainfall intensity, and avoid development in flood and landslide-prone zones. Strict government regulations and restrictions on construction in such high-risk areas are essential. Designs should also include sediment management and safety measures for seismic and slope instability to ensure long-term reliability.

Policy and Regulatory Framework

Effective mitigation requires adherence to environmental policies and Environmental Impact Assessment (EIA) guidelines set by the Ministry of Environment, Forest and Climate Change (MoEFCC). Planning should promote climate-resilient infrastructure, sustainable water management, and disaster risk reduction, while aligning with frameworks like the National Action Plan on Climate Change (NAPCC) and Sustainable Development Goals (SDGs) to ensure sustainable development.

Compliance with Codal Provisions and Standards

All design and construction must follow codal

provisions and engineering standards to ensure safety. Relevant Indian Standards (IS codes), along with guidelines from the Central Water Commission (CWC) and Bureau of Indian Standards (BIS), should be applied for hydrology, structural, and seismic design to withstand extreme events like floods and landslides. However, due to the ever-changing climatic conditions, it is advisable to plan and design for the safety of the habitants (humans and animals) and plants as well, so that a habitable earth remains for future generations.

Landslide Susceptibility Mapping and Risk Assessment

A landslide susceptibility map is essential for identifying slope instability zones. In India, such mapping has already been carried out by ISRO through the Landslide Atlas of India (2023). It highlights high-risk zones based on factors like Multitemporal SAR interferometry for Landslide prediction, Debris Flow Modelling, UAV data in landslide modelling, Landslide Susceptibility Zonation (LSZ), Rainfall-threshold based landslide early warning, Mobile Application for landslide data collection (FLIM), to identify vulnerable areas. That information helps in safe planning, avoiding hazard-prone areas, and supporting targeted stabilisation and disaster management strategies.

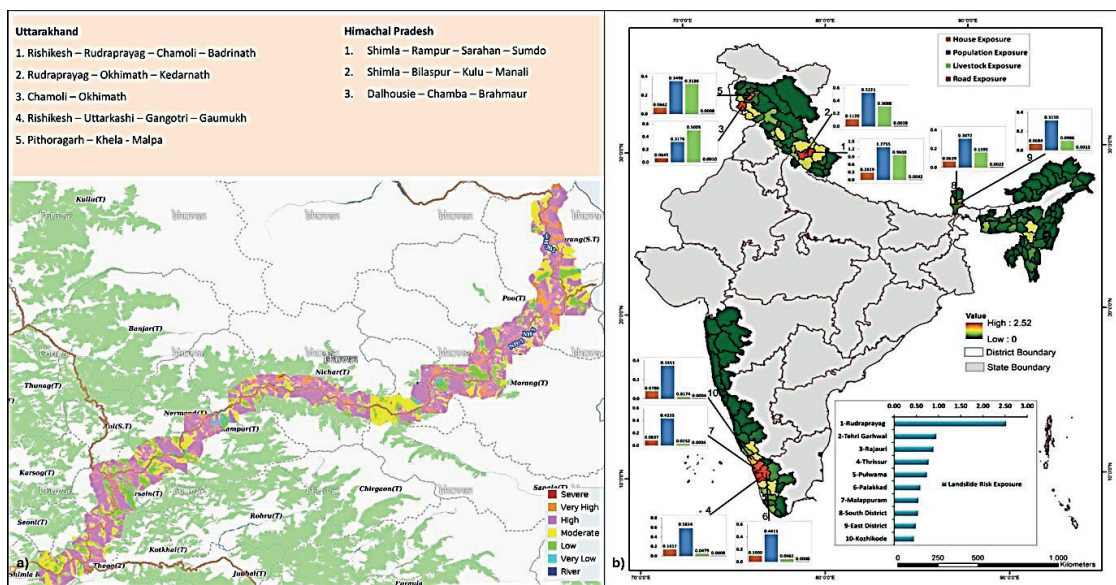


Figure 9: a) LSZ map for Shimla – Rampur – Sarahan– Sumdo Route. b) Socio-economic parameter risk exposure map, the contribution of each exposure element for the top ten landslide exposed districts is shown in bar diagram (Source: ISRO; Landslide Atlas of India (2023))

Conclusion

The case studies of the Dharali debris flow (2025), Yamuna flooding in Delhi (2023), and the Teesta III dam failure (2023) collectively underscore the increasing frequency and complexity of climate-induced multi-hazard events in both mountainous and urban environments. While each event was triggered by distinct mechanisms - intense rainfall, glacial lake outburst, and extreme river discharge - the underlying drivers, including climate change, geomorphological fragility, and unplanned anthropogenic interventions, remain common. These examples demonstrate that extreme hydro-meteorological events are no longer isolated but increasingly interconnected, often resulting in cascading impacts such as landslides, debris flows, flash floods, and infrastructure failure. The analysis highlights the critical gaps in existing planning frameworks, including inadequate land-use regulation, insufficient drainage and monitoring systems, and lack of climate-resilient design standards. Effective mitigation, therefore, requires an integrated and multidisciplinary approach that combines structural interventions, ecosystem-based solutions, real-time monitoring, and community preparedness. Furthermore, basin-scale planning, strict enforcement of environmental regulations, and adoption of advanced technologies are essential for reducing vulnerability. In conclusion, building resilience to future climate risks necessitates a shift from reactive disaster management to proactive, adaptive, and sustainable planning strategies that align engineering practices with ecological and climatic realities.

Acknowledgement

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Disclaimer:

This study is based on publicly available information and case-based analysis. While due care has been taken in the interpretation of data, the authors do not assume responsibility for any unintended inaccuracies. The views expressed are solely those of the authors.

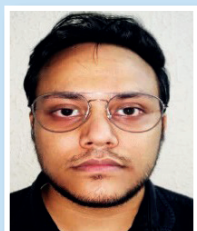
Slope Stability Analysis and Landslide Protection Measures – A Case Study



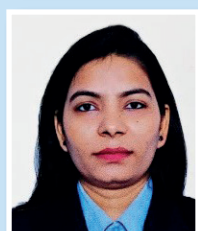
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Abstract

Landslides pose a significant threat to highway infrastructure in mountainous terrains, particularly under conditions of intense rainfall, weak geological formations, and anthropogenic slope modifications. This study presents a systematic approach for slope stability assessment and mitigation for a landslide-affected highway section in a hilly region of Kashmir. Detailed geotechnical and geophysical investigations, including borehole exploration and seismic refraction tomography, were conducted to characterise subsurface conditions comprising colluvial deposits over weathered rock. Slope stability analyses under static and seismic loading conditions indicated Factors of Safety of 1.393 and 1.124, respectively, satisfying the codal requirements. Stability analysis was carried out using limit equilibrium method as per Slide2 software, and stabilisation measures were designed using ground

anchors, slope drainage and erosion control system. Comparative evaluation highlights the superiority of ground anchors over self-drilling anchors in achieving reliable load transfer to competent strata. The study emphasises the importance of integrated investigation-based design and provides a practical framework for selecting cost-effective and technically sound slope protection measures for similar highway projects.

Introduction

A landslide is the movement of rock, soil, or debris down a slope due to gravity. It occurs when the material on a slope becomes unstable and moves downward. The term “landslide” encompasses five main types of slope movement: fall, topple, slide, spread, and flow. Common examples of landslides include rock falls and debris flows (mudflows).

Almost every landslide has multiple causes. It occurs when the forces acting downslope, mainly due to gravity, exceed the strength of the materials forming the slope. Landslides can be triggered by factors such as heavy rainfall, snowmelt, changes in water level, river erosion, groundwater fluctuations, earthquakes, volcanic activity, and human activities. Landslides can also occur underwater, known as submarine landslides, which can sometimes generate tsunamis and cause damage to coastal areas¹.

The expansion of National Highways in hilly and steep terrains, entailing extensive hill cutting, has increased slope instability and consequent landslides, including on older hill roads. Therefore, proper slope stabilization measures are required for the hillside as well as the valley side slopes, which may be implemented during construction or as remedial measures after landslide events. Various protection and mitigation measures such as vegetation, rockfall barriers, surface protection, and structural measures are available for slope stabilization. Topographic, geological, and geophysical investigations are carried out to assess slope conditions and select suitable mitigation measures. Although design guidelines are available in IRC SP 48² and IRC SP 106³, gaps still exist in identifying appropriate investigations and selecting suitable mitigation measures for different slope conditions. That often leads to inconsistency in investigation practices and the adoption of costly structural measures without adequate technical justification.

For ease of understanding and implementation by field Engineers and Consultants working for National Highway projects, it is, therefore, desirable to have a matrix of the site investigations to be carried out for different types of slopes as characterised by different geological formations, rainfall, snowfall, etc. Similarly, there is a need to have a matrix of cost-effective protection/ mitigation measures to be used for different types of slopes as determined based on the site investigations.

Methodology for preparation of Matrices

Three lists were developed to prepare the matrices: a) Site Inspection Parameters; b) Field Investigations, and c) Mitigation Measures. The matrices were then

prepared by intercorrelation of these lists. The details of preparation of these lists and matrices are given below.

- a) The site inspection parameters considered during investigation were:
 - Type of existing rock (soft, hard), boulder, soil, existing moisture
 - Rockfall and loose soil /debris movement
 - Additional surcharge due to avalanche or sudden slope failures of canopy
 - Traffic-induced live loads acting on the canopy and roadway
 - Cut slope

- b) Field Investigations list

The Consultants, based on their diverse experiences in the field contribute valuable insights into the various aspects of landslide investigations. Those included root cause analysis, geological mapping, slope stability assessment, and the evaluation of human and environmental impacts. The Consultants prepared a note of the various field investigation methodologies in common practice and their efficacy.

- c) Mitigation Measures list

By pooling their collective expertise, taking reference of the mitigation measures mentioned in the codes and common practices, an exhaustive list of mitigation measures is prepared. The Experts thereafter deliberate the efficacy of each system for various slope types and terrain.

Developing the Matrix: For building the matrices, the slope is categorised into three types, namely, Rock Slope, Debris/Soil Slope (refer IRC SP 106)³ and Talus Slope (i.e., a combination of Rock and Debris Slopes).

Literature Review

A study conducted in the Potrero Hill area of San Francisco reported significant surface and subsurface movements following the construction of a 20 m

highway cut and a rock-bolted retaining wall, which caused minor damage to nearby buildings and foundations. Movements were also observed in an unreinforced masonry railroad tunnel located approximately 10 m below the base of the wall. To mitigate the problem, a system of 30 reinforced concrete portals was constructed around and over the tunnel. The design was based on finite element analysis, and after their construction, the instrumentation results showed good agreement between the measured and predicted stresses and strains⁴.

This paper has two objectives: First, to examine the frequency and conditions of occurrence of landslides during earthquakes due to soil liquefaction. In addition to discussing individual events during particular earthquakes, it is necessary, in order to evaluate the severity of the problem, to compile a list of known slides in India, in which liquefaction has played a part. A review of the list shows that the landslides have invariably been initiated by liquefaction of saturated sandy soils in a loose to medium dense condition as a result of earthquakes varying in magnitude from 5.5 to 8.5 points on the Richter scale and at epicentral distances varying from several miles to hundreds of miles. This type of slide is indeed a serious problem in seismically active regions of the world. The second objective is to illustrate the importance of minor geologic and technical details in determining the occurrence and nature of landslides during earthquakes due to soil liquefactions^{5,6}.

Globally, a significant share of extreme landslides occur in mountainous areas during the rainy season⁷. The rainfall-induced landslides represent recurrent and highly destructive natural hazards, with severe and long-term consequences for human lives, livelihoods, critical infrastructure, and sustainable development^{8,9}.

The occurrence and intensity of landslides are driven by a combination of natural factors, including topography, geology, soil characteristics, and climatic conditions. In addition, climate change has increased these risks, contributing to an increase in the frequency and severity of rainfall-driven landslides⁹. Some activities

have caused depletion of green cover or obstructed natural run-off paths.

Unscientific Slope Cutting: Heavy machinery has been used to cut into the base of upslopes for highway widening. This unscientific slope alteration leaves top-heavy mountain faces completely unsupported.

Tunneling Failures: Repeated attempts by the National Highways Authority of India (NHAI) to build a bypass tunnel have repeatedly collapsed. Blasting and mechanical drilling have further shaken and fractured the already highly unstable mountain zone.

Deforestation: The rapid removal of natural forest cover and vegetation to make way for expansion has destroyed the root networks that historically held the loose topsoil together.

Debris flow on the existing rainwater channel obstructs natural flow path of rain water resulting in land slide.

In the Chittagong area, elevation strongly controls landslide susceptibility by influencing slope stability, rainfall distribution, and human activity. The elevation ranges from 100 m to more than 1000 m, creating distinct risk zones. Steep upper slopes (25°–45°) are highly unstable, while mid-elevation zones (100–300 m) with loose sediments are vulnerable to monsoon-induced landslides. Higher elevations receive heavy rainfall (up to 3810 mm), leading to increased soil saturation, whereas lower elevations are affected by landslide deposition and urbanisation. The elevation map used in this study was prepared at a 30 m × 30 m resolution. Elevation is considered a primary factor in landslide susceptibility and housing vulnerability mapping¹⁰.

Slope is one of the most important factors in the analysis of landslide susceptibility, because it directly affects gravity and slope stability, with the steeper slope being more prone to landslide. The study analysed the slope, a measure of the change in altitude over a distance, by using a slope map with a resolution of 30 m for the study area¹¹.

Summary from Literature Review

Based on the literature review surveys, the following points emerge:

- In a rock bolted retaining wall in the Potrero Hill area of San Francisco, surface and subsurface movements of sufficient magnitude to cause minor building and foundation damage were observed directly above and adjacent to the wall.
- A significant share of extreme landslides occur in mountainous areas during rainy season.
- Rainfall-induced landslides represent recurrent and highly destructive natural hazards, with severe and long-term consequences for human lives, livelihoods, critical infrastructure, and sustainable development.
- Elevation has a critical influence on the susceptibility to landslides by affecting the stability of slopes, rainfall patterns and human activity. The varying altitude of the area (100 m to > 1000 m) creates different risk zones
- Steep upper slopes (25–45 degrees) are unstable, while medium-elevation areas (100–300 m) with loose sediments are vulnerable to monsoon landslides.

Objectives and Scopes

Landslide occurred on the hilly area of Kashmir during which the existing canopy was damaged and the service road was washed out. Analysis of remedial measures were studied and following objectives were adopted for analysis:

- Ensure long-term slope stability using reinforced fascia, anchors, and erosion control measures.
- Safeguard structural integrity of the canopy against landslide or debris-induced loads.
- Mitigate surface erosion and sub-surface slope movement during heavy rainfall or extreme events.
- Protect adjoining valley slopes from progressive degradation and scouring.
- Maintain roadway/ canopy serviceability under critical loading conditions.
- Design accounts for seismic and adverse hill slope

instability scenarios.

- Technical feasibility ensured for weathered rock and debris-covered slopes.
- Integrated approach reduces maintenance and enhances long-term resilience.

Based on these objectives, the following scope is finalised in this present study:

- Identify the preliminary causes of landslides.
- Visual inspection
- Geotechnical and Geophysical investigations.
- Identify suitable protection measures
- Conducting final design
- Conclusion.

Case Study

The project location is characterised by a steep hill slope with weathered and weak rock strata, posing a risk of slope instability and debris movement, particularly during adverse weather conditions and seismic events. The presence of an existing canopy structure necessitates a robust and carefully engineered slope protection and strengthening system to safeguard against:

- Rockfall and loose soil/ debris movement
- Additional surcharge due to avalanche or sudden slope failures of canopy
- Traffic-induced live loads acting on the canopy and roadway



Figure 1: Typical Photograph of Slope Failure

Major Factors Contributing to Failure

- Failure of the embankment and adjoining hillside slopes in the vicinity of the canopy structures.
- Significant loose debris accumulation and ongoing valley side erosion. Embankment washout has led to deposition of loose soil on the slopes, creating unstable conditions. That increases the risk of slope failure and landslides, requiring immediate and robust stabilisation and protective measures.
- The observed hill slope instability, characterised by deep rain-induced erosion gullies and removal of overburden material, may trigger large-scale slope failure and mass movement. This poses a risk to the stability of the canopy structure; therefore, immediate slope stabilization and erosion control measures are recommended.

Design Basis and Loading Considerations

The design of the slope stabilisation and strengthening system was carried out considering the following critical load cases:

a) Maximum Canopy Load: 400 kN

- ◇ This includes the self-weight of the canopy structure
- ◇ Additional load due to avalanche impact and accumulation of loose soil/ debris during critical hill slope failure scenarios

b) Distributed Surcharge Load: 100 kN

- ◇ Representing muck, loose debris deposition along the slope and canopy
- ◇ Superimposed traffic live load acting on the roadway

These load combinations were considered to represent the most critical and governing conditions for design.

Geotechnical Basis of Design

A detailed, location-specific investigation of the prevailing site conditions and subsurface strata were

carried out. The scope of investigations undertaken are summarised herein.

Geotechnical Investigation (GTI)

Geotechnical Investigation (GTI) including borehole drilling, sampling, laboratory testing, and evaluation of engineering properties of subsurface materials. A total of five (05) location-specific boreholes of adequate depth were executed to ensure comprehensive analysis of the entire hill and valley stretch, including characterisation of the in-situ subsurface strata.

Among the boreholes conducted, the most critical borehole locations, based on subsurface conditions and geotechnical parameters encountered, were primarily considered and incorporated in the design analysis and subsequent recommendations.

Geophysical Investigation (Seismic Refraction Tomography – SRT)

Geophysical Investigation (Seismic Refraction Tomography – SRT) was to assess subsurface stratification and depth to competent strata. It is a method used to determine subsurface stratification and depth to competent strata by measuring the velocity of seismic (P) waves through soil and rock layers. Since wave velocity increases with material density and stiffness, it helps distinguish loose overburden, weathered rock, and hard rock formations.

The SRT provides (Figure 2) a continuous subsurface profile across the hill and valley section, which is crucial for determining suitable foundation depths, assessing slope stability, and recommending appropriate stabilization measures.

