Hydrological Impacts of Climate Change

Insights from Nepal's River Basins

by

Suresh Baral and Binaya Kumar Mishra

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Preface

Addressing global change has emerged as one of the most pressing challenges of the 21st century. The increasing variability of climate and its profound impacts on water resources and the broader environment demand a thorough understanding, not only of the phenomena themselves but also of effective adaptation strategies. This book presents a comprehensive examination of global change and its implications, employing both numerical modelling and experimental approaches to explore the complex interactions between climate, hydrology, and human activity.

The book is organized into nine chapters, each building on the previous to provide a holistic understanding of the subject. The opening chapter introduces the background of global change, identifies research gaps, and outlines the objectives guiding this study. Chapter two offers an extensive literature review, focusing on numerical modelling of water-related climate scenarios and summarizing findings from previous studies on rainfall–runoff simulation. Chapter three details the methodology adopted for this work, including both computational models and experimental setups.

Subsequent chapters present detailed investigations into specific aspects of climate change in Nepal. Chapter four examines projected precipitation extremes in the Gandaki Province, employing indices developed by the Expert Team on Climate Change Detection and using both observed data and CMIP6 simulations. Chapter five explores the impacts of climate change on water resources and hydropower sustainability, with a case study of the Seti Gandaki River using the HEC-HMS model under IPCC AR6 scenarios. Chapter six emphasizes streamflow simulation in ungauged basins, illustrated through the Fusre River basin, while chapter seven addresses sedimentation challenges arising from changing hydrological regimes.

Chapter eight explores the effects of urbanization on groundwater recharge and surface runoff in Pokhara, highlighting the consequences of expanding built-up areas on water resources and quality. It also presents experimental observations of sediment dynamics in Nepalese river basins. The final chapter synthesizes the findings, offering recommendations and outlining future research directions for policymakers, water resource managers, and other stakeholders engaged in environmental planning and climate adaptation.

This book is intended to serve as a valuable resource for researchers, practitioners, and decision-makers interested in understanding and addressing the multifaceted impacts of global change on water and environmental systems. By combining rigorous analysis with practical insights, it seeks to advance knowledge and support informed action toward a more sustainable and resilient future.

Introduction

Water scarcity and flooding are recurring challenges in mountainous river systems, and their intensity is rising due to rapid variations in land use and changing climatic conditions. Human-driven factors such as urbanization, industrialization, demographic shifts, and economic development policies have profoundly altered the natural landscape, directly influencing both climate systems and water ecology. Within the Himalayan region, river systems are especially vulnerable to global warming and the accumulation of greenhouse gases in the atmosphere. Nepal's river basins, in particular, are vital watersheds that sustain agriculture, hydropower, and ecosystem services. However, these basins are increasingly threatened by climate extremes and anthropogenic pressures.

This book chapter presents a comprehensive study of precipitation extremes and water resource challenges. Using five precipitation indices and outputs from Global Climate Models (GCMs) under CMIP6, the study assesses rainfall behavior during both the monsoon season (June–September) and annual cycles, across multiple future climate scenarios. Results indicate a significant rise in the Simple Daily Intensity Index (SDII) in both near- and far-future projections, pointing toward an increase in extreme precipitation days. Increased hydrological extremes pose risks to social infrastructure, agricultural productivity, and environmental health.

Beyond precipitation extremes, the study emphasizes the implications of climate change for hydropower sustainability. A case study of the Seti Gandaki River, modeled using HEC-HMS with IPCC AR6 climate scenarios, demonstrates substantial changes in seasonal flow patterns. Simulations suggest possible drought periods, an earlier onset of monsoon, and an overall increasing trend in flood magnitudes across all projected periods. Such changes could undermine hydropower production reliability, highlighting the urgent need for adaptive water resource planning. The content of book also addresses challenges in ungauged basins, where limited hydrological data complicates water management. In the Fusre River basin, rainfall–runoff simulations (2007–2019) with the HEC-HMS model provided valuable insights into flood dynamics. Flood-frequency analysis projected peak discharges across different return periods, underscoring the importance of accurate hydrological modeling in risk management.

