



Towards science-based climate policy in Kerala: Integrating adaptation and mitigation for a climate-resilient future

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Abstract

Kerala has experienced a succession of climate extremes, including intense rainfall and heat stress, along with associated floods, landslides, and droughts, highlighting the urgent need to transition from uncoordinated climate responses to a science-based, integrated policy framework. Despite a growing body of scientific evidence documenting these trends, policy interventions remain inadequately aligned with empirical assessments and often lack consistency across sectors and scales. This perspective argues for embedding climate policy in robust scientific evidence, high-resolution climate datasets, and integrated vulnerability assessments that encompass both biophysical and socioeconomic dimensions. Drawing on observed climate variability, future projections, and recent climate-induced disasters, the study identifies critical gaps in data infrastructure, institutional coordination, climate finance, climate change impact assessments, and implementation capacity. It advances watershed-based planning as a scientifically grounded spatial unit for climate action and underscores the importance of systematic monitoring, climate auditing, and adaptive governance. Furthermore, the article advocates establishing a dedicated Climate Change Adaptation Cadre in the state to strengthen the science-policy-practice interface and facilitate effective decentralised implementation. Integrating mitigation, adaptation, and disaster risk reduction within a coherent governance framework is essential for advancing climate-resilient development in Kerala and other climate-vulnerable regions of the Global South.

Keywords: Climate policy, Climate governance, Climate change adaptation, Climate resilience, Disaster risk reduction, Science-policy interface

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1 Introduction

Climate change is an unequivocal global phenomenon that increasingly affects environmental systems, economic stability, human well-being, and overall quality of life. Although climate change operates at a global scale, its impacts are manifested regionally and locally, shaped by specific socio-ecological and climatic conditions (Byg and Salick, 2009). Kerala, a densely populated tropical state, is experiencing significant and multifaceted impacts of climate change. In recent years, the state has experienced an increasing frequency and intensity of climate-induced hazards, highlighting its growing vulnerability. These emerging risks underscore the need for a robust climate policy framework

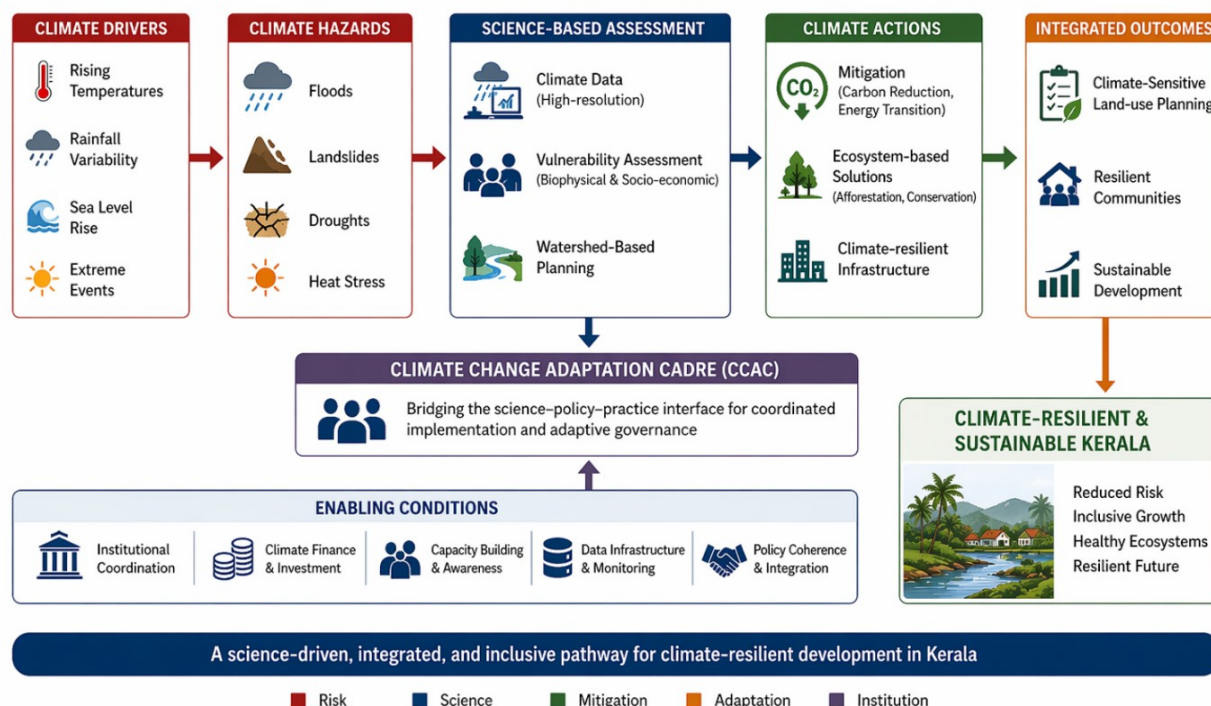
grounded in scientific evidence, systematic risk assessment, and regional context. Therefore, climate change adaptation and mitigation strategies must be region-specific and scientifically informed, rather than relying on generalized global approaches or ad hoc interventions.

The southwest coast of India, particularly Kerala, represents a climatically sensitive region influenced by complex topography, the Arabian Sea, and dynamic monsoonal processes. Recent studies report intensified convective activity and increased extreme rainfall events, which have contributed to recurrent floods and landslides, resulting in significant human and economic losses over the past decade (Antony et al., 2025; Sreenath et al., 2023). Long-term observational analyses further reveal statistically significant

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Integrating Adaptation and Mitigation for a Climate-Resilient Future



Graphical Abstract

increases in air temperature, relative humidity, and sea surface temperature over Kerala, while precipitation trends exhibit strong seasonal variability (Gunaseelan and Dris-sia, 2024; Surendran et al., 2020). These consistent warming trends and associated atmospheric changes indicate a strengthening climate change signal, likely to increase the frequency and intensity of extreme weather events across the state.

Despite the growing body of empirical evidence on climate variability and the increasing frequency and intensity of extreme events in Kerala, a critical gap persists in translating scientific knowledge into coherent, actionable, and integrated policy frameworks. Current climate responses remain largely fragmented across sectors, often lacking alignment with high-resolution climate data, site-specific downscaling outputs (David Raj et al., 2024), and localized vulnerability assessments. This disconnect limits the effectiveness of policy interventions in addressing region-specific climate risks. Furthermore, insufficient emphasis has been placed on integrating interdisciplinary insights and operationalizing science-policy linkages through spatially explicit planning units, such as watersheds and landscape-level frameworks, which are crucial for regions with complex terrain and hydrological dynamics. Institutional mechanisms for adaptive governance, cross-sectoral coordination, and evidence-based implementation also remain underdeveloped, constraining the scalability and sustainability of climate actions. Addressing these gaps requires a systematic, science-based, and integrated policy framework that explicitly links climate evidence, vulnera-

bility assessments, and governance structures. Such an approach is essential to enhance climate resilience, ensure policy coherence, and support informed decision-making tailored to Kerala's unique socio-ecological context.

1.1 Evidence of Climate Change in Kerala – Observed Trends and Future Projections

Several studies provide robust evidence of changing climate patterns in Kerala, reflected in shifts in rainfall variability, increasing frequency of extreme events, and rising temperatures (Fig. 1). These changes indicate a transition toward a more variable and risk-prone hydroclimatic regime.

1.1.1 Temperature Trends and Heat Extremes

Temperature records show a consistent warming trend across Kerala. Daily average temperatures increased by approximately 0.54 °C between 1980 and 2019, with statistically significant warming observed across all districts (Valappil et al., 2022). Similarly, Ajithkumar and Riya (2022) reported significant increases in maximum temperatures during 1980–2020, with projected warming rates of about 0.03 °C year⁻¹ under the RCP 4.5 scenario and 0.05–0.06 °C year⁻¹ under the RCP 8.5 scenario. This warming has led to the emergence of heatwave conditions in Kerala, which were previously absent. While earlier assessments (1971–2000) reported no heatwaves (Pai et al., 2022), recent analyses (1991–2020) identify Kerala as an emerging heatwave-prone region, particularly during March and in