Key Geophysical (SRT) Observations

Velocity of seismic waves,

- Loose to medium soil, $V_p = 425\text{--}600$ m/s
- Intermediate $600\text{--}900$ m/s
- Limited & discontinuous $V_p > 1200$ m/s

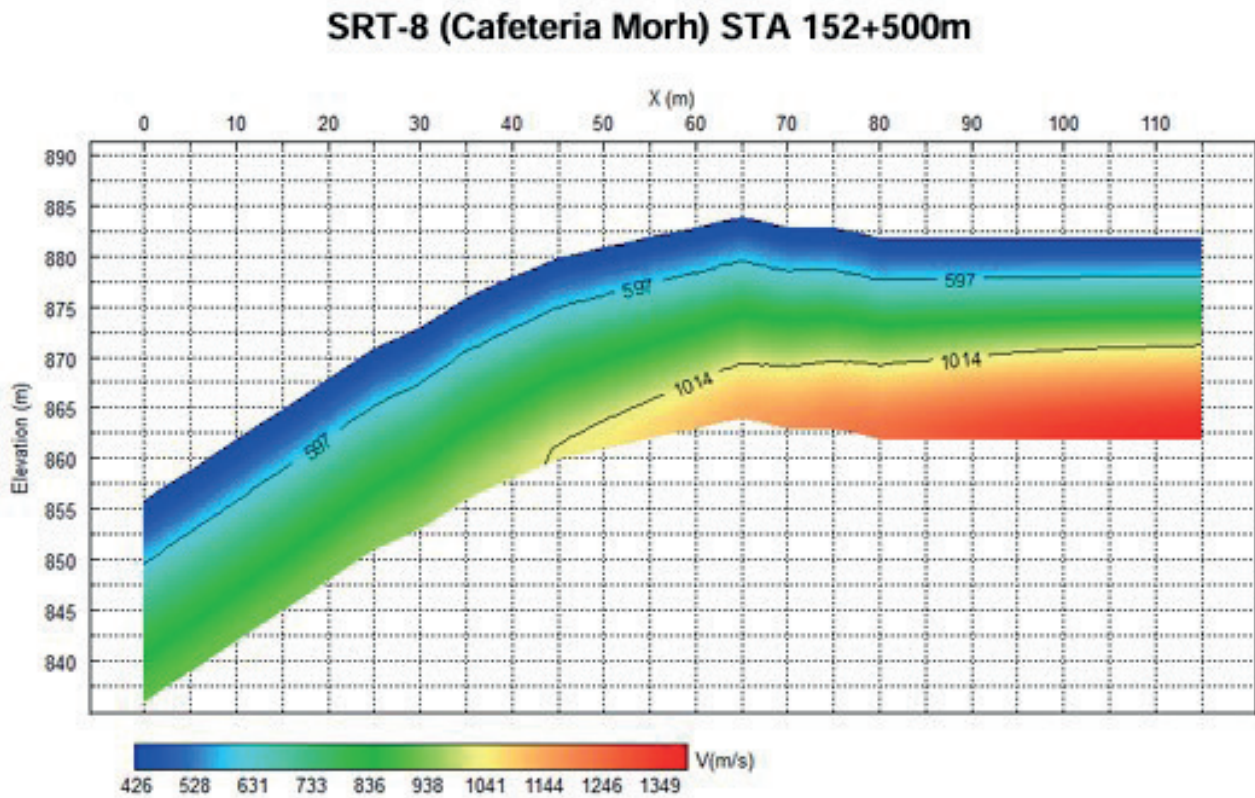


Figure 2: SRT along the Failure Location

The detailed SRT profile illustrates the variation of seismic wave velocities with depth, clearly identifying different subsurface layers. Since wave velocity increases with material density and stiffness, the test effectively distinguishes loose overburden, weathered rock, and competent rock strata.

This investigation provides a reliable basis for assessing subsurface conditions, foundation depth, and slope stability at the location.

Geological Survey and Detailed Mapping

A geological survey and detailed mapping of the entire stretch was carried out for the said location involving systematic field examination of surface and near-surface geological conditions to identify the lithology, structural features, discontinuities (joints, fractures, faults), weathering patterns, and geomorphological characteristics.

The rock mass encountered at the project site primarily consisted of greyish coloured quartzitic phyllite, which is a medium to low grade metamorphic rock characterized by its fine-grained texture and well-developed foliation. The foliation is thinly spaced, indicating frequent planes of weakness along which the rock may preferentially split or fail. The material strength of the rock was classified as weak to medium strong, suggesting varying competence across the exposed sections. The rock mass was observed to be highly to moderately weathered, which implied that both mechanical and chemical weathering processes have significantly altered the original rock fabric and reduced its engineering strength, particularly near the surface and along discontinuities.

The chronic landslides are caused by a deadly combination of highly fragile geological formations, severe weather conditions, and disruptive human engineering. A massive, regionally critical tectonic fault system passes near the project area.

This investigation helps in understanding slope-forming materials, rock mass behaviour, groundwater conditions, and potential instability zones, thereby providing essential inputs for foundation design, slope stabilisation measures, and overall geotechnical planning.

Key Geological Observations

The slope is primarily composed of weathered metamorphic rock overlain by a substantial thickness of colluvial deposits.

Inadequate surface and subsurface drainage, leading to saturation of the overburden material, significantly contributes to slope instability by reducing shear strength and increasing the likelihood of mass movement.

The design has been developed based on the available Geotechnical Investigation (GTI) report, with particular reference to the weakened Borehole-3 obtained from the geotechnical properties of three bores drilled during preparation of the report which governs the critical subsurface conditions at the site. The following aspects were considered by comparing the same with the SRT data and detailed investigations carried out at the location, to determine (conservative) design parameters for design:

- Subsurface stratification comprising overburden soil, highly to completely weathered rock, and underlying competent strata
- Engineering properties of soil and rock layers as derived from laboratory and field investigations
- Groundwater conditions as reported in the GTI

All design parameters adopted were conservative and reflected the weakest encountered strata to ensure safety under worst-case conditions.

Slope Stability Analysis

Comprehensive slope stability analyses were carried out using **SLIDE 2 software**, considering both **static**

and seismic loading conditions. The analyses include:

- Global slope stability checks
- Local stability of retained and reinforced zones
- Effect of canopy loads, debris surcharge, and traffic loads

The design satisfies the following **minimum Factors of Safety (FoS)**:

- **Static condition:** $\text{FoS} \geq 1.30$
- **Seismic condition:** $\text{FoS} \geq 1.10$

All potential critical slip surfaces and failure mechanisms have been evaluated, and the results demonstrate adequate stability under both loading scenarios. Factors of Safety were found to be 1.393 and 1.124 for the static and dynamic cases, respectively.

Slope Protection and Re-Strengthening Scheme

Considering the prevailing subsurface and slope conditions, two (02) types of retaining/ slope protection and re-strengthening solutions were proposed along the valley side, categorised under two distinct cases based on site-specific requirements, availability of space and stability considerations.

Case-1: Design of Existing Slope Protection System for Strengthening of Valley-Side Slope Considering Canopy Loads within the Available Functional Road/ Approach width of 3.0 m.

Formation of an approximate cut slope ranging between 70°-75°, with full-face protection using a systematic arrangement of Slope Drainage Arrangement (SDA) along the fascia, combined with installation of pre-stressed ground anchors to provide active stabilisation of the valley slope against horizontal thrust and lateral movements.

Case-2: Design of Existing Slope Protection System for Strengthening of Valley-Side Slope Considering Canopy Loads with no available Functional Road or

washed off valley section.

The existing critical valley slope to be stabilised by removing loose and unstable debris, followed by installation of suitable SDA along the slope fascia using tripod or suspended methods based on site constraints and construction feasibility.

In addition, two SDA units to be provided at the canopy foundation levels of suitable depths to enhance anchorage and resistance against any horizontal thrust and lateral movements.

Design Compliance and Safety

All critical design checks were carried out in accordance with relevant IRC guidelines, codal provisions, and standard geotechnical engineering practices. The proposed system ensures:

- Adequate safety against slope failure under extreme loading conditions
- Protection of the existing canopy and roadway infrastructure
- Long-term durability and serviceability of the stabilization system

Construction Methodology

The adopted slope protection scheme comprised a top-down stabilization approach, integrating structural and geotechnical measures, including:

- 1) Ground/ rock anchors to be installed along the centreline of the 3.0 m wide roadway, aligned longitudinally with 10° incline along the existing canopy structure, at a spacing of 5.0 m c/c along the length of the canopy structure.
- 2) Ground/ rock anchors to be embedded up a designed length of 18.0 with free length of 7m, to provide sufficient bonding and strength to be achieved from the rocky strata, to resist primary vertical and lateral thrusts.
- 3) That should be followed by the installation of SDA

on the slopes to designed lengths of 22 m and 20 m respectively and to be drilled, installed in a continuous and systematic pattern throughout the slope.

- 4) Install PVC drainage pipes at suitable interval and spacing (as per design) to ensure effective surface and subsurface drainage and to relieve pore water pressure within the slope mass from top to bottom, one by one, along the slope.
- 5) Final protection system comprised installation of slope erosion control fascia integrated with green erosion control mats, followed by provision of double-twisted (DT) wire mesh securely anchored using U-pins, to effectively mitigate surface erosion and prevent soil loss during intense rainfall and downpour events.

Result and Discussion

The SRT-8 profile at Cafeteria Morh (≈115 m length) showed P-wave velocities ranging from 425 to 1350 m/s. Low velocities (425–600 m/s) indicate loose to medium dense soil near the surface, underlain by medium dense to dense soil (600–900 m/s). Higher velocities (900–1200 m/s) at depth represent dense soil to highly weathered rock, with localised zones exceeding 1200 m/s. The subsurface conditions indicated a thick upper weak soil layer over denser material, and slope stability was mainly controlled by the thickness of that weak layer, with the left and central portions being more prone to rainfall-induced instability.

The geotechnical investigation (borehole data) indicated that the subsurface profile mainly consisted of overburden/ fill material in the upper layers followed by highly fractured to moderately fractured rock at depth. The upper strata showed very low Total Core Recovery (TCR) and RQD values, indicating poor rock mass quality and loose soil conditions near the surface. With increasing depth, TCR, RQD, cohesion, and UCS values generally improve, indicating comparatively stronger and less fractured rock formations. However, most boreholes show highly fractured rock with low RQD values, suggesting overall poor to fair rock

mass conditions in the study area. These subsurface conditions indicate weak upper strata over fractured rock, which may significantly influence slope stability and foundation performance in the area.

Conclusion

Based on the detailed design analyses, slope stability evaluations, and geotechnical considerations, the slope protection and strengthening scheme proposed for the section, were found to be technically sound and structurally adequate.

The design satisfied all governing stability and safety requirements under both static and seismic conditions and provided a reliable solution for the protection of the existing canopy and roadway against future slope-related hazards.

The design satisfied the governing stability criteria under both static and seismic loading conditions and provided a reliable long-term solution for safeguarding the existing canopy structure and adjoining roadway against potential slope instability hazards.

Geotechnical interpretation indicates that the existing canopy stability suggests the presence of competent rock strata beneath the foundation level, presently overlain by accumulated debris /muck deposits. However, installation of Self-Drilling Anchors (SDA) exceeding 12 m in length is likely to encounter constructability limitations, and the anchors may not effectively penetrate up to the underlying competent rock layer.

Hence, in this case, SDAs have been considered with high-pressure grouting to improve bond strength and pull-out resistance within the overburden strata. Nevertheless, from a structural and geotechnical reliability perspective, provision of ground anchors along the slope fascia is a more robust solution. Ground anchors can be socketed directly into competent rock, thereby providing superior anchorage, improved load transfer mechanisms, and enhanced overall stability to both the canopy structure and the roadway.

Accordingly, installation of ground anchors along the fascia is assessed to be the technically preferable and more dependable stabilisation measure for the prevailing site conditions.

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Brahmaputra-Tista-Ganga Link for Water Transfer, Hydropower Development & Flood Control



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Introduction

India possesses only 4% of world's water resources to feed its 17.8% of the world's population. Most of the water resources in India lie in the north and north-east India due to the high rainfall in the region. The Brahmaputra-Ganga link was envisaged for transfer of excess water from the Brahmaputra and Ganga basins to the drought prone areas in the south and south-west

regions of the country (Table 1). Obviously, that would result in flood control due to reduction of flood peaks in the surplus basins. Apart from water supply, it would also help in hydropower development. In this paper, the author has discussed details of the scheme proposed by the Government of India. The basins having less than 1000 m³ of water available per year are termed as scarce basins.

Table 1: Surplus and Scarce Basins in India

Surplus Basins		Scarce Basins	
Basins	Per Capita Water Availability in M ³ Per Year	Basins	Per Capita Water Availability in M ³ Per Year
Brahmaputra Basin	18,417	East flowing Rivers between Mahanadi and Pennar	919
Barak Basin	7,646	Cauvery	666
East flowing Rivers between Tadri and Kanyakumari	3,538	Pennar	648
East flowing Rivers between Tapi and Tadri	3,194	West flowing River Basin of Kutch and Saurashtra including Luni	631
Narmada	2,855		
Brahmani-Baitarani	2,696		
Mahanadi	2,546	East flowing River Basins between Pennar and Kanyakumari	383
Godavari	2,026		
Indus	1,757		
Ganga	1,473		

Historical Development of the National Water Grid

The National water grid for effective management of flood and drought situations in India was proposed by eminent persons in the past - Sir Arthur Cotton, Dr. K L Rao, Captain M N Dastur, Parashar and many others. But the proposals were rejected as they were found to be techno-economically not viable at that time. Former Prime Minister Indira Gandhi set up the National

Water Development Agency (NWDA) in 1982 to study the possibility of water transfer from surplus basins to drought prone areas. The NWDA proposed the National Perspective Plan (NPP) consisting of 14 river links under the Himalayan component and 16 river links under the peninsular component as shown in Figure-1 (in red colour). Links 1 to 14 lie in the Himalayan regions and 15 to 30 lie in the peninsular regions of the country.

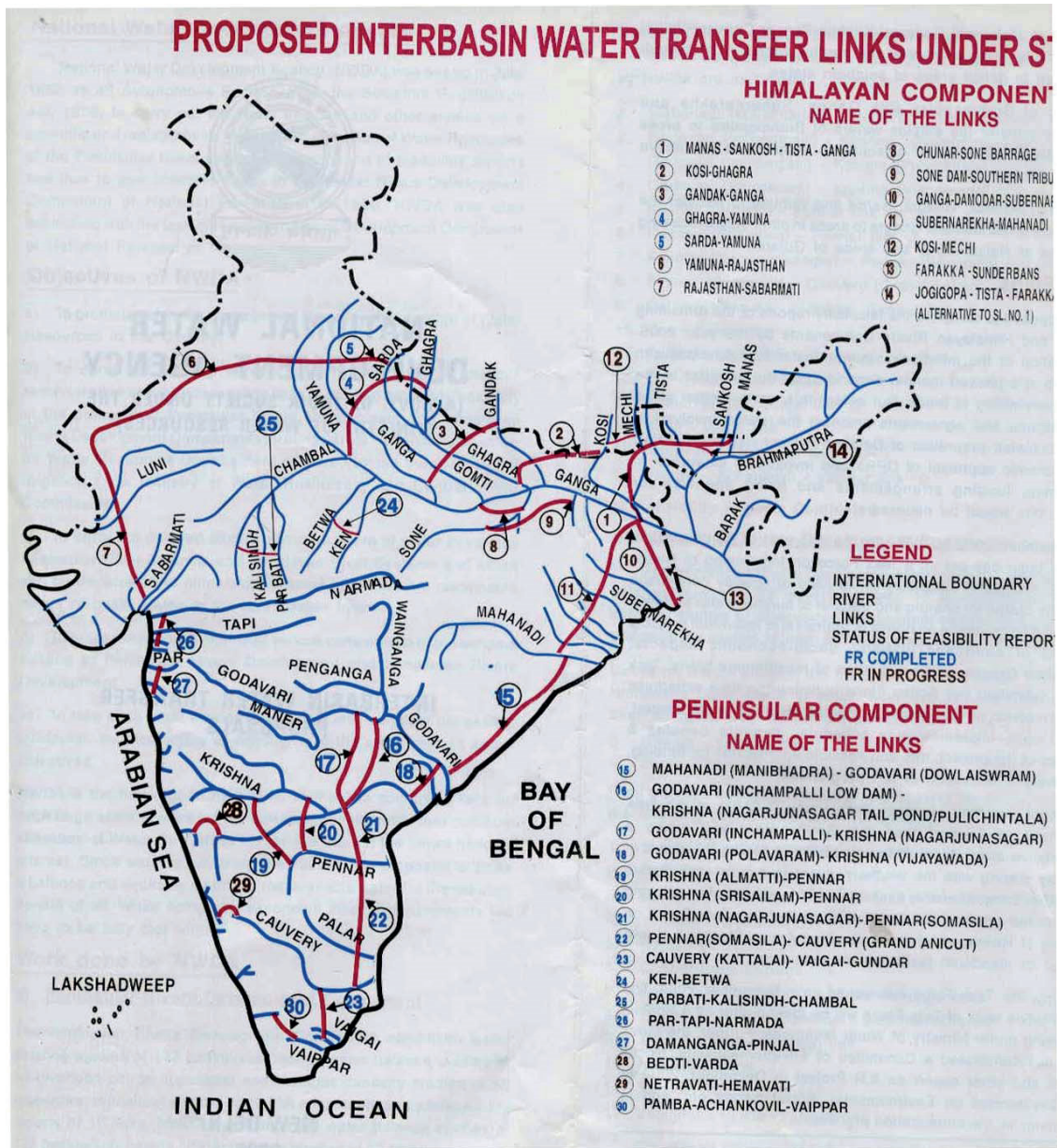


Figure 1: Interlinking Indian Rivers (Link canals are shown in red colour)

After the Supreme Court of India ordered completion of the project in a period of 15 years by 2012, a Task Force was appointed by Former Prime Minister Vajpayee who led the NDA Government to execute it. The National Commission of Integrated Water Resources Development (NCIWRD), however, was not in favor of long-distance river links in the first stage and suggested constructing only the short distance river links at that time. The UPA Government wanted to hear the views of all the stakeholders and experts (including the author) before taking a final decision. A Committee of Parliament was formed under the chairmanship of Sh. Sambashiva Rao, M.P., to hear the views of stakeholders from diverse disciplines. Most of the short distance links are either completed or in the process of completion.

Brahmaputra-Ganga -Link

Since most of the surplus water lies in the Brahmaputra-Ganga basins, National Water Grid-1 was recommended by NWDA (Figure 2 in red colour) for the following reasons:

- Reduction of floods in Ganga-Brahmaputra basins causing recurring damages
- Transfer of excess water in the surplus basins to drought prone areas in the south and the west
- Generate hydro-power available in the basins (Table- 2)
- Provide navigation facilities in the river basins
- Water supply for domestic use, industry, irrigation, etc.
- Employment opportunities in rural areas
- Resolving water dispute between India and Bangladesh for sharing Ganga water

Hydro Power Potential of India

Table -2 gives the Hydro-Power potential in the different River Basins in India. It may be noticed that most of the potential lies in the Brahmaputra and Ganga basins. The state of Arunachal Pradesh with a major potential of about 50,000 MW has developed only 5-6% of hydropower so far.