Sediment generation and deposition are identified as further critical issues. Applying the SWAT model and rainfall simulator in the Fusre basin, the study revealed how sedimentation reduces reservoir capacity and degrades water quality, with negative implications for hydropower and water storage projects. Laboratory experiments supported the modeling results, stressing the urgency of effective erosion control. Recommendations include redesigning settling basins using empirical and site-specific approaches to mitigate sedimentation in hydropower infrastructure.

Finally, the study extends to urban water challenges in Pokhara. Satellite-based land-use analysis revealed rapid urban expansion, leading to increased surface runoff and reduced groundwater recharge. These changes threaten groundwater sustainability, which is essential for ensuring water security in urban centers. The findings advocate for sustainable urban planning, groundwater management, and eco-friendly infrastructure development to mitigate adverse impacts.

In conclusion, this book brings together climate modeling, hydrological simulations, sediment analyses, and urban water assessments to emphasize the interconnected challenges posed by climate change and human activities on Nepal's water resources. The insights presented here serve as a valuable resource for policymakers, engineers, and researchers in their efforts to enhance hydropower sustainability, strengthen flood resilience, and secure long-term water availability in the Himalayan region.

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Part I

Climate Change and Water Resources

Chapter One
Background

Water resources are among Nepal's most critical natural assets, underpinning economic growth, agricultural productivity, hydropower generation, and overall development. In a mountainous country such as Nepal, rivers and streams not only serve as vital lifelines for communities but also represent the backbone of national energy production through hydropower. However, these Himalayan river basins are extremely sensitive to variations in precipitation and temperature, making them particularly vulnerable to the effects of climate change. Even minor shifts in climate conditions can significantly disrupt the hydrological cycle, leading to wide-ranging socio-economic consequences.

Over the past few decades, Nepal has faced mounting challenges related to water scarcity, extreme precipitation, floods, landslides, and sedimentation. Climate-induced hydrological extremes have disrupted agriculture, damaged infrastructure, and posed increasing risks to urban water supply and groundwater recharge. At the same time, rapid urbanization, population growth, and land-use changes have intensified these stresses by reducing infiltration, accelerating runoff, and altering local water balances. These combined pressures create a dynamic and uncertain water environment that demands urgent adaptation and sustainable management strategies.

This book is situated at the intersection of climate science, hydrology, and sustainable development. It provides a holistic perspective on how climate change and human activities are reshaping Nepal's water resources, with particular emphasis on river basins in the Gandaki

Province. By integrating state-of-the-art hydrological modeling tools, experimental approaches, and field-based studies, the book seeks to highlight pressing challenges while also identifying strategies to enhance resilience and sustainability.

Climate change is one of the defining challenges of the 21st century, exerting profound impacts on global and regional water cycles. For Nepal, where the hydrological system is intricately tied to monsoon variability, the risks are particularly acute. Even small changes in rainfall intensity, timing, or duration can trigger disproportionate impacts such as floods, prolonged droughts, and shifts in groundwater recharge. Projections suggest that the future climate will be marked by more intense rainfall events, longer dry spells, and an increasingly energized water cycle. These hydrological shifts could exacerbate flooding, accelerate erosion, reduce groundwater recharge, and further strain water supply systems.

Simultaneously, rapid urban expansion and land-use changes are mirroring many of the hydrological consequences of climate change. Increasing impervious surfaces in cities reduce infiltration capacity, increase surface runoff, and heighten the risks of flash flooding and water scarcity. Thus, Nepal's water resources and the sectors that depend upon them—such as agriculture, hydropower, and urban water supply—face dual stresses: climatic and anthropogenic.

Despite the severity of these issues, there is still a limited application of quantitative and optimized water management strategies in Nepal to address climate-induced changes. The uncertainties associated with climate projections further complicate planning, investment, and adaptation, leaving policymakers and practitioners with few evidence-based solutions. This situation calls for an integrative, flexible, and adaptive framework that can safeguard Nepal's water resources under uncertain future scenarios.