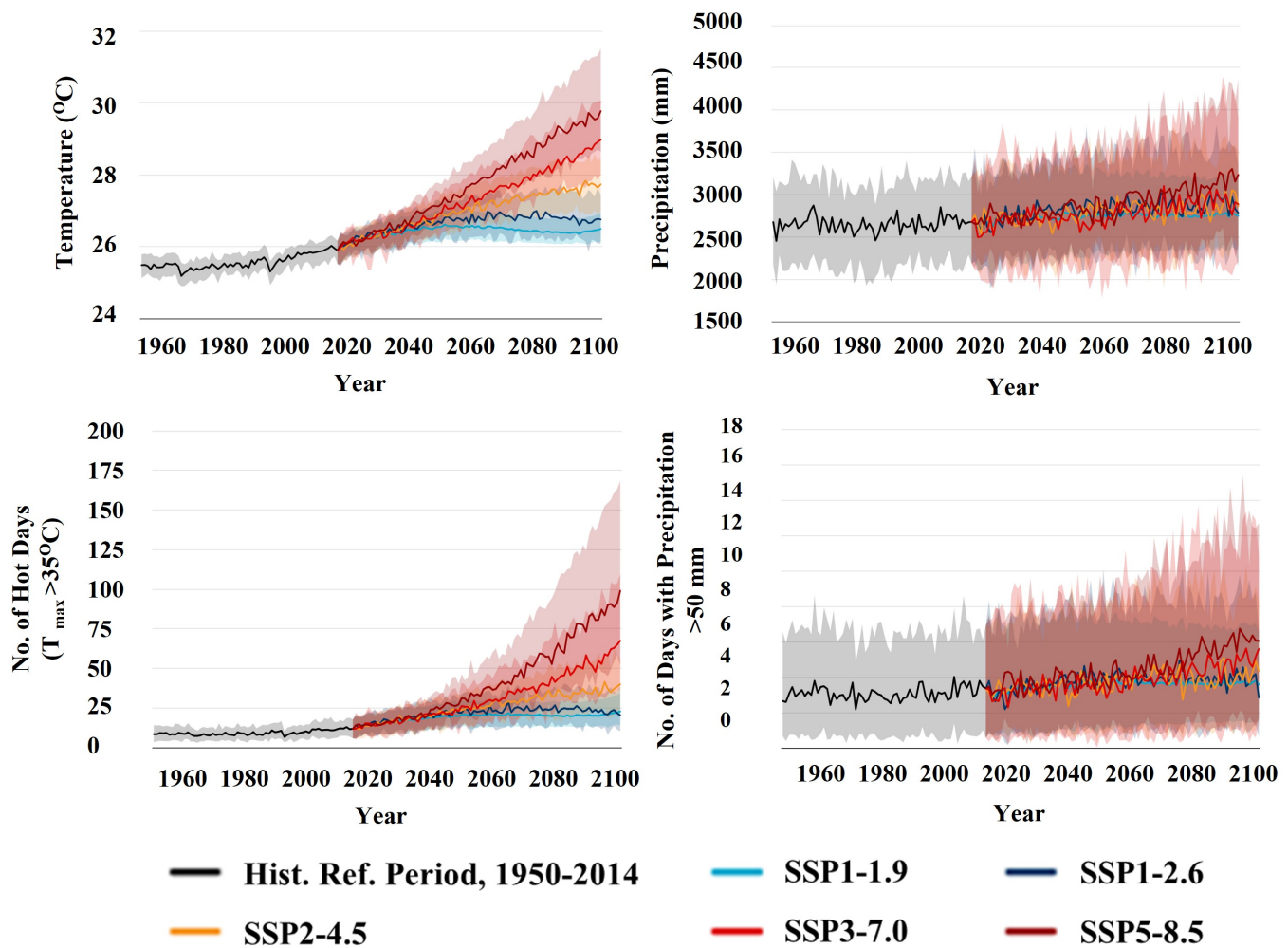


Fig. 1. Projected time-series anomalies of major climate indicators over Kerala, India (1950–2100) based on a multi-model ensemble, expressed relative to the 1950–2014 reference period: (a) mean surface air temperature, (b) precipitation, (c) number of days with heat index > 35 °C, and (d) number of days with precipitation > 50 mm. (Source: *Climate Change Knowledge Portal, World Bank, n.d.*)

the last decade (Singh et al., 2020; Tyagi et al., 2025). Future projections suggest an increase of nearly 2 °C in mean temperature by 2050, with districts such as Palakkad likely to experience more frequent hot days and heatwaves (Reejo and Soumya, 2025). Broader scale projections also indicate increasing heatwave intensity and frequency across southern and coastal India (Das and Umamahesh, 2021; Singh and Mall, 2023).

1.1.2 Rainfall Variability and Extreme Events

Kerala has witnessed significant changes in rainfall characteristics over the past few decades. Pal and Al-Tabbaa (2009) reported long-term shifts in seasonal precipitation extremes, indicating emerging signals of climate change. Although the state receives an average annual rainfall of nearly 3,000 mm, it remains vulnerable to both floods and droughts. For instance, the severe drought of 2017 and declining rainfall trends in Thiruvananthapuram highlight increasing hydroclimatic variability (Reejo and Soumya, 2025). At the same time, extreme rainfall events have intensified. Sudheer et al. (2023) demonstrated that the catas-

trophic floods of 2018 and 2019 were driven by complex interactions among large-scale atmospheric processes, hydrological responses, and anthropogenic factors, significantly amplifying disaster risks. While long-term southwest monsoon rainfall (1998–2019) shows no significant trend, recent decades indicate a weak increasing tendency in annual and monsoon rainfall, largely attributed to the rising frequency of extreme precipitation events and enhanced cyclonic activity over the Arabian Sea (David Raj et al., 2021).

A key transformation in rainfall dynamics is the shift from stratiform to convective precipitation systems. Since the early 2000s, the west coast of India, including Kerala, has experienced an increase in deep, convective, and ice-rich cloud systems, leading to more intense, short-duration rainfall events (Sreenath et al., 2022). The 2019 Kerala flood exemplifies this trend, meeting the criteria of a mesoscale cloudburst, driven by anomalously warm sea surface temperatures and high atmospheric instability (Vijaykumar et al., 2021). These changes have led to irregular rainfall patterns, increasing the frequency of floods, landslides, and hydrological stress.

1.1.3 Cyclonic Activity and Ocean–Atmosphere Interactions

Recent studies indicate a significant rise in the frequency, intensity, and duration of cyclonic storms over the Arabian Sea, in contrast to relatively stable trends in the Bay of Bengal (Deshpande et al., 2021; Fan et al., 2020; Labban et al., 2024). Notably, the number of rapidly intensifying cyclones has nearly doubled since 2013, expanding the spatial extent of high-risk zones (Li et al., 2025; Pourkerman et al., 2023). This trend is closely associated with rising sea surface temperatures and evolving monsoon dynamics, which exacerbate extreme weather events, including intense rainfall, storm surges, and coastal flooding, thereby amplifying climate risks along the Kerala coast.

1.1.4 Future Hydroclimatic Projections

Hydroclimatic projections suggest further intensification of climate variability in Kerala (Fig. 1). Haridas and Manoj (2025) projected increases in both monsoon and post-monsoon rainfall over the west coast during 2024–2050, accompanied by greater variability and intensified drought conditions, particularly in eastern hilly regions. Under SSP2-4.5 and SSP5-8.5 scenarios, these regions may experience prolonged extreme droughts lasting more than 90 cumulative months. In addition, projections indicate a significant increase in extremely heavy rainfall events across all districts under both RCP 4.5 and RCP 8.5 scenarios compared to historical baselines (DoECC, 2022). These findings point toward a future characterized by more frequent and intense extremes, including floods, droughts, and heatwaves.

1.2 Existing Climate-Related Policy Framework in Kerala

Kerala has a structured climate policy framework and governance mechanisms within its broader development agenda. The foundation of this framework is the State Action Plan on Climate Change (SAPCC), aligned with the National Action Plan on Climate Change (NAPCC) and guided by global commitments such as the Paris Agreement. Initially endorsed in 2014 and recently revised as SAPCC 2023–2030, the plan identifies state-specific vulnerabilities and outlines sectoral strategies across agriculture, water resources, forestry, coastal management, and energy (DoECC, n.d.). Notably, it proposes a substantial financial outlay of INR 52,238 crore for mitigation and INR 38,407 crore for adaptation, underscoring the scale of Kerala's climate response (DoECC, n.d.). Institutionally, the Directorate of Environment and Climate Change (DoECC) functions as the nodal agency coordinating climate actions, supported by the State Level Steering Committee (SLSC) and a dedicated Climate Change Cell that enhances interdepartmental coordination, technical capacity, and monitoring. Decentralization of climate governance is a key feature, with Local Climate Change Cells and the integration of Local Adaptation Plans into Local Self Government (LSG) institutions enabling localized, context-specific interventions (DoECC, n.d.).

Complementing this policy framework, Kerala has implemented a range of thematic missions and programmes that operationalize climate actions at multiple scales. Initiatives such as the Haritha Keralam Mission and Suchitwa Mission promote sustainable waste management, water conservation, and resource efficiency (Hareesha and Ruby, 2025; Neriamparampil, 2018), while the Haritha Karma Sena strengthens grassroots-level waste collection and recycling through community-based micro-enterprises (Chathukulam, 2024). Post-disaster resilience and green recovery are addressed through the Rebuild Kerala Initiative, which focuses on building a resilient and environmentally sustainable development pathway (Neeraj et al., 2021). Sectoral and social resilience is further enhanced through targeted missions such as the Aardram Mission, which improves climate-sensitive public health systems (Sreekumar and Ravindran, 2023). In the transport sector, climate-resilient initiatives, including the state's electric vehicle policy, the expansion of CNG use, and the Kochi Water Metro, contribute to reducing emissions and enabling sustainable mobility transitions. Additionally, the Kerala State Biodiversity Strategy and Action Plan (Kerala State Biodiversity Board [KSBB], 2025) provides a comprehensive roadmap for biodiversity conservation and ecosystem-based adaptation, integrating ecological sustainability into climate policy. At the strategic level, Kerala integrates climate action into broader development planning through instruments such as the 14th Five-Year Plan (LSGD), which emphasises local economic development, climate resilience, and alignment with the Sustainable Development Goals. Long-term decarbonization pathways are articulated through the Carbon Neutral Kerala 2050 initiative, supported by grassroots movements such as the Net Zero Carbon Keralam Campaign, which promotes low-carbon lifestyles and local-level climate action (Chathukulam, 2024).

Building on this policy and governance architecture, Kerala's climate framework is further strengthened by a network of dedicated research institutions and academic initiatives. A significant policy-oriented academic initiative is the College of Climate Change and Environmental Science under Kerala Agricultural University. Initially launched as the Academy of Climate Change Education and Research (ACCER) in 2010–11 and later renamed in 2020, the institution represents a pioneering effort in Asia to integrate climate science with agriculture and environmental management at the undergraduate and postgraduate level (College of Climate Change and Environmental Science, Kerala Agricultural University [CCCES-KAU], n.d.). It functions as a major centre for climate change education, research, and capacity building, addressing the growing demand for expertise in climate change, variability, adaptation, mitigation, policy development and disaster risk management. The college plays a crucial role in supporting policy and planning by developing skilled human resources, conducting interdisciplinary research across domains such as meteorology, hydrology, climate modelling, land degradation, natural resource management, and remote sensing, and facilitating collaborations with national and international institutions. Its academic and extension activities contribute to

strengthening climate-informed decision-making, particularly in agriculture, forestry, veterinary, fisheries, and other allied sectors. By aligning education, research, and outreach with state priorities, the institution enhances Kerala's capacity to respond to climate change through scientifically informed adaptation and resilience strategies.

Complementing this, the Institute for Climate Change Studies (ICCS), established in 2014 and later brought under the Kerala State Council for Science Technology and Environment in 2019 as a research and development institution, plays a central role in operationalizing climate policy. As the state's first dedicated climate change institute headquartered in Kottayam, ICCS contributes to implementing the SAPCC through state-specific research, impact assessments, and vulnerability analyses. It supports policy formulation by integrating adaptation strategies into developmental planning and guiding climate risk management, while also addressing gaps in data infrastructure and institutional coordination through funded projects, capacity building, and public engagement ([Institute for Climate Change Studies \[ICCS\], n.d.](#)).