Table 2: Hydropower Potential in Different River Basins in India

Basins	Hydropower Potential (MW)
Indus Basin	33,832
Ganga Basin	20,711
Central Indian River system	4,152
Western Flowing Rivers of southern India	9,430
Eastern Flowing Rivers of southern India	14,511
Brahmaputra Basin	66,065
Total	1,48,701

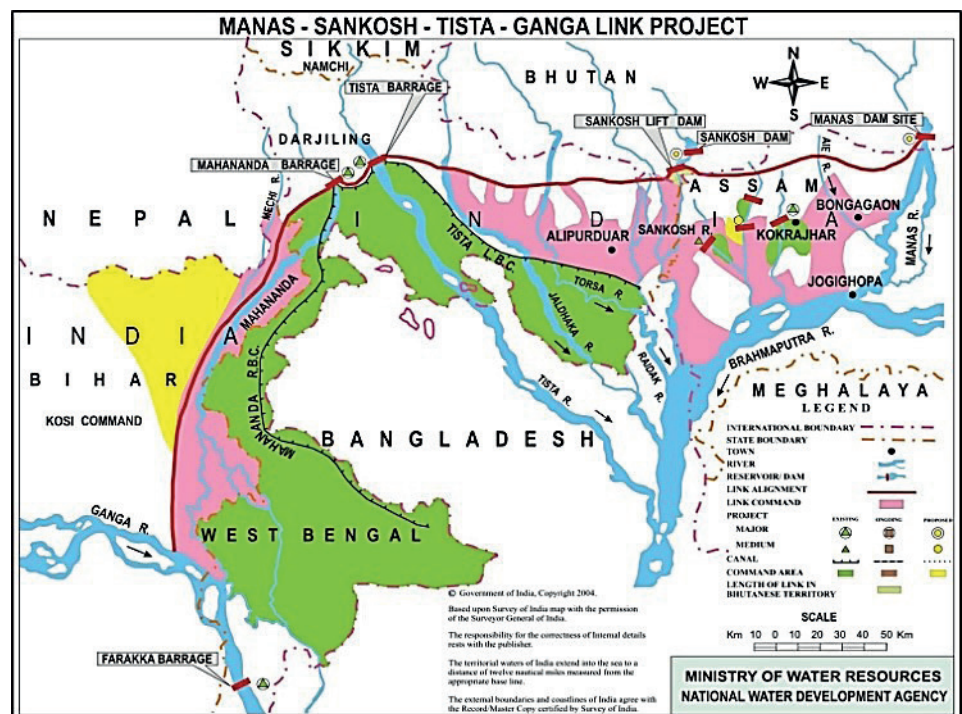


Figure 2: Brahmaputra-Ganga Link Via Tista River

Original and Revised Proposal for Link Canal-1 (Figure 1)

India's original proposal consisted of construction of a barrage 2460 m long across the Brahmaputra River at Jogigopa in Assam with a link canal 324 km long, 274 metre wide and 9 metre deep (passing mostly through Bangladesh) up to a point upstream of the Farakka barrage in West Bengal. It was the shortest link between the Brahmaputra and the Ganga. It had no lift component, and the flow was entirely through gravity. However, the proposal was rejected by the Bangladesh Government due to political reasons. In its revised proposal, the Government of India decided to connect Jogigopa barrage with Tista and Ganga bypassing Manas and Sankosh rivers. The proposal envisaged construction of several large dams on tributaries of River Brahmaputra, namely, Sankosh, Manas, Subansiri, Dihang, and Lohit rivers (Figure 3) with a view to augment dry weather flow in the

Brahmaputra at Jogigopa barrage. Eventually, Link-1 would be connected to links 10, 13 and 15 of NPP (Figure 1). The eastern foothills of the Himalayas supplement the dry season flow of the Brahmaputra at Jogigopa. The idea is to divert water to the Ganga basins from February to April when water is abundant in the Brahmaputra basin and scarce in the Ganga basin due to late arrival of Monsoon in Ganga basin as compared to Brahmaputra basin. Dihang and Subansiri reservoirs were estimated to lower the flood peak in Bangladesh by 1.3m. The Tipaimukh dam (completed), shown in Figure 3, reduces the flood in the Meghna basin in Bangladesh, especially in Dhaka. In the revised plan, Link-1 passes through the 32 km narrow belt (known as the Chicken Neck) which separates India from Nepal and Bangladesh (dotted line in Figure 3). It is proposed to lift the Brahmaputra water from Jogigopa barrage to the Tista barrage from where water would flow by gravity to Farakka barrage on Ganga River.

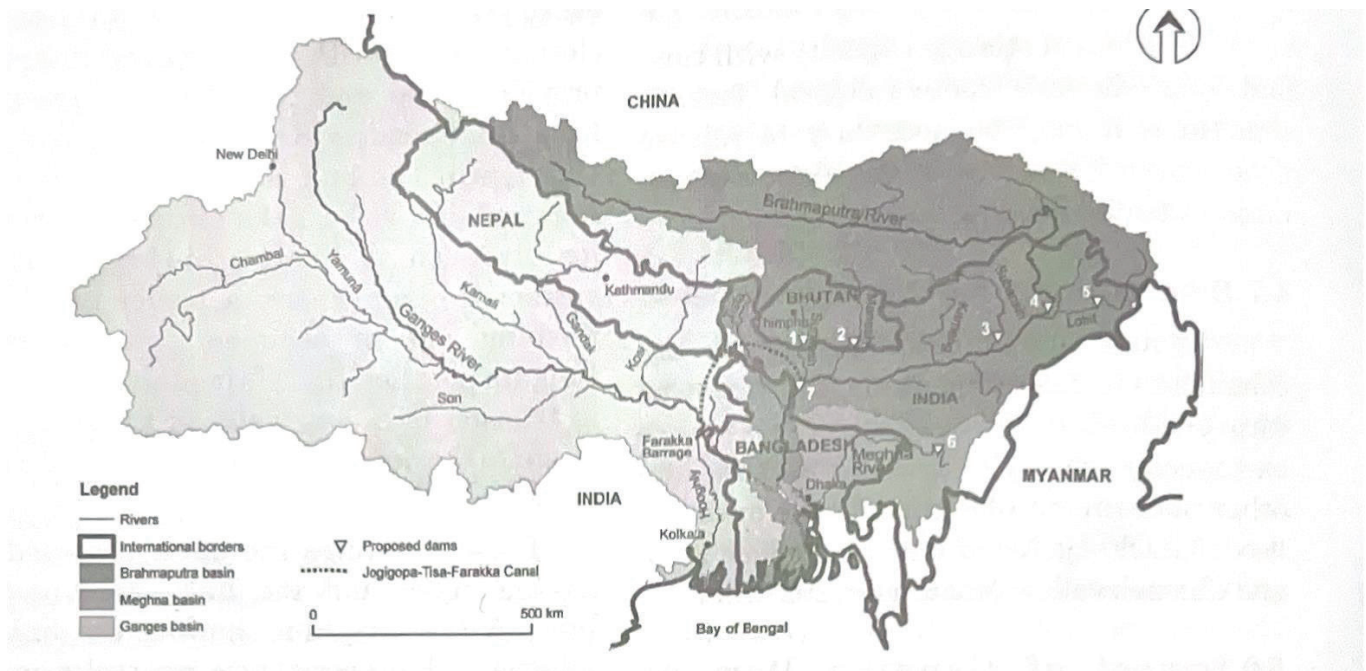


Figure 3: Revised Plan of Brahmaputra-Tista- Ganga Link Canal (Dotted line) with Dams on rivers Shankosh (1), Manas (2), Subansiri (3), Dihang (4), Lohit (5), Tipaimukh (6) and Jogigopa (7)

Urgency to Execute Brahmaputra-Ganga Link

China has constructed several dams on the Yarlung-Tsangpo river (name of Brahmaputra River in Tibet) and proposes to construct the Gangtuo dam, which would be the world's biggest dam, for diversion of Brahmaputra flow to drought prone areas in Northern China. Unless the proposed Brahmaputra-Ganga link with all the proposed dams is executed on a priority basis, there may not be any dry weather flow available for India and Bangladesh. A treaty must be executed immediately between China, India and Bangladesh like the treaty between India and Bangladesh over sharing of Ganga water after construction of the Farakka Barrage. Similar treaty exists between China, Myanmar, Laos, Thailand and Cambodia for sharing of water of the Mekong River that originates in China.

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Integrating Flood Risk and Climate Resilience in Critical Infrastructure Planning and Design



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Abstract

Climate change and rapid urbanisation are significantly increasing flood risks to critical infrastructure systems worldwide, necessitating a shift from traditional planning approaches to more resilient and adaptive frameworks. This article emphasises the importance of the integration of climate resilience and flood risk management into the planning and design of critical infrastructure, with a focus on long-term sustainability and operational reliability.

It highlights the importance of systematically identifying diverse sources of flood risk, including fluvial, pluvial, coastal, and groundwater flooding through site investigations and data-driven assessments. The article emphasises the need to incorporate future uncertainties arising from anthropogenic changes, such as land use transformation and urban development, alongside evolving climate conditions informed by advanced modelling frameworks and projections.

Hydrological and hydraulic modelling techniques are presented as essential tools for quantifying flood hazards, supported by emerging technologies such as artificial intelligence and scenario-based analysis. The article further discusses the role of sustainable drainage systems, nature-based solutions, and risk-informed design strategies in mitigating flood impacts. A structured approach to assessing asset vulnerability,

criticality, and required standards of protection is also outlined, enabling prioritisation of resilience measures.

Finally, the article underscores the importance of integrating adaptive design, operational planning, and stakeholder collaboration to ensure infrastructure systems can withstand, recover from, and adapt to changing flood risks. Overall, the article advocates for a holistic, forward-looking approach to infrastructure development that strengthens resilience against climate-induced flood hazards.

Introduction

Climate change is increasingly shaping the planning, design, and management of critical infrastructure systems across the globe. Urban development and major infrastructure assets such as airports, transportation networks, utility networks and communication systems are highly vulnerable to climate-induced hazards, particularly flooding.

India and other countries of the World have witnessed several extreme flood events which caused major disruptions to life and operation of infrastructure assets contributing to significant economic loss. These risks are intensifying due to changes in precipitation patterns, rising sea levels, and increasing urbanisation. As a result, traditional infrastructure planning approaches are no longer deemed adequate.

Climate resilience refers to the ability of infrastructure systems to anticipate, absorb, adapt to, and rapidly recover from climate-related disruptions. Integrating climate resilience and flood risk considerations into infrastructure planning and design is therefore essential for ensuring long-term service Reliability, Economic Stability, and Public Safety.

Identifying Sources of Flood Risk

During the feasibility or preliminary planning stage of infrastructure projects, it is essential to systematically identify and characterise all potential sources of flood risk that may affect the site. These sources typically include fluvial flooding from rivers and drainage channels (nallahs), pluvial flooding due to surface water accumulation from intense rainfall, coastal flooding driven by tidal influences, storm surges, and wave action, as well as groundwater-related flooding in low-lying areas.

A combination of site reconnaissance and desk-based assessment should be undertaken to develop

a comprehensive understanding of these risks. Key information to be collected includes the presence and characteristics of nearby water bodies such as rivers, lakes, reservoirs, channels, and drainage networks; historical flood records, photographs, and documented flood marks; as well as anecdotal evidence from local stakeholders.

Observations of surface water ponding, areas with inadequate or poorly maintained drainage infrastructure, and the condition of existing flood protection measures such as embankments and flood walls are also critical.

Additional considerations should include the extent of vegetation overgrowth and potential blockage of flow paths, indicators of water quality issues, identification of low-lying zones susceptible to groundwater inundation, prevailing soil conditions influencing infiltration and runoff, and site exposure to tidal or wave impacts, particularly within Coastal Regulation Zone (CRZ) areas.

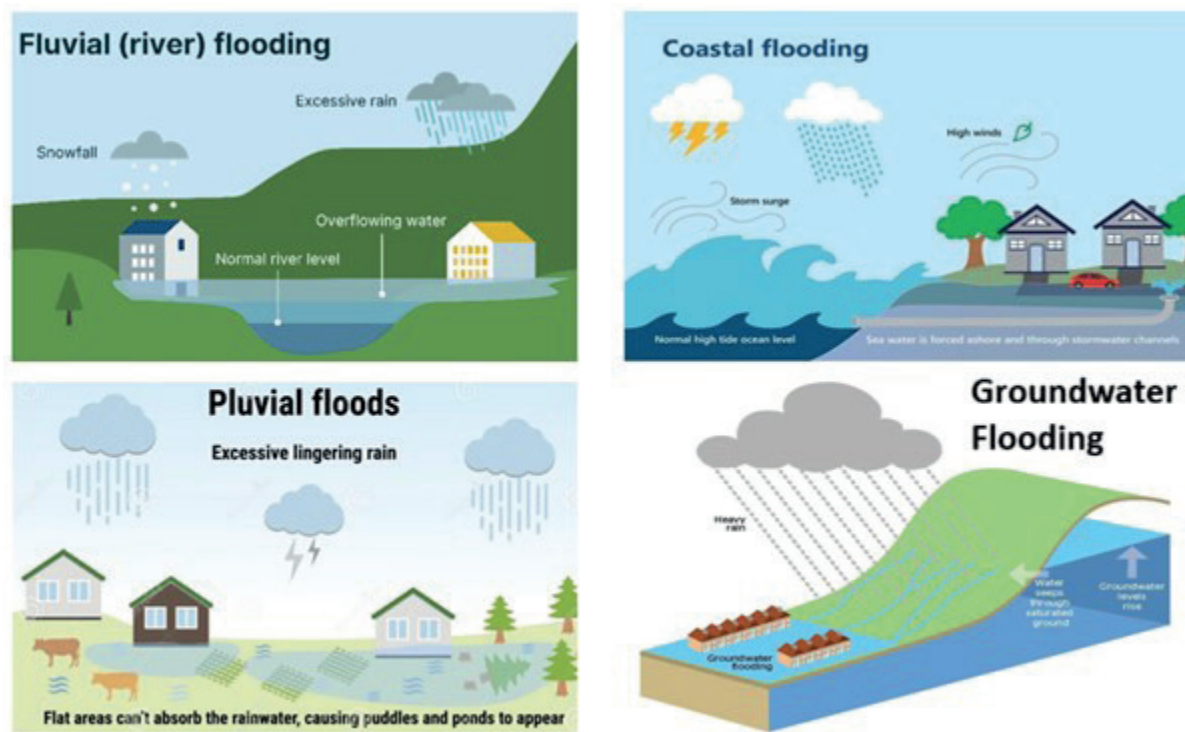


Figure 1: Sources of Flood Risk ^{1, 2, 3, 4}

Understanding Impacts of Climate Change

While site reconnaissance and desk-based assessments provide valuable insights into existing flood risk conditions based on historical data and present-day observations, they are inherently limited when applied to long-term infrastructure planning. To ensure durability and performance over the full lifecycle of infrastructure assets, it is essential to consider how future anthropogenic and climatic changes may alter flood risk profiles at the project site and within the broader catchment.

Anthropogenic influences can significantly modify hydrological responses over time. These include planned or unplanned urban development in the project vicinity, changes in land use patterns such as urban expansion or deforestation within the catchment and evolving regulatory or planning frameworks. Alterations to natural drainage patterns, increased impervious surfaces, and inadequate stormwater management in upstream areas can exacerbate flood risks at downstream infrastructure sites. Additionally, activities such as excessive groundwater abstraction, irrigation practices, or saltwater intrusion in coastal regions may contribute to rising groundwater levels, further increasing flood susceptibility.

While best practice dictates that future developments should not aggravate flood risks in surrounding areas, regulatory enforcement in India remains limited compared to countries such as the United Kingdom or Australia, where flood risk neutrality is often a prerequisite for planning approval. Consequently, infrastructure planning must proactively account for these potential changes.

Equally important is the consideration of climate change impacts, which introduce additional uncertainty and variability into hydrological systems. Advances in climate science, including successive modelling frameworks such as CMIP5, CMIP6, and emerging CMIP7 projections, provide increasingly refined estimates of future climate conditions under different emission or socio-economic scenarios.

These models can be used to assess projected changes in rainfall intensity, frequency, and extremes, which are critical inputs for fluvial and pluvial flood risk analyses. For coastal infrastructure, projections of sea level rise, storm surge behaviour, wind patterns, and wave dynamics are particularly relevant. Resources such as the India-WRIS platform can offer baseline guidance on storm surge characteristics under Climate Change, although detailed, site-specific studies are often required for accurate risk quantification.

Ultimately, the selection of appropriate climate scenarios should be aligned with the criticality and design life of infrastructure assets, ensuring that resilience considerations are embedded from planning through to design and implementation stages.

Assessing Flood Risk

Hydrological and hydraulic modelling have long been established as fundamental tools for assessing fluvial and pluvial flood risks in support of infrastructure planning and design. These model-based approaches enable a quantitative understanding of flood behaviour under varying conditions and are increasingly being enhanced using advanced computational techniques, including Artificial Intelligence (AI) and automation.

Such advancements allow practitioners to efficiently simulate hundreds of scenarios, capturing a wide range of uncertainties associated with rainfall events, catchment responses, and climate influences. In Australia for example, modelling frameworks within the Melbourne Flood Mapping programme consider multiple rainfall return periods (e.g., 1-in-2 to 1-in-100-year events, including climate change allowances), a range of storm durations, and diverse temporal rainfall distributions and antecedent moisture conditions. Several hundreds of simulations are carried out with the help of cloud computing infrastructure and automation tools such as Flood Platform and Auto CAL which facilitate this kind of large-scale flood risk assessment studies.

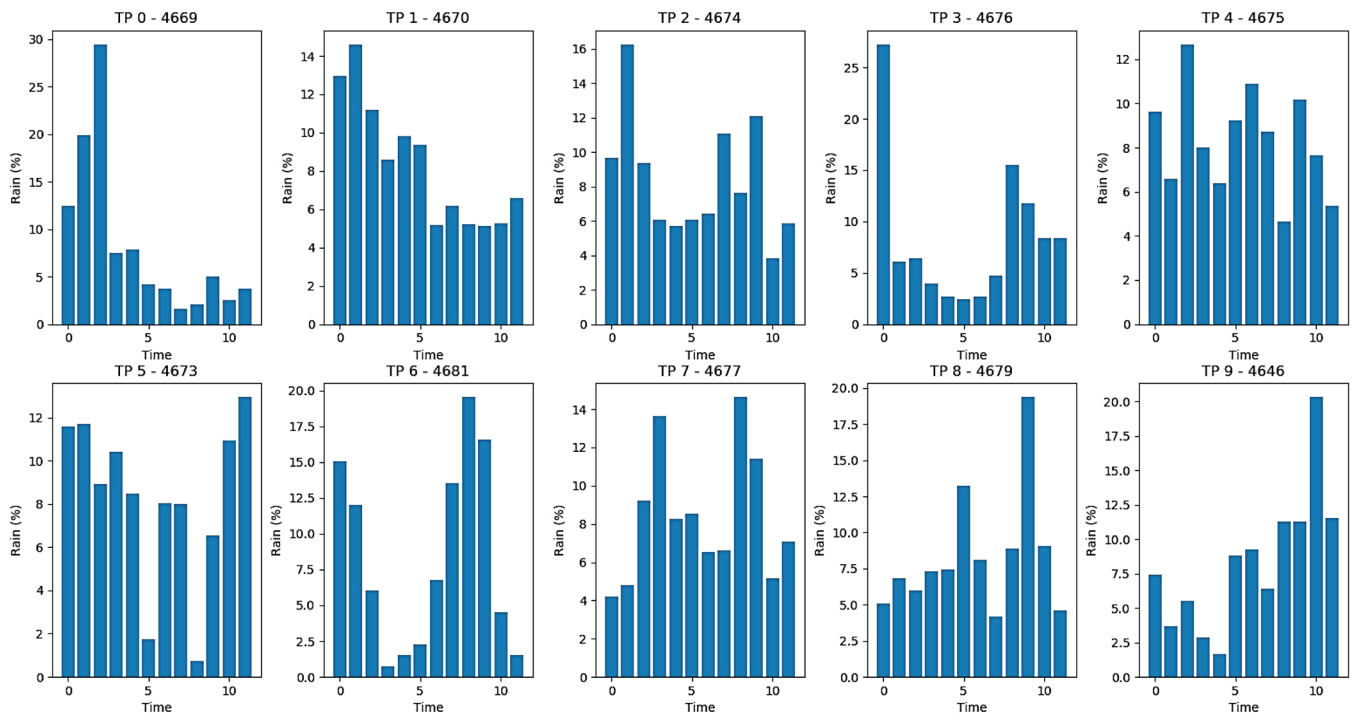


Figure 2: Multiple temporal patterns of rainfall distribution considered for modelling frameworks as per the Australia Rainfall and Runoff Guidelines ⁵

This comprehensive scenario-based analysis supports the evaluation of baseline risks, comparison of post-development impacts, and development of optimised flood mitigation strategies.