Although global research has made significant strides in understanding the impacts of climate change and urbanization on water systems, critical gaps remain in the Nepalese context:

- Uncertainty in climate projections: Rainfall predictions from different climate models vary widely, complicating long-term water security planning.
- Limited focus on local hydrological processes: Few studies capture the fine-scale characteristics of Nepal's unique river basins.
- Weak integration of modeling and field experiments: Research often isolates numerical modeling and experimental hydrology rather than employing them in a complementary manner.
- Neglect of sediment dynamics: Despite being a major threat to hydropower and reservoir capacity, sedimentation remains understudied.
- Insufficient attention to groundwater: Urban groundwater recharge and quality have not been adequately addressed, even though they are crucial for water security.
- Lack of holistic frameworks: Existing approaches rarely integrate climate dynamics, hydrological processes, sediment transport, and urbanization into a unified water management strategy.

Addressing these research gaps is essential for developing adaptive measures that are scientifically robust and context-specific to Nepal.

In response to these challenges and gaps, this book pursues the following objectives:

1. Assess future rainfall and temperature changes under climate change scenarios, focusing on the Gandaki Province.

2. Analyze direct hydrological impacts, including variations in streamflow, flood risks, and drought conditions.
3. Investigate sediment yield dynamics and their implications for reservoir storage and hydropower sustainability.
4. Examine groundwater recharge processes and assess the hydrological consequences of rapid urbanization, particularly in Pokhara.
5. Validate hydrological processes experimentally using rainfall simulators and sediment analysis at hydropower sites.
6. Propose adaptive water management measures that combine modeling, experimentation, and scenario analysis to enhance resilience under climate uncertainty.

This introductory chapter underscores the central importance of water resources in Nepal's socio-economic and environmental systems, while also highlighting the dual threats posed by climate change and rapid urbanization. The discussion reveals significant knowledge gaps that hinder effective adaptation and calls for an integrated approach combining hydrological modeling, experimental validation, and context-specific management strategies.

By identifying these gaps and outlining the research objectives, the chapter establishes the foundation for the book's broader investigation into climate projections, hydrological impacts, sediment dynamics, urban water challenges, and experimental hydrology. The subsequent chapters build upon this foundation, offering both analytical insights and practical recommendations to strengthen resilience and ensure the sustainable management of Nepal's water resources.

Chapter Two
Hydrological and Sediment Modeling

This chapter reviews the literature on numerical modeling of hydrological processes using diverse techniques. Numerical hydrological models are essential tools for simulating water resources, allowing researchers to evaluate existing systems, explore new approaches, test innovative applications, identify problem areas, and reduce the costs associated with ad hoc experimentation. These models are primarily based on differential equations that describe the temporal and spatial variations of hydrological parameters. Running a model involves solving these equations under defined boundary conditions, capturing the system's dynamic behavior over time and space. The outcomes of numerical modeling provide valuable insights into the hydrological impacts of global changes, including climate variability, land-use transformations, and population growth, as well as the effectiveness of alternative water management strategies. In the context of Nepal's river basins, these models are critical for understanding how climate change affects river flow, water availability, and flood risk. They help identify vulnerable regions, assess potential adaptation measures, and support evidence-based planning for sustainable water resources management under changing climatic conditions.

2.1 Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS)

The HEC-HMS model is a powerful tool widely used for simulating rainfall-runoff processes in watersheds, capturing both spatial and temporal variations in hydrologic responses. Numerous studies have highlighted its significance in flood estimation and forecasting, water resources management, dam safety, climate change impact assessment, and watershed management (Athira et al., 2023; Sahu et al., 2023; Yousfi et al., 2023; Kaberia et al., 2023; KC et al., 2022; Javadinejad et al., 2019). Among the various algorithms available in HEC-HMS, the Soil Moisture Accounting (SMA) method is particularly useful for simulating watershed water balance (Vrugt et al., 2006).

Gebre (2015) analyzed the long-term impacts of climate change on water resources in the Blue Nile River basin, demonstrating that HEC-HMS is effective for accurately assessing and predicting catchment hydrological responses. The study also recommended incorporating land-use changes in future modeling efforts. Hydrological modeling, therefore, plays a critical role in guiding developers, planners, and land managers.

The HEC-HMS model has been successfully applied for watershed analysis, floodplain mapping, and water resources planning and management. However, its application in ungauged basins remains challenging due to limited streamflow data for calibration and validation. To address this, several studies have incorporated innovative methods for estimating missing data and improving model reliability in ungauged watersheds. HEC-HMS is capable of simulating rainfall-runoff dynamics in dendritic watersheds, both spatially and temporally. It has been applied in river basins worldwide, including in Nepal (Basnet et al., 2020; Poudel et al., 2021).

For example, Rahman and Rashid (2017) applied HEC-HMS to the ungauged Kinta River Basin in Malaysia. They calibrated the model with limited streamflow data and validated it with observed data, using the SCS-CN method to estimate curve numbers. The study concluded that HEC-HMS can reliably simulate streamflow in ungauged basins if properly calibrated and validated, and that the SCS-CN method provides reliable curve number estimates.

Guduru et al. (2023) developed a HEC-HMS-based flood prediction model, which performed well during both calibration and validation periods. By combining statistical parameters with the Generalized Extreme Value method, the study enhanced the credibility of its findings. Predicted floods at various return periods (2, 10, 25, 50, and 100 years) offered valuable guidance for flood mapping and mitigation planning. Chakraborty and Biswas (2021) applied HEC-HMS to estimate daily runoff from May to October using the SCS-CN and SCS unit hydrograph methods. The model was calibrated for 2001 and 2006 and validated for extreme years (2004, 2012, 2013, 2016) by comparing computed and observed data at two upstream gauging stations. Statistical evaluation, including percentage error in peak flow (PEPF), percentage error in volume (PEV), Nash-Sutcliffe efficiency (NSE), and R^2, demonstrated a strong correlation between simulated and observed runoff.

Several studies demonstrate a growing interest in the application of advanced hydrologic models based on HEC-HMS. For example, Juma et al. (2022) highlighted the high flood risk faced by low-income urban populations in developing countries due to limited continuous monitoring. They employed HEC-HMS to estimate flood characteristics in the Ngong River Basin, Kenya, and found that extreme rainfall events could have catastrophic impacts, providing essential information for flood risk mitigation. Gumindoga et al. (2017) used HEC-HMS to simulate runoff in 10 gauged and ungauged subcatchments of the Upper Manyame catchment in Zimbabwe. By integrating remote sensing and GIS techniques to estimate model parameters, the study successfully predicted runoff and peak flows in gauged catchments, demonstrating HEC-HMS's suitability for continuous runoff simulation in complex watersheds and its relevance for water resources management. Lin et al. (2022) developed a web-based flood forecasting system (WSFF) that integrates HEC-HMS with Jython scripts, employing empirical relationships between model parameters and time series characteristics. The system was evaluated using 12 flood events in China, showing satisfactory performance in peak flow, total flood volume, peak flow timing, and hydrograph fitting. Ayalew et al. (2022) compared the rational formula with two rainfall-runoff models—EBA4SUB and COSMO4SUB—in four small catchments in Ethiopia. The study found that advanced models produced more realistic peak discharge values compared to the rational formula. Song et al. (2011) estimated flood parameters in an ungauged basin using the Muskingum model for flood routing. By coupling HEC-HMS with the HEC-GeoHMS geospatial analysis module, the study successfully extracted channel and watershed characteristics, showing good agreement between modeled and observed flood events. Halwatura and Najim (2013) calibrated and validated HEC-HMS 3.4 for the Attanagalu Oya catchment, Sri Lanka, generating long-term flow data using daily rainfall, evaporation, and flow data from 2005 to 2010.

In addition, Dzirekwa et al. (2023) assessed the potential impacts of climate change on surface water resources in the semi-arid Tugwi Mukosi catchment, Zimbabwe, using Mann-Kendall trend analysis, climate downscaling, and HEC-HMS streamflow modeling. Results indicated decreasing rainfall trends and a reduction in predicted runoff by 17% and 28.41% in the 2030s and 2060s under the GCM-CanESM RCP 4.5 model. Areri and Bibi (2023) identified potential sites for small-scale hydropower along the Awata River, Ethiopia. Using HEC-HMS to simulate rainfall-runoff and GIS to estimate head and discharge, the study identified 28 potential sites, with site 29 ranked first, estimating power outputs of 45.26 MW and 6.74 MW at

50% and 90% capacity, respectively, highlighting the potential of small-scale hydropower in rural areas. Sarhadi et al. (2012) proposed a methodology for floodplain mapping in ungauged rivers using regional flood frequency analysis and multivariate regression models. Applied in the Halilrud basin and Jiroft city, Iran, the study combined satellite imagery and HEC-RAS to delineate flood hazard maps and identify vulnerable areas. Finally, Talebmorad and Ostad-Ali-Askari (2022) evaluated the HydroGeoSphere fully integrated hydrologic model in the Hamadan-Bahar basin, an area experiencing severe groundwater withdrawal. By simulating integrated surface and subsurface flows, the study effectively captured interdependent processes such as aquifer drainage and recharge, demonstrating the model's reliability for hydrologic simulation in the basin.

2.2 Soil and Water Assessment Tool (SWAT)

In order to present some data and conclusions from previous research related to estimating sediment production using the SWAT and other methods. This section provides a concise overview of the literature related to the main goal of the research. According to (Daramola et al., 2019) utilized SWAT to forecast hydrological processes, sediment transport and sediment yield in the Kaduna watershed from 1990 to 2018. The model was calibrated and validated using observed data on flow and suspended sediment concentration. The findings indicate that approximately 84.1 t/ha/yr of suspended sediment yield was deposited during the period under investigation. Similarly, (Chinnasamy et al., 2020) utilized SWAT to assess sedimentation yields in the Kaligandaki basin, which is a crucial tributary of the Ganges, in Nepal. The model utilized multiple sources of data and revealed that 73% of the entire sediment load originated from the upstream regions, while only 27% was contributed by the Middle and High Mountain regions. The findings of the study showed that there was an average sediment concentration of 1986 mg/kg, as well as high sedimentation rates that could negatively impact river ecosystems and hydropower generation. The results emphasize the necessity for better observation data and can assist in the improvement of watershed management to minimize sedimentation load and preserve the Himalayan rivers.

In addition, another study conducted by (Neitsch et al., 2011) assessed the hydrological regime and modeled the impacts of environmental change in a watershed. Human activities were identified as increasing pressures on land and water resources. SWAT was used for modeling with meteorological and streamflow data. Calibration and evaluation at three gauging stations showed NSE values ranging from 0.64 to 0.80. Simulated flows filled data gaps and generated complete daily time series of streamflow. Statistical trends and flow duration curves indicated declining magnitudes of seasonal and annual flows, suggesting changes in stream-flows over time with potential implications for development and water-dependent ecosystems. Likewise, (Shrestha and Shrestha, 2019) analyzed sediment data to assess the siltation rate and active volume of a reservoir in Nepal. Their findings suggest that the annual siltation rate is 0.65 Mm^3, and the active volume will be filled by sediment in 2100 AD. As a result, the energy generation capacity of the power plant is decreasing, and the revenue generation will be almost zero after 80 years.

(Khanchoula et al., 2020) used SWAT interfaced with GIS to predict sediment yield in a Kebir watershed, Algeria from 1982 to 2014. The model was calibrated and validated using observed data, and the results show a mean annual sediment yield of 856.14 $t/km^2/yr$. The study identified the most erosion vulnerable sub-basins, with sub-basins 16, 14, 13, 11, and 8 being the most significant contributors to sediment yield. Best management practices are recommended to maintain land sustainability due to high sediment supply to the dams. Likewise, another study conducted by (Nasrin Zalaki-Badil et al., 2017) applied the SWAT model to simulate inflow and sediment yield in Maroon Dