

Extreme Hydrometeorological Events under Climate Change Scenarios in South Asia: A PRISMA-Guided Review

Muhammad Rezaul Rakib

gs74985@student.upm.edu.my

Universiti Putra Malaysia

Balqis Mohamed Rehan

Universiti Putra Malaysia

Nor Azlina Alias

Universiti Putra Malaysia

Mohd. Shahrizal Bin Ab Razak

Universiti Putra Malaysia

Systematic Review

Keywords: Climate Change, Hydrometeorological, Flood, Resilience, South Asia, PRISMA-guided

Posted Date: June 23rd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10107263/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: The authors declare no competing interests.

Abstract

Climate change emerged as one of the key global challenges linked to hydrometeorological extremes and intensifying environmental stability and susceptibility. This study critically reviewed 84 peer-reviewed publications relevant to climate change from Scopus (2006–2026) by PRISMA-guided semi-systematic approach to synthesize current evidence on climate change impacts on hydrometeorological extremes in South Asia. The findings reveal that warming level has increased by 0.5°C to 1.5°C. Under the SSP5-8.5 scenario, the average temperature will rise by 3.5°C to 5°C, and extreme rainfall intensity will increase by 10% to 30% by the year 2100. Such extreme conditions of temperature and precipitation are associated with increased floods, cyclones, droughts, and heatwaves. Flood magnitude and severity will increase by 15–40% and 20–50%, respectively, by mid-century, particularly in flood-prone areas. The scale of damage will exceed historical records due to the compounding of various cascading and compound hazards, exceeding those of single flood events. These events are not distributed uniformly, and unplanned urbanization and economic inequality exacerbate the risks. The Ganges-Brahmaputra floodplains, coastal areas, and Himalayan foothills have severe floods, whereas drought risks are increasing in arid regions. Annual economic losses from climate-induced disasters are currently 10 to 15 billion USD, and are projected to increase by 2 to 3 times by 2050. Existing studies have several limitations, including weak integration of datasets with hydrological and hydrodynamic model research. Gauge station density is extremely low, and compound analysis of various hazards and the accurate scenarios of disaster-affected communities is not adequately presented in the studies. These gaps need to be filled in the further research by integrating CMIP6 projections combining advanced modeling, and remote sensing methods to improve uncertainty analysis and inform decision-making processes and regional collaboration for risk assessment that can strengthen resilience for adaptation decisions especially for wetland environments and highly vulnerable floodplains in South Asia.

1. Introduction

The Earth's climate system has been changing due to natural and artificial factors, and their combined effects since the beginning of the Earth. Greenhouse gases act as the main driver for global warming and climate change (Hansen 2010; IPCC 2021). Increasing global temperatures potentially influence atmospheric circulation systems and alter the intensity and variability of weather conditions as well as shift long-term baselines of climate (Church 2013; Oppenheimer et al. 2019). Accordingly, climate change has emerged as one of the key global challenges linked to human livelihoods, water resources, and environmental stability (Field et al. 2014).

Global warming influences increasing of evaporation rates and atmospheric moisture content which finally disrupts the hydrological cycle (Trenberth 2011). Theoretically, these changes influence precipitation patterns, intensifying rainfall and causing pronounced changes in seasonal distribution, as well as expected longer dry periods (Allan and Soden 2008). Besides, glacier and snowpack melting are accelerating, which changes river flow systems and increases uncertainty in hydrological systems (Milly 2008). Such dry and wet periods in the hydrological systems due to climate change directly reflected in the occurrences of extreme hydrometeorological events with more severe, less predictable floods, flash

floods, cyclones, and droughts are becoming frequent across many parts of the world (Hirabayashi et al. 2013; Rehan and Hall 2016; IPCC 2021). Even, excessive rainfall reduces the soil's absorption capacity and extreme heatwaves increase the severity of droughts; the interaction of these factors creates compound hazards and multiplies the resulting damage (Zscheischler 2018).

Due to diverse geographical features and low socio-economic conditions, South Asia is a disaster-prone region (Fig. 1), and this type of extreme hydrometeorological event occurs frequently in this area (Eckstein 2021). Nearly one quarter of the global population resides in this region, most of whom rely on the climate-sensitive agricultural sector, thereby increasing their exposure to climate variability (Mirza 2011). Recent studies indicate increasing variability in the South Asian monsoon system, characterized by longer dry periods and a greater frequency of extreme rainfall events (by about 10–20% in parts of India and Bangladesh). Recurrent floods and prolonged droughts intensity is increasing due to such climatic variability in several countries, including Bangladesh, India, and Pakistan.

In the Himalayan region, glaciers are melting faster, resulting in an estimated 20–30% mass loss since the late 20th century. This melting of glaciers leads to increased river discharge, outburst floods, rapid-onset flash floods, and widespread destruction (Bolch 2012). At the same time, additional threats to coastal zones include more intense cyclones, sea-level may rise nearly 3-4mm per year in the Bay of Bengal, and storm surges (Knutson 2020). Overall, the multiple, interacting, and evolving nature of hazards amplifies vulnerability due to the more frequent occurrence of hydrometeorological extremes in South Asia; while cascading and compound risks are becoming more prominent and pose key challenges to risk reduction and adaptation planning.

Understanding the current state of knowledge on climate change and its impacts on hydrometeorological extremes in South Asia is pertinent to strengthening climate change adaptation in the region and the community's resilience. Effective and targeted adaptation strategies can be developed based on consolidated knowledge to help outline climate-resilient policy planning and to inform practical interventions for disaster risk reduction in South Asia. The motivation for this review is to systematically compile evidence, adopting a PRISMA-guided semi-systematic approach, from peer-reviewed climate change studies to synthesize current evidence on climate change and its impacts on hydrometeorological extremes in South Asia. Also, the review helps identify gaps in studies related to the topic. A common understanding of the current state of knowledge will help provide evidence for additional research avenues and the support required to strengthen the regions and the community's adaptation efforts.

2. Methodology

This study adopts the PRISMA method for the systematic review, involving identification, analysis, synthesis and providing outputs (Fig. 2). The literature search was made using peer-reviewed databases of Scopus between 2006 and 2026, with a particular focus on publications after 2020. Journals are searched based on keywords "Climate Change", or "Global Warming", "Climate Change Impact", AND "Hydrometeorological events" OR "Climatic Hazards", OR "Extreme Events" OR "Flood" OR "heatwave" AND "Prediction and Flood Modelling" AND "Climate change projections" AND "South Asia" OR "Bangladesh" OR

"India" OR "Nepal" OR "Pakistan" OR "Sri Lanka" OR "Bhutan" OR "Maldives". In addition, IPCC assessment reports, and grey literature from recognized sources such as the World Bank, ADB, FAO and UN agencies were used to identify backward and forward citation tracking, where peer-reviewed evidence was limited, particularly for adaptation-relevant policies and strategies.

A qualitative thematic analysis approach was taken in this study to synthesize the extracted data rather than taking a quantitative meta-analysis. Quantitative meta-analysis is not feasible due to differences in scales, heterogeneous data, and analysis techniques and methodologies. Thus, this study focuses more on narrative synthesis to support comparative assessment across South Asia and hazard categories.

2.1 Screening and Eligibility Criteria

A two-stage screening process is conducted to select the articles. Firstly, titles and abstracts are checked with inclusion criteria; and secondly, all articles are fully assessed to clearly exclude duplicates and non-relevant studies (Fig. 3). The studies relevant to non-climatic hazards, non-hydrometeorological processes, and those with insufficient analytical methods are excluded. Conceptual studies of compound risks, adaptation frameworks, and governance challenges are included, along with relevant articles. Overall, this study includes studies that: (a) evaluate the impacts of climate change on hydrometeorological extremes, related events, or climatic hazards; (b) study area focuses on South Asia or any individual South Asian country; (c) focus model-based analysis and relevant to simulated or observed changes with empirical findings and analysis; (d) published in English.

Based on those criteria 1166 published Scopus articles were identified, among them 35% in Environmental Science, 25% in Earth and Planetary Sciences, with smaller contributions from Agricultural Sciences, Engineering, and Social Sciences, reflecting the interdisciplinary nature of hydrometeorological research. Only the most relevant studies are retained after applying the exclusion criteria. Finally, 84 relevant journal articles are identified for this systematic review.

2.2 Data Extraction Process and Thematic Analysis

Relevant data and information were extracted using a structured systematic framework. Publication year, hazard type, data sources, study location, analytical methods (e.g., climate or hydrological modelling, observational analysis), major outcomes, impacts, and detected uncertainties were chosen for the thematic analysis (Fig. 4). This study mainly focused on the national perspective hazards data for critical analysis. The review classifies key themes and synthesis those themes into distinct sections relevant to hydrometeorological extremes such as climatic factors, impact of climate change, socio-economic and environmental impact, and resilient responses. By enabling a comparative analysis of trends, convergence, and divergence across the literature, these themes were used to categorize the selected studies and organize the results systematically. Also, this thematic framework enabled the identification of the areas of uncertainty and key knowledge gaps within and across hazard types.

3. Climate Change and Hydrometeorological Dynamics in South Asia

In this section, a critical evaluation has been demonstrated regarding the climatic drivers and how those drivers influence climate change, hydrometeorological processes and hazards dynamics of South Asia. At first, temperature, rainfall, and moisture trend have been analyzed, along with how the combined mechanism of these variables brings about changes in climate and hydrometeorological events. Secondly, it examined how climate change is influencing the ocean-atmosphere relationship, monsoon system variability, tropical cyclones, and the Himalayan cryosphere.

3.1 Climate Change and Hydro-Meteorological Dynamics

The Earth's climate has changed for various reasons and its changing trend is still observable even at present. One of the key causes of this is changes in meteorological parameters, the atmospheric cycle, land-ocean interactions, atmospheric feedbacks, and the drift of moisture (IPCC 2021; Trenberth 2011). These changing factors influencing hydrometeorological processes over the years in South Asia (Kripalani et al. 2007; Turner and Annamalai 2012). Human-induced warming is also affecting the Earth's hydrological circulation system in various ways, such as: the intensity and recurrence of rainfall, the presence of humidity, and the rate of evaporation are changing. This change in trend is further increasing the mean state of those parameters (Allan and Soden 2008; Held and Soden 2006). This thermodynamic relationship can be properly analyzed from the equation of Clausius-Clapeyron scaling.

$$e_s(T) \propto e^{0.07T}$$

where a 1°C increase occurs while a 6–7% increase in atmospheric moisture occurs (O’Gorman and Schneider 2009; Trenberth 2011).

The hydrometeorological variability and the nature of extreme rainfall in South Asia are consistent with the principles of this thermodynamic. For this reason, the region is facing intense rainfall in a short period of time, prolonged droughts, and various types of riverine and coastal disasters (Westra et al. 2014; Prakash et al. 2025). Recent decades’ temperature records show that South Asia experienced a consistent trend, with regional increases ranging from 0.5°C to 1.5°C. In comparison, the projected mean surface temperature may rise by 3.5°C to 5°C by the end of the century (Emanuel 2013; IPCC 2021). This temperature increases influences precipitation characteristics, including higher rainfall frequency and intensity, greater seasonal variability, and a different distribution of seasonal shifts (Donat 2016).

Annual precipitation is likely to increase by 7–20% due to global climate change and rising temperatures, while a 10–15% increase in monsoon rainfall is expected in many regions, particularly in the Brahmaputra-Meghna river basin, the foothill regions of the Himalaya, and central India (Gunathilaka et al. 2017; IPCC 2021). Moreover, on average, there are 5–15% rainy days in India, while heavy rainfall intensity and frequency increase, resulting in a 5–25% decline in drought-prone central India, and a drastic decrease in winter rainfall is projected in northern India (Roxy 2015; Gunathilaka et al. 2017). According to the analysis of long-term climate trends, the amount of total monsoon rainfall varies heterogeneous in spatial distribution. These changing patterns directly affect flooding intensity, flash flood frequency and

magnitude, evapotranspiration, and soil moisture dynamics, even in regions where total annual rainfall shows insignificant trends (Goswami 2006; Carrivick and Tweed 2016; Awange et al. 2017).

The moisture-holding capacity increases with the rise in atmospheric warming (Janizadeh et al. 2024; Jayasuriya et al. 2024). According to the principles of hydrodynamics, additional warming causes intense rainfall over large areas within a short period, resulting in increased rainfall intensity and variability in flow discharge. This phenomenon is evident in the flood-prone cities of South Asia (Westra et al. 2014; Rani et al. 2022). According to Ali et al., (2024), Cho, (2020), and Dahutia et al., (2018), cloudburst and convective storm triggers surface runoff, amplify river discharge as well as hydrological cycle system. Studies also explain 20 to 25% flash flood events have increased due to those processes.

3.2 Climate Change Driven Spatiotemporal Regional Processes

The monsoon system, ocean dynamics, and the Himalayan cryosphere are closely linked to hydrometeorological processes in South Asia. Atmospheric warming and temperature variability influence monsoon variability in South Asia, triggering regional hydrometeorological extremes (Emanuel 2013; Wijeratne et al. 2023). Climate change impacts the onset, delayed, erratic progression, and abrupt withdrawal phases, and alters monsoon characteristics in their entirety (Turner and Annamalai 2012; Ray et al. 2021). Around 15–25% intense rainfall has increased, while the occurrence of dry and extreme wet conditions has increased due to increased intra-seasonal and inter-annual variability within the same monsoon season (Roxy et al. 2017; Wickramasinghe et al. 2021). These changes disrupt across many sectors of South Asia, including water resource planning, flood management, and crop calendars.

Ocean warming is also one of the key driven factors to accelerated hydrometeorological extremes. Latent heat energy increases due to rising sea temperatures, which also intensifies tropical cyclone frequency, increases precipitation, and storm surge magnitude (Emanuel 2013; Wijeratne et al. 2023). According to climate projection studies, cyclone-induced precipitation and extreme rainfall rates may increase by 10–30% under high-emission scenarios of RCP8.5/SSP5-8.5 (Knutson 2020). This cyclone causes higher storm surges, coastal flooding, salinity intrusion into agricultural fields, and infrastructure damage, particularly in low-lying deltaic areas such as eastern India and Southern Bangladesh (Nicholls and Cazenave 2010; Hill et al. 2020). Sea level rise in coastal regions is another critical dimension of hydrometeorological risks.

The Himalayan cryosphere is one of the regulatory major sources of seasonal availability of water in downstream rivers and water basins in South Asia. Under the influence of climate change, the Himalayan glacier is melting at a rapid rate, and this meltwater is significantly increasing river discharge and greatly intensifies the magnitude of summer flash floods, causing damages far greater than those of typical flash floods. Moreover, when new glacial lake outburst floods (GLOFs) occur, the resulting damage often exceeds human imagination. Such flood events are increasingly occurring due to the compound hazards induced by global warming (Carrivick and Tweed 2016; Daron et al. 2022). On the other hand, excessive glacier melting eventually reduces water availability during dry seasons, leading to water scarcity and severe drought conditions (Bolch 2012; Shrestha and Aryal 2011). Huss (2018) indicates, 15% to 25% peak

river discharge is projected to increase under RCP8.5 scenarios which will trigger higher peak of downstream floods in more extent areas. Thus, the interaction among the monsoon system, ocean–atmosphere processes, ocean warming, and the cryosphere is generating compound dimensions of various climate-induced hazards across South Asia.

4. Climate Change Impacts on Extreme Hydrometeorological Events

This section depicts an evidence-based analysis of the impacts of climate change on extreme hydrometeorological events in South Asia. It discusses the relationship between climate change–induced variations in rainfall pattern, and the occurrence of floods, as well as how the scale and severity of flood damages have increased and regional drivers influences these evolve. This understanding synthesizes the threats posed by cyclones, droughts, and heatwaves risk trends under the influence of climate change.

4.1 Extreme Rainfall and Flood Dynamics

Climate change directly intensifies the drivers of climate change, leading to higher magnitudes, spatial variability and complexity of hydrometeorological extreme events in South Asia(IPCC 2021; Trenberth 2011). These hazards are altered according to thermodynamic mechanisms through atmospheric, terrestrial, and oceanic interactions (Table 2).

Basin scale empirical studies demonstrate that enhanced atmospheric moisture availability has increased by approximately 6–7% per 1°C of warming, thereby amplifying short-duration rainfall (1–5 days) by 20–40% during the historical period (1980–2014) in the Ganges-Brahmaputra-Meghna basin and Central India(Goswami 2006; Pathirana et al. 2007; Allan and Soden 2008; O’Gorman and Schneider 2009). Additionally, CMIP6 and CMIP5 ensemble studies using regional and global climate models (HadGEM2-ES, MPI-ESM-LR, and CESM1) with RCP8.5 and SSP5-8.5 scenarios reveal that high-intensity rainfall events, show extreme precipitation intensity increases of 10–30% over India and neighboring regions at the end of the 21st Century(IPCC 2021; Sabeerali et al. 2014; Turner and Annamalai 2012).

SWAT, HEC-HMS, and VIC-based hydrological simulations suggest that, due to extreme monsoon rainfall and declining water storage, discharge can increase by 15–25% and lead to higher riverine flood peaks across South Asia, including the Indus, Ganges, and Brahmaputra river basins (Hirabayashi et al. 2013; Zam et al. 2021). Jayapadma et al. (2024) and Westra et al. (2014) argued that due to 20 to 40% exceeding extreme rainfall events caused large scale flash floods in the Western Ghats and the Himalayan foothills and pluvial floods in rapidly urbanized city areas and creates compound landslides. Rani et al. (2022), and Wickramasinghe et al. (2021) also depicts similar trend of flash floods characteristics with an increasing trend of 20 to 25% which causes significant damages and exacerbating the combined impacts of climate change and constrain the disaster management system.

In addition, climate change melting Himalayan glaciers, thereby intensifying monsoon floods magnitude and duration in transboundary, densely populated river systems such as Bangladesh(Bolch 2012; Huss 2018). Sea level rise, estimated at 0.5–0.8 meter by 2100, also increases backwater effects, storm surge,

and salinity intrusion in the coastal flooding areas (IPCC 2021; Nicholls and Cazenave 2010). These combined floods caused massive damage to resources, particularly disproportionately affecting the marginalized communities, which could increase by 10–20% at the end of the century (Field et al. 2014; Ranasinghe et al. 2022).

4.2 Threats from Cyclone, Drought and Heatwaves

Climate change-induced cyclones, storm surge and coastal flooding critically threat low-lying deltaic regions and coastal areas of Bangladesh, Sri Lanka and eastern India (Nicholls and Cazenave 2010; Perera et al. 2018). Due to increasing sea surface temperatures, more intense categories of 4 and 5 cyclones also increasing in the North Indian Ocean according to CMIP5 and CMIP6 climate projections (Emanuel 2013; Knutson 2020). In the recent decades, annual cyclone frequency anomalies also exist in the Bay of Bengal and the Arabian Sea (Balaguru et al. 2020). Ensemble studies under RCP8.5/SSP5-8.5 scenarios (2050–2100 period) demonstrate that 10–30% rainfall and storm surge will increase due to cyclonic effects (Knutson 2020; Wijeratne et al. 2023).

Droughts are becoming more frequent, and heatwaves are among the most robust climate signals over South Asia (IPCC 2021). RCP4.5 and RCP8.5 scenarios studies depict a 5–25% decrease in precipitation in drought-affected areas, while extreme temperatures are rising with spatial variation. SPI and SPEI indices commonly employ in drought assessments with baseline periods scaling from 1951 to 2000 to 1981 to 2010 (Sheffield and Wood 2008; Vicente-Serrano et al. 2010; Dai 2013). In contrast, due to the impacts of climate change heatwave duration and severity have increased since the 1980s in the semi-arid and arid regions (Herweijer and Seager 2008; Perkins-Kirkpatrick and Lewis 2020). According to future projections, studies under the SSP2-4.5 and SSP5-8.5 scenarios, a 2-4-fold increase in heatwave frequency by 2050, while temperatures rise by 1.5 to 3.5°C, particularly in Pakistan and northwestern India (IPCC 2021; Rohini et al. 2016). Heatwave projections demonstrate strong inter-model agreement, indicating high confidence in these trends, in contrast to precipitation. Droughts and heatwaves have wide-ranging impacts in different sectors, particularly by water availability, disrupting crop production due to shortages of water resources, and posing severe threats to marginalized communities and public health (Amarasinghe et al. 2021; Ali et al. 2024).

Based on IPCC projected quantification (2021) and others various researcher's analyses, an infographic summary has been prepared to interpret the impacts of climate change and the physical interactions among climatic drivers and intensity of extreme hydrometeorological events across South Asia (Table 1).

Table 1

Climate model comparison matrix and evidence of quantified hydrometeorological impact studies in South Asia.

Climate Models	Scenario(s)	Baseline Period	Future Period	Scale	Key Findings	Sources
CMIP5 (HadGEM2-ES, MPI-ESM	RCP8.5	1971–2000	2070–2100	South Asia (regional)	10–30% increase in extreme rainfall	Turner and Annamalai (2012)
HEC-HMS)			2050–2100	South Asia (sub-basin)	20–25% increase in flash floods	Wickramasinghe et al. (2021)
CMIP5 (RCM	RCP4.5, RCP8.5	1980–2010	2050–2100	India (regional)	Intensification of monsoon extremes	Sabeerali et al. (2014)
GFDL, HadGEM	RCP8.5			Bay of Bengal	10–30% increase in cyclone rainfall	Perera et al. (2018)
SWAT/VIC)			2070–2100	Indus–Ganges–Brahmaputra (basin)	15–25% increase in peak discharge	Zam et al. (2021)
CMIP5/6 ensemble	RCP4.5, RCP8.5	1951–2000	2050–2100	South Asia (regional)	5–25% decline in precipitation (drought regions)	Amarasinghe et al. (2021)
CMIP6 + Delft3D	SSP5-8.5	1995–2014	2070–2100	Coastal South Asia	0.5–0.8 m SLR; 10–20% increase in flood exposure	Ranasinghe et al. (2022)

5. Socio-Economic Impacts

Nearly 25% of the global population in South Asia with high density, poverty, and greater use of natural resources, is exposed to a wide range of climate change-driven impacts, along with increasing hazard intensity and the persistence of structural vulnerabilities (de Silva et al. 2007; Kurukulasuriya and Ajwad, 2007). This region experienced 80–90% of losses due to climate-driven disasters, including floods, cyclones, heatwaves, and drought (Field et al. 2014).

5.1 Economic Losses-Damage and Public Health Effects

Local development and national economies are affected by climate-induced hydrometeorological extremes, resulting in rising economic costs across South Asia (Samarasinghe et al. 2018). Current annual

damages are estimated at 10–15 billion USD based on CMIP5/CMIP6 regional assessments using SWAT and VIC hydrological modeling, while projections depict, they could increase 2-3-fold by 2050(Hirabayashi et al. 2013). Each year, the losses and damages directly hinder the national development budget, with a significant portion of the budget being spent on recovery measures. The scale of indirect economic losses is immeasurable and irreversible. Reduced production, supply shortages leading to price increases, insurance and construction costs together have risen by 30% to 50%. These additional expenditures adversely affect national development, living standards, and investment (Awange et al. 2017).

Over the past two decades, urban areas of Dhaka, Mumbai, and Karachi have suffered 20–40% higher flood-induced losses due to the high concentration of valuable assets, limited resilience infrastructure, and insufficient drainage capacity(Hallegatte et al. 2013). According to crop models such as APSIM and DSSAT, with bias -corrected climate projections (2050–2100), estimations show that extreme events caused crop damages around 10–30% per event in agricultural systems of rural areas, particularly within the Indus and Ganges-Brahmaputra-Meghna (GBM) basins, with higher hits in flood and drought-prone areas(Rosenzweig et al. 2014).

Besides, public health risks are increasing through both direct and indirect pathways due to hydrometeorological extremes. Water-borne diseases are rising 15–25% and spreading through contaminated water supplies and favorable breeding conditions, leading to post-flood conditions in densely populated peri-urban and urban areas(Rimi et al. 2022). According to SSP2-4.5 and SSP5-8.5 scenarios, heatwave-related mortality and illnesses such as headaches, fainting, skin burns, and dehydration, particularly among outdoor workers and urban poor populations, are projected to increase by 10–20% with the highest risks observed in Pakistan and India until 2040 to 2060(Gasparrini et al. 2015). Dengue and malaria are also spreading as climates become warmer and more humid (Ryan et al. 2019). Overall, different types of frequent hazards also affect victims' mental health, which leads to anxiety, stress, and extreme trauma(Dahutia et al. 2018).

5.2 Impacts on Human Lives, Livelihoods and Food Security

Hydrometeorological events caused massive damages to resources, livelihood and people (Table 2). Floods, cyclones, drought, heatwaves and landslide etc. affected more than 20 million people of South Asia. Many people losses their households and displaced from their original households due to river bank erosion. All aged population are not affected by the hazards equally whereas children, aged, and women are always more vulnerable to the hazards (Internal Displacement Monitoring Centre 2023). The farmers are usually depending on favorable climatic condition for their cultivation but 40 to 60 percent of them are facing challenges to extreme climate risks (Jayathilaka et al. 2012; Kumaran et al. 2013). Excess precipitation and recurrent flood cause massive damages to crops and reduce yields up to 40% whereas around 35% yields decline due to drought and extreme heat waves (Lobell et al. 2011; Rosenzweig et al. 2014).

The expected increase in irrigation demand is 15–25% due to rising temperatures, which intensify stress on already constrained water resources(Withanachchi et al. 2014). Coastal flooding and salinity intrusion also affect nearly 1–2 million hectares of agricultural land, causing further crop losses and reduced water

availability in deltaic regions like Bangladesh(Nicholls and Cazenave 2010). In addition, glacier meltwater alters the sources of river flow, affecting annual and seasonal water availability, particularly during the dry season (Huss 2018). Overall, those factors create stress and pressure on food security, where 10–20% of the population in vulnerable regions is experiencing ultra-food insecurity. Due to high food import prices, many people face challenges buying adequate food, leading to accelerated nutritional deficiencies and food insecurity among vulnerable communities(FAO 2022).

According to DICE, FUND, PAGE, and CGE macroeconomic frameworks, on average, GDP is projected to decline by 1–2% across the region, while in highly vulnerable countries such as Bangladesh and Nepal, the reduction could reach 3–4% (Nordhaus 2017; Tol 2018). Various studies also indicate that the impacts will not be limited to direct losses; rather, numerous sectors such as disaster preparedness and recovery, long-term development planning, social stability, and environmental sustainability will face severe indirect risks and long-term challenges.

Table 2

Climate change–induced extreme events affected various socio-economic sectors and associated risks across spatial scales.

Sector	Spatial Scale	Scenario(s)	Future Period	Key Findings	Source
Economy	South Asia	RCP4.5, RCP8.5	2050– 2100	1–2% GDP loss annually; up to 3–4% in vulnerable countries	Kumarasinghe and Basnayake (2009)
				USD 10–15 billion loss; 2–3× increase by 2050	Samarasinghe et al. (2018)
				Indirect losses exceed direct by 30–50%	Awange et al. (2017)
Agriculture	GBM & Indus basins	RCP4.5, RCP8.5	2050– 2100	10–30% crop loss per extreme event	Chen et al. (2017); Nay et al. (2018)
	South Asia	SSP5-8.5		20–40% yield loss (flood); 10–35% (drought/heat)	Withanachchi et al. (2014)
	Coastal/delta			1–2 million ha affected by salinity intrusion	Coastal Bangladesh studies
Public health	India, Pakistan	SSP2-4.5, SSP5-8.5	2040– 2060	10–20% increase in heatwave mortality	Dahutia et al. (2018)
	Urban/regional	RCP4.5, RCP8.5	2050– 2100	15–25% increase in water-borne diseases	Regional epidemiological studies
Livelihoods, displacement	South Asia	Historical + projections	2050	15–20 million people displaced annually	Jayathilaka et al. (2012); Amoako Johnson and Hutton (2014)
Multi-sector	South Asia	Historical	—	80–90% disaster losses from hydrometeorological hazards	de Silva et al. (2007); Kurukulasuriya and Ajwad (2007)

6. Adaptation Strategies and Policy Implications

A complete set of adaptation strategies is required to mitigate the diverse impacts of climate change and hydrometeorological events in South Asia. These include advanced research and modeling, structural to nature-based adaptation, climate-sensitive agricultural practices, implications of indigenous knowledge, and enhanced concrete policy planning for the government (Raj 2010; IPCC 2022). These adaptation

measures can be effective if the study is designed on various scales, from the regional to basin or local levels, and transferred into a holistic adaptation framework. According to climate projections (CMIP5/CMIP6), the annual adaptation costs in developing Asia could increase to approximately USD 40–50 billion (Asian Development Bank 2020; IPCC 2022).

6.1 Advance Research and Modelling Approaches

Hydrological and hydrodynamic flood modeling plays a significant role in evaluating South Asian climate change impacts and adaptation strategies in extreme risk scenarios (Bajracharya et al., 2023; Dahal et al. 2020; Raj et al. 2013; Shrestha et al. 2016; Shrestha et al. 2025). At the catchment scale, hydrological models are widely used to simulate hydrological events, such as HEC-HMS, SWAT, and VIC. In contrast, MIKE, HEC-RAS, and LISFLOOD-FP are used to simulate hydrodynamic characteristics of flood, such as extent, velocity, and depth (Ansari et al. 2020; Ansari et al. 2025; Dissanayaka and Rajapakse 2019; Moazzam et al. 2022; Sengupta and Nigam 2019; Libanda and Ngonga 2018; Muthuwatta et al. 2017).

The key challenges in implementing this advanced model are climatic uncertainty, limited observed station data, bias correction (CMIP5/CMIP6), and parameter calibration, especially across different types of river systems and transboundary basins (Dorji et al. 2017; Jiang et al. 2025; Mondal et al. 2017; Tandon et al. 2026). Therefore, the integrated adaptation framework needs to enhance data assimilation, scenario-based uncertainty assessment, and model improvement.

The Early Warning System (EWS) plays the most effective non-structural adaptation measure in reducing flood loss. According to national and regional evidence, timely flood and cyclone alerts can reduce mortality by 30–50%, particularly in densely populated floodplains of India, Sri Lanka, and Bangladesh (United Nations Office for Disaster Risk Reduction 2019). Flood and cyclone forecasting capabilities have been improved with short-term forecast accuracy to nearly 70–90% for lead times of 1–5 days in South Asia through advanced remote sensing (e.g., TRMM, GPM), real-time hydrological modeling, and numerical weather prediction (NWP) (Webber et al. 2018).

6.2 Climate-Resilient Infrastructure and Nature-based Solutions (NbS)

The use of climate-resilient adaptation, such as sustainable drainage networks, coastal protection, and embankments, is vital in providing protection in the South Asian region. According to engineering-based studies, around 40–60% of economic losses can be reduced by climate-resilient infrastructure under moderate flood scenarios, despite compound and extreme events reducing this infrastructure's effectiveness (Hallegatte et al. 2013). Nature-based solutions (NbS) are increasingly identified as cost-effective alternatives, lessening flood peaks by 10–30% and coastal storm surge by 20–50%, enhancing and enhancing groundwater recharge through wetland conservation, floodplain restoration, river restoration, and mangrove rehabilitation (Nisansala et al. 2020; Rayan et al. 2022). In addition, hybrid approaches such as grey and green infrastructure offer the most robust and effective adaptation measures.

6.3 Regional Cooperation and Governance Implications

Many rivers in South Asia originate in the Himalayan highlands, and around 70% of major river basins are transboundary, including the Indus and Ganges-Brahmaputra-Meghna (GBM) systems. Effective flood adaptation frameworks require regional cooperation within those transboundary river basins. Regional studies explain that geopolitical relations, limited data-sharing and institutional communication, declining effective flood forecasting accuracy, and risk management at the downstream (Hill et al. 2020). Enhancing regional cooperation, transboundary data sharing, and scientific knowledge can benefit all parties by improving flood forecasting accuracy, thereby significantly reducing downstream exposure and damage by 20–30% (Asian Development Bank 2020).

The effectiveness of adaptation to hydrometeorological extremes varies due to several factors, including weak communication, limited public awareness and education, less trust on forecasting, and inadequate institutional coordination. Proactive measures to hazards loss mitigation can lessen 30 to 40% of total loss (Chathuranika et al. 2022; IPCC 2022). Disaster relevant authorities and institutions should enhance their coordination to rapidly transform the decision and immediate response to the victims. Good governance emphasis more advanced technological research for formulating reliable decision planning integrates local indigenous knowledge and raise awareness to the affected community in disaster preparedness, responses, risk management and resilience.

7. Research Gaps and Future Directions

According to this PRISMA-based review, extreme hydrometeorological events in South Asia in climate change scenarios are highly fragmented, with most of the studies (70–80) focusing on single hazards like floods, cyclones, or droughts, and fewer than 20% focusing on multi-hazards or compound processes. Such a disproportion in the studies restricts the comprehension of more complex climate-driven extremes, and multi-hazard interactions increase the impacts (IPCC 2021; Zscheischler et al. 2018). Moreover, most case studies target some data-rich areas, which in turn are underrepresented by the transboundary areas that are climate sensitive. Even in some parts of South Asia, although climate projections have suggested that extreme precipitation and frequency of floods will increase by 10–30% and 20% respectively by the end of the century, contemporary studies usually do not translate these projections into integrated risk and adaptation frameworks (Hirabayashi et al. 2013; Westra et al. 2014). In this regard, an actionable gap in research still exists between actionable hazard characterization and policy relevant outcomes.

A key limitation lies that many regions of South Asia suffer from availability of long-term data and insufficient high-quality hydro-climatic observation stations; in some areas, there is fewer than one-gauge station per 1,000–5,000 square kilometers (Huffman et al. 2007; Hersbach et al. 2020). Most river basins lack continuous records that rarely exceed 20–30 years, whereas at least 50 years of continuous observational records are required for typically robust extreme value analysis (Katz et al. 2002). Most studies rely on easily accessible, low-resolution open-source Global Climate Models (GCMs). However, these datasets are often inadequate for capturing complex topography and localized extreme events, which reduces the reliability of model outputs (Giorgi and Gutowski 2015; Moriasi et al. 2007). Therefore,

future research should place greater emphasis on the use of high-resolution satellite data, regional climate models (10–25 km resolution) and reanalysis datasets (ERA5) to improve the precision, climate projections consistency and impact assessments (Huffman et al. 2007; Hersbach et al. 2020).

There is a remarkable gap between various models and their reliability of the results. Fully coupled hydrological and hydrodynamic modeling studies are less than 30% of the reviewed studies. Among the models, results range often vary from 10 to 30% which influence the uncertainty. But this uncertainty is not systematically and effectively integrated into modeling outputs of multi-model ensembles which could exceed 50% of streamflow and 40–60% in extreme event projections. This disconnection limits their application in decision-making and reduces the reliability of flood simulations (Kundzewicz et al. 2014). In this context, there is a pressing need for advanced machine learning, sensitivity-driven, ensemble-based, and probabilistic approaches to improve uncertainty quantification and research credibility for decision-making (Kundzewicz et al. 2018).

Compound and cascading events arise, but quantitative modeling and empirical studies of such events remain limited in South Asia. Flood magnitudes can increase by 20–50% due to compound processes rather than single-hazard scenarios, but they remain inadequately quantified (Zscheischler et al. 2018). Addressing this gap, systematic frameworks are required to capture compound hazards using multi-hazard modeling in future research to understand the compound and cascading mechanisms under changing climatic conditions.

The integration of socio-economic vulnerability and resilience remains underrepresented alongside physical processes. Nearly 30% of studies use only socio-economic indicators in their analyses, such as livelihood dependence, population exposure, or adaptive capacity. Addressing this gap is very significant, particularly in flood-prone critical environments, where 80–90% of damage and economic losses occur due to hydrometeorological disasters (Field et al. 2014). Socio-hydrological and impact-based frameworks should prioritize future research by integrating hazard modeling with vulnerability and resilience measures to achieve a more comprehensive risk assessment.

Large-scale modeling and localized case studies are occasionally combined by most studies, leaving wetland and floodplain systems wanting across South Asia. 30–50% of seasonal floodwater can be stored in the wetland system, which helps regulate flood peaks, but this crucial role is rarely accurately represented in conventional models (Mitsch and Gosselink 2015). Local research can be very challenging to transfer or scale, and local understanding is often unavailable in basin-scale analyses. Therefore, multiscale research involves filling in these gaps by developing ecosystem-based modeling techniques which incorporate wetland hydrodynamics and connectivity.

Comparatively fewer than 25% of the reviewed studies evaluate the effectiveness of flood adaptation strategies under future climate change scenarios (SSP-RCP) and solution-oriented analysis is less common than hazard projection (Ansari et al. 2025; IPCC 2022). Therefore, scenario-based evaluation of non-structural and structural resilience strategies should be prioritized in future studies to develop robust, adaptive solutions under uncertain future climatic conditions.

Overall, these gaps highlight the need for a transition toward multi-scale, integrated, and solution-oriented research approaches (Table 3). In this perspective, there is a clear research direction regarding evaluating flood resilience within highly vulnerable and dynamic environments, particularly in the wetland ecosystem, integrating community-based indigenous vulnerability assessment with hydrological modeling under climate change scenarios where local stakeholders' perceptions and co-production of knowledge can improve adaptation strategies and enhance the relevance and legitimacy of planning implementation.

Table 3

Synthesis of the main gaps applicable to hydrometeorological research and further avenue to research.

Theme	Key gaps	Quantitative evidence	Future research directions
Observe and projected hydrometeorological data	Observed data is short period with a few recording hydro-climatic observation stations; Coarse-resolution GCM outputs	Availability of around 30 years observed data and 1 gauge station per 1,000–5,000 square kilometers.	Establishing more monitoring stations and recording high resolution datasets integrating remote sensing (e.g., TRMM, GPM, ERA5; CORDEX)
Multi-hazards complexity	Lacking of cascading and compound hazards complexity assessment	Multi-hazards relevant studies around 20%	Interacting multi-hazard system-based modeling by integrating cryosphere and hydrometeorological.
Urban risk	Limited assessment of urban systems	Urban areas studies are about 25% while annual urban growth 3 to 5%	Develop advanced hydroclimatic models to evaluate flood, heat island and landslide susceptibility (e.g., SWMM, WRF-Hydro)
Spatiotemporal scale mismatch	Difficult to transfer or integrate various scale of studies from local to regional	Basin scale and local studies are not integrated with national scale assessments	Design community participation based multiscale studies with transboundary knowledge sharing
Uncertainty and modelling systems	High uncertainty exists within various models and their results with limited integration of uncertainty into models	Around 30% studies integrate hybrid model while uncertainty in projections exist 20 to 40%	Ensemble hybrid data driven models with CMIP6 projections and SSP frameworks to analysis uncertainty into models (e.g., SWAT + machine learning)
Extremes dynamics	Partial representation of extreme events and monsoon dynamics	Extreme rainfall simulated significantly in bias	Regional climate models need to improve bias correction for proper representation of topographic influences to extreme events

8. Conclusion

The observed and model-based evidence suggests that climate change is affecting the intensity, frequency and complexity of hydrometeorological events in South Asia with significant spatial variation. The increased temperature trend reflects around 0.5–1.5°C warming with the projections of 3–5°C at the end of this century, whereas increase in extreme precipitation is projected as 10–30% with profound impact on monsoon dynamics, enhancing intra-seasonal variability and causing flood-drought co-occurrence, especially in the foothills of the Himalayan region and Indo-Gangetic plains. The changes in the glacier mass and the projected reduction by 30–50% in the Himalayan regions further increase the risks of GLOFs and trigger landslides. These upstream changes propagate downstream because these changes in discharge can be extreme, and in fact can be as much as about 50%, which creates challenges for forecasting and basin-scale flood management.

The intensity of cascading and compound hazards is also increasing due to climate change, leading to greater socio-economic losses. In particular, floods can trigger landslides, cyclones can exacerbate coastal flooding, and the sequential occurrence of floods and droughts can amplify overall impacts. These hazards are further intensified by land-use change, rapid urbanization, economic inequality, and government policies, especially in vulnerable coastal regions, mountainous regions, floodplains, and deltas.

The findings of this study were derived through a PRISMA-guided review and analysis of a limited set of available data sources and uneven thematic literature with spatial coverage. Therefore, variations and inconsistencies in the underlying datasets and research trends and effect sizes are evident and should be considered when interpreting the results. Despite significant progress in climate and disaster-related research, several important research gaps still remain. Among the most notable are the limited use of hydro-climatic long-term big data (< 30 years) approaches and the inadequate density of monitoring stations (< 1 per 1,000–5,000 km²), both of which constrain the accuracy and reliability of climate and risk assessments.

Less than 20% of the modeling chains have a physical climate–hydrology–hydrodynamic model, and less than 30% have a cascade hazard analysis, while the uncertainty of extreme projections in the model chain remains high and is not commonly used in decision-making processes. These research gaps need to be filled by combining hydrodynamic modeling, hydrological modeling, and remote sensing methods to improve uncertainty analysis and inform decision-making processes for risk assessment that can bolster resilience for adaptation decisions. Improve transboundary data sharing and regional collaboration, while adopting exposure, vulnerability and adaptive capacity in these processes to boost the resilience-based approaches to adaptation, especially for wetland environments and highly vulnerable floodplains.

Declarations

Competing Interests

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.

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Author Contributions

Muhammad Rezaul Rakib was responsible for conceptualization, methodology, formal analysis, data curation, original draft writing, visualization of the study, and manuscript revision. He also played a central role in the review process, collaborating with the co-authors. Balqis Mohamed Rehan contributed to the conceptualization and supervision and took primary responsibility for revising the manuscript, including substantial input during the review and editing. Nor Azlina Alias and Mohd. Shahrizal Bin Ab Razak contributed to the manuscript's review, ensuring the clarity of the research and editing stages. All authors have read and approved the final version of the manuscript.

References

1. Allan RP, Soden BJ (2008) Atmospheric warming and the amplification of precipitation extremes. *Science* (1979) 321:1481–1484
2. Amarasinghe UA, Amarnath G, Alahacoon N et al (2021) Adaptation to climate variability in sri lanka: A case study of the huruluwewa irrigation system in the dry zone. *IWMI Working Papers* 2021:. <https://doi.org/10.5337/2021.229>
3. Ansari MA, Jacob J, Deodhar A et al (2020) Stable isotopic ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) and geospatial approach for evaluating extreme rainfall events. *Glob Planet Change* 194. <https://doi.org/10.1016/j.gloplacha.2020.103299>
4. Ansari R, Casanueva A, Liaqat MU, Grossi G (2025) Changes in the probability of temporally compound wet and dry events in a warmer world: case study in the Upper Jhelum Basin—South Asia. <https://doi.org/10.1007/s10113-025-02367-z>. *Reg Environ Change* 25:
5. Asian Development Bank (2020) Asian Water Development Outlook
6. Awange JL, Kuhn M, Anyah R, Forootan E (2017) Changes and variability of precipitation and temperature in the Ganges–Brahmaputra–Meghna River Basin based on global high-resolution reanalyses. *Int J Climatol* 37:2141–2159. <https://doi.org/10.1002/joc.4842>
7. Bajracharya SR, Pradhananga S, Shrestha AB, Thapa R (2023) Future climate and its potential impact on the spatial and temporal hydrological regime in the Koshi Basin, Nepal. *J Hydrol Reg Stud* 45. <https://doi.org/10.1016/j.ejrh.2023.101316>

8. Balaguru K, Foltz GR, Leung LR, Emanuel KA (2020) Increasing magnitude of tropical cyclone rapid intensification in the North Indian Ocean. *Nat Commun* 11:2185. <https://doi.org/10.1038/s41467-020-16025-7>
9. Bolch T et al (2012) The state and fate of Himalayan glaciers. *Science* (1979) 336:310–314
10. Carrivick JL, Tweed FS (2016) A global assessment of the societal impacts of glacier outburst floods. *Glob Planet Change* 144:1–16. <https://doi.org/10.1016/j.gloplacha.2016.07.001>
11. Chathuranika IM, Gunathilake MB, Azamathulla HMd, Rathnayake U (2022) Evaluation of Future Streamflow in the Upper Part of the Nilwala River Basin (Sri Lanka) under Climate Change. *Hydrology* 9. <https://doi.org/10.3390/hydrology9030048>
12. Church JA, CPUACAGJMJSLS& UAS (2013) Sea level change. *Climate Change 2013: The Physical Science Basis*
13. Dahal P, Shrestha ML, Panthi J, Pradhananga D (2020) Modeling the future impacts of climate change on water availability in the Karnali River Basin of Nepal Himalaya. *Environ Res* 185. <https://doi.org/10.1016/j.envres.2020.109430>
14. Dahutia P, Pathak B, Bhuyan PK (2018) Aerosols characteristics, trends and their climatic implications over northeast india and adjoining South Asia. *Int J Climatol* 38:1234–1256. <https://doi.org/10.1002/joc.5240>
15. Dai A (2013) Increasing drought under global warming in observations and models. *Nat Clim Chang* 3:52–58. <https://doi.org/10.1038/nclimate1633>
16. Daron J, Bruno Soares M, Janes T et al (2022) Advancing climate services in South Asia. <https://doi.org/10.1016/j.cliser.2022.100295>. *Clim Serv* 26:
17. Dissanayaka KDCR, Rajapakse RLHL (2019) Long-term precipitation trends and climate extremes in the Kelani River basin, Sri Lanka, and their impact on streamflow variability under climate change. *Paddy Water Environ* 17:281–289. <https://doi.org/10.1007/s10333-019-00721-6>
18. Donat MG et al (2016) More extreme precipitation in the world's dry and wet regions. *Nat Clim Chang* 6:508–513
19. Dorji S, Herath S, Mishra BK (2017) Future climate of Colombo downscaled with SDSM-neural network. <https://doi.org/10.3390/cli5010024>. *Climate* 5:
20. Emanuel K (2013) Downscaling climate models shows increased tropical cyclone activity. *PNAS* 110:12219–12224
21. Field CB, DDJ BVR, MKJ, MMD, BTE, CM, EKL, EYO, GRC, GB, KES, LAN, MS MPR,WLL (eds) (2014) *Climate Change 2014: Impacts, Adaptation, and Vulnerability*. <https://doi.org/DOI:10.1017/CBO9781107415379>
22. Field CB (2014) others *Climate Change 2014: Impacts, Adaptation, and Vulnerability*
23. Food OA (2022) *The State of Food Security and Nutrition in the World 2022*
24. Gasparrini A, Guo Y, Hashizume M (2015) others Mortality risk attributable to high and low ambient temperature. *The Lancet* 386:369–375. [https://doi.org/10.1016/S0140-6736\(14\)62114-0](https://doi.org/10.1016/S0140-6736(14)62114-0)

25. Goswami BN et al (2006) Increasing trend of extreme rain events over India. *Science* (1979) 314:1442–1445
26. Govindha Raj BK, Kumar VK, Remya SN (2013) Remote sensing-based inventory of glacial lakes in Sikkim Himalaya: Semi-automated approach using satellite data. *Geomatics Nat Hazards Risk* 4:241–253. <https://doi.org/10.1080/19475705.2012.707153>
27. Gunathilaka RPD, Smart JCR, Fleming CM (2017) The impact of changing climate on perennial crops: the case of tea production in Sri Lanka. *Clim Change* 140:577–592. <https://doi.org/10.1007/s10584-016-1882-z>
28. Hallegatte S, Green C, Nicholls RJ, Corfee-Morlot J (2013) Future flood losses in major coastal cities. *Nat Clim Chang* 3:802–806. <https://doi.org/10.1038/nclimate1979>
29. Hansen J, RRRSM& LK (2010) Global surface temperature change. *Rev Geophys* 48:RG4004. <https://doi.org/10.1029/2010RG000345>
30. Held IM, Soden BJ (2006) Robust responses of the hydrological cycle to global warming. *J Clim* 19:5686–5699
31. Hersbach H, Bell B, Berrisford P (2020) others The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society* 146:1999–2049. <https://doi.org/10.1002/qj.3803>
32. Herweijer C, Seager R (2008) The global footprint of persistent extra-tropical drought in the instrumental era. *Int J Climatol* 28:1761–1774. <https://doi.org/10.1002/joc.1590>
33. Hill AF, Rittger K, Dendup T et al (2020) How Important Is Meltwater to the Chamkhar Chhu Headwaters of the Brahmaputra River? *Front Earth Sci* (Lausanne) 8. <https://doi.org/10.3389/feart.2020.00081>
34. Hirabayashi Y, Mahendran R, Koirala S et al (2013) Global flood risk under climate change. *Nat Clim Chang* 3:816–821. <https://doi.org/10.1038/nclimate1911>
35. Huffman GJ, Adler RF, Bolvin DT, Gu G (2007) The TRMM multi-satellite precipitation analysis. *J Hydrometeorol* 8:38–55. <https://doi.org/10.1175/JHM560.1>
36. Huss M, HR (2018) Global-scale hydrological response of mountain glaciers to future climate change. *Earths Future* 6:721–740. <https://doi.org/10.1002/2017EF000790>
37. Internal Displacement Monitoring Centre (2023) Global Report on Internal Displacement
38. IPCC (2021) Climate Change 2021: The Physical Science Basis. Cambridge University Press
39. IPCC (2022) Climate Change 2022: Impacts, Adaptation and Vulnerability. Cambridge University Press
40. Janizadeh S, Kim D, Jun C et al (2024) Impact of climate change on future flood susceptibility projections under shared socioeconomic pathway scenarios in South Asia using artificial intelligence algorithms. *J Environ Manage* 366. <https://doi.org/10.1016/j.jenvman.2024.121764>
41. Jayasuriya C, Palliyaguru C, Basnayake V et al (2024) Modelling Impact of Land Use Changes and Climate on Soil Erosion in the Uma Oya River Basin, Sri Lanka. *J Environ Inf Lett* 11:82–92. <https://doi.org/10.3808/jeil.202400127>
42. Jayathilaka PMS, Soni P, Perret SR et al (2012) Spatial assessment of climate change effects on crop suitability for major plantation crops in Sri Lanka. *Reg Environ Change* 12:55–68.

<https://doi.org/10.1007/s10113-011-0235-8>

43. Jiang Y, Song G, Zhai S et al (2025) The heterogeneous impacts of climate change on food security under SSP-RCPs scenarios: Evidence from Brazil, China, India, Russia, and the United States. *J Agric Food Res* 24:102467. <https://doi.org/https://doi.org/10.1016/j.jafr.2025.102467>
44. Katz RW, Parlange MB, Naveau P (2002) Statistics of extremes in hydrology. *Adv Water Resour* 25:1287–1304. [https://doi.org/10.1016/S0309-1708\(02\)00056-8](https://doi.org/10.1016/S0309-1708(02)00056-8)
45. Knutson T, CSJCJCLEKHC-HKJMMSSMSMWK&, WL (2020) Tropical cyclones and climate change assessment: Part II: Projections. *Bull Am Meteorol Soc* 101:E303–E322. <https://doi.org/10.1175/BAMS-D-18-0194.1>
46. Knutson T et al (2020) Tropical cyclones and climate change assessment. *BAMS* 101:E303–E322
47. Kripalani RH, Oh JH, Kulkarni A et al (2007) South Asian summer monsoon precipitation variability: Coupled climate model simulations and projections under IPCC AR4. *Theor Appl Climatol* 90:133–159. <https://doi.org/10.1007/s00704-006-0282-0>
48. Kumaran KPN, Limaye RB, Puneekar SA et al (2013) Vegetation response to South Asian Monsoon variations in Konkan, western India during the Late Quaternary: Evidence from fluvio-lacustrine archives. *Quatern Int* 286:3–18. <https://doi.org/10.1016/j.quaint.2012.03.010>
49. Kundzewicz ZW, Kanae S, Seneviratne SI (2014) others Flood risk and climate change: global and regional perspectives. *Hydrological Sciences Journal* 59:1–28. <https://doi.org/10.1080/02626667.2013.857411>
50. Kundzewicz ZW, Krysanova V, Benestad RE et al (2018) Uncertainty in climate change impacts on water resources. *Environ Sci Policy* 79. <https://doi.org/10.1016/j.envsci.2017.10.008>
51. Libanda B, Ngonga C (2018) Projection of frequency and intensity of extreme precipitation in Zambia: A CMIP5 study. *Clim Res* 76:59–72. <https://doi.org/10.3354/cr01528>
52. Lobell DB, Schlenker W, Costa-Roberts J (2011) Climate trends and global crop production since 1980. *Science* (1979) 333:616–620. <https://doi.org/10.1126/science.1204531>
53. Mitsch WJ, Gosselink JG (2015) *Wetlands*. Wiley
54. Moazzam MFU, Rahman G, Lee BG, Ansari NA (2022) Trend of snow cover under the influence of climate change using Google Earth Engine platform: A case study of Astore (Western Himalayas) and Shigar (Karakoram region). *Front Environ Sci* 10. <https://doi.org/10.3389/fenvs.2022.1006399>
55. Mondal S, Chockalingam C, Amarnath G, Pani P (2017) Time-series cloud noise mapping and reduction algorithm for improved vegetation and drought monitoring. *Glsci Remote Sens* 54:202–229. <https://doi.org/10.1080/15481603.2017.1286726>
56. Moriasi DN, Arnold JG, Van Liew MW et al (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans ASABE* 50:885–900. <https://doi.org/10.13031/2013.23153>
57. Muthuwatta LP, Perera HPTW, Eriyagama N et al (2017) Trend and variability of rainfall in two river basins in Sri Lanka: an analysis of meteorological data and farmers' perceptions. *Water Int* 42:981–999. <https://doi.org/10.1080/02508060.2017.1406784>

58. Nicholls RJ, Cazenave A (2010) Sea-level rise and its impact on coastal zones. *Science* (1979) 328:1517–1520
59. Nisansala WDS, Abeysingha NS, Islam A, Bandara AMKR (2020) Recent rainfall trend over Sri Lanka (1987–2017). *Int J Climatol* 40:3417–3435. <https://doi.org/10.1002/joc.6405>
60. Nordhaus WD (2017) Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences* 114:1518–1523. <https://doi.org/10.1073/pnas.1609244114>
61. O’Gorman PA, Schneider T (2009) The physical basis for increases in precipitation extremes. *PNAS* 106:14773–14777
62. Oppenheimer M (2019) others Sea level rise and implications for low-lying islands, coasts and communities. IPCC Special Report on the Ocean and Cryosphere
63. Pathirana A, Herath S, Yamada T, Swain D (2007) Impacts of absorbing aerosols on South Asian rainfall: A modeling study. *Clim Change* 85:103–118. <https://doi.org/10.1007/s10584-006-9184-5>
64. Perera KARS, de Silva KHWL, Amarasinghe MD (2018) Potential impact of predicted sea level rise on carbon sink function of mangrove ecosystems with special reference to Negombo estuary, Sri Lanka. *Glob Planet Change* 161:162–171. <https://doi.org/10.1016/j.gloplacha.2017.12.016>
65. Perkins-Kirkpatrick SE, Lewis SC (2020) Increasing trends in regional heatwaves. *Nat Commun* 11:3357. <https://doi.org/10.1038/s41467-020-16970-7>
66. Prakash A, George R, Barua A (2025) Socio-hydrological frameworks for adaptive governance: addressing climate uncertainty in South Asia. *Frontiers in Water* 7
67. Ranasinghe T, Gunawardena G, Wimalasiri EM, Rathnayake U (2022) Analyzing Relationships Between Rainfall and Paddy Harvest using Artificial Neural Network (ANN) Approach: Case Studies from North-Western and North-Central Provinces, Sri Lanka. *J Agricultural Sci - Sri Lanka* 17:44–59. <https://doi.org/10.4038/JAS.V17I1.9610>
68. Rani A, Sharma D, Babel MS, Sharma A (2022) Spatio-temporal assessment of agro–climatic indices and the monsoon pattern in the Banas River Basin, India. *Environ Challenges* 7. <https://doi.org/10.1016/j.envc.2022.100483>
69. Ray S, Das SS, Mishra P, Al Khatib AMG (2021) Time Series SARIMA Modelling and Forecasting of Monthly Rainfall and Temperature in the South Asian Countries. *Earth Syst Environ* 5:531–546. <https://doi.org/10.1007/s41748-021-00205-w>
70. Rayan M, Gruehn D, Khayyam U (2022) Frameworks for Urban Green Infrastructure (UGI) Indicators: Expert and Community Outlook toward Green Climate-Resilient Cities in Pakistan. *Sustainability* (Switzerland) 14:. <https://doi.org/10.3390/su14137966>
71. Rimi RH, Haustein K, Barbour EJ et al (2022) Risks of seasonal extreme rainfall events in Bangladesh under 1.5 and 2.0°C warmer worlds - how anthropogenic aerosols change the story. *Hydrol Earth Syst Sci* 26:5737–5756. <https://doi.org/10.5194/hess-26-5737-2022>
72. Rohini P, Rajeevan M, Srivastava AK (2016) On the Variability and Increasing Trends of Heat Waves over India. *Sci Rep* 6. <https://doi.org/10.1038/srep26153>

73. Rosenzweig C, Elliott J, Deryng D et al (2014) Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Nat Clim Chang* 4:287–291. <https://doi.org/10.1038/nclimate2141>
74. Roxy MK et al (2015) Drying of Indian subcontinent by rapid Indian Ocean warming. *Nat Commun* 6:7423
75. Roxy MK, Ghosh S, Pathak A et al (2017) A threefold rise in widespread extreme rain events over central India. *Nat Commun* 8. <https://doi.org/10.1038/s41467-017-00744-9>
76. Ryan SJ, Carlson CJ, Mordecai EA, Johnson LR (2019) Global expansion and redistribution of Aedes-borne virus transmission risk with climate change. *PLoS Negl Trop Dis* 13:e0007213. <https://doi.org/10.1371/journal.pntd.0007213>
77. Sabeerali CT, Rao SA, George G et al (2014) Modulation of monsoon intraseasonal oscillations in the recent warming period. *J Geophys Res* 119:5185–5203. <https://doi.org/10.1002/2013JD021261>
78. Samarasinghe CRK, Meegahakumbura MK, Dissanayaka HDMAC et al (2018) Variation in yield and yield components of different coconut cultivars in response to within year rainfall and temperature variation. *Sci Hortic* 238:51–57. <https://doi.org/10.1016/j.scienta.2018.03.058>
79. Sendanayake S, Miguntanna NP, Jayasinghe MTR (2014) Validation of design methodology for rainwater harvesting for tropical climates. *Asian J Water Environ Pollut* 11:87–93
80. Sengupta A, Nigam S (2019) The northeast winter monsoon over the Indian subcontinent and Southeast Asia: Evolution, interannual variability, and model simulations. *J Clim* 32:231–249. <https://doi.org/10.1175/JCLI-D-18-0034.1>
81. Sheffield J, Wood EF (2008) Projected changes in drought occurrence under future global warming from multi-model, multi-scenario climate simulations. *J Clim* 21:432–458. <https://doi.org/10.1175/2007JCLI1717.1>
82. Shrestha AB, Aryal R (2011) Climate change in Nepal and its impact on Himalayan glaciers. *Reg Environ Change* 11:65–77. <https://doi.org/10.1007/s10113-010-0174-9>
83. Shrestha F, Uddin K, Maharjan SB, Bajracharya SR (2016) Application of remote sensing and GIS in environmental monitoring in the Hindu Kush Himalayan region. *AIMS Environ Sci* 3:646–662. <https://doi.org/10.3934/environsci.2016.4.646>
84. Shrestha R, Kadel R, Shakya S et al (2025) Awareness and Understanding of Climate Change for Environmental Sustainability Using a Mix-Method Approach: A Study in the Kathmandu Valley. *Sustain (Switzerland)* 17. <https://doi.org/10.3390/su17072819>
85. Tandon A, Pattnayak KC, Awasthi A (2026) Integrating IMDAA Regional Reanalysis and Machine Learning for Enhanced Detection of Extreme Precipitation Over Complex Himalayan Terrain. *Earth Syst Environ*. <https://doi.org/10.1007/s41748-026-01117-3>
86. Tol RSJ (2018) The economic impacts of climate change. *Rev Environ Econ Policy* 12:4–25. <https://doi.org/10.1093/reep/rex027>
87. Trenberth KE (2011) Changes in precipitation with climate change. *Clim Res* 47:123–138. <https://doi.org/10.3354/cr00953>

88. Turner AG, Annamalai H (2012) Climate change and the South Asian summer monsoon. *Nat Clim Chang* 2:587–595. <https://doi.org/10.1038/nclimate1495>
89. United Nations Office for Disaster Risk Reduction (2019) Global Assessment Report on Disaster Risk Reduction
90. Vicente-Serrano SM, Beguería S, López-Moreno JI (2010) A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *J Clim* 23:1696–1718. <https://doi.org/10.1175/2009JCLI2909.1>
91. Webber BGM, Matthews AJ, Vinayachandran PN et al (2018) The dynamics of the southwest monsoon current in 2016 from high-resolution in situ observations and models. *J Phys Oceanogr* 48:2259–2282. <https://doi.org/10.1175/JPO-D-17-0215.1>
92. Westra S, Alexander LV, Zwiers FW (2014) Global increasing trends in annual maximum daily precipitation. *J Clim* 26:3904–3918
93. Wickramasinghe MRCP, de Silva RP, Dayawansa NDK (2021) Climate Change Vulnerability in Agriculture Sector: An Assessment and Mapping at Divisional Secretariat Level in Sri Lanka. *Earth Syst Environ* 5:725–738. <https://doi.org/10.1007/s41748-021-00206-9>
94. Wijeratne VPIS, Li G, Mehmood MS, Abbas A (2023) Assessing the Impact of Long-Term ENSO, SST, and IOD Dynamics on Extreme Hydrological Events (EHEs) in the Kelani River Basin (KRB), Sri Lanka. *Atmos (Basel)* 14. <https://doi.org/10.3390/atmos14010079>
95. Withanachchi SS, Köpke S, Withanachchi CR et al (2014) Water resource management in dry zonal paddy cultivation in mahaweli river basin, Sri Lanka: An analysis of spatial and temporal climate change impacts and traditional knowledge. *Climate* 2:329–354. <https://doi.org/10.3390/cli2040329>
96. Zam P, Shrestha S, Budhathoki A (2021) Assessment of climate change impact on hydrology of a transboundary river of bhutan and India. *J Water Clim Change* 12:3224–3239. <https://doi.org/10.2166/wcc.2021.338>
97. Zscheischler J, Westra S, van den Hurk BJJM et al (2018) Future climate risk from compound events. *Nat Clim Chang* 8:469–477. <https://doi.org/10.1038/s41558-018-0156-3>

Figures

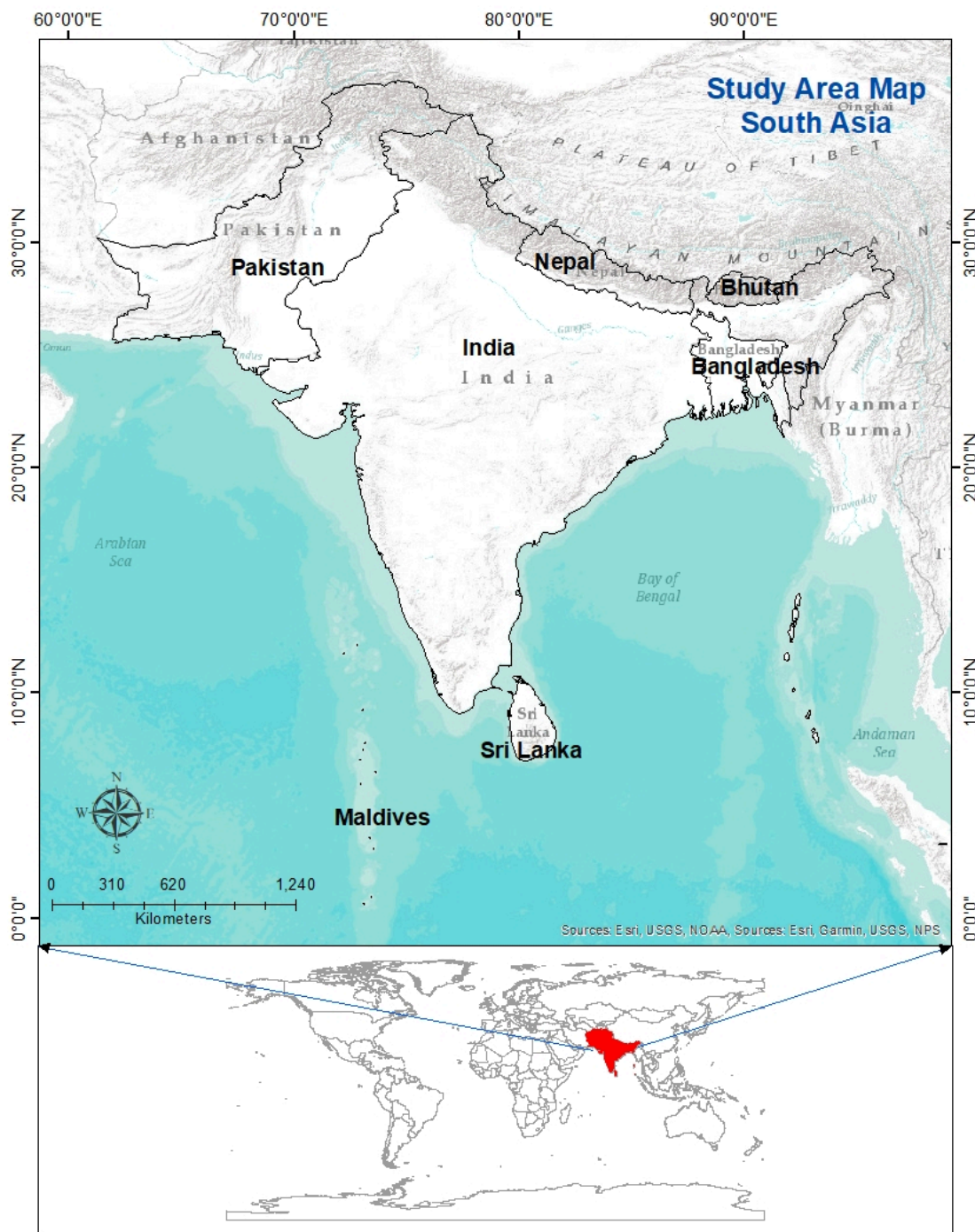


Figure 1

Study area map indicates South Asian seven countries (Source: USGS, complied by Author, 2026).

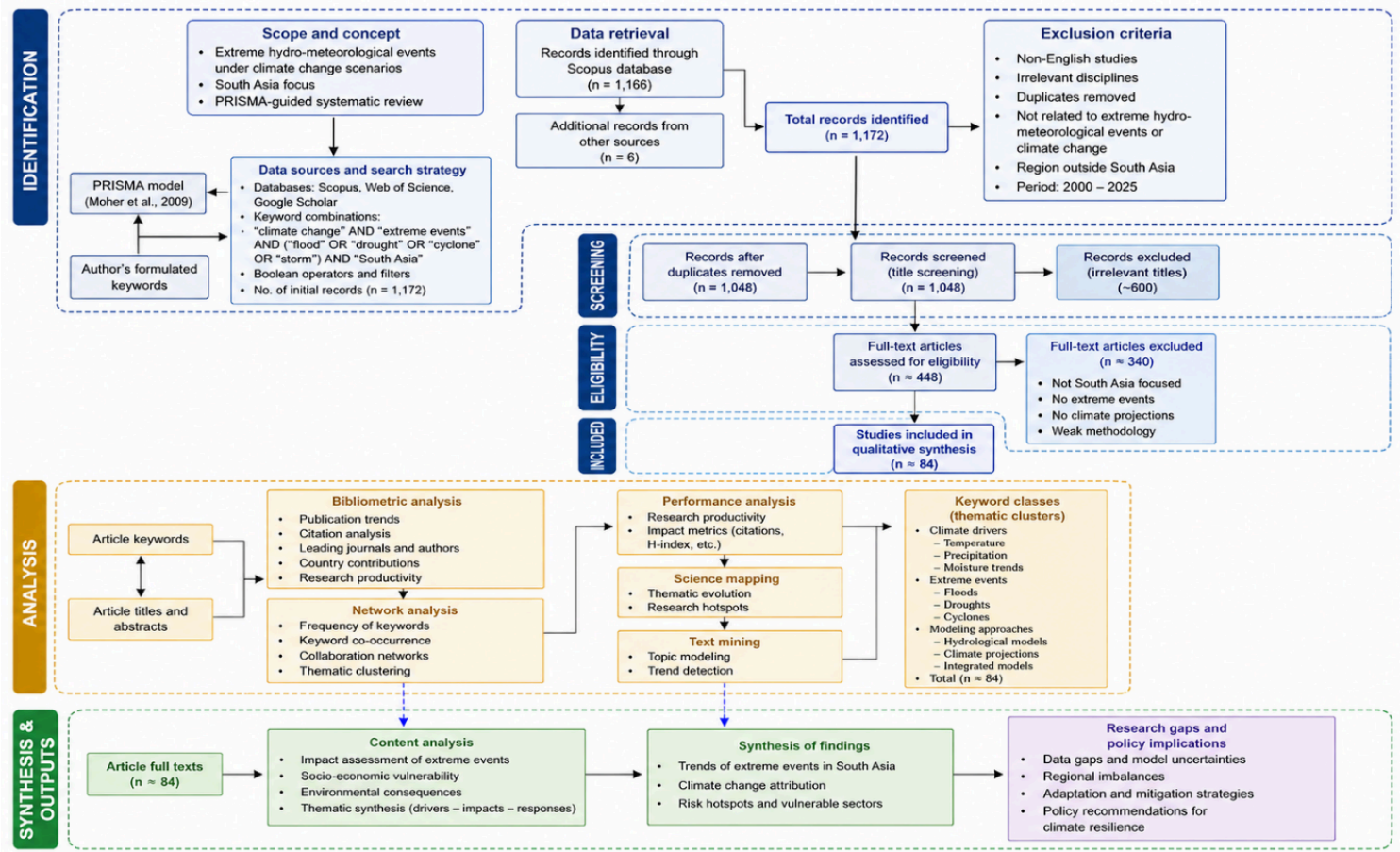


Figure 2

Flow diagram of PRISMA systematic research review process for evaluating hydrometeorological events under climate change scenarios in South Asia (2006-2026).

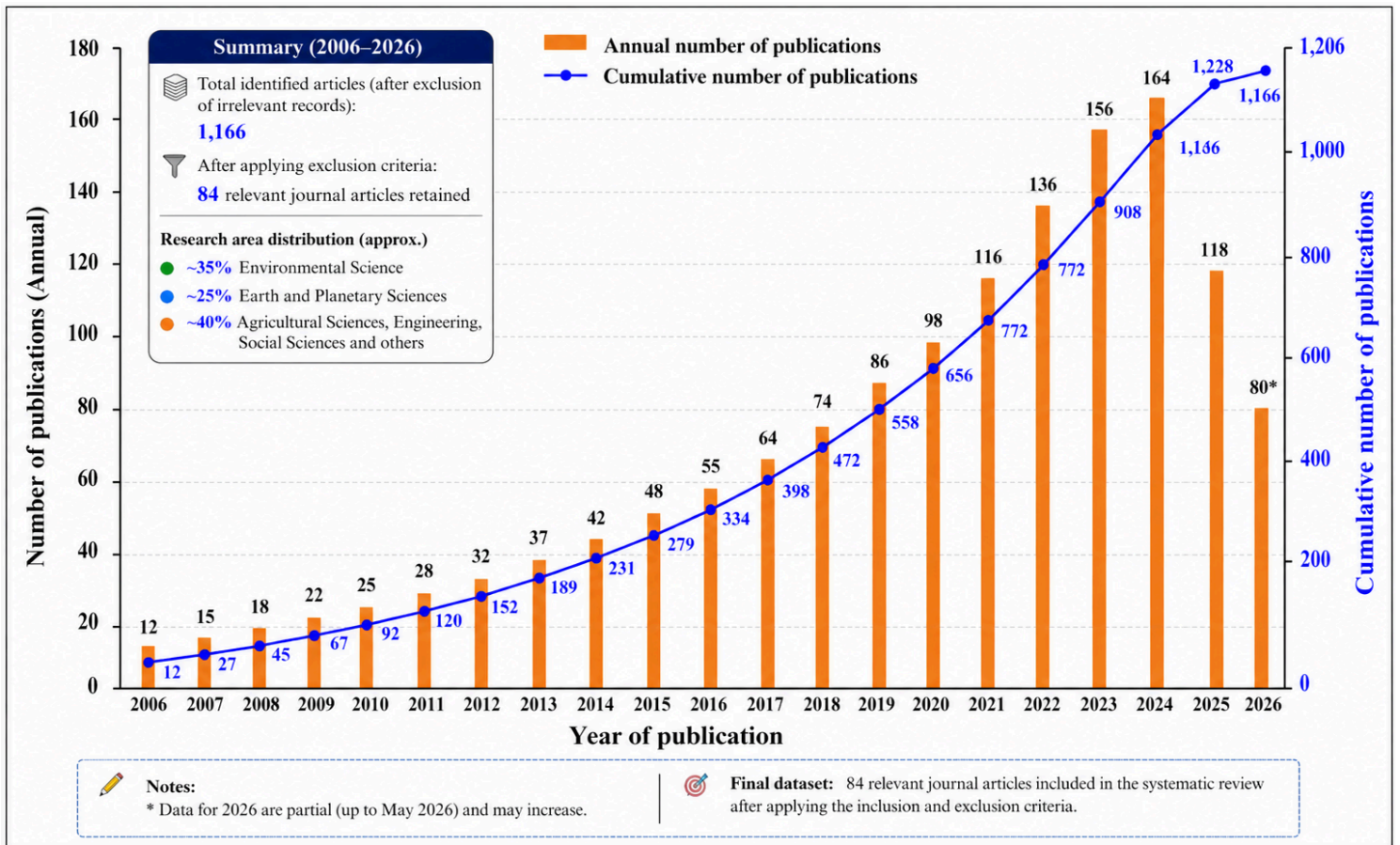
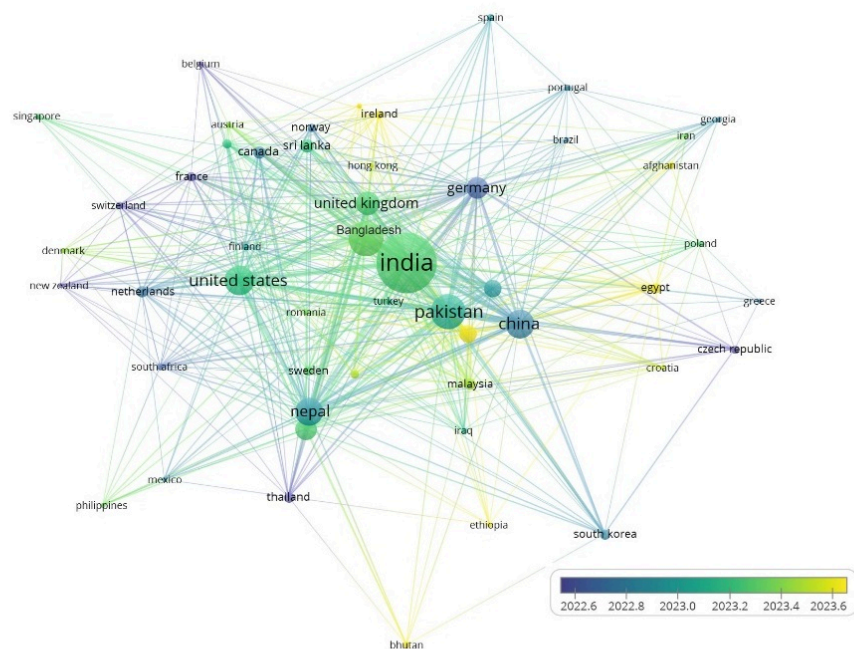


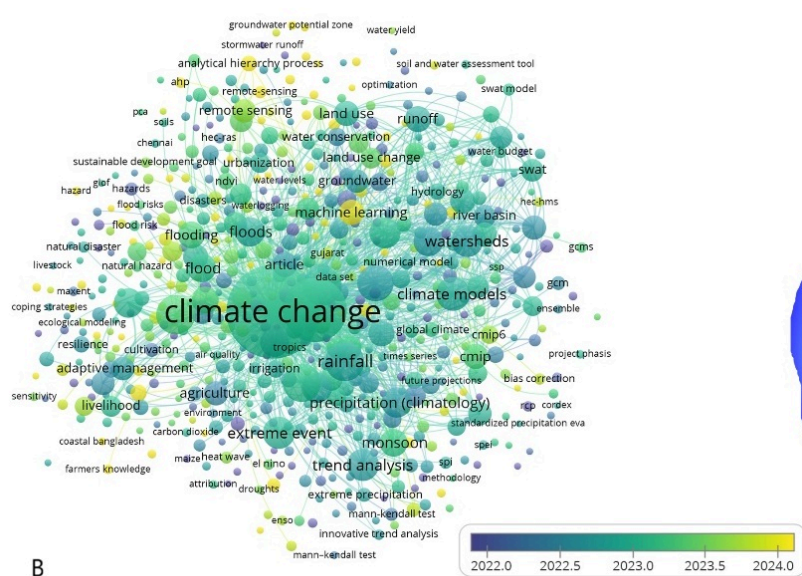
Figure 1. Annual and cumulative number of publications on hydro-meteorological events under climate change scenarios in South Asia between 2006 and 2026 (after exclusion of irrelevant articles).

Figure 3

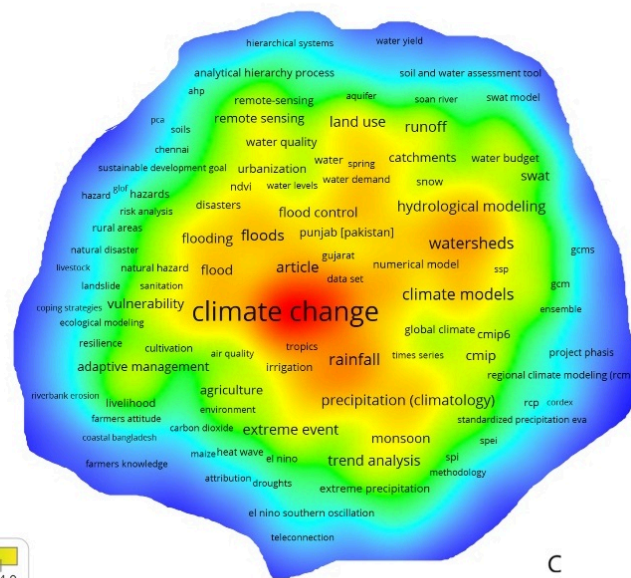
Hydrometeorological events related annual and cumulative number of publications in South Asia (2006-2026).



A



B



C

Figure 4

Overlay visualization of country collaboration network and keyword co-occurrence analysis for (a) timeline overlay network; (b) item density relevant to climate change and hydrometeorological events in South Asia.