For infrastructure projects exposed to fluvial flood risk, hydrological modelling is essential to estimate peak flows and runoff volumes across different storm events and climate scenarios. These outputs are subsequently integrated into hydraulic models, which simulate the routing of flows through rivers, floodplains, and drainage networks to determine critical parameters such as flood extents, velocities, and High Flood Levels (HFLs).

The derived HFLs are particularly important during the design stage, as they inform decisions on minimum platform levels, foundation elevations, and stormwater outfall conditions to ensure safe and resilient infrastructure performance. The selection of appropriate modelling approaches, software platforms, and input data quality plays a significant role in determining the reliability and accuracy of these assessments.

In parallel, the design of stormwater management systems within infrastructure projects has evolved beyond conventional drainage practices to incorporate integrated and sustainable solutions. Modern approaches emphasise not only the efficient conveyance of runoff but also the attenuation of peak flows, reduction of downstream impacts, and alignment with broader catchment management objectives.

Key design principles include the incorporation of climate resilience by evaluating system performance under extreme rainfall events exceeding design thresholds, and the provision of safe exceedance pathways to direct overflow away from critical assets. Sustainable Urban Drainage Systems (SuDS) or Nature-Based Solutions (NBS), such as retention ponds, bioswales, and permeable pavements, are increasingly adopted to enhance infiltration, improve water quality, and create ecological and amenity value.

Furthermore, contemporary design practice integrates water conservation and reuse opportunities, such as

rainwater harvesting and managed aquifer recharge, while ensuring that runoff does not adversely affect downstream water quality or ecosystems. Importantly, flood risk assessment outputs such as detailed flood hazard maps are used to evaluate the exposure of proposed infrastructure components to flooding hazards.

These insights enable planners and designers to implement targeted mitigation measures, optimise site layouts, and ensure that infrastructure systems are robust, adaptable, and aligned with long-term resilience objectives within the wider catchment context.

Assessing Asset Vulnerability and Determining the Required Standard of Flood Protection

Infrastructure vulnerability is determined by three key factors: exposure, sensitivity, and adaptive capacity. Exposure refers to the extent to which infrastructure is in hazard-prone areas; sensitivity relates to how severely systems are affected by hazards; and adaptive capacity reflects the ability to adjust and recover.

A key concern in infrastructure resilience is the risk of cascading failures. For example, flooding of a power substation can disrupt electricity supply, which in turn affects all walks of life - transport systems, healthcare facilities, communication networks, production, etc. These interdependencies amplify the overall risk and highlight the need for integrated planning approaches.

During the Master Plan phase of an infrastructure project, workshops with key stakeholders, planners, asset owners should be facilitated to collaboratively identify direct, indirect and cascading climate-related impacts on the project. This broad engagement approach ensures that diverse perspectives are captured early in the planning process.

While it is ideal to design all assets to be resilient to future climatic conditions, the approach may not be economically feasible. Therefore, it may be practical to adopt a criticality approach for resilience planning. Under this approach, all critical assets essential for operations, safety and continuity of the proposed infrastructure should be identified and resilience measures should be prioritised accordingly.

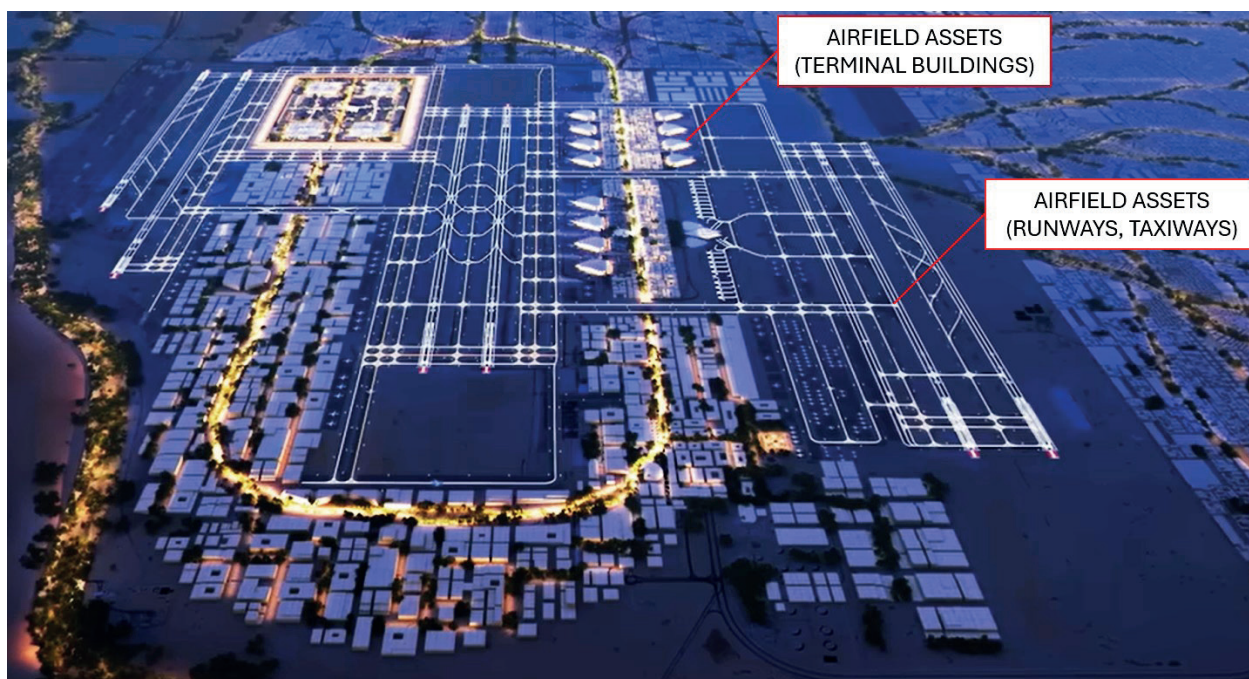


Figure 3: Asset classification and risk rating development for integration of flood risk and climate resilience within the design of the new King Salman International Airport in Riyadh.⁶

For example, assessing asset vulnerability and integrating climate resilience within the design has been given a major importance within the design of the new King Salman International Airport in Riyadh, Kingdom of Saudi Arabia. The critical assets within the airport, such as the airfield (runways, taxiways, aprons), airfield infrastructure (AGL substations, Radar facilities), buildings (Terminals, Air Traffic Control tower) were grouped into key categories based on their type or function, and vulnerability to climate change impacts. A risk rating has been developed for each asset component to support targeted and effective resilience strategies. The outcome of this exercise is a spatial map of all critical assets and the required standard of protection against various extreme rainfall events based on the determined asset risk rating. For example, assets with the highest risk rating have adopted flood risk protection for rainfall events above the 1 in 500-year return period, whereas assets with slightly lower risk rating have adopted 1 in 100-year as the standard of protection.

Integrating Flood Risk and Climate Resilience in Design of Critical Infrastructure Assets

Integrating flood risk and climate resilience measures into the design ensures that critical infrastructure remains operational under extreme weather conditions. The flood hazard maps which are the main outcome of flood risk assessment, and maps of critical asset locations maybe superimposed to assess risk to each critical asset and determine appropriate risk mitigation measures that can be adopted in the design.

The mitigation measures could vary from critical asset relocation, to incorporating various site-wide nature-based solutions or structural and non-structural mitigation measures, to setting asset finished floor levels above the high flood levels including a freeboard, and finally to adopting asset or property level flood protection systems.

Asset design should include robustness to withstand shocks such as due to sudden flash floods, should incorporate redundancy, and recovery capacity. Adopting design flexibility by understanding the importance of adaptive pathways, where infrastructure systems evolve

over time in response to changing conditions, ensures long-term infrastructure resilience.

In addition to climate resilience design, adaptive operations and maintenance practices should be embedded into the long-term planning to support resilience under changing climate conditions. The practices should integrate across strategic planning, emergency preparedness, and day-to-day operations to support a proactive and flexible approach to managing uncertainty, evolving risks, technological advancement, and regional interdependencies. To effectively manage climate risks beyond the design and construction phase, the project team should implement a structured handover process to the operational phase team.

Conclusion

In conclusion, integrating climate resilience and flood risk considerations into the planning and design of critical infrastructure is essential to ensure long-term functionality, safety, and sustainability in increasingly uncertain climatic conditions.

This article has demonstrated that a robust approach begins with a comprehensive understanding of the existing flood risk sources, followed by a forward-looking assessment of how anthropogenic changes and evolving climate conditions may alter those risks over time. The application of advanced hydrological and hydraulic modelling, combined with risk-informed design practices and sustainable drainage strategies, enables accurate quantification and effective mitigation of flood hazards.

Equally important is the evaluation of asset vulnerability and criticality, allowing for prioritisation of resilience measures and adoption of appropriate standards of protection. By integrating these elements within a holistic framework supported by interdisciplinary collaboration, adaptive design principles, and proactive operational strategies, planners and engineers can develop infrastructure systems that are not only robust against current risks but also adaptable to future challenges.

Ultimately, embedding resilience into infrastructure planning is a strategic investment that safeguards critical

services, minimises economic losses, and enhances the capacity of communities to withstand and recover from climate-driven flood events.

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The great glacier meltdown has begun — and it's coming for our rivers

A new UN report warns that glaciers are melting at record speeds, threatening the water security of billions. From the Himalayas to the Andes, the collapse of Earth's 'water towers' signals a deepening global climate and resource crisis

Mountains, glaciers and alpine snowpacks, which collectively support the freshwater needs of over half the world's population, are undergoing rapid, irreversible change. A newly released United Nations report, launched to mark the first-ever World Day for Glaciers on March 21, delivers a stark message: the cryosphere is collapsing faster than ever.

The 'United Nations World Water Development Report 2025 – Mountains and Glaciers: Water Towers' presents one of the most detailed and pressing pictures yet of how global warming is undermining the high-altitude hydrological systems that sustain life across continents.

Published by UNESCO and coordinated by the World Water Assessment Programme (WWAP), the report is part of a broader international effort to focus attention on mountain water systems, launched during the International Year of Glaciers' Preservation. It marks the beginning of a Decade of Action for Cryospheric Sciences (2025-2034).

In India, the stakes are especially high. The Himalayan glaciers feed several major rivers — including the Ganges and the Indus — which provide critical water supplies to hundreds of millions. According to the report, an estimated 129 million farmers in the Indus and Ganges basins depend on glacier and snow-fed irrigation systems. These river systems support food production, hydropower, and domestic water needs in some of India's most densely populated and agriculturally vital regions.

The Ganges covers over 1 million sq km across northern and eastern India, supporting major cities like Delhi, Kanpur, Patna, and Kolkata. It irrigates large parts of Uttar Pradesh, Bihar, and West Bengal, underpinning one of the world's most densely populated agricultural regions. The Indus basin, spanning parts of Jammu & Kashmir, Himachal Pradesh, Punjab, and Ladakh, is crucial for pre-monsoon irrigation.

Over the last three years alone, glaciers worldwide have experienced the largest mass loss on record. According to the World Glacier Monitoring Service (WGMS), glaciers lost 450 gigatons of mass in 2024 alone — part of a long-term decline of over 9,000 billion tonnes since 1975. "That's equivalent to a block of ice the size of Germany and 25 metres thick," says Michael Zemp, WGMS director. "Five of the last six years have seen the largest losses."

As per the report, world over, 'glaciers are losing, on average, 273 billion tonnes of mass every year. This level of loss, is roughly equivalent to the total annual water intake of the global population for 30 years'.

Excerpts from: <https://timesofindia.indiatimes.com/toi-plus/environment/the-great-glacier-meltdown-has-begun-and-its-coming-for-our-rivers/articleshow/120231326.cms>

Managing Climate Risks in Infrastructure: A FIDIC-Based Approach to Urban Flooding and Landslides



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Abstract

Climate change is fundamentally altering the risk landscape for infrastructure projects worldwide. Urban flooding and landslides, once considered exceptional events, are becoming increasingly frequent and severe, challenging traditional assumptions in engineering design and construction contracting. For consulting engineers, this shift demands not only technical adaptation but also a sophisticated understanding of how construction contracts allocate climate-related risks. This article examines the FIDIC contract framework as a tool for managing these risks, drawing on recent real-world events and case law. It explores risk allocation mechanisms across different FIDIC contract forms (Red, Yellow, Silver, and Gold Books), analyses critical procedural requirements that determine the success or failure of climate-related claims, and examines the consulting engineer's professional responsibilities under the FIDIC Code of Ethics. The article offers practical recommendations for consulting engineers advising clients on infrastructure projects vulnerable to climate-induced hazards, with particular reference to the Indian context.

Introduction: The New Climate Reality for Infrastructure

The consulting engineering profession has long understood the importance of robust design standards and prudent risk management. For decades, infrastructure projects have been designed based on historical weather data, using return periods and probability analyses that assumed a stable climate. However, the accelerating impacts of climate change are challenging these fundamental assumptions. Historical weather data - once considered a reliable predictor of future conditions - no longer provides adequate guidance when rainfall patterns become increasingly erratic and extreme events occur with unprecedented regularity.¹

The scientific consensus, as reflected in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, confirms that human-induced climate change is intensifying the hydrological cycle, leading to more intense and frequent extreme rainfall events across many regions of the world.² For urban areas, this translates directly into increased flood risk. For mountainous and hilly regions, intensified rainfall

combined with changing land use patterns elevates landslide risk. Infrastructure projects are long-lived assets - a bridge designed today may be expected to function for 50 to 100 years. The climate conditions that asset will face over its operational life may differ significantly from historical patterns.³

Consider the United Arab Emirates in April 2024. On 16 April 2024, the country experienced its heaviest rainfall since records began in 1949. In a single day, more than a year's quantum of rain fall occurred - a once-in-75-year event that brought major infrastructure projects to a standstill. Dubai International Airport was forced to suspend operations temporarily. Construction sites were inundated. The UAE government subsequently allocated Dhs1.439 billion to stormwater drainage projects under the *Tasreef* programme, aiming to increase drainage capacity by 700 per cent.⁴

This event was not an isolated anomaly. Across South Asia, the Himalayan region, and urban centres worldwide, landslides triggered by unprecedented rainfall are destroying infrastructure and displacing communities. In India, the 2023 monsoon season saw devastating floods in Himachal Pradesh and Uttarakhand, with landslides cutting off entire regions and causing extensive damage to roads, bridges, and buildings.⁵ The consulting engineer's role has therefore expanded: beyond designing resilient structures, professionals must now understand how construction contracts, particularly FIDIC forms, allocate the risks associated with these climate-induced events.

Understanding FIDIC'S Risk Allocation Framework

The International Federation of Consulting Engineers (FIDIC) publishes several standard contract forms, each reflecting a different allocation of risk between employer and contractor. These forms are widely used internationally, particularly for infrastructure projects financed by multilateral development banks.

The FIDIC Contract Suite

Contract Form	Risk Allocation	Relevance to Climate Events
Red Book (Construction)	Balanced risk; Employer provides site data	Most common for infrastructure; includes explicit adverse weather clauses
Yellow Book (Plant & Design-Build)	Contractor assumes design responsibility	Relevant where design affects flood/landslide resilience
Silver Book (EPC/Turnkey)	Heavy Contractor risk; limited relief for unforeseen conditions	Riskiest for climate events; adverse weather clause typically removed
Gold Book (DBO)	Includes long-term operation; features Exceptional Risks rather than Force Majeure	Critical where climate affects ongoing operations

The Red Book, formally titled *Conditions of Contract for Construction*, is the most commonly used FIDIC form. Under this form, the employer provides site data and takes responsibility for its accuracy, while the contractor bears the risks associated with construction execution. The Yellow Book shifts more risk to the contractor by requiring design responsibility. The Silver Book represents the highest risk transfer to contractors, with very limited relief for unforeseen conditions. The Gold Book includes provisions for long-term operation and maintenance, making it particularly relevant where climate impacts may manifest over an extended operational period.⁶

Key Clauses for Climate-Related Events

Extension of Time for Exceptionally Adverse Climatic Conditions

Under Sub-Clause 8.4 of the 1999 Red Book and Sub-Clause 8.5 of the 2017 Red Book, contractors are

entitled to an extension of time (EOT) if completion is delayed by *exceptionally adverse climatic conditions*.⁷

The FIDIC Contracts Guide (2000) provides critical guidance: an event qualifies as *exceptionally adverse* if its probability of occurrence is four to five times the Time for Completion.⁷ For example, if a project is scheduled for four years, a weather event with a recurrence interval of 16–20 years would meet the threshold. This approach ties the assessment to the specific project duration.

However, the 2017 edition introduces an important nuance. Sub-Clause 2.5 requires consideration of weather data published in the country where the works are located. An event is only *exceptionally adverse* if it is Unforeseeable - defined in Sub-Clause 1.1.6.8 as *not reasonably foreseeable by an experienced contractor by the date for submission of the Tender*.⁷

Employer's Risks: Forces of Nature

Where the adverse weather clause has been removed - common in Middle East contracts and in Silver Book forms - contractors may seek relief under Sub-Clause 17.3(h). This sub-clause defines Employer's Risks to include *any operation of the forces of nature which is Unforeseeable or against which an experienced contractor could not reasonably have been expected to have taken adequate preventative precautions*.⁸

This provision offers two alternative bases for relief: unforeseeability (the event could not have been predicted) or impossible prevention (even if foreseeable, no reasonable precautions could have prevented the damage). For the UAE floods of April 2024, contractors may argue that despite advance warnings, the volume of water made protection impossible in worst-hit areas - potentially satisfying the second limb.

Under Sub-Clause 17.4, if the employer's risks result in loss or damage, and the Engineer instructs rectification, the contractor is entitled to payment including profit. This is an important distinction from other relief provisions where only time relief is available.⁸

Force Majeure/ Exceptional Events

Clause 19 in the 1999 editions and Clause 18 in the 2017 editions address events that prevent performance

entirely. The 2017 editions renamed *Force Majeure* to *Exceptional Events* to avoid legal complexities across different jurisdictions.⁹

Definition of an Exceptional Event (Sub-Clause 18.1): An event or circumstance that:

- a) is beyond a Party's control;
- b) could not reasonably have been provided against before entering into the Contract;
- c) having arisen, could not reasonably have been avoided or overcome; and
- d) is not substantially attributable to the other Party.⁹

Critical Distinction: The threshold for exceptional events is significantly higher than for adverse weather. A party must be *prevented* from performing its obligations - mere disruption is insufficient.⁹

Notice Requirements (Sub-Clause 18.2): The affected party must give notice within 14 days. Failure to comply means the party cannot claim relief for the period before notice was given.⁹

Cost Recovery Limitations (Sub-Clause 18.4): Natural catastrophes are explicitly excluded from cost entitlement - only time relief is available. The 2017 Silver Book maintains this distinction, with political events qualifying for cost recovery while natural events do not.⁹

Termination Rights (Sub-Clause 18.6): Either party may terminate if works are prevented for a continuous period of 84 days or for multiple periods totalling more than 140 days due to the same notified exceptional event.⁹

Alternative Relief Provisions

Sub-Clause 8.5 (Delays Caused by Authorities) provides that if authorities cause Unforeseeable delay despite the contractor's diligent compliance, an EOT is available. Sub-Clause 13.7 (Change in Laws) entitles the contractor to both EOT and cost recovery if laws change after the Base Date - relevant when governments enact new climate-related regulations following major disasters.¹⁰

The Critical Importance of Procedural Compliance

Contractors often fail to recover compensation for climate-related delays not because the events were insufficiently severe, but because they failed to follow contractual procedures.

The OHL v Government of Gibraltar Case (2014)

This English Technology and Construction Court (TCC) case involved a FIDIC Yellow Book contract for a Gibraltar airport tunnel. The case has become a leading authority on the interpretation of FIDIC notice provisions.¹¹

Key Facts:

- The contract was for a tunnel under the Gibraltar airport runway.
- The contractor encountered unforeseen rock conditions and exceptionally adverse weather.
- The contractor claimed EOTs under Sub-Clauses 4.12 and 8.4.
- The employer terminated the contract, citing failure to progress.

Critical Findings:

Issue	Court Ruling	Practical Lesson
Notice Timing	The 28-day period runs from when the contractor became aware of the delay - not from the event itself	Track when delay actually manifests
Notice Content	A monthly progress report stating <i>adverse weather condition (rain) have affected the works</i> was NOT sufficient notice	Use clear language identifying a claim
Notice Validity	Service at site office was valid despite contract specifying Madrid office	Courts take a commercially realistic interpretation

Mr Justice Akenhead stated: *"I see no reason why this clause should be construed strictly against the Contractor and can see reason why it should be construed reasonably broadly, given its serious effect on what could otherwise be good claims."*¹¹

The court also held that even if Sub-Clause 4.12 would entitle the contractor to relief, the contractor must still comply with Sub-Clause 20.1 notice requirements. This established that notice provisions are substantive conditions precedent to entitlement.¹¹

Notice Requirements Under the 2017 Editions

The 2017 FIDIC editions introduced a more sophisticated claims procedure.⁷

Initial Notice (Sub-Clause 20.2.1): Must be given within 28 days, include a preliminary description, and be clearly identified as a claim.

Engineer's Preliminary Response (Sub-Clause 20.2.2): If the Engineer believes the notice was late, they must notify the claiming party within 14 days. Failure to do so renders the notice deemed valid.

Fully Detailed Claim (Sub-Clause 20.2.4): Must be submitted within 84 days, including detailed description, contractual basis, contemporary records, and supporting particulars.

Consequences of Non-Compliance: The claiming party *shall not be entitled to any additional payment or extension of time.*⁷

The Duty of Early Warning

Under the **1999 Red Book**, the early warning duty lies solely with the contractor (Sub-Clause 8.3). Under the **2017 Red Book**, Sub-Clause 8.4 extends this duty to both parties, reflecting a more collaborative approach.¹²

The Consulting Engineer's Professional Responsibility

The FIDIC Code of Ethics

The FIDIC Code of Ethics establishes four key principles guiding engineers' conduct regarding climate issues.¹³

Principle	Requirement	Application to Climate Theme
Responsibility to Society	<i>Seek solutions compatible with sustainable development</i>	Design must consider long-term climate projections
Competence	<i>Maintain knowledge consistent with development</i>	Stay current on climate science and FIDIC developments
Integrity	<i>Act in the legitimate interest of the client</i>	Advise on climate risk allocation before contract signing
Impartiality	<i>Be impartial in professional advice and judgement</i>	Balance employer and contractor interests fairly

The Code is incorporated by reference into FIDIC contracts. Under Sub-Clause 3.1 of the 2017 Red Book, the Engineer is required to *act fairly* and *make determinations in accordance with the Contract*.¹⁴

4.2 The Engineer's Role Under FIDIC Contracts

Responsibility	FIDIC Clause	Practical Application
Determining Exceptionally Adverse	Sub-Clause 8.4/8.5	Assess weather events against 4–5× project duration threshold
Instructing Remedial Works	Sub-Clause 17.4(a)	Timely instruction triggers EOT entitlement
Evaluating Foreseeability	Sub-Clause 1.1.6.8	Review information available at tender
Notice Compliance	Sub-Clause 20.1/20.2	Enforce requirements; give preliminary response within 14 days
Programme Assessment	Clause 8	Determine if delays affect critical path

Under Sub-Clause 3.7 of the 2017 editions, the Engineer must provide a *reasoned* determination for any claim, explaining the basis for the decision including any expert judgment exercised.¹⁴

Conclusion

The accelerating impacts of climate change are forcing the consulting engineering profession to rethink fundamental assumptions about risk, responsibility, and resilience. Urban flooding and landslides - once considered rare and exceptional - are becoming increasingly common, challenging traditional design standards and contractual frameworks. The scientific consensus confirms that these trends will continue, with extreme rainfall events becoming more frequent and intense across many regions of the world.²

The FIDIC contract suite provides a sophisticated set of tools for allocating and managing these risks. From the extension of time provisions for exceptionally adverse climatic conditions to the force majeure/exceptional events framework, consulting engineers have a well-established contractual architecture to draw upon. The distinctions between the Red, Yellow, Silver, and Gold Books offer different risk allocations suited to different project contexts. The 2017 editions introduced significant refinements to claims procedures, providing greater clarity and reducing the potential for procedural disputes.⁷

However, these tools are only effective when properly understood and rigorously applied. The OHL v Gibraltar case reminds us that procedural compliance is as critical as substantive entitlement - a claim that is not properly noticed is a claim that may be forever lost.¹¹ The case established that FIDIC's notice provisions are conditions precedent to entitlement, and that non-compliance can defeat otherwise valid claims. For consulting engineers, this reinforces the importance of diligent contract administration and contemporaneous record-keeping.

For consulting engineers, these developments bring both challenge and opportunity. The challenge lies in mastering increasingly complex contractual

frameworks while maintaining technical excellence in climate-resilient design. The opportunity lies in leading the industry toward a more sustainable, resilient future - one where the infrastructure built today can withstand the climate challenges of tomorrow.

The Consulting Engineers Association of India, as India's Member Association of FIDIC, is uniquely positioned to drive this transformation. By deepening one's understanding of FIDIC's risk allocation mechanisms and sharing experiences through platforms like VIEWPOINT, one can ensure that Indian infrastructure projects are resilient to climate change.

Acknowledgement

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East Coast Railway invites bids for Brahmapur Railway Station Redevelopment

under Phase-1. The project aims to upgrade passenger facilities and transform the station into a modern transport hub. The work falls under the Khurda Road division and will be executed through the Engineering, Procurement and Construction (EPC) model. Brahmapur is one of the major railway stations in Odisha and serves thousands of passengers travelling across eastern and southern India. The redevelopment project forms parts of Indian Railways broader station modernisation programme.

Source: Metro Rail News

Flexible Pavement Design - Need for Revision for Roads in Coastal Areas due to Climate Changes



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Abstract

Coastal communities with road infrastructure close to the shoreline are vulnerable to the effects of sea level rise caused by climate change. The sea level in coastal area is projected to rise by 1.2 m to 2.0 m by the year 2100. Climate change vulnerability and adaptation studies have focused on surface water flooding caused by sea level rise; however, little attention has been given to the effects of climate change on the groundwater level. The groundwater level is expected to rise along with the rise in sea level and would intersect the unbound layers of the coastal road infrastructure, which would result in reducing the service life of the pavement. Air temperature and pavement temperature would also be rising by 2-3° C by the year 2100. Vulnerability studies are an essential part of adaptation planning, and pavement engineers are looking for methods to identify roads that may experience premature failure. In this study, the rise in the water table level in coastal areas was used to identify road infrastructure since

the rising groundwater would move into the unbound materials during the design service life of the pavement. Multilayer elastic theory was used to analyse typical pavement profiles in several functional classifications of roadways to determine the magnitude of fatigue and rutting life reduction expected from the rise in sea level. The use of this methodology would enable pavement engineers to target coastal road adaptation projects effectively and would result in significant cost savings compared with implementation of broad adaptation projects or the cost due to no action taken.

A few case studies were carried out and it was found that an additional 45-50 mm thick Dense Bituminous Macadam (DBM) is required to compensate for the climate change condition. That would increase the pavement cost from 30.55–35.17 million Rs/km (IRC condition) to 34.40–39.03 million Rs/km (climate change condition) for a two-lane road.

Introduction

Coastal areas worldwide are being developed more and more. The roads, constructed to service the built environment along the shore, are increasingly at risk from sea level rise, more intense coastal storms, and storm surge¹. Although the shoreline in many locations could be fortified in the future to protect the property from coastal storms, access roads in coastal communities are vulnerable to rising groundwater caused by sea level rise. The sea level in coastal areas is projected to rise by 1.2 m to 2.0 m by the year 2100². Ground water is expected to rise with rising sea level not only along the coast but also spread out to significant distances inland³ which would result in reducing the land availability for crop cultivation. In some locations, rising groundwater caused by sea level rise would intersect the unbound layers of coastal road infrastructure, thus weakening the pavement structure. The pavement design criteria currently is based on historical information that assumes the environmental parameters are stationary or, on average, not changing with time. However, recent advances in climate change science have shown that the climate parameters are no longer stationary, they are dynamic. Transportation engineers are therefore concerned that the pavement design criteria of the past are no longer valid, and are looking for new guidance for designing and restoring pavement systems. Anticipated changes in groundwater levels would change the frequency, duration, and severity of road failures as well as the time and cost of repair. Sea level rise can cause erosion and storm surge damage, flood the coastal communities, and damage the coastal infrastructure⁴. The causes of sea level rise are (a) thermal expansion of ocean waters, (b) water transfer between glaciers and oceans, (c) vertical land movement, (d) shifts in the Earth's magnetic field, and (e) ocean dynamics⁵. There is uncertainty in projections of sea level rise in part because no one knows how quickly global economies would reduce greenhouse gas emissions and because of the ice-loss dynamics of the Greenland. A study linking global sea level rise to global-temperature projected global sea level rise ranging from 0.76 to 1.9 m between the years 1990 and 2100⁶. The National Oceanic and Atmospheric Administration (NOAA) assessed several

studies of sea level rise and produced scenarios of global mean sea level rise ranging from 0.2 m to 2 m by the end of this century⁵. The lowest figure is an extrapolation of the historical record, and the highest is based on the Intergovernmental Panel on Climate Change AR4 projections of global sea level rise combined with an estimate of the maximum amount of glacial and ice sheet loss by the end of the century.

The soil beneath the groundwater table is fully saturated, and unsaturated soil above the groundwater table. Typical values of Resilient Modulus and Poisson's ratio of unbound materials were assigned to each litho graphic layer according to its AASHTO soil classification. These values were obtained from Level 3 inputs in the Mechanistic-Empirical Pavement Design Guide (MEPDG)⁷. Typical Resilient Modulus values at optimum moisture content were used for the unbound materials above the water table, and typical Resilient Modulus values at full saturation were used for the unbound materials below the water table. The ratio of Resilient Modulus at full saturation to Resilient Modulus at optimum moisture content (MR_{sat}/MR_{opt}) was assumed to be 0.5 for the unbound materials in this analysis, as based on guidance from the MEPDG⁷. Although the dynamic modulus of the asphalt layer fluctuates with temperature and seasonal frequency, the steady state analysis did not consider seasonal variability. The average dynamic modulus was assumed to be constant at 35°C. However, it would be increased to 37°C at the end of this century for Indian condition. These two aspects impact on the initial construction cost of pavement layers.

From the above, two important points emerge:

1. Resilient Modulus of granular layer would be reduced by half value due to full saturation of granular soil on account of rise in ground water level in coastal areas.
2. Average Annual Pavement Temperature is assumed in India is 35 °C and that would increase to 37°C. The Resilient Modulus of bituminous mix would be decreased to 2600 MPa as per Table 9 of IRC:37-2018⁸.

3. Earlier for pavement design, climate conditions were assumed to be stationary but due to climate change, they would be dynamic. These variables would need to be considered while updating pavement design.

The above factors would result in increased pavement thicknesses and cost of pavement construction cost.

Pavement Design Indian Condition

Multilayer Elastic Analysis IITPave, computer software was used to determine changes in the pavement response to loading resulting from rising groundwater level related to sea level rise. Loading was kept constant at 4000 kN single-axle single tire with a contact pressure of 0.56 MPa. As the groundwater table rises in the soil profile with each sea level rise scenario, the lithologic layer in which the groundwater table resides is divided into an unsaturated section above the water table and a saturated section below the water table. The change in unbound material stiffness is modeled by reducing the Resilient Modulus under optimum moisture conditions (MR_{opt}) to the Resilient Modulus under saturated conditions (MR_{sat} = 0.5MR_{opt}), and the thickness of the saturated portion of the layer is changed accordingly. Horizontal tensile strain was calculated at the bottom of the asphalt concrete layer and vertical compressive strain was calculated at the top of the subgrade layer for the various groundwater levels predicted in the sea level rise scenarios.

Strain was converted to number of cycles to failure (N_f) for fatigue cracking and rutting with equations developed for dense-graded asphalt mixtures by the IRC:37-2018 using the two equations for fatigue life and rut life (Equations 1 and 2) as given therein.

As per IRC: 37 - 2018, an average rut depth of 20 mm or more, measured along the wheel paths, is considered in this guideline as critical or failure rutting condition. The equivalent number of standard axle load (80 kN) repetitions that can be served by the pavement, before the critical average rut depth of 20 mm or more occurs, is given by equation 1 considering 90 % reliability level⁸.

$$N_R = 1.4100 \times 10^{-08} [1/\varepsilon_v]^{4.5337} \quad (1)$$

where,

N_R = subgrade rutting life; and

ε_v = vertical compressive strain at the top of the subgrade.

As per IRC:37-2018, the occurrence of fatigue cracking (appearing as inter connected cracks), whose total area in the section of the road under consideration is 20% or more than the paved surface area of the section, is considered to be the critical or failure condition. The equivalent number of standard axle (80 kN) load repetitions that can be served by the pavement, before the critical condition of the cracked surface area of 20% or more occurs, is given in Equation 2 respectively for 90 % reliability level⁸.

$$N_f = 0.5161 * C * 10^{-04} [1/\varepsilon_t]^{3.89} [1/M_{Rm}]^{0.854} \quad (2)$$

where,

C = 10^M, and M = 4.84(

For the project road having more than 6 years of service life, the air voids (V_a) are taken as 4.5% and the effective bitumen content (V_{be}) as 11.5%.

The remaining service life is then determined using the fatigue equation (3) given below.

$$N_f = 0.711 * 10^{-04} [1/\varepsilon_t]^{3.89} [1/M_{Rm}]^{0.854} \quad (3)$$

V_a = per cent volume of air void in the mix used in the bottom bituminous layer;

V_{be} = per cent volume of effective bitumen in the mix used in the bottom bituminous layer;

N_f = fatigue life of bituminous layer (cumulative equivalent number of 80 kN standard axle loads that can be served by the pavement before the critical cracked area of 20 % or more of paved surface area occurs);

ε_t = maximum horizontal tensile strain at the bottom of the bottom bituminous layer (DBM); and

M_{Rm} = resilient modulus (MPa) of the bituminous mix.

Resilient Modulus of subgrade and granular layer are determined using the following three equations (Equations 4,5 and 6)

Resilient modulus for subgrade and sub base are determined using the following equations:

Subgrade⁸:

$$M_r (\text{MPa}) = 10 \times \text{CBR (California Bearing Ratio) for CBR} \leq 5 \text{ and} \quad (4)$$

$$= 17.6 \times \text{CBR}^{0.64} \text{ for CBR} > 5 \quad (5)$$

Granular Sub base and Base

$$M_{r2} = M_{r3} \times 0.2 \times h^{0.45} \quad (6)$$

M_{r2} = Composite elastic modulus of sub base and base (MPa)

M_{r3} = Elastic modulus of subgrade (MPa)

H = Layer thicknesses of granular layer

CASE STUDIES

A few case studies are adopted for pavement thicknesses and presented herein.

CBR of subgrade is adopted 10 %, design traffic is assumed 50, 75, 100, 125, 150 and 175 MSA. Conventional Flexible pavement designs are considered. Pavement design has been finalised based on following two assumptions:

Pavement temperature would be 37°C and E value of bituminous mix would be 2600 MPa. E value of granular layer would be reduced by 50 % as obtained using Equation 6.

It is assumed that CBR of subgrade is 10 % and Pavement Design would be carried out for design traffic 50, 75, 100, 125, 150 and 175 MSA.

E value of subgrade = $17.6 \times 10^{0.64} = 76.8 = 77 \text{ MPa}$

It is also assumed that 250 mm Wet Mix Macadam (WMM) and 200 mm Granular Subbase (GSB) would be provided beside DBM and BC.

E value of Granular layer is calculated using Equation 6 and found to be:

$$M_{r2} = 77 \times 0.2 \times 450^{0.45} = 240 \text{ MPa (say).}$$

Due to climate change, it would be reduced to 120 MPa.

E value of bituminous layer at 37°C Centigrade is found from Table 9.2 of IRC :37-2018 for using VG 40 bitumen 2600 MPa.

In normal conditions and as per IRC:37: 2018, E value of bituminous mix is 3000 MPa at 35°C Centigrade and E value of granular layer is 240 MPa. Pavement thicknesses are determined both two conditions and presented in Table 1. Only variation of Dense Bituminous Macadam (DBM) is noticed from Table 1. 50 mm Bituminous Concrete (BC) is provided as per IRC:37 2018. DBM thickness varies from 45 mm to 50 mm i.e., to cater for climate change at the end of this present century around 45-50 mm extra DBM layer thickness are to be provided.

Table 1: Pavement Composition for Case Studies

CBR	MSA	BC (mm)	DBM* (mm)	WMM (mm)	GSB (mm)
10	50	50	165/115	250	200
10	75	50	180/135	250	200
10	100	50	200/150	250	200
10	125	50	210/160	250	200
10	150	50	215/170	250	200
10	175	50	225/175	250	200

Note:* First DBM thickness required for climate change and second term required as per IRC:37: 2018.

DBM thickness variation is also presented graphically and shown in Figure 1. From Figure 1, it is found that DBM thickness increases with increasing design MSA, more or less upward linearly with positive slope. The gap between two lines are more or less constant since difference in the thickness variation is 45 mm to 50 mm only.

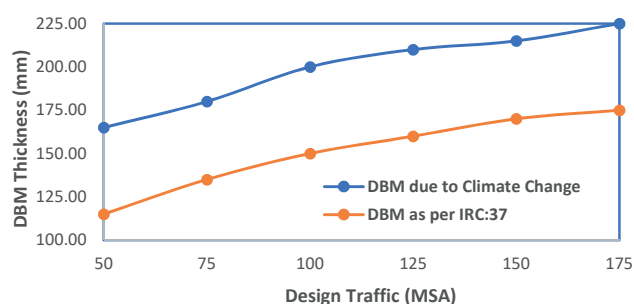


Figure 1: Variation DBM Thickness due to Climate Change
Considering two lane roads, pavement cost has also

been determined for both cases and summarised in Table 2. Basic costs of BC, DBM, WMM and GSB are taken to be Rs12000, Rs11000, Rs 6000 and Rs 5000 respectively and width of pavement is considered to be 7 m for cost estimation.

Table 2: Cost Comparisons

MSA	Cost as per IRC:37 (Rs Million)	Cost Due to Climate Change (Rs Million)
50	30.555	34.405
75	32.095	35.560
100	33.250	37.100
125	34.020	37.870
150	34.790	38.255
175	35.175	39.025

From Table 2, the cost per km varies from Rs 30.555 million to Rs 35.175 million as per IRC:37, whereas it varies from Rs 34.405 million to Rs 39.025 million due to climate change conditions. The difference in cost varies from Rs 3.465 million to Rs 3.85 million.

Conclusions

Based on the present study the following conclusions may be drawn:

- Rising sea levels and associated groundwater rise, significantly affect the performance of flexible pavements in coastal regions.
- The assumption of stationary environmental conditions in conventional pavement design (IRC:37-2018) is no longer valid under climate change scenarios.
- Full saturation of granular layers due to rising groundwater leads to a reduction in Resilient Modulus by approximately 50%, resulting in decreased structural stiffness.
- Increase in average pavement temperature from

35°C to 37°C reduces the bituminous mix modulus to about 2600 MPa, thus weakening the asphalt layer.

- Combined effects of reduced modulus in both granular and bituminous layers lead to higher tensile and compressive strains, accelerating pavement distress.
- Mechanistic analysis using IITPave shows that additional DBM thickness of about 45–50 mm is required to maintain pavement performance under future climate conditions.
- The increase in DBM thickness is consistent across different traffic levels (50–175 MSA), indicating a uniform impact due to climate change.
- Pavement fatigue life and rutting resistance are significantly reduced due to adverse environmental changes, leading to earlier failures and necessitating increased maintenance.
- Pavement layers construction cost increases by approximately Rs 3.46 million to Rs 3.85 million per km for a two-lane road under climate change conditions.
- Overall pavement cost rises from Rs 30.55–35.17 million /km (IRC condition) to Rs 34.40–39.03 million /km (climate change condition).
- Climate change impacts must be incorporated into pavement design through modified material properties, design parameters, and thickness requirements.
- There is a strong need to develop climate-resilient pavement design guidelines to ensure long-term durability, sustainability, and economic efficiency of coastal road infrastructures

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India's poverty map bends under climate pressure: NISER study across 593 districts links erratic weather patterns to shifting livelihoods, unstable incomes

Climate shocks, ranging from erratic rainfall and rising temperatures to floods and droughts, are worsening poverty across India

Poverty at climate's edge

Flood shock

Flood exposure is linked to higher poverty due to damage to infrastructure, displacement, and livelihood loss. A one-unit rise in flood-affected areas increases poverty probability by 1.4%

Rainfall deficit

Lower and uneven precipitation is associated with higher poverty, particularly in agriculture and water-dependent sectors. A one-unit rise in yearly average minimum precipitation increases poverty probability by 1.9%

Temperature volatility

Maximum temperature variation is the strongest climatic driver of poverty. A one-unit increase raises poverty probability by 31.1%

Diversified economies

A larger services (tertiary) sector reduces poverty risk. A one-unit rise in its GSDP share lowers poverty probability by 1.9%

Social exposure

Higher ST population share is associated with higher poverty risk, reflecting structural disadvantages. A one-unit increase raises poverty probability by 1.9%

Excerpted Source: https://www.business-standard.com/economy/news/climate-shocks-worsening-poverty-across-india-finds-niser-study-126041200832_1.html

Working with Extremes and Uncertainties: Reframing Climate through Water



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Abstract

The issues with climate change are at their very core about interactions of humans with water - the uncertainties and extremes of excess, absence, and degradation of water. This article proposes that climate-responsive design and engineering must move beyond siloed responses to floods, droughts, and surface or groundwater pollution, and instead adopt an integrated water systems perspective. Drawing upon observations and work in locations including Pokhara (Nepal) and Mau (India) it highlights how managing 'too much water', 'too little water,' and 'water quality' are interdependent matters and an integrated approach in adapting to climate change will aim to account for all such extremes, every single time. The paper further emphasises the critical role of prioritised investment planning in embedding long-term, systemic water management approaches within routine budgeting processes, avoiding reactive and fragmented responses to climate extremes.

Climate Change and Water

Climate change is often framed and communicated through metrics such as temperature rise, carbon emissions, and energy transitions. However, in practice, and particularly within the domains of design and engineering, climate change manifests most tangibly through water. It can be experienced in

the form of intense rainfall and flooding, prolonged periods of scarcity, and even declining water quality (such as catalysing algal bloom or nitrification). These are not symptomatic of isolated phenomena but interconnected symptoms of a shift in the hydrological cycle. They point towards a reframing of how climate is approached in the built environment - placing water at the centre of analysis and design intervention.

It may be considered pragmatic to treat flooding, drought, and pollution as separate hazards, each addressed through specialised interventions. For instance, flood control is pursued through drainage infrastructure and embankments, water scarcity through supply augmentation and extraction, and pollution through treatment systems. While each of these responses has its place, their separation often obscures the systemic relationships between them. Measures designed to address one dimension can inadvertently exacerbate another, reinforcing cycles of vulnerability rather than resolving them.

A more comprehensive (albeit complex) approach begins by recognising that water binds these challenges together. Too much water, too little water, and poor water quality are different conditions within a single hydrological system (also referred to as the water cycle). Designing for climate resilience, therefore, requires engaging with this continuum, understanding

how landscapes, infrastructure, and human activity shape, promote or inhibit the movement, storage, cleansing and transformation of water across time and space.

The issue of ‘too much water, is most visible in episodes of flooding, where intense rainfall overwhelms natural and engineered systems. Yet the severity of flooding is rarely determined by rainfall alone. It is shaped by how landscapes have been altered through urbanisation, deforestation, river channelisation, and the loss of wetlands, reducing their capacity to absorb and store water. In many cases, water is no longer held within the landscape but rapidly flows across it, increasing peak flows and downstream risks. Talking of risks, flooding is only a problem (or risk) for humans where it damages or disrupts physical assets and economic activity. It is worth highlighting though that flooding at large scale can be the norm in an entirely natural system and can go entirely unnoticed where there is no human presence or activity.

In the Sustainable Tourism Action Plan (STAP) prepared for Pokhara, Nepal, a complex aspect of water stress was addressed. The lake system, which forms the core of Pokhara’s identity and economy, has been gradually receding over time. The decline is driven by a combination of siltation from the surrounding steep catchments and increasing variability in inflows linked to changing rainfall patterns. Sediments carried from upstream have progressively reduced the depth and storage capacity of the lakes, while fluctuations in the catchment have made water levels less predictable. As a result, areas that were once permanently submerged are now seasonally exposed, altering both the ecological character of the lakes and their role in supporting local livelihoods (particularly tourism). Construction, human activity within and around the lake has also changed the drainage pattern of the lake.

At the same time, pressures from tourism had intensified water quality challenges along the lake edges. Rapid and often unregulated development brought hotels, restaurants, and recreational activities closer to the shoreline, all leading to increased risk of

wastewater and solid waste entering the lake system. The encroachment of built surfaces has also disrupted natural drainage paths, exacerbating both sediment inflow and pollutant accumulation.



Figures 1&2: Disruption of Natural Drainage Paths from human interventions in and around the lake

This simultaneous process of physical shrinkage and environmental degradation reflects a broader disconnect between development and the underlying hydrological system, where the value of the lakes as an economic asset has not been matched by investment in their ecological health.

The Sustainable Tourism Action Plan (STAP) for Pokhara therefore focused on proposing the restoration

of the lakes not only as scenic and economic resources but as functioning hydrological systems. That involved strengthening the health of the catchments by clearing waste, sediment debris and encroachment from inlet channels, alongside interventions to improve water quality by managing wastewater and limiting direct pollution from human activities such as discarded plastics. Linking the main lake with other lakes in the region and developing them as eco-tourism sites also intended to take the visitor strain off specific tourism sites.

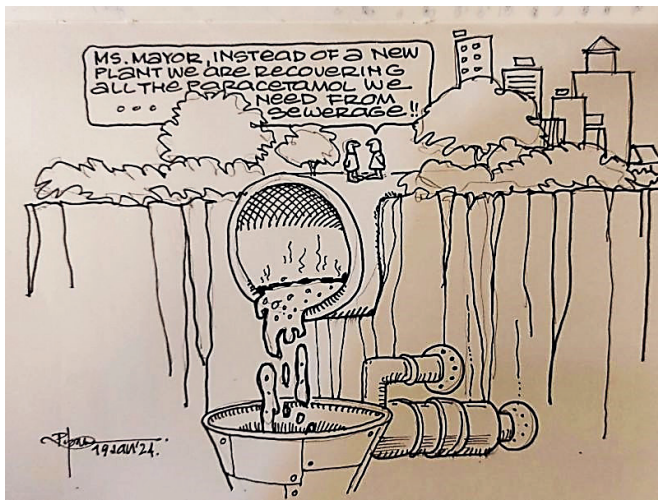


Figure 3: Extracting nutrients and debris from wastewater is key to managing pollution from Human Activities

For Mau, in the state of Uttar Pradesh in India, flooding is not simply a hazard but a dynamic force that continues to redefine the relationship between the river and its surrounding environment.



Figure 4: Erosion causing land loss

During periods of high discharge, the river exerts pressure on its banks, accelerating erosion and causing significant land loss. Agricultural fields, housing, and local infrastructure are progressively damaged or lost, while the river channel itself shifts, altering long-established spatial patterns of habitation and use. At the same time, these changes disrupt ecological habitats.

These dynamics highlight the complex nature of water systems. The same flows that drive destructive erosion during the monsoon are part of a broader hydrological cycle that, if managed effectively, could support bio-diversity, groundwater recharge and ecological resilience.

However, conventional responses to flooding and erosion have tended to prioritise short-term stabilisation. Hard engineering measures such as embankments and revetments are often employed to contain the river and protect adjacent land. While these interventions can provide short term relief, they frequently alter natural sediment transport processes, constraining the lateral movement of the river, and severing the connection between the channel and its floodplain. In doing so, they cause erosion further downstream or intensify them in adjacent areas, while also reducing opportunities for water to spread, slow, and infiltrate.

Addressing extreme erosion driven by flooding therefore requires moving beyond defensive strategies towards a more integrated understanding of riverine systems. That involves recognising erosion not solely as a problem to be fixed at a specific location, but as part of a broader set of processes that shape the river corridor over time. Interventions such as restoring vegetated buffers, maintaining or re-establishing floodplain connectivity, and introducing permeable surfaces can help dissipate flow energy, stabilise banks in a more adaptive manner, and enhance the landscape's ability to moderate extremes. Slowing water during peak flows not only reduces erosive force but also allows for greater infiltration, supporting the longer-term availability of water within the system. It is with this in mind that development of protected bio-diverse natural zones along the river is being conceptualised

in Mau as a co-collaboration with local communities and authorities. These will also present growth and livelihood opportunities for the local community.

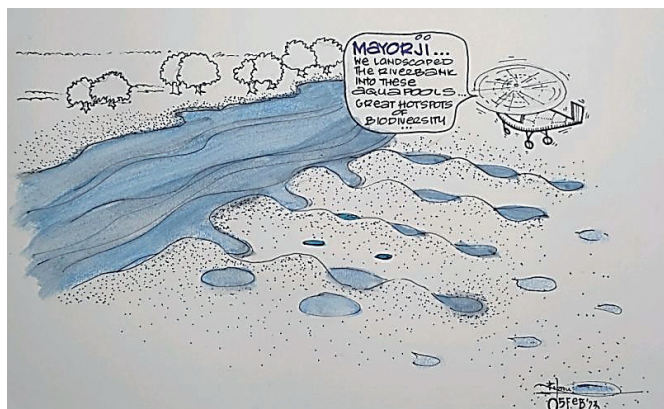


Figure 5: Biodiversity can be a source of tourism, learning and skills development.

Mau is not an isolated example, the challenge (and opportunity) is therefore not only to prevent land loss during floods but to reconfigure the relationship between water, land, and settlement in a way that accommodates variability across the entire length of the river system.

The third dimension of climate-related water challenges - water quality - is often less visible but fundamentally shaped by the interaction between landscape change and human activity. Alterations to land cover, drainage patterns, and soil structure directly influence how water moves through and across the ground, carrying with it a range of dissolved and suspended substances. When combined with human interventions such as the discharge of untreated or inadequately treated wastewater into the ground, these changes can significantly alter the bio-chemical composition of both the surface and the groundwater systems. Flood events can wash-in contaminants from urban and agricultural areas, allowing them to infiltrate soil layers or spread across water bodies, while low-flow conditions during droughts concentrate pollutants, intensifying their effects. Temperature changes further accelerate biological and chemical processes, often leading to deterioration in water quality.

These processes are particularly evident in rapidly transforming landscapes where development outpaces

infrastructure provision. For instance, the discharge of human waste into the ground - whether through septic systems, informal drainage, or direct release - introduces nutrients, pathogens, and chemical compounds into subsurface flows. Over time, these pollutants migrate into aquifers, altering groundwater chemistry, and eventually re-emerge in surface water bodies such as lakes, rivers, and wetlands. The connectivity between groundwater and surface water means that contamination is rarely confined to a single location.

Addressing these challenges requires recognising water quality as an outcome of both ecological processes and human behaviour embedded within the landscape. Interventions must, therefore, extend beyond end-of-pipe treatment to include the regulation of land use, improved sanitation systems, and the restoration of natural filtration functions within soils and vegetation. Approaches such as constructed wetlands, controlled wastewater management, and the protection of recharge zones can help intercept pollutants before they enter wider water systems. By understanding and managing the pathways through which contaminants move - above and below ground - it becomes possible to safeguard the bio-chemical integrity of water bodies and ensure that both surface and groundwater remain viable resources in the face of increasing environmental pressure.

Across these contexts, a common theme emerges: addressing climate through water requires moving from isolated interventions to systemic thinking. However, achieving this shift is not only a technical challenge but also an institutional and financial one. One of the key barriers to integrated water management is the way in which investments are planned and allocated. Too often, funding mechanisms are reactive, triggered by crises such as floods or droughts. That leads to 'knee-jerk' responses, where resources are directed towards immediate, visible solutions without sufficient consideration of long-term system behaviour.

Investment planning plays a crucial role in breaking this cycle. Embedding water systems thinking

into budgeting processes at multiple levels - local, regional, and national - can ensure that resources are allocated more strategically. Rather than funding discrete projects focused narrowly on flood control or water supply, investment frameworks need to support interventions that address multiple aspects of water simultaneously. That includes landscape-based solutions that enhance infiltration, storage, and quality, as well as infrastructure that is designed to operate effectively under variable conditions.

A systems-oriented approach to investment also requires aligning time horizons. While political and administrative cycles often prioritise short-term outcomes, water systems evolve over longer periods. Planning processes must therefore incorporate longer-term perspectives, recognising that benefits such as groundwater recharge, improved water quality, and reduced flood risk accrue gradually. By integrating these considerations into routine budgeting, it becomes possible to move away from reactive expenditure towards proactive and adaptive investment.

Furthermore, investment planning must recognise the interconnected nature of urban, rural, and ecological systems. Water does not adhere to administrative boundaries, and interventions in one location can have significant impacts elsewhere. Coordinated planning across sectors and jurisdictions is therefore essential. That includes integrating water considerations into land use planning, infrastructure development, and economic activities such as tourism and agriculture.

Ultimately, the challenge of climate extremes is not simply about managing individual events but about reshaping the relationship between human systems and water. The experiences from Pokhara and Mau illustrate that this requires both technical innovation and institutional change. It involves designing

landscapes and infrastructure that can accommodate variability, restoring natural processes where possible, and ensuring that investments support long-term system resilience rather than short-term fixes.

Conclusion

Climate change is experienced through water in its multiple and interrelated forms - excess, scarcity, and degradation. Treating these as separate problems risks reinforcing vulnerabilities and missing opportunities for more effective, integrated solutions. By placing water at the centre of design and engineering practice, it becomes possible to address these challenges as part of a single system. The case studies discussed demonstrate that working with water, rather than against it, can lead to more resilient and adaptive outcomes. However, achieving this requires not only changes in design approaches but also in how investments are planned and prioritised. Embedding systems thinking into budgeting and decision-making processes is essential to avoid reactive responses and to enable sustained, long-term resilience. Through such an approach, climate adaptation can be grounded in the realities of place, shaping environments that are better equipped to respond to the uncertainties of a changing climate.

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AI Declaration: The author wishes to voluntarily confirm the use of generative AI in an initial drafting of some sections that have been further detailed, refined and finalised through manual review and editing by the author.

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Urban Flooding in India: Bridging the Legal Gap Through Sponge City Principles



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Abstract

Urban flooding has become a recurring challenge across Indian cities, affecting infrastructure, economic activity and everyday urban life. While climate change and extreme rainfall have intensified flooding events, the crisis also reflects deeper gaps within existing urban planning and regulatory frameworks. Rapid concretisation, shrinking wetlands and inadequate water-sensitive planning have significantly reduced the ability of cities to absorb and manage rainwater effectively. This article examines urban flooding in India through a legal and regulatory lens. It analyses how existing planning and environmental frameworks continue to prioritise infrastructure expansion without adequately integrating urban hydrology into mainstream governance. It further explores sponge city principles as a global model for flood-resilient urban development and highlights the absence of their formal integration within India's legal framework.

Introduction

Cities today are flooding faster than they are growing. Urban flooding in India is no longer an isolated event linked only to heavy rainfall. It has become a recurring urban crisis. Cities such as Delhi, Gurgaon, Mumbai, Chennai and Bengaluru frequently witness severe flooding that disrupts transport systems, public infrastructure and everyday life. While climate change

and extreme rainfall have intensified these events, the problem also reflects deeper weaknesses in the way Indian cities are planned and regulated.

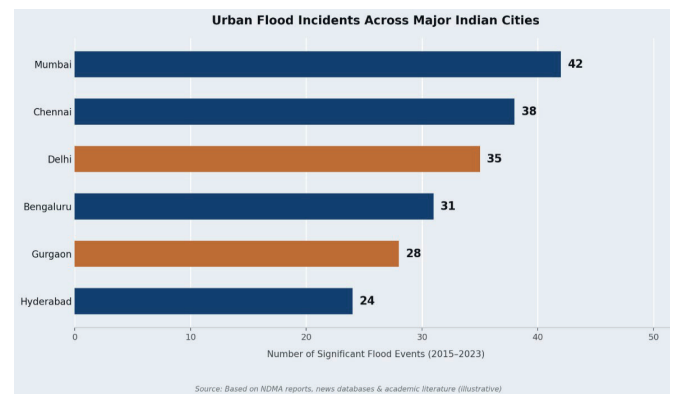


Figure 1: Urban Flood Incidents across Major Indian Cities (2015–2023)

Rapid urbanisation has transformed wetlands, lakes and open spaces into concretised urban landscapes. Natural drainage channels have been encroached upon. At the same time, stormwater infrastructure has failed to keep pace with urban growth. As a result, cities are no longer able to absorb and channelise rainwater effectively and flooding has become more frequent.¹

The problem, therefore, is not only environmental or infrastructural. It is also regulatory. Existing planning laws and development frameworks continue to focus on construction, land use and urban expansion. Very little

attention is given to water-sensitive urban planning and flood resilience.

That is where the sponge city approaches become important. Sponge cities are designed to absorb, store and slowly release rainwater through wetlands, green spaces, permeable pavements, rainwater harvesting systems and other forms of blue-green infrastructure. Instead of quickly draining rainwater away through concrete systems, these approaches help cities manage water in a more natural and sustainable manner.

Several countries have started adopting sponge city principles as part of climate-resilient urban development. India, however, has not formally integrated these principles into its legal or regulatory framework. Against this backdrop, this article examines the planning and legal gaps that contribute to urban flooding in India. It further explores the need for water-sensitive and climate-resilient urban regulation.

Urban Flooding and the Limits of Existing Urban Development Frameworks

Indian cities are expanding in ways that leave very little room for water. Urban flooding in India is not caused by rainfall alone. It is also a consequence of the manner in which cities are planned and developed. Existing urban development frameworks continue to prioritise construction, infrastructure expansion and land utilisation without adequately accounting for natural water systems and urban hydrology.²

Urban planning in India is largely governed through master plans, zonal development plans and municipal building regulations. These frameworks regulate land use, construction density, road networks and urban expansion. However, flood resilience and water management remain secondary concerns within the planning process. As cities continue to expand, wetlands, lakes, floodplains, and open spaces are increasingly being converted into commercial and residential developments. This has significantly reduced the ability of cities to absorb excess rainwater.³

The consequences of such planning failures are

particularly visible in rapidly expanding cities such as Delhi, Gurgaon, Mumbai and Bengaluru. In many urban areas, natural drainage channels and water bodies have been altered, encroached upon or built over to accommodate roads, real estate projects and infrastructure development. At the same time, stormwater drainage systems have failed to expand at the same pace as urban growth. Even short periods of heavy rainfall are, therefore, capable of overwhelming existing infrastructure and causing severe flooding.

Moreover, the same approach is reflected in municipal building regulations. Existing building bye-laws primarily focus on structural compliance, setbacks, floor area ratios and plot utilisation. Limited emphasis is placed on how urban developments impact drainage, groundwater recharge or rainwater absorption. While some cities have introduced mandatory rainwater harvesting systems, broader planning measures relating to permeability and stormwater retention remain inadequate. As a result, flood management continues to be treated largely as a drainage and engineering issue rather than as an integral part of urban planning.

The limitations of existing frameworks are also visible within environmental regulation. Frameworks such as the Environmental Impact Assessment Notification, 2006 and the Wetlands (Conservation and Management) Rules, 2017 recognise the environmental significance of wetlands and ecological systems. However, these frameworks largely operate through project-specific approvals and environmental safeguards. They do not comprehensively address how rapid urbanisation alters city-wide drainage patterns, flood absorption capacity and urban hydrology.

The combined effect of these planning and regulatory gaps is increasingly visible across Indian cities. Urban development frameworks continue to focus primarily on construction and infrastructure expansion, while limited attention is paid to long-term urban water management and flood resilience. As climate-related flooding events become more frequent, the limitations of existing planning systems are becoming increasingly difficult to ignore.

Sponge City Principles: Global Practice and China's Urban Flood Model

Around the world, cities are beginning to realise that rainwater cannot simply be drained away faster than it falls. As urban flooding became more frequent across

growing cities, several countries started exploring more sustainable approaches towards flood management. The focus gradually shifted from rapidly draining rainwater away to improving the ability of cities to absorb, store and manage excess water more effectively.

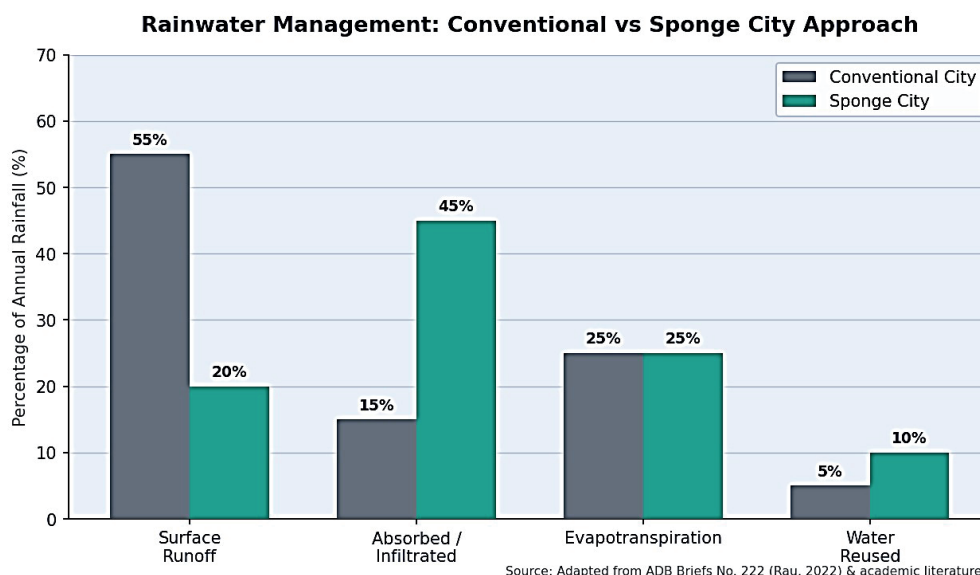


Figure 2: Rainwater Management – Conventional vs Sponge City Approach

It is within this context that sponge city approaches gained global attention. Sponge cities are designed to absorb, store and gradually release rainwater through wetlands, green spaces, permeable pavements, rainwater harvesting systems and other forms of blue-green infrastructure. Unlike conventional concrete-

heavy drainage systems, these approaches seek to make cities function more like natural hydrological systems. The broader objective is not only to reduce flooding, but also to improve groundwater recharge, water quality and long-term climate resilience.⁴

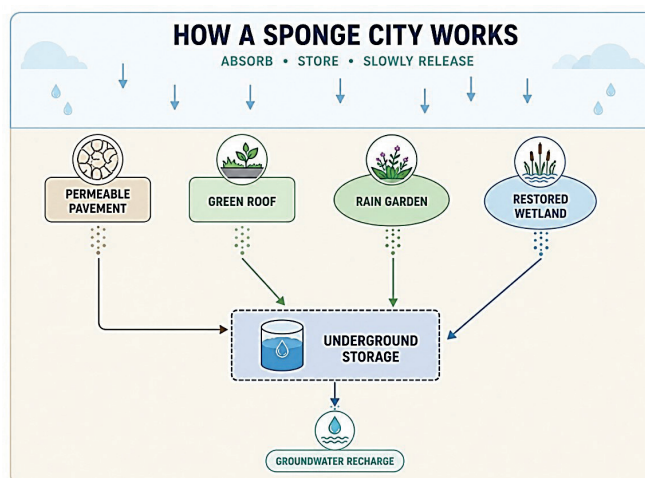


Figure 3: How a Sponge City Works – Absorb, Store, Slowly Release

The most prominent example of this approach can be seen in China. Rapid urbanisation, large-scale concretisation and recurring urban flooding pushes Chinese cities to reconsider traditional flood-management systems. In many cities, natural lakes and water channels had significantly reduced due to land expansion and infrastructure growth, weakening the natural capacity of urban areas to store and regulate rainwater.

In response, China formally introduced the Sponge City programme in 2015 through a joint policy framework issued by the Ministry of Housing and Urban-Rural Development, the Ministry of Finance and the Ministry of Water Resources. The programme sought to integrate water-sensitive planning directly into urban development and infrastructure governance. Pilot cities such as Wuhan, Shanghai and Shenzhen were encouraged to adopt permeable pavements, rain gardens, green roofs, restored wetlands, ecological drainage corridors and rainwater storage systems as part of mainstream urban planning.⁵

Wuhan emerged as one of the leading sponge city pilot projects under the programme. Known as the “city of one hundred lakes”, Wuhan has long struggled with severe waterlogging due to rapid urbanisation, shrinking lakes and inadequate drainage infrastructure. To address these challenges, the city adopted a combination of nature-based solutions and grey infrastructure measures. Sponge infrastructures in Wuhan included grass swales, bio-retention facilities, permeable pavements, infiltration trenches and rainwater storage modules. The programme also focused on protection and restoring urban lakes, rivers and wetlands as part of the city’s larger water-management strategy.

Importantly, China’s sponge city framework was institutionalised through measurable planning and governance mechanisms. Wuhan introduced clear runoff-control targets requiring large portions of urban rainfall to be naturally absorbed, stored or reused within the city instead of being immediately discharged through drainage systems. The city aimed for 20% of its urban area to meet sponge city standards by 2020 and 80% by 2030, with the capacity to absorb 60%–85% of annual rainfall.⁶

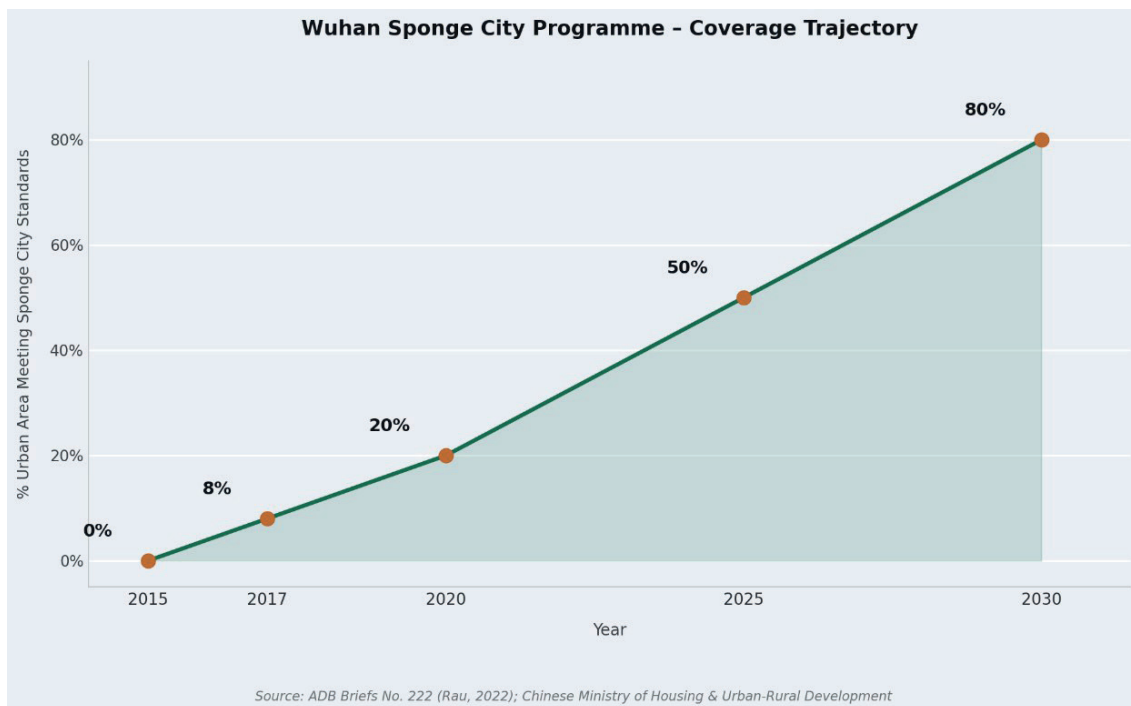


Figure 4: Wuhan Sponge City Programme – Coverage Trajectory (2015–2030)

one reportedly launched hundreds of sponge infrastructure projects through public and private participation. China's experience demonstrates that urban flood management requires planning systems that integrate water management directly into urban development. India, however, has yet to formally incorporate similar principles into its urban planning and regulatory framework.

Bridging the Legal Gap: Towards Water-Sensitive Urban Regulation

India's cities are being forced to confront a reality that existing planning laws were never designed to address. While current legal frameworks regulate construction, land use and environmental protection, they do not adequately integrate flood resilience and urban hydrology into mainstream urban planning systems.⁷

Despite growing recognition of climate-resilient urban development, India still lacks a legally integrated water-sensitive urban planning. Existing planning and environmental regulations operate through fragmented institutional mechanisms, with limited coordination between urban development authorities, municipal bodies and environmental regulators. As a result, flood-resilience measures often remain project-specific rather than becoming part of mainstream urban governance.

This fragmentation is particularly visible in the manner urban flooding is addressed across regulatory frameworks. Municipal laws, planning authorities, environmental regulators and disaster-management bodies continue to function through separate institutional structures with overlapping responsibilities. Urban flood management therefore remains dispersed across multiple agencies without a unified planning or governance framework.

Regulatory Gap Assessment: India's Urban Planning Frameworks

Regulatory Framework	Flood Resilience	Water-Sensitive Planning	Runoff Targets	Blue-Green Infra Standards	Inter-Agency Coordination
Master Plans	Absent / Weak	Absent / Weak	Absent / Weak	Absent / Weak	Absent / Weak
Municipal Bye-laws	Absent / Weak	Absent / Weak	Absent / Weak	Absent / Weak	Absent / Weak
EIA Notification 2006	Partial	Absent / Weak	Absent / Weak	Absent / Weak	Partial
Wetlands Rules 2017	Partial	Partial	Absent / Weak	Absent / Weak	Absent / Weak
AMRUT 2.0	Partial	Partial	Absent / Weak	Partial	Partial

Coverage Level

- Strong
- Partial
- Absent / Weak

Figure 5: Regulatory Gap Assessment – India's Urban Planning Frameworks

A similar gap can be seen in development regulation and infrastructure planning. Existing building bye-laws and urban approval mechanisms continue to prioritise construction and infrastructure expansion, while limited enforceable standards exist for permeability, stormwater retention, ecological drainage systems and blue-green infrastructure. Unlike China's sponge city framework, India does not currently impose measurable runoff-control targets or legally integrated flood-resilience standards within urban planning systems.

At the same time, India has gradually started moving towards water-sensitive and blue-green urban approaches, although not through a formal sponge city framework. Recent initiatives have increasingly focused on restoration of urban water bodies, sustainable stormwater management and climate-resilient infrastructure. Chennai's blue-green infrastructure projects, including lake restoration and sponge park initiatives, reflect a growing recognition of nature-based urban planning approaches. Policy

discussions under programmes such as AMRUT 2.0 have similarly emphasised urban water security, reuse of water resources and sustainable drainage planning.⁸

However, these efforts continue to operate largely as policy initiatives and city-specific projects rather than binding legal obligations. The absence of enforceable planning standards means that flood resilience still depends heavily on administrative implementation and local governance priorities. As a result, water-sensitive planning remains inconsistent across cities and urban development projects.

Even if India does not currently have a standalone sponge city legislation, existing planning and environmental frameworks could substantially reform to incorporate water-sensitive urban planning principles into mainstream urban governance. Integrating permeability standards, blue-green infrastructure requirements and ecological drainage protection into planning regulations could help cities become more climate-resilient and better equipped to manage future flooding risks.

Conclusion

India is gradually moving towards more climate-responsive and water-sensitive models of urban development through blue-green infrastructure initiatives and sustainable urban planning measures. As cities continue to expand and climate risks intensify, global approaches such as China's sponge city framework offer useful lessons on integrating flood resilience into long-term urban governance and infrastructure planning. Adapting some of these principles within India's evolving urban development

framework could play an important role in building more sustainable and resilient cities.

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The CEAI team would like to thank Mr A P Mull and Ms Jamini Goel for providing interesting and relevant snippets of information for this June 2026 edition of ViewPoint

An Overview on the Effects of Climate Change in Nepal



Thakur P Sharma

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Introduction

Climate change is causing severe problems worldwide, like extreme weather, rising sea levels, and ecological shifts. Nepal, located in the lap of the Himalayas, is a prime example of how vulnerable a country can be due to climate change. The effects of climate change encompass the melting of glaciers, changing weather patterns, and an increase in both landslides and floods. Given its status as a developing country, Nepal encounters unique obstacles in effectively addressing these concerns, necessitating a collaborative approach from local and international entities.

Nepal's vulnerability when dealing with unexpected weather events

Nepal's land is experiencing more frequent and stronger extreme weather conditions, causing calamities like floods and landslides. Rising global temperatures cause more rain and glacial melt, leading to sudden floods and glacial lake floods. The country's mountains and monsoon weather (typically from June to September) make it highly susceptible to monsoon-related floods, causing widespread damage and loss of life. Also, deforestation and unstable soil from climate change make slopes more prone to landslides after heavy rain.

Tragedy Strikes Sankhuwasabha District: A Sobering Reality

A horrific occurrence that highlights Nepal's vulnerability happened on June 17th 2023 in the Sankhuwasabha district of Eastern Nepal under Koshi Province. Unrelenting rains caused disastrous floods and landslides that claimed many lives, significant property damage, and destroyed crucial hydropower installations. The catastrophe reverberated deeply through the communities of eastern Nepal, resulting in not only human suffering but also dealing blows to crucial infrastructures. As reported, 22 individuals, including 17 workers working on the ongoing Super Hewakhola Hydropower Project, went missing after being swept away by flooding caused by the swollen Hewakhola river. The flooding and landslides were



initiated by continuous rainfall. The path to recovery is projected to be prolonged and resource-intensive, necessitating substantial financial backing and unwavering commitment to rebuilding the afflicted regions.

Monsoon Trials and Tribulations on the Narayangadh-Mugling Road

During the rainy season, the significant national highways, especially the Narayangadh-Mugling road, encounter added challenges. The road plays a crucial role in connecting various regions of Nepal, but it frequently becomes impassable due to landslides and heavy rainfall. The need for improved strategies to address these rainy season difficulties becomes evident when considering the necessary road repairs. Despite its relatively short length of approximately 36 kilometers, traveling becomes very difficult during the rainy season. In 2023, there were 19 reported landslides solely along this stretch of road, resulting in delays. In comparison to 139 landslides on national highways throughout the country, the Narayangadh-Mugling road's vulnerability becomes evident. The impact of these challenges was pronounced, with the road being obstructed for more than 90 hours due to these issues.



Urban Inundation and Drainage Predicaments in Kathmandu Valley

The Kathmandu Valley faces repeated waterlogging and flooding in the monsoon due to poorly managed drainage systems and fast urban growth. This leads to congested roads, blocked waterways, worsened

by climate change-induced heavy rainfall and river surges. Asphalt roads and concrete structures prevent water from soaking into the ground, straining drainage. Insufficient environmental planning intensifies the problem, endangering health and the environment as sewage mixes with floodwaters. Urban settlements areas like Balkhu, Kuleshwar, Narephant, Balaju, Dhumbrahi, Mulpani, etc. experience the most impact, while significant road portions in Kumaripati, Tinkune, Jamal, Baluwatar, Bhadrakali, and certain segments of the Araniko Highway are flooded during the monsoon season, with a particular focus on the Banepa, Punyamati river region. The Kapan-Tarkari Bazaar-Sat Tale Road segment faces annual flooding during the monsoon due to river encroachment and inadequate drainage.

Himalayan Glacial Retreat and Its Wider



Ramifications

The increasing melting of glaciers in Nepal due to climate change leads to various linked problems. Glacial lake outburst floods (GLOFs) are a major concern as they can be dangerous when breached moraines release a lot of water suddenly. Unpredictable water flows cause sudden floods and landslides, which disrupt communities, farming, and infrastructure. Less melting of glacial ice means less water, affecting homes, power, and farming. Nepal's diverse ecosystems, important for its biodiversity, are also threatened, impacting tourism and mountain activities. These issues add to economic challenges, emphasizing the need for strategies to protect Nepal's future. For instance, a flood occurred in Barun Valley, eastern Nepal, on April 20, 2017, blocking the confluence of Barun and Arun Rivers, creating a potentially hazardous 200m lake due to glacier melt and rockfall.

Technology to Fight Climate Challenges

Nepal is taking quick action to adapt to climate change by using technology like drones, satellites, and maps. Drones, which were first used after the 2015 earthquake, have become a vital tool. They help respond to disasters and assess risks, collecting and analyzing data in tough areas. Nepal's drone network shows how local skills can be powerful in managing disasters and climate changes. The success of using local drone experts during the Melamchi disaster proves how fast data can be gathered and analyzed during emergencies. That approach makes disaster responses quicker, more effective, and affordable, improving how risks and crises are dealt with.



Conclusion

The country's vulnerability to harsh weather and tragic events such as the Sankhuwasabha flooding, and difficulties on crucial all weather highways emphasize the urgent requirement for careful planning and investment to handle climate impacts. The recurring issues of urban inundation, glacial retreat, and their broader consequences highlight the complex interplay between climate change and various sectors, demanding innovative solutions. Nepal's commendable use of technology, particularly drones, showcases the power of local expertise in mitigating climate challenges. As Nepal faces the challenges caused by climate change and other human activities like river encroachment and unplanned settlements, it shows the way for other countries to work together in protecting the planet's future.

Acknowledgement

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UNESCO - The Ethical Principles of Climate Change

Climate change not only threatens our ecosystems, it undermines the foundation of our fundamental rights, deepens inequalities and creates new forms of injustice.



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18 January 2024

Adapting to climate change and trying to mitigate its impacts are not just a matter of scientific knowledge and political will; it also demands a broader view of a complex situation.

In order to help Member States and other stakeholders to make appropriate decisions and implement effective policies for sustainable development, adaptation to climate change and the mitigation of its negative effects, UNESCO adopted a *Declaration of Ethical Principles in relation to Climate Change* in November 2017.

Ethics constitute the substantial core of any commitment. As a mobilizing force, ethics can steer action, facilitate arbitration, resolve conflicting interests, and establish priorities. Ethics have the capacity to connect theory with practice, general principles with political will, and global awareness with local actions.

The Declaration adopted by UNESCO is based on six ethical principles:

1. *Prevention of harm*: To better anticipate the consequences of climate change and implement responsible and effective policies to mitigate and adapt to climate change, including through low greenhouse gas emissions development and initiatives to foster climate resilience.
2. *Precautionary approach*: Do not postpone the adoption of measures to prevent or mitigate the adverse effects of climate change on the grounds of a lack of definitive scientific evidence.
3. *Equity and justice*: Respond to climate change in a way that benefits all, in a spirit of justice and equity. Allow those who are unjustly affected by climate change (due to insufficient measures or inadequate policies) to access judicial and administrative proceedings, including redress and remedy.
4. *Sustainable development*: Adopt new paths for development that make it possible to sustainably preserve our ecosystems, while building a more just and responsible society that is more resilient to climate change. Special attention must be paid to areas where the humanitarian consequences of climate change can be dramatic, such as food, energy, water insecurity, the oceans, desertification, land degradation and natural disasters.
5. *Solidarity*: Support, individually and collectively, the people and groups most vulnerable to climate change and natural disasters, particularly in the Least Developed Countries (LDCs) and Small Island Developing States (SIDS). Strengthen timely co-operative action in various areas, including technology development and transfer, knowledge-sharing and capacity-building.
6. *Scientific knowledge and integrity in decision-making*: Strengthen the interface between science and policy to optimally aid decision-making and the implementation of relevant long-term strategies,

including risk prediction. Promote the independence of science and widely disseminate its findings to as many people as possible, for the benefit of all.

UNESCO has long-standing experience in environmental ethics, supported by the World Commission on the Ethics of Scientific Knowledge and Technology (COMEST), created in 1998. As an advisory body and a forum for reflection, COMEST has published a series of reports over the past decade, that have helped to inform public debate. Its 2015 report served as the basis for the *Declaration of Ethical Principles in relation to Climate Change*.



The philosophical and ethical issues of climate change

Feltz, Bernard

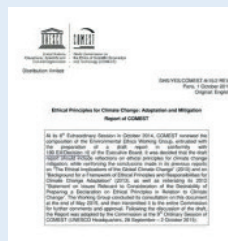
July-September 2019



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UNESCO

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1 Oct. 2015

Source: <https://www.unesco.org/en/articles/ethical-principles-climate-change-0>

ETHICS IN CONSTRUCTION

BUILDING RESPONSIBLY. PROTECTING LIVES.

1. QUALITY OVER COMPROMISE

✗

CUT CORNERS
RISK LIVES

✓

STRONG TODAY
SAFE TOMORROW

2. HONEST DESIGN & REPORTING

✗

FALSE REPORT
• HIDDEN RISKS
• WRONG DATA

TRUTH HIDDEN,
DISASTER UNFOLDS

✓

HONEST REPORT
✓ ACCURATE DATA
✓ REAL RISKS

TRUTH SHARED,
LIVES SAVED

3. PLAN FOR SAFETY, NOT JUST COST

✗

LOWEST COST

SHORT TERM SAVINGS,
LONG TERM LOSSES

✓

SAFETY FIRST

SMART INVESTMENT,
SAFE COMMUNITIES

4. PUT PEOPLE FIRST

✓

SAFE BUILDING
• PROPER DRAINAGE
• STRONG STRUCTURE
• FLOOD RESILIENT

PUTTING PEOPLE FIRST
BUILDS TRUST AND SAVES LIVES

5. RESPECT NATURE, BUILD SUSTAINABLY

✗

IGNORE NATURE,
INCREASE FLOOD RISK

✓

WORK WITH NATURE,
REDUCE FLOOD RISK

ETHICS TODAY, SAFETY TOMORROW.
BUILD WITH INTEGRITY.
PROTECT WHAT MATTERS MOST.

'Ethics in Construction' contributed by Vandana Randhawa

CEAI NEWS

❖ CEAI ACADEMY

The CEAI Academy continued its professional development initiatives through a series of technical, workplace, and industry-focused programmes delivered in both online and in-person formats..

PMP® Precursor Webinar on 14th April 2026 | Online

The Academy conducted a PMP® Precursor Webinar, bringing together engineers and professionals seeking clarity on the Project Management Professional (PMP®) certification. The 90-minute session focused on addressing some of the most common areas of uncertainty-eligibility, application processes, exam structure, and preparation strategy-through a practical, experience-led discussion.

The session was marked by strong participation and thoughtful questions, reflecting the growing interest in structured project management capabilities across the engineering and infrastructure ecosystem.

Primavera (P6) Training on 24th-25th April 2026 | CEAI Academy Premises

Under training initiatives, a 2-day training programme on Oracle Primavera (P6) was also conducted, for project professionals from a member organisation.

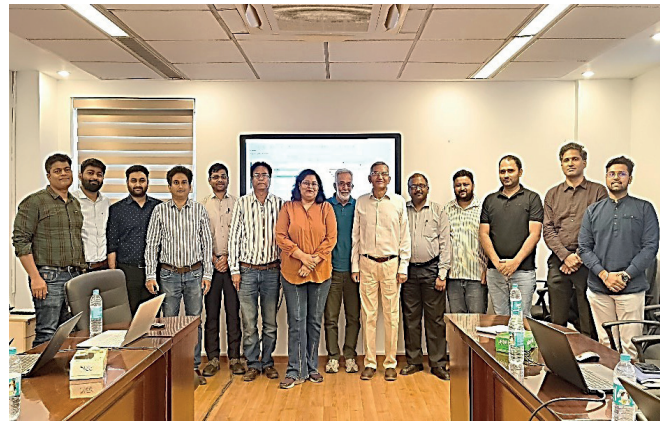
The session focused on building hands-on capability in project planning, scheduling, resource management, and tracking, covering key areas such as WBS development, activity relationships, critical path identification, baseline creation, and reporting.

Participant feedback highlighted:

- Strong emphasis on practical, application-based learning

- Improved clarity on end-to-end project workflows within Primavera
- Increased confidence in using the tool in real project environments

The programme was designed as a part of the Academy's ongoing efforts to strengthen project execution capabilities within the industry.



Construction Law Programme on 8th May 2026 | Chandigarh

One of the major accomplishments in the Northern Region was the *Construction Law Programme* held in Chandigarh. Professionals came together to learn about and explore the legal and contractual aspects of engineering and infrastructure projects. Discussions included practical considerations in project execution, contract administration, and risk awareness to ensure more informed project delivery.

Several dignitaries graced the event with their presence and support. The programme was inaugurated by the Chief Guest, Rajya Sabha MP **Sh. Satnam Singh Sandhu**. He emphasised the importance of understanding legal and contractual intricacies in India's rapidly growing infrastructure sector. The

valedictory session of the workshop was addressed by Haryana Chief Information Commissioner cum former Chief Secretary **Sh. T V S N Prasad**.



Precursor Webinar: Interfacing Artificial Intelligence with Engineering and Construction Work' 8th May 2026| Online

As a lead-up to CEAI's upcoming AI training initiatives, this webinar introduced participants to emerging applications of Artificial Intelligence across engineering and construction. The session explored opportunities in decision-making, efficiency, and technology-enabled project practices.

POSH Training Programme 14th May 2026 | Online

The Academy also conducted an online training programme on Prevention of Sexual Harassment (POSH), focusing on workplace awareness, professional conduct, legal responsibilities, and building safer and more inclusive organisational environments.

Mastering Communication, Email Etiquette and Interpersonal & Professional Dynamics on 14th & 15th May 2026 | CEAI Academy Premises

Delivered at the CEAI premises for a member organisation, the training programme focused on strengthening workplace communication, and professional email practices. There were in-depth sessions on self-discovery, interpersonal effectiveness, and business etiquette through practical and application-oriented discussions.

In-class assignments, writing practice, roleplays, group discussions, individual coaching, and peer-led learning formed some of the key methods used in this programme. Participants found the programme very effective, and immediately applicable to their everyday work life.



Precursor Webinar on Project Financing 22nd May 2026 | Online

An introductory webinar, it examined the growing importance of project financing in infrastructure and engineering, covering concepts related to investment, project viability, funding structures, and financial decision-making.

Practical Management of FIDIC Contracts 10th & 11th June 2026 | CEAI Academy Premises

On 10 June, 2026 and 11 June, 2026, the CEAI Academy conducted a two-day programme at the CEAI premises in New Delhi. This programme was designed as an open-house programme and member

organisations from all across the country sent in their delegates for this practical training.

The content covered not only theoretical knowledge,

but also case studies, group work, assignments in the classroom, to ensure that participants could apply the knowledge on real business scenarios.



❖ CEAI EVENTS

Webinar: Importance of Face Logging and Geological Characterisation in Tunnel Construction on 20th May 2026

The webinar titled *“Importance of Face Logging and Geological Characterisation in Tunnel Construction”* was organised on 20th May 2026. The session focused on the critical role of geological observations and face logging in ensuring safe, efficient, and successful tunnel construction projects.

Dr. Juned Alam, Deputy Manager and Engineering Geologist, Intercontinental Consultants and Technocrats Pvt. Ltd. were the speaker.

The webinar aimed to enhance participants’ understanding of:

- The importance of geological investigations during tunnel excavation.
- Face logging techniques and their role in documenting ground conditions.
- Geological characterisation methods for identifying rock types and rock mass quality.
- The application of geological data in excavation planning, support design, and tunnel safety.

The Key Topics Covered: Face Logging in Tunnel Construction, Geological Characterisation, Role in Decision-Making, Practical Challenges, Modern Technologies

❖ MEMBER NEWS

Mr Alok Bhowmick, CEAI GC Member was honoured with the S D Limaye Award for Excellence in Structural Engineering. The Award was given to him on 25th April 2026 at a function organised by ICI-Pune Chapter.



❖ OTHER NEWS

Mr Prashant Kapila, President - CEAI participated as a speaker at the Abu Dhabi Infrastructure Summit 2026, contributing to discussions on the future of

infrastructure delivery, collaboration, procurement, contracts, and sustainable development.

The summit brought together global infrastructure leaders, policymakers, investors, and industry experts to exchange perspectives on building resilient and future-ready infrastructure ecosystems.

Social Media Initiatives

CEAI is actively strengthening its social media outreach to increase the visibility of the engineering profession, especially the Consulting Engineering, to showcase member achievements, promote industry conversations, and expand awareness of CEAI's initiatives, programmes, events, and opportunities.

All members are encouraged to actively participate in the initiative by following CEAI across social media platforms and engaging with the content through likes, comments, shares, reposts, and mentions within the professional networks.

Every interaction helps in CEAI's collective reach, thus amplifying the voice of **Consulting Engineers**, and strengthening CEAI's ability to build visibility and influence for the profession at a national and global level.

❖ FORTHCOMING PROGRAMMES

CEAI Academy

Looking ahead, the Academy has planned a series of programmes in the coming quarter to support young engineers in enhancing their technical, managerial, and professional capabilities.

Following the successful PMP® precursor webinar, a comprehensive 5-day online PMP® Certification Training Programme is being planned, which would enable participants to fulfil the 35-hour training requirement necessary to pursue PMP® certification.

Additional programs in the pipeline include Primavera Training, Forensic Engineering: Learning from Failures

in the Built Environment, AI Training, Leadership Development, FIDIC-focused training initiatives, Business Communication and Soft Skills programs, Industry Readiness & Personality Development workshops for students, and an AR/VR workshop.

Further, under a MoU signed with SRM University, Sonepat, the CEAI Academy is also collaborating to design and deliver specialised programmes aimed at preparing students for successful entry into the workforce and improving their placement readiness.

The CEAI Academy remains committed to supporting engineers and professionals with relevant, future-oriented learning opportunities across technical and professional domains.

CEAI President's Lecture Series on Consulting Excellence

The first lecture in the upcoming series will be delivered by Er. Devendra Kumar Sharma, President of the International Commission on Large Dams (ICOLD), headquartered in France, on 17th July 2026.

CEAI Future Leader Forum is organising a webinar on "Design for Deconstruction" on 10th July 2026 at 4:00 PM

Design for Deconstruction (DfD) is a sustainable approach that plans buildings so they can be easily dismantled instead of demolished. Unlike traditional "build-use-demolish" methods, DfD supports a circular system where materials are recovered and reused. Using modular design, prefabrication, and mechanical connections, it reduces construction waste and the need for new raw materials. This lowers energy use, emissions, and preserves embodied energy. DfD also reduces demolition costs and promotes resource efficiency, making construction more environmentally responsible and sustainable.

Dr. Sarath S, Associate Professor - Department of Civil Engineering, UKFCET will be the speaker.

FIDIC Global Infrastructure Conference 2026

The **FIDIC Global Infrastructure Conference 2026** will be hosted in New Delhi, India from 13th to 15th September 2026. As FIDIC's flagship annual event which has been taking place since 1930, the conference provides a global platform for the infrastructure industry to come together to exchange knowledge, share experience and strengthen collaboration across regions.

New Delhi offers a highly relevant setting for the conference, reflecting India's growing influence and leadership in global infrastructure development. As one of the world's fastest-growing major economies, India is at the forefront of large-scale infrastructure delivery, innovation and capacity building, making it an ideal location for the global infrastructure community to meet.

FIDIC's flagship annual event brings together the full spectrum of the infrastructure industry, including clients, governments, policy makers, consulting engineers, contractors, lawyers, financiers and architects. The conference offers high-level dialogue, knowledge sharing and valuable networking opportunities with peers and partners from across the globe.

Registration is Open for the FIDIC Global Infrastructure Conference 2026!

Join global leaders of the infrastructure sector in New Delhi, India, during 13th to 15th September 2026 for one of the industry's most influential gatherings.

Under the theme **"Engineering a Bright Future, Together: Quality Infrastructure for People and Prosperity"**, the conference will bring together industry leaders, policymakers, financiers and engineers from over 100 countries to address the most pressing challenges in infrastructure delivery.

Learn more and register ↓ <https://lnkd.in/eTdwMPVA>

VIEWPOINT SEPTEMBER 2026

The themes for the quarterly issues of CEAI's magazine "ViewPoint" for the balance period of 2026 are given below:

September 2026	Urban Rejuvenation - A Tech-Enabled Approach
December 2026	Smart Cities or Smart Villages: Where Should India Invest More

The September 2026 edition of ViewPoint **"Urban Rejuvenation - A Tech Enabled Approach"** calls for deep thinking as to where technology should and **where it should not be incorporated** since more than half of the world's population live in urban areas.

By 2050, that figure is expected to rise to include two thirds of all humanity. Technology can help urban and infrastructure planners proactively take this challenge head on and tackle it. Technology used for urban rejuvenation can integrate digital tools to transform undeveloped areas/ areas requiring rehabilitation into sustainable, efficient, and livable spaces, by simulating development scenarios.

At the planning stage, this would be data-driven and could utilise simulation by digital twinning, geographic information systems and predictive analytics - to assess the impact of new developments and infrastructure upgrades for different scenarios before implementation. Machine learning models should be used to analyse historical data to project population growth, traffic patterns, and environmental changes. Systems could analyse spatial data for land-use planning, identify areas for infrastructure renewal and manage transportation networks.

Public infrastructure needs to be smart and sustainable and enable monitoring of environmental conditions viz. air, water, land and noise levels; the structural health of buildings; smart services including grid and energy management ensuring optimal use of renewable energy to reduce carbon emissions and provide resilient sustainable means of energy; tech enabled intelligent mobility and transport, safety and security coupled with emergency services

Digital tools, besides being an aid for engagement of the citizen, and non-citizen (visitors) alike, also serve to create feedback systems to enhance efficiency in decision making to improve planning and services to align with the actual needs of the community.

All Professionals are encouraged to contribute articles on the theme, based on their experience/ expertise and recommend ways to urban rejuvenation or regeneration, and revitalise declining city neighbourhoods by enhancing public spaces, upgrading infrastructure, and improving living conditions sustainably.

Articles (of 1500-3000 words) for the September 2026 edition of ViewPoint need to reach CEAI by 25 August 2026. Articles have to be in MS Word - Times New Roman 12 with single line spacing with before and after 6 pt and normal margin, on A4 size. A recent, clear and bright passport-size photograph on a plain light-coloured background of the author(s) is to be sent along with the article. For details of formatting, please refer to 'Format for Articles for CEAI Viewpoint' on CEAI's

website, under 'Publications'. The 'CEAI Conditions of Publication' can also be seen on the website.

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Tech Quiz

1. **What aspect of flood control measures considers the cost-effectiveness of different strategies?**
 - a) Flood zoning
 - b) Land-use planning
 - c) Economic Analysis
 - d) Flood forecasting
2. **Flood routing refers to the process of**
 - a) Predicting the occurrence of floods
 - b) Diverting floodwaters to urban areas
 - c) Managing the flow of floodwaters through channels
 - d) Mapping flood-prone area
3. **Which of the following is a non-structural flood control measure?**
 - a) Floodplain mapping
 - b) Construction of dams
 - c) Erosion control
 - d) Flood insurance
4. **Which of the following methods is used to study past CO₂ levels?**
 - a) Tree rings
 - b) Ice cores
 - c) Fossil records
 - d) Sediment layers
5. **What is one effect of increased greenhouse gas emissions?**
 - a) Lower global temperatures
 - b) Rising sea levels
 - c) Decreased solar activity
 - d) Stable weather patterns
6. **Which region in India is worst affected by landslides?**
 - a) Himalayas including North-eastern mountains ranges
 - b) Western Ghats
 - c) Vindhya
 - d) Deccan Plateau
7. **What is the main factor contributing to landslides in Peninsular India?**
 - a) Earthquakes
 - b) Volcanic eruptions
 - c) Torrential rainfall on deforested slopes
 - d) Mining activities
8. **How can afforestation help in reducing landslides?**
 - a) By increasing surface runoff
 - b) By reducing soil erosion
 - c) By increasing water infiltration
 - d) By binding the soil with roots and reducing surface runoff
9. **Which of the following geological factors contributes to landslides??**
 - a) Weakness in the composition and structure of rock or soil
 - b) Presence of dense vegetation
 - c) Flat topography
 - d) High ground table
10. **What is the role of hazard mapping in mitigating landslide risks?**
 - a) To predict the exact time of a landslide
 - b) To identify high-risk area and guide development restrictions
 - c) To calculate the economic losses from a landslide
 - d) To study the impact of landslides on wildlife

The first person to email the correct answers to CEAI info@ceai.org.in will get a congratulatory email and be acknowledged by publishing the person's photograph in the next issue.

Compiled by Rajiv Maini with inputs from Neha Jain

CEAI Answers to Tech Quiz **March 2026** issue

1 (d), 2 (d), 3 (b), 4 (c), 5 (d), 6 (d), 7 (a), 8 (b), 9 (d), 10 (c)



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