Despite the comprehensive and progressive nature of Kerala's SAPCC, several structural and operational limitations constrain its effectiveness in achieving long-term climate resilience and low-carbon development. [Gupta \(2025\)](#) provided a detailed overview of strengths and major pitfalls in Kerala's Climate Policy. A key limitation lies in the policy-implementation gap, where climate strategies, although well-articulated at the planning level, are not consistently translated into actionable outcomes across sectors. Climate change considerations are often treated as supplementary rather than systematically mainstreamed into core development planning, leading to fragmented implementation. This challenge is further exacerbated by weak inter-departmental coordination, as sectoral agencies tend to operate in silos with limited integration of climate objectives, resulting in inefficiencies and duplication of efforts. Another critical gap is the absence of a robust monitoring and evaluation framework. The current system lacks standardized indicators, real-time tracking mechanisms, and iterative feedback processes necessary for adaptive policy management. This limits the ability to assess policy effectiveness and make evidence-based adjustments in line with evolving climate risks. Financial constraints also pose a significant barrier. The absence of a dedicated climate budget and heavy reliance on external funding mechanisms hinder the scalability and continuity of climate interventions. Accessing international climate finance remains complex, requiring institutional capacity that is still developing at the state level.

Further, data and technological limitations restrict the precision and responsiveness of climate actions. The lack of high-resolution, localized climate data and advanced modelling tools undermines the development of context-specific adaptation strategies, particularly at the level of LSGs. In addition, the integration of emerging technologies such as remote sensing, real-time monitoring systems, and predictive analytics remains limited. The framework also reflects a degree of community-policy disconnect, where insufficient awareness and engagement at the grassroots level affect the adoption of climate-resilient practices. Finally, political and

governance challenges, including misalignment across administrative tiers and limited prioritization of long-term climate goals, further impede coherent policy implementation ([Gupta, 2025](#)). Addressing these gaps through strengthened institutional coordination, dedicated financing, data-driven decision-making, and inclusive governance will be critical for enhancing the effectiveness of Kerala's climate policy framework.

To further contextualize these systemic gaps, [Table 1](#) presents a sector-wise synthesis of key climate risks in Kerala, along with observed impacts, policy limitations, scientific data requirements, and recommended institutional responses. The table highlights how diverse and interconnected risks, ranging from extreme rainfall and flooding to land degradation, coastal erosion, heat stress, agricultural productivity loss, ecosystem degradation, and public health challenges, are currently constrained by fragmented governance, inadequate data systems, and limited integration of scientific inputs into policy. It underscores the need for high-resolution, real-time data, improved risk assessment tools, and stronger institutional coordination across sectors and scales. Importantly, the identified gaps align with the broader structural limitations discussed above, particularly in terms of weak monitoring frameworks, insufficient localization of climate strategies, and the absence of dedicated institutional mechanisms. By systematically linking risks to actionable responses, the table underscores the need for a structured, science-driven framework such as the proposed Climate Change Adaptation Cadre (CCAC), which can address these gaps through coordinated implementation, data-driven decision-making, and adaptive governance.

2 Development of a Comprehensive Climate Policy

Global warming, driven by persistent greenhouse gas emissions from fossil fuel use, is increasingly disrupting ecosystem functioning and intensifying extreme events, thereby threatening multiple sectors and underscoring the urgent need for site-specific, policy-driven strategies to build climate-resilient and sustainable communities ([Mariappan et al., 2023](#)). A policy is a formally articulated set of principles, guidelines, and rules adopted by governments, institutions, or organisations to guide decision-making and ensure coherent actions within a specific domain. Within this framework, climate policy is a specialised form of public policy that encompasses laws, regulations, strategies, and institutional mechanisms designed to address climate change ([Alves et al., 2020](#); [Di Gregorio et al., 2019](#); [Schoenefeld et al., 2022](#)). It encompasses both mitigation, through reductions in greenhouse gas emissions, and adaptation, by managing the impacts of climate change on human and natural systems ([Morrison et al., 2017](#)). The development of effective climate policy must be grounded in robust scientific evidence and empirical research to ensure that policy interventions are credible and effective. Accordingly, a comprehensive climate policy framework requires adequate financial resources, well-defined institutional arrangements, well-trained professionals, reliable data and information systems, systematic vulnerability assessments, and the identification of appropriate mitigation and adaptation strategies.

Table 1. Major climate risks and required institutional responses for strengthening climate governance in Kerala.

Climate Risk	Observed/Emerging Issues	Current Policy Gaps	Scientific Data Requirements	Recommended Institutional Responses
Extreme Rainfall & Flooding	Increased high-intensity rainfall, cloudburst-like events, recurrent floods (e.g., 2018, 2019)	Lack of real-time flood forecasting; weak integration of watershed-level planning	High-resolution rainfall data (sub-daily), flood inundation maps, and river basin modelling	Establish real-time flood forecasting systems; integrate river basin management authorities.
Landslides (Western Ghats)	Frequent landslides triggered by intense rainfall and land-use changes (e.g., Mundakkai & Chooralmala-Wayanadu, Pettimudi-Idukki)	Inadequate micro-level zonation; weak enforcement of land-use regulations	High-resolution landslide susceptibility maps, slope stability models, and soil moisture data	District-level landslide early warning systems, strict land-use zoning and hilly and mountainous area regulations
Drought & Water Scarcity	Increasing dry spells despite high annual rainfall; seasonal water stress	Poor groundwater monitoring; limited drought preparedness planning	Groundwater recharge data, soil moisture indices, and long-term rainfall variability datasets	Strengthen watershed management; develop drought early warning and water budgeting systems; and lake and river rejuvenation
Cyclones & Coastal Hazards	Increasing frequency and rapid intensification of Arabian Sea cyclones; coastal erosion	Limited coastal vulnerability mapping; insufficient marine ecosystem monitoring	Coastal inundation models, sea-level rise projections, shoreline change data	Strengthen coastal zone management; develop climate-resilient coastal infrastructure.
Land Degradation & Soil Erosion	Severe soil erosion, loss of topsoil, declining soil fertility, sedimentation in rivers and reservoirs	Poor integration of soil conservation with watershed planning; weak monitoring of erosion hotspots	Soil erosion maps, sediment yield data, land-use/land-cover change analysis, soil health data, and a watershed gauging station	Integrated watershed management; promote agroforestry and contour bunding; erosion monitoring systems
Urban Flooding & Infrastructure Pressure	Increased urban flooding due to poor drainage and extreme rainfall	Lack of climate-resilient urban planning; outdated drainage systems	Urban flood models, drainage capacity mapping, and land-use change data	Implement sponge city concepts; upgrade urban drainage infrastructure
Heatwaves & Rising Temperature	Emergence of heatwaves; increasing temperature trends across districts	Lack of heat action plans at local levels; limited urban heat mitigation strategies	High-resolution temperature datasets, urban heat island mapping, heat stress indices	Implement Heat Action Plans; promote climate-resilient urban planning (green spaces, cool roofs)
Agricultural/Livestock Vulnerability	Crop losses due to erratic rainfall, heat stress, pest outbreaks and decreased milk production	Limited adoption of climate-resilient crops and livestock practices; feeble agro-advisory systems	Crop-climate models, agro-meteorological data, pest/disease forecasting systems	Strengthen climate-smart agriculture (CSA) and livestock systems; real-time agro-advisory services.
Ecosystem Degradation	Loss of wetlands, mangroves, and forest cover reduces natural buffers	Weak ecosystem-based adaptation implementation	Biodiversity monitoring data, carbon stock assessments, ecosystem service valuation	Promote ecosystem-based adaptation (EbA); strengthen conservation policies.
Public Health Risks	Rise in vector-borne diseases, heat stress, and water-borne diseases	Weak integration of climate data into health planning	Climate-health linkage datasets, disease surveillance systems, heat-health risk maps	Develop climate-resilient health systems; integrate early warning with public health services
Data & Governance Gaps	Fragmented data systems; limited accessibility and coordination	Absence of an integrated climate data platform; weak M&E framework	Integrated climate database, real-time monitoring systems, GIS-based decision platforms	Establish centralized climate data repository; strengthen the Climate Change Cell/CCAC for coordination

2.1 Climate Finance

Climate finance constitutes a fundamental requirement for the effective development and implementation of climate policies. It refers to financial resources mobilized from public, private, and alternative sources at local, national,

and international levels to support climate change mitigation and adaptation (Hong et al., 2020; Newell, 2024) under global frameworks such as the United Nations Framework Convention on Climate Change, the Kyoto Protocol, and the Paris Agreement. Climate finance operates under

the principle of Common but Differentiated Responsibilities and Respective Capabilities, which emphasizes that developed countries should provide financial assistance to developing nations that are more vulnerable to climate change impacts. Substantial financial investments are therefore required both to reduce greenhouse gas emissions and to strengthen adaptive capacity and climate resilience.

Major international institutions supporting climate finance include the Global Environment Facility and the Green Climate Fund, along with mechanisms such as the Least Developed Countries Fund, Special Climate Change Fund, and the Adaptation Fund (Peake and Ekins, 2017). Beyond international funding mechanisms, central and state governments must also mobilise adequate domestic financial resources to support mitigation and adaptation initiatives. Dedicated climate funds can be generated through targeted fiscal instruments such as climate-related taxes, cesses, and emission-based levies on greenhouse gas-intensive sectors and activities. The central government should establish clear policy guidelines, while state governments and local self-governments should ensure effective implementation and enforcement. Additional measures such as climate cesses on fossil fuel consumption, penalties for inefficient practices (e.g., single-occupancy vehicle use), and emission-based property taxes linked to building size can further generate sustained domestic finance for climate action. To ensure effectiveness, robust accountability and monitoring mechanisms are essential to guarantee transparent and efficient utilization of climate funds, prevent misuse, and enhance the impact of mitigation and adaptation interventions across governance levels.

2.2 Institutional Mechanisms

Institutional mechanisms in climate policy refer to the formal structures, organizations, and governance arrangements established at international, national, and sub-national levels to design, implement, monitor, and finance climate action. At the global level, the United Nations Framework Convention on Climate Change provides the overarching framework for international climate governance, supported by institutions such as the Conference of the Parties, the Conference of the Parties serving as the Meeting of the Parties to the Paris Agreement, the Green Climate Fund, the Global Environment Facility, the Adaptation Fund, and the Standing Committee on Finance.

At national and sub-national levels, climate policy is operationalised through nodal ministries, climate change councils, national designated authorities, regulatory agencies, state governments, and local self-governments. These institutions ensure that climate actions are aligned with broader development priorities. Research institutions, including universities, national research laboratories, and policy think tanks, play a crucial role in this institutional framework by generating scientific evidence, climate projections, impact assessments, and technological innovations that support evidence-based policymaking, Nationally Determined Contributions, and Measurement, Reporting and Verification systems (Abanda et al., 2023; Jernnäs, 2023). Effective institutional mechanisms, therefore, depend on

strong inter-institutional coordination, transparency, accountability, stakeholder participation, and robust science-policy linkages.

In Kerala, however, specialized climate change research and expertise remain relatively limited, creating a gap between scientific understanding and policy implementation. Climate change is inherently interdisciplinary, affecting multiple sectors and varying across space, time, socio-economic conditions, and ecological contexts. Addressing these complex challenges requires qualified experts and strengthened research capacity to generate region-specific evidence that can guide policy formulation. Therefore, higher education and research institutions must be strengthened through dedicated climate change research programs, interdisciplinary curricula, and increased investment in climate-related studies. One notable initiative in this direction is the B.Sc.-M.Sc. (Integrated) programme in Climate Change Adaptation that was introduced at Kerala Agricultural University in 2010. The programme focuses on climate change mitigation and adaptation across major climate-sensitive sectors, including agriculture, agricultural engineering, forestry, fisheries, and veterinary sciences. Its interdisciplinary curriculum integrates climate science, emerging technologies, and sector-specific applications, enabling graduates to contribute to research, field-level implementation, and evidence-based policy development.

Despite the availability of such specialized human resources, their systematic integration into government administration and climate governance remains limited. This gap between academic capacity and policy implementation has become increasingly evident in the wake of recent climate-induced disasters in Kerala. Addressing this disconnect by establishing a dedicated Cadre within the governance framework could significantly strengthen the formulation and implementation of climate policies, enhance adaptive capacity, and support sustainable development and improved quality of life in the state.

2.3 Data

Data plays a critical role in climate change policy by enabling detection, attribution, and prediction, thereby providing the scientific foundation for effective and equitable policy formulation (Ali and Thakkar, 2023). Robust data analysis further supports evidence-based planning, informed implementation, and systematic evaluation of policy outcomes by facilitating the assessment of climate variability across spatial and temporal scales (Li, 2025). In this context, the increasing availability of diverse datasets and advancements in data-driven decision-making have significantly strengthened climate governance and policy implementation (Hughes et al., 2020). However, the effectiveness of climate policy is fundamentally constrained by the availability of long-term, high-quality climate observations at appropriate spatial and temporal resolutions. Global precipitation monitoring remains critically inadequate in the context of accelerating climate change, with only 13.4% of the global land surface meeting World Meteorological Organization standards, thereby limiting the reliability of

climate projections and water resource assessments. Under future high-emission scenarios, nearly 32.1% of global land is expected to require urgent expansion of precipitation gauge networks, particularly in climate-sensitive and socioeconomically vulnerable regions such as India, China, and Central Africa (Su et al., 2026). At the regional scale, similar limitations are evident in Kerala, where the sparse distribution and limited continuity of meteorological stations constrain comprehensive assessments of spatial and temporal climate variability. This data gap highlights the urgent need to strengthen observational networks and integrate alternative data sources to capture climate dynamics in data-scarce regions better and support robust climate risk assessment and planning (Valappil et al., 2022).

Automatic Weather Stations (AWS) offer a cost-effective, operationally efficient approach to monitoring key climatic parameters through autonomous operation and real-time data transmission. Nevertheless, adequate station density is essential to capture localized climatic variability. The World Meteorological Organization (WMO) recommends that, in tropical regions, a rainfall monitoring network should have a minimum station density corresponding to approximately 100-250 km² per station. It further provides more specific guidance for complex terrains, suggesting a density of about one station per 25 km² for small mountainous catchments with highly variable rainfall, and a higher density of 10-20 km² per station in urban areas. Overall, for small mountainous regions with irregular precipitation, the WMO recommends an observational density of approximately one station per 25 km² to ensure adequate spatial representation of rainfall variability (World Meteorological Organization [WMO], 1994). Although the India Meteorological Department has expanded its observational network in recent years, important gaps persist, particularly in topographically complex regions such as the Western Ghats and other mountainous areas. Strengthening the observational network through block-level AWS, panchayat-level Automatic Rain Gauges (ARGs), and district-level climate monitoring stations would significantly improve spatial coverage and forecasting accuracy. In addition, modernising the monitoring infrastructure, improving real-time data transmission, and investing in trained technical personnel are necessary to ensure reliable data quality and continuity.

Beyond atmospheric observations, effective climate policy also requires comprehensive hydro-meteorological and geospatial datasets. These include river discharge and water level records, sediment load data, and spatial information such as digital elevation models, soil maps, land-use and land-cover data, transportation networks, and administrative boundaries. Integrating these datasets with improved observational networks is essential for robust climate risk assessment, evidence-based policy formulation, and adaptive planning.

2.4 Vulnerability Assessment

Building on the availability of reliable climate and environmental data, vulnerability assessment is a critical component of climate policy development, identifying re-

gions, sectors, and communities most at risk from climate change impacts. Vulnerability is generally conceptualized as the combined outcome of a system's level of exposure to climate-related hazards, its sensitivity to climatic fluctuations, and its capacity to adapt to changing conditions. According to the Intergovernmental Panel on Climate Change (IPCC), vulnerability is the extent to which a system is prone to harm or is unable to effectively manage and respond to the negative impacts of climate change, including both variability and extreme climatic events (Intergovernmental Panel on Climate Change [IPCC], 2001). Systems that exhibit high sensitivity and limited adaptive capacity are therefore more vulnerable to climatic stressors. Subsequent conceptual frameworks emphasize the interaction between biophysical climate impacts and socio-economic conditions in determining vulnerability (Brooks, 2003; Intergovernmental Panel on Climate Change [IPCC], 2007).

Given the multidimensional nature of vulnerability, integrated assessment approaches are increasingly adopted to capture both environmental and socio-economic dimensions of climate risk. Such approaches combine hazard-risk frameworks with social vulnerability perspectives, recognizing that vulnerability arises not only from external climatic stressors but also from the internal characteristics and response capacities of social systems (Cutter, 1993). These assessments are commonly operationalized through composite indicators and geospatial techniques, including GIS-based vulnerability mapping. By integrating indicators of exposure, sensitivity, and adaptive capacity, spatially explicit vulnerability assessments help identify climate risk hotspots and support targeted adaptation planning.

In Kerala, vulnerability assessments have become increasingly important due to the rising frequency of hydro-meteorological hazards and climate-induced disasters. Systematic evaluation of vulnerability to floods, landslides, sea-level rise, soil erosion, heat waves, and droughts is essential for effective climate risk management. These hazards are often spatially interconnected and intensified by the state's complex topography, dense population, and dependence on climate-sensitive sectors. Beyond hazard-specific analysis, vulnerability must also be assessed across key socio-economic and ecological sectors, including agriculture, livestock, fisheries, and forests. Sectoral assessments should consider impacts on agricultural productivity and food security, changes in livestock health and productivity, fluctuations in fisheries resources, and shifts in biodiversity, ecosystem services and impact on land degradation and soil erosion (David Raj et al., 2022; Sooryamol et al., 2022). Developing robust baseline datasets and spatially explicit vulnerability assessments is therefore crucial for identifying priority areas, guiding adaptation strategies, and supporting evidence-based climate policy and resilient development planning.

3 Climate Change Response – Mitigation and Adaptation

The accelerating pace of global warming poses a significant challenge to human societies and natural ecosystems, necessitating coordinated global action to limit the

rise in mean global temperature to well below 2°C above pre-industrial levels. Addressing climate change, therefore, involves two interrelated challenges: reducing greenhouse gas emissions to limit future warming and managing the impacts that are already unavoidable. These challenges form the two fundamental pillars of climate policy—mitigation and adaptation—which together shape the global response to climate change and guide strategies aimed at achieving climate-resilient and sustainable development.

3.1 Climate Change Mitigation

Climate change mitigation refers to actions aimed at addressing the root causes of climate change by reducing greenhouse gas emissions or enhancing their removal from the atmosphere. The IPCC defines mitigation as anthropogenic interventions that reduce the sources or enhance the sinks of greenhouse gases, thereby lowering the long-term risks and hazards of climate change (Intergovernmental Panel on Climate Change [IPCC], 2014). Mitigation strategies include emission reductions across key sectors such as energy, industry, agriculture, and transport, along with carbon sequestration through natural and engineered sinks such as forests, soils, and carbon capture technologies. Effective mitigation reduces the magnitude and rate of climate change, thereby limiting the scale of impacts that societies and ecosystems must adapt to in the future.

In Kerala, significant opportunities exist to strengthen mitigation efforts across multiple sectors. The extensive forest ecosystems of the Western Ghats play a vital role in carbon sequestration and contribute substantially to climate regulation. In addition to ecosystem-based mitigation, sustainable consumption patterns and lifestyle changes can further reduce greenhouse gas emissions, particularly in regions experiencing increasing pressure on natural resources. A systematic evaluation of mitigation efforts is essential to understand their effectiveness and guide future strategies. Carbon footprint and carbon neutrality assessments provide a useful framework for quantifying emissions and carbon sequestration across different activities and land-use systems. Conducting such assessments at multiple scales, including individuals, households, institutions, and industries, can help identify major emission sources and inform targeted mitigation interventions. Institutionalizing these assessments would support evidence-based mitigation planning, strengthen accountability, promote behavioural change, and facilitate the transition toward low-carbon development pathways in Kerala while aligning state-level actions with national and global climate commitments.

3.2 Climate Change Adaptation

Climate change adaptation focuses on managing the impacts of climate variability and change by adjusting natural and human systems to actual or expected climatic stimuli. The IPCC defines adaptation as adjustments that moderate harm or exploit beneficial opportunities arising from climate change (Intergovernmental Panel on Climate Change [IPCC], 2014). Because of the inertia of the climate system and the legacy of past greenhouse gas emissions, some degree of climate impact is unavoidable, and adaptation is

an essential complement to mitigation efforts. Adaptation therefore functions as a form of risk management aimed at reducing vulnerability and strengthening resilience to hazards such as extreme weather events, sea-level rise, and ecosystem degradation. Earlier assessments have emphasized that the severity of climate impacts depends on the combined effectiveness of mitigation and adaptation strategies (Klein et al., 2007). Without sufficient mitigation, however, climate change may reach levels that exceed the adaptive capacity of many human and natural systems.

Effective adaptation strategies must be grounded in robust vulnerability assessments that consider the spatial distribution, intensity, and frequency of climate-related hazards. Such assessments enable governments and institutions to move from reactive responses toward proactive planning and targeted risk reduction. For example, reliable baseline information on flood extent, flood severity, and rainfall thresholds can support the identification and mapping of high-risk zones. These insights can guide land-use planning by restricting permanent construction in flood-prone areas and allocating such zones to compatible uses such as agriculture, wetlands, or seasonal activities. Science-based vulnerability assessments, therefore, provide the foundation for site-specific adaptation planning. By integrating empirical data, geospatial analysis, and sectoral risk assessments, governments can design targeted adaptation measures that reduce people's and infrastructure's exposure, minimise economic losses, and improve disaster preparedness. Ultimately, well-informed adaptation strategies contribute to safer settlements, sustainable livelihoods, and climate-resilient development pathways.

3.3 Interlinkages Between Mitigation and Adaptation

The interactions between mitigation and adaptation are increasingly recognized as central to climate policy and sustainable development planning. Strong mitigation efforts can limit the magnitude and rate of future climate change, thereby reducing long-term adaptation needs. In contrast, inadequate mitigation increases the intensity and frequency of climate extremes, placing greater pressure on adaptation systems and making them more difficult and costly to implement. Fig. 2 illustrates the dynamic relationship among adaptation, adaptation limits, and risk, highlighting how systems move from acceptable to tolerable, and eventually to intolerable, risk levels under increasing climate stress. Adaptation measures can effectively reduce risk within certain thresholds, but only up to a point, beyond which systems reach their adaptation limits and existing strategies fail to cope with impacts. In the context of climate change in Kerala, measures such as improved drainage systems, advanced early warning systems, and climate-resilient infrastructure can help manage flood risks within the tolerable zone. However, extreme events such as the 2018 Kerala floods demonstrate that unprecedented rainfall and repeated flooding can exceed these adaptive capacities. Events that were once considered rare are becoming more frequent and intense, overwhelming existing coping mechanisms and pushing systems into the intolerable risk zone. Such transitions are often associated with

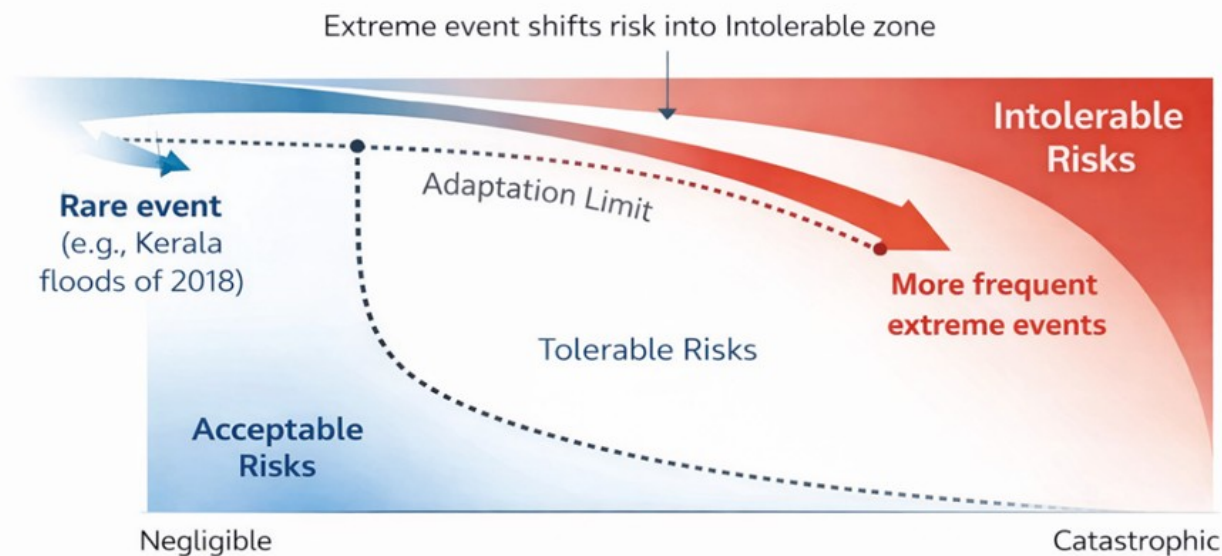


Fig. 2. Relationship between adaptation, adaptation limits, and risk under climate change. Risks shift from acceptable to intolerable as impact and frequency increase, with adaptation effective only within tolerable limits (Modified from Dow et al., 2013).

severe consequences, including infrastructure breakdown, economic losses, social disruption, and reduced accessibility to insurance and financial protection. This underscores the urgent need to move beyond incremental approaches and adopt transformative adaptation strategies, alongside strong mitigation efforts, to ensure long-term resilience under a rapidly changing climate.

Building on this, it is important to recognise that the relationship between mitigation and adaptation is not always in conflict but is often complementary in practice. Direct trade-offs between the two are relatively uncommon, as they typically involve different actors, operate across different timeframes, and rely on distinct policy instruments. In many cases, mitigation actions can enhance adaptive capacity by promoting sustainable development pathways, improving resource efficiency, and reducing environmental degradation. Similarly, several adaptation measures, such as afforestation, ecosystem restoration, and sustainable land management, can generate significant co-benefits for mitigation by enhancing carbon sequestration. These synergies highlight opportunities for integrated approaches that simultaneously address both the causes and impacts of climate change.

However, not all interactions are positive, and certain adaptation responses may conflict with mitigation objectives. For instance, adaptation strategies that increase energy demand from carbon-intensive sources can lead to higher greenhouse gas emissions. A common example is the widespread use of air conditioners during heatwaves, which often raises electricity demand supplied by fossil fuels, thereby contributing to further global warming. Importantly, such trade-offs are not inevitable. If adaptation measures are designed using renewable energy sources or passive cooling techniques, they can reduce vulnerability while also supporting mitigation goals. Recognizing and managing these synergies and trade-offs is therefore essential for developing integrated policies that align mitigation

and adaptation within a coherent framework for climate-resilient and sustainable development.

4 Implementation of Climate Policy

The successful formulation of climate policies must be followed by effective, context-sensitive implementation to achieve intended outcomes. Implementation should be guided by well-defined frameworks and standard operating procedures, with a strong emphasis on site-specific execution. Given the pronounced spatial variability of climate risks, localized implementation requires skilled personnel, adequate institutional capacity, and technical expertise to translate policy objectives into actionable interventions. In this context, decentralized and adaptive governance mechanisms are essential, as they enhance flexibility, responsiveness, and institutional effectiveness in addressing complex and evolving climate risks. Recent flood and landslide events in Kerala further highlight these implementation challenges. Although many disasters were geographically localized, institutional responses were often constrained by limited preparedness, absence of well-defined preventive protocols, and gaps in recovery and restoration mechanisms. These constraints indicate that managing larger and more complex climate-related disasters would require significantly stronger implementation capacity and trained human resources. Strengthening implementation structures therefore necessitates the development of skilled adaptation personnel, clear disaster-prevention protocols, and robust recovery frameworks. In this regard, the establishment of a CCAC could play a transformative role by enhancing institutional preparedness, ensuring operational continuity during extreme events, and improving the overall effectiveness of climate policy implementation.

Fig. 3 presents an integrated framework for climate policy implementation, linking climate drivers, risks, institutional mechanisms, and outcomes within a multi-level gov-

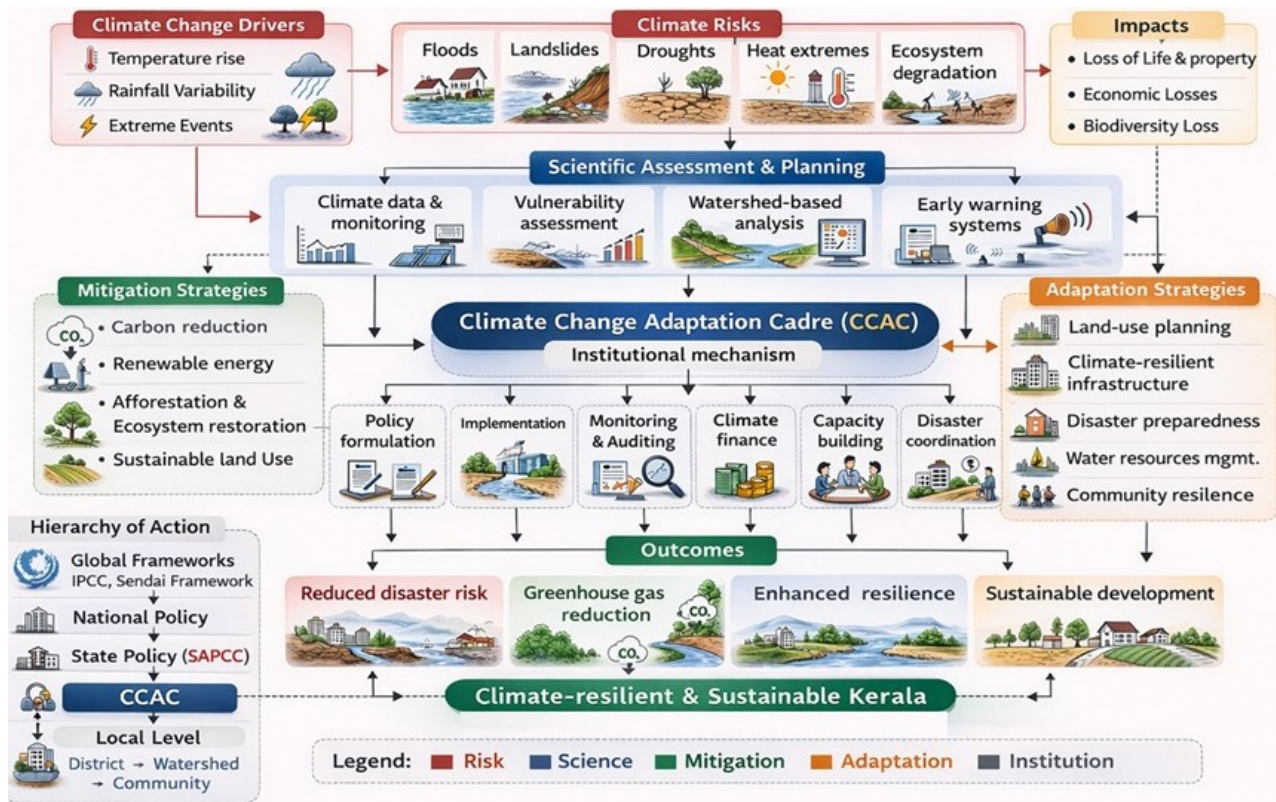


Fig. 3. Conceptual framework for science-based climate governance and climate-induced disaster risk reduction integrating adaptation and mitigation strategies. Climate drivers such as temperature rise, rainfall variability and extreme events generate multiple risks, including floods, landslides, droughts, heat extremes and ecosystem degradation, leading to socio-economic and ecological impacts. These are addressed through scientific assessment and planning, including climate monitoring, vulnerability assessment, watershed-based analysis and early warning systems. The Climate Change Adaptation Cadre (CCAC) functions as an institutional mechanism integrating policy formulation, implementation, monitoring, climate finance, capacity building and disaster coordination. The framework incorporates both mitigation and adaptation strategies across governance levels, leading to reduced disaster risk, greenhouse gas reduction, enhanced resilience and sustainable development.

ernance structure. The framework begins with climate change drivers including temperature rise, rainfall variability, and extreme events which trigger a cascade of climate risks such as floods, landslides, droughts, heat extremes, and ecosystem degradation. These risks ultimately translate into tangible impacts, including loss of life and property, economic damages, and biodiversity loss. To address these challenges, the framework positions scientific assessment and planning at its core, encompassing climate data monitoring, vulnerability assessment, watershed-based analysis, impact assessments and early warning systems. These scientific components provide the evidence base necessary for informed decision-making and feed directly into the CCAC, which serves as the central institutional mechanism coordinating climate action. The CCAC operates through six key functional pillars- policy formulation, implementation, monitoring and auditing, climate finance, capacity building, and disaster coordination. Together, these pillars ensure that climate strategies are not only designed effectively but also executed, evaluated, and continuously improved. Flanking this institutional core are two complementary strategic pathways: mitigation strategies (such as carbon reduction, renewable energy, afforestation, and sustainable land use) and adaptation strategies (including land-use planning, climate-resilient infrastructure, disaster

preparedness, water resource management, and community resilience). These dual pathways highlight the need for simultaneous and integrated action to address both the causes and impacts of climate change.

The framework further establishes a hierarchy of action, linking global frameworks (e.g., IPCC and the Sendai Framework) with national and state policies (SAPCC), institutional mechanisms (CCAC), and finally local implementation at district, watershed, and community levels. This multi-scalar structure ensures vertical integration of policies while enabling localized action. The coordinated functioning of these components leads to four key outcomes: reduced disaster risk, greenhouse gas reduction, enhanced resilience, and sustainable development. These outcomes collectively contribute to the overarching vision of a climate-resilient and sustainable Kerala. Importantly, the framework incorporates a feedback loop, where observed outcomes and impacts inform ongoing scientific assessment and planning, ensuring that the system remains adaptive, evidence-based, and responsive to emerging climate challenges. This approach provides a holistic and integrated governance model that bridges science, policy, and community action, providing a robust pathway for addressing climate-induced risks and advancing sustainable development in Kerala.

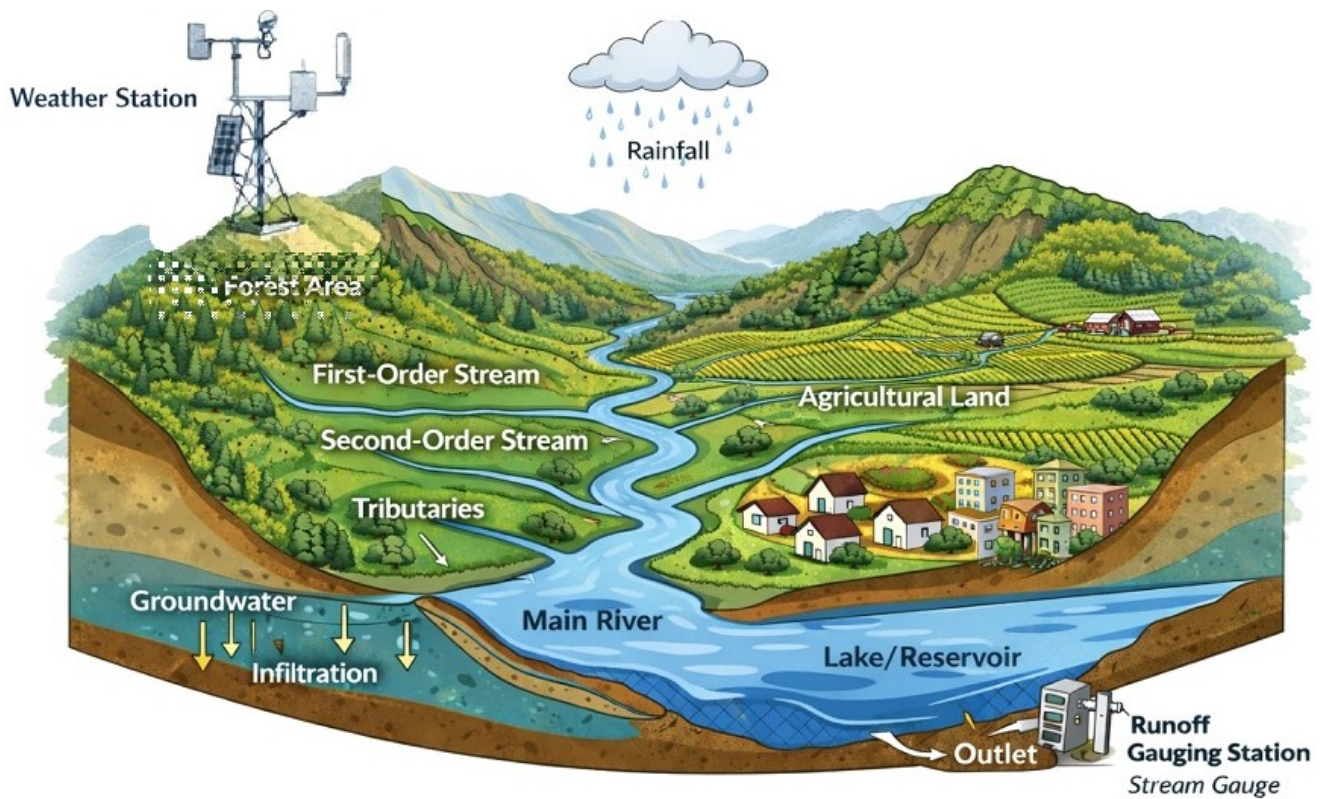


Fig. 4. Conceptual diagram of a watershed showing key components (streams, tributaries, main river, and land use), hydrological processes (rainfall, runoff, infiltration), and monitoring systems including weather stations and a runoff gauging station.

4.1 Watershed as a Basic Unit for Climate Change Adaptation and Mitigation

Climate change adaptation and mitigation strategies are often more effective when implemented at the scale of natural systems rather than within administrative boundaries, which may not adequately reflect underlying environmental processes. Natural units provide a more coherent framework for understanding and managing climate-related risks. Among these, the watershed represents (Fig. 4) a fundamental landscape unit within which hydrological and hydro-meteorological processes such as rainfall, runoff, soil erosion, sediment transport, and flooding originate and interact (Kumar et al., 2024, 2025).

Because climatic drivers and their impacts, including floods, landslides, and droughts, typically manifest within watershed boundaries, aligning policy interventions with watershed units enables more precise and integrated planning. For example, rainfall occurring within a particular catchment primarily influences river discharge and flood dynamics within that watershed, rather than affecting neighbouring river systems. Consequently, adaptation and mitigation measures such as flood management, land-use regulation, afforestation, and soil and water conservation are most effective when planned at the watershed scale. Despite this scientific rationale, many climate policies continue to be framed primarily within administrative jurisdictions. Integrating watershed-based planning into climate policy would improve alignment between ecological processes and governance structures, enhance climate risk management, and support sustainable landscape management.

Such an approach also promotes cross-sectoral coordination and strengthens the effectiveness of both adaptation and mitigation strategies under changing climatic conditions.

4.2 Monitoring and Auditing of Climate Policy Effectiveness

The development and implementation of climate policies must be supported by robust monitoring and auditing mechanisms to ensure their effectiveness and long-term relevance. This function can be institutionalized within a dedicated CCAC composed of trained professionals responsible for tracking policy performance, identifying implementation gaps, and assessing unintended outcomes. Continuous monitoring enables the timely detection of systemic weaknesses and supports evidence-based corrective actions. Since climate policies operate within dynamic environmental and socio-economic contexts, periodic evaluation and revision are essential to maintain their relevance and effectiveness. Monitoring systems also help validate the vulnerability assessments that underpin policy design by comparing projected risks with observed impacts. Such feedback improves assessment methodologies, enhances data reliability, and strengthens evidence-based decision-making. Establishing a structured auditing system carried out by skilled professionals can therefore enhance transparency, accountability, and institutional learning in climate governance.

4.3 Corrective Mechanisms

Corrective mechanisms are an essential component of adaptive climate governance and should be integrated

within the institutional framework of the CCAC. When mitigation or adaptation measures prove ineffective, underperforming, or misaligned with policy objectives, timely policy revisions and alternative strategies are necessary. Adaptive management approaches that incorporate feedback from monitoring and auditing processes allow continuous refinement and improvement of climate policies. Timely corrective interventions enhance policy efficiency, prevent resource misallocation, and reduce long-term climate risks. Institutionalising such mechanisms ensures that climate policies remain flexible, evidence-driven, and responsive to emerging challenges. By linking monitoring, evaluation, and corrective action within a unified institutional framework, the CCAC can strengthen policy effectiveness and support long-term climate-resilient development.

5 Way Forward: Climate-Induced Disaster Risk Reduction Mechanism

Implementing climate-responsive disaster risk reduction strategies is particularly critical for Kerala, where increasing climate variability has intensified the frequency and severity of hydro-meteorological hazards such as floods, landslides, droughts, and heat extremes. These measures align with the priorities of the Sendai Framework for Disaster Risk Reduction (2015–2030), which emphasizes understanding disaster risk, strengthening governance, investing in resilience, and enhancing preparedness for effective response and recovery. Systematic identification of vulnerable regions, supported by robust scientific assessments, is central to reducing climate-induced disaster risks. Evidence-based analysis of hazard drivers, exposure patterns, and underlying vulnerabilities enables proactive interventions such as risk-informed land-use planning, early warning systems, ecosystem-based adaptation, and climate-resilient infrastructure. Such approaches minimize loss of life and property while also contributing to emission reduction and carbon sequestration through sustainable land and resource management, thereby reducing long-term economic losses.

Within Kerala's disaster management framework, effective coordination between climate policy, disaster preparedness, and development planning is essential. Establishing a specialised CCAC would significantly strengthen this integration. The cadre would function as the technical backbone for climate-induced disaster risk reduction by supporting vulnerability assessments, monitoring adaptation measures, coordinating with disaster management authorities, and translating scientific knowledge into operational strategies. Institutionalising climate expertise within governance structures would enhance preparedness, improve response efficiency, and support resilient recovery, thereby strengthening Kerala's capacity to manage climate-induced disasters in a systematic and sustainable manner.

5.1 Need for a Climate Change Adaptation Cadre in Kerala

The increasing frequency and intensity of climate-induced hazards in Kerala including floods, landslides, heat stress, land degradation, coastal erosion, ecosystem degra-

dation, and biodiversity loss highlight the urgent need for a dedicated CCAC to strengthen climate governance in the state. Kerala's diverse physiography, high population density, and dependence on climate-sensitive livelihoods necessitate a decentralized yet scientifically robust institutional mechanism capable of translating climate policies into effective action at local, district, and state levels. Effective climate policy implementation requires governance systems supported by qualified climate professionals with expertise in climate science, vulnerability assessment, adaptation and mitigation planning, and climate risk management, rather than relying solely on conventional administrative structures. Embedding scientific research, climate and geospatial data management, and evidence-based decision-making within governance frameworks would significantly strengthen science-policy-practice linkages and improve institutional accountability. In this context, proactive investment in a specialized climate cadre is essential to avoid maladaptive responses and reduce the long-term risks of climate-induced disasters.

The proposed CCAC addresses critical systemic gaps in Kerala's existing climate governance framework by strengthening implementation capacity and enabling adaptive, evidence-based governance. First, it bridges the long-standing policy-implementation gap that limits the effectiveness of the SAPCC by translating policy directives into structured, location-specific interventions. Second, it enhances institutional coordination by reducing sectoral silos and promoting convergence across key sectors such as soil, water resources, agriculture, forestry, livestock, disaster management, and urban planning. Third, it strengthens data-driven decision-making through systematic climate data collection, monitoring, and vulnerability assessment, thereby supporting evidence-based planning at the LSG level. Fourth, it establishes robust monitoring and evaluation (M&E) systems with continuous tracking, auditing, and feedback mechanisms to ensure accountability and adaptive policy refinement. Finally, it promotes adaptive governance by enabling iterative learning, where policies evolve based on real-time outcomes, emerging risks, and best practices, while also strengthening local participation and decentralized climate action.

Fig. 5 illustrates the conceptual framework of the CCAC, which operationalizes the climate policy implementation cycle for adaptive governance in Kerala. The process begins with climate data and monitoring, where observational networks, remote sensing, and hydro-meteorological systems generate the scientific evidence base. This feeds into vulnerability assessment, which identifies hazard-prone areas, exposure levels, and risk hotspots. Based on these insights, the cadre supports policy design by integrating mitigation and adaptation strategies tailored to local contexts. These strategies are then translated into action through implementation mechanisms such as local action plans, nature-based solutions, and capacity-building initiatives. The CCAC also plays a central role in monitoring and auditing, ensuring systematic progress tracking, evaluation, and accountability, while enabling corrective feedback for policy improvement. A key strength of the framework is its emphasis on adaptive learning and scaling, allowing contin-

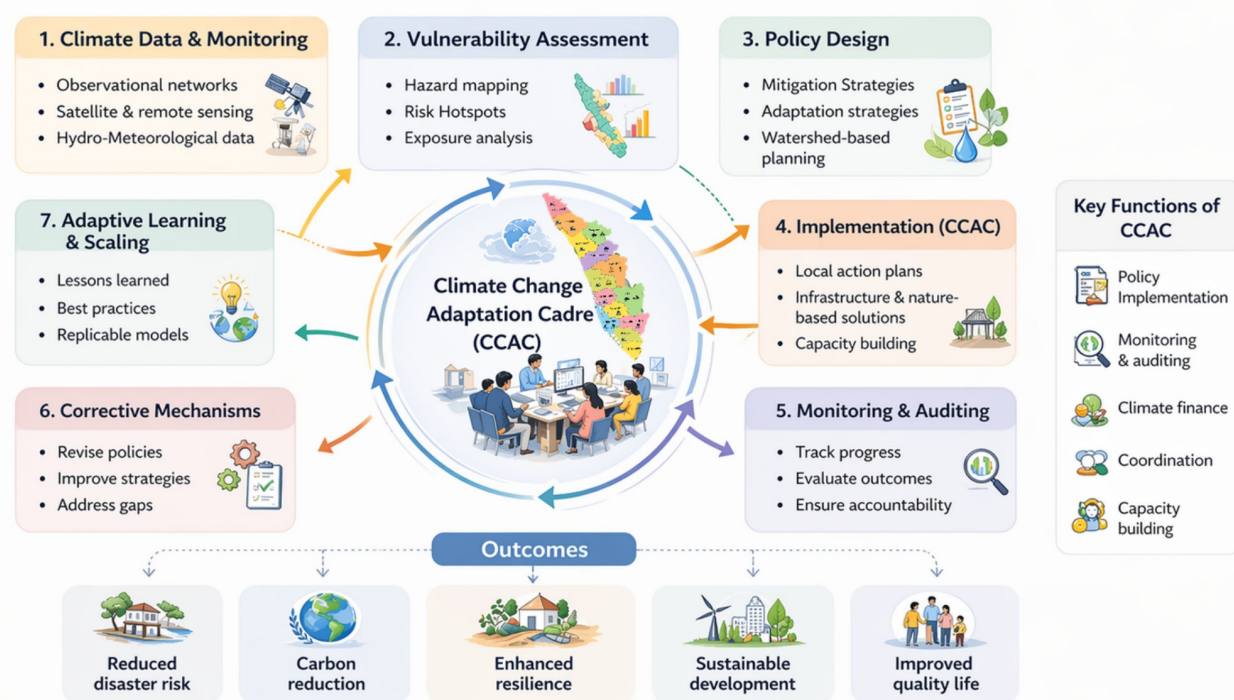


Fig. 5. Cyclical framework for climate change adaptation through the Climate Change Adaptation Cadre (CCAC). The CCAC is conceptualized as an iterative, science-informed process linking climate data and monitoring, vulnerability assessment, and policy design with implementation, monitoring and auditing, and corrective mechanisms. These stages are embedded within a continuous feedback loop that enables adaptive learning and scaling of best practices. Core functions of the CCAC include policy implementation, monitoring and auditing, climate finance, coordination and capacity building, with a focus on disaster risk reduction. The framework integrates mitigation and adaptation pathways across sectors, resulting in reduced disaster risk, carbon reduction, enhanced resilience, sustainable development, Improved climate governance, climate resilient livelihood and improved quality of life, ultimately contributing to a climate-resilient and sustainable Kerala.

uous refinement through lessons learned and best practices. Overall, this cyclical and integrated approach transforms climate governance from a static, plan-based system into a dynamic, responsive, and adaptive model.

Hence, the establishment of a CCAC would enable Kerala to transition from reactive, post-disaster responses toward proactive, cost-effective climate adaptation and mitigation strategies. By improving coordination, strengthening institutional capacity, and embedding science-based decision-making into governance, the CCAC enhances resilience, supports sustainable development, reduces disaster risks, and improves long-term quality of life.

5.2 Institutional Framework for Operationalizing the Climate Change Adaptation Cadre

To ensure that the proposed Climate Change Adaptation Cadre (CCAC) is policy-relevant, implementable, and aligned with governance realities, the framework is structured around four interlinked pillars: administrative, legal, financial, and functional. Collectively, these pillars enable the transition of the CCAC from a conceptual model into an operational institutional mechanism for climate governance in Kerala.

From an administrative perspective, it is proposed that the CCAC be established within a newly constituted Directorate of Climate Change (DoCC), envisioned as the dedicated department for climate change, with functions span-

ning state, district, block, and village levels. The framework ensures vertical integration from state-level policy coordination to district-level execution through District Climate Action Cells (DCACs) and implementation at the LSG level. At the grassroots, it builds on decentralized governance structures such as Village Climate Risk Management Committees (VCRMCs), which facilitate community participation and scaling of climate-resilient practices (Ministry of Environment, Forest and Climate Change [MoEFCC], 2025). The legal framework adopts a phased approach to institutionalization. Initially, the CCAC can be operationalized through a Government Order (G.O.), followed by formal integration into the SAPCC. In the long term, the framework envisions the enactment of a dedicated Kerala Climate Change Act to ensure statutory backing. To strengthen transparency and accountability, provisions such as mandatory climate risk assessments, periodic reporting, and independent review mechanisms are incorporated. The financial design of the CCAC is based on a diversified and resilient funding strategy. It includes state budgetary allocations, convergence with ongoing development schemes, and access to national and international climate finance instruments such as the National Adaptation Fund for Climate Change (NAFCC) and the Green Climate Fund (GCF). Additional support is envisaged through green bonds, carbon markets, and climate budget tagging to enhance transparency and efficiency. The framework also

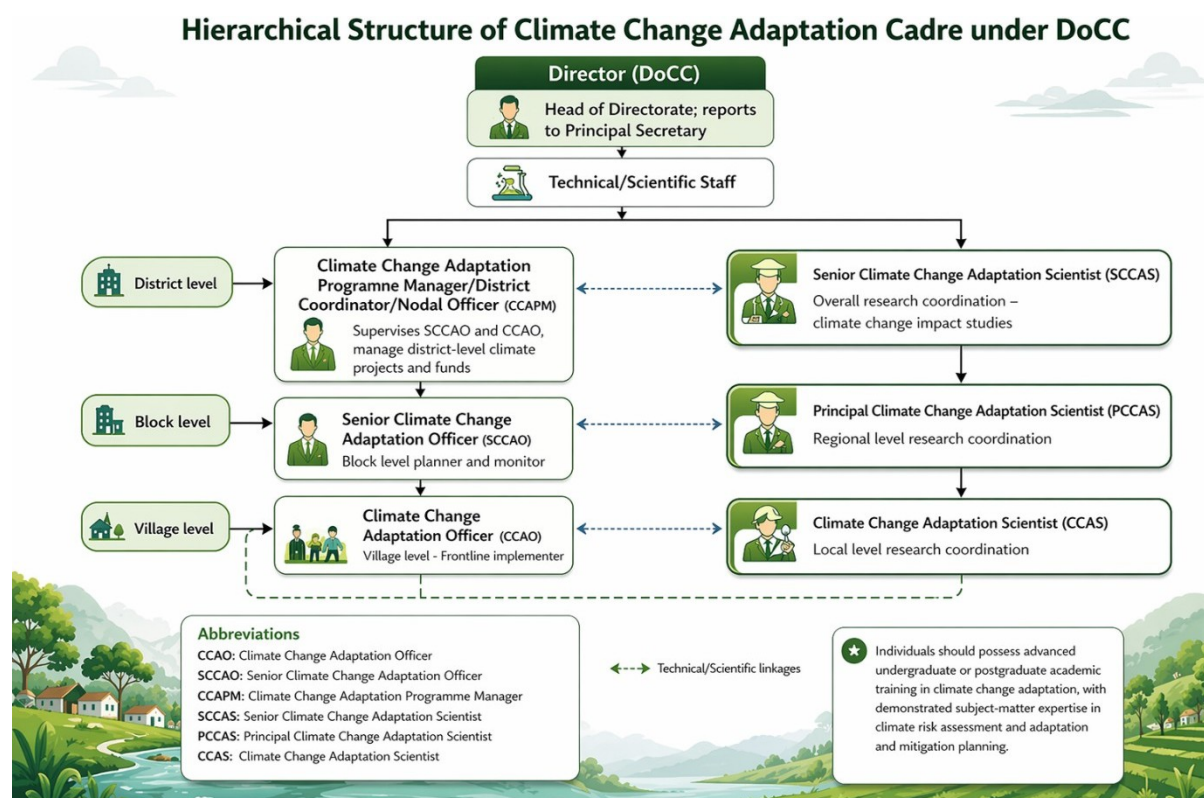


Fig. 6. Proposed hierarchical structure and functional linkages of the Climate Change Adaptation Cadre. The framework illustrates administrative and scientific coordination across governance levels, linking state leadership with district-, block-, and village-level implementation units (CCAPM, SCCAO, CCAO) and a parallel scientific hierarchy (SCCAS, PCCAS, CCAS). Solid arrows indicate administrative reporting lines, while dashed arrows represent technical and research linkages enabling integrated risk assessment, evidence-based planning, and local implementation. Abbreviations are defined within the figure.

proposes targeted climate-related cesses and environmental levies as supplementary revenue streams, aimed at strengthening long-term adaptation financing while promoting environmentally responsible behaviour.

Functionally, the CCAC operates as a science-driven and multi-tiered system integrating implementation, planning, monitoring, and research. At the field level, the Climate Change Adaptation Officer (CCAO) acts as the front-line implementer, responsible for executing adaptation interventions and collecting structured data on climate impacts and vulnerabilities. At the block level, the Senior Climate Change Adaptation Officer (SCCAO) ensures coordination, supervision, and data validation, while at the district level, the Climate Change Adaptation Programme Manager (CCAPM) oversees planning, resource allocation, and implementation convergence. Parallel to this administrative hierarchy is a scientific stream comprising Climate Change Adaptation Scientists (CCAS), Senior CCAS, and Principal CCAS, responsible for analysing field data, conducting multi-scalar assessments, and generating policy-relevant insights. These outputs are synthesized through an internal coordination mechanism that informs evidence-based decision-making and adaptive policy design. At the apex, the Director of the DoCC ensures integration between scientific analysis, field implementation, and policy formulation, reporting to the Principal Secretary (Fig. 6).

Overall, the CCAC covers the full climate policy cycle, including climate data management, vulnerability as-

essment, policy support, preparation of Local Climate Action Plans (LCAPs), monitoring and evaluation, and adaptive feedback. It further emphasizes capacity building and technology dissemination through structured training, field demonstrations, and stakeholder engagement to strengthen climate-resilient livelihoods, particularly in agriculture and allied sectors. From a policy design perspective, the CCAC represents a shift from fragmented climate interventions to an integrated governance architecture that explicitly links science, administration, and local implementation. Its strength lies in embedding adaptive learning within institutional structures, thereby enabling continuous refinement of climate strategies. However, its effectiveness will depend on clear role demarcation, sustained financial provisioning, and strong inter-departmental convergence to avoid bureaucratic duplication and ensure operational efficiency.

6 Conclusions

This perspective underscores the urgent need for a science-based climate policy framework in Kerala in the context of escalating climate change impacts and increasing climate-induced disaster-related losses across the state. Climate change is no longer a future concern but a present reality, evident in rising temperatures, intensified rainfall extremes, greater seasonal variability, recurrent droughts despite high annual rainfall, and an increasing frequency of hydro-meteorological disasters. These trends clearly indi-

cate the need to transition from reactive disaster response to anticipatory, evidence-based climate governance.

Effective climate resilience requires the integration of robust climate data, comprehensive vulnerability assessments, coherent mitigation-adaptation strategies, and sustained climate finance within a strengthened institutional framework. In this context, the establishment of a dedicated Climate Change Adaptation Cadre (CCAC) is critical. It can translate scientific evidence into policy and practice, strengthen disaster risk reduction, and ensure continuous monitoring, evaluation, and adaptive correction, thereby bridging persistent gaps between science, policy, and implementation. At the spatial planning level, watershed-based approaches provide a scientifically appropriate framework for climate action, as they align interventions with natural ecological and hydrological systems rather than administrative boundaries. Strengthening adaptive learning, accountability, and flexibility within governance systems further enhances the capacity to respond to evolving and uncertain climate risks.

The integration of mitigation, adaptation, and disaster risk reduction within a unified, science-driven framework can significantly reduce climate-induced losses, improve societal resilience, and enhance overall well-being. This approach also offers important lessons for other climate-vulnerable regions of the Global South. Ultimately, building resilient systems requires institutionalizing climate expertise, strengthening observational and analytical capacities, and ensuring that policy decisions are firmly grounded in scientific evidence. Overall, this study advocates a clear transition toward proactive, integrated, and institutionally embedded climate governance.

7 Policy Implications

1. Establish a dedicated Climate Change Adaptation Cadre (CCAC) within a newly constituted Directorate of Climate Change (DoCC) envisioned as a standalone department for climate change to embed domain-specific expertise across administrative levels. This will directly address existing gaps in translating Kerala's State Action Plan on Climate Change (SAPCC) into effective field-level implementation, particularly at the Local Self-Government (LSG) level.
2. Decentralized and watershed-based planning: Operationalize watershed- and river basin-based planning approaches in Kerala's midland and highland regions, where hydrological connectivity and land-use changes significantly influence flood risks, landslides, and soil erosion. This aligns with the state's physiographic diversity and recurring disaster patterns.
3. Strengthening data and decision systems: Develop a state-wide, high-resolution climate data infrastructure, including real-time hydro-meteorological monitoring, flood and landslide early warning systems, and LSG-level vulnerability assessments. This will enable location-specific planning and reduce reliance on coarse or fragmented datasets currently limiting effective decision-making.

4. Dedicated climate financing mechanisms: Establish a Kerala-specific climate finance architecture that integrates state budget allocations, climate budget tagging, and access to national and global funds (e.g., NAFCC, GCF). Additionally, introduce targeted climate cesses or environmental taxes to generate sustained funding for adaptation and resilience-building initiatives.
5. Integrated monitoring, evaluation, and accountability: Institutionalize robust monitoring and evaluation (M&E) frameworks within the CCAC, including real-time tracking, independent audits, and feedback loops to ensure accountability and adaptive policy refinement addressing current weaknesses in implementation tracking.
6. Context-specific adaptation and co-benefits: Promote locally relevant adaptation strategies such as climate-resilient agriculture, ecosystem restoration in the Western Ghats, and coastal protection through nature-based solutions, ensuring co-benefits for mitigation, biodiversity conservation, and livelihoods while avoiding maladaptation.
7. Replicable but contextualized model: While rooted in Kerala's governance structure and climate risks, the CCAC framework provides a scalable model for other Indian states; however, its design emphasizes contextual adaptation to local socio-ecological and institutional conditions rather than a one-size-fits-all approach.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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CRedit statement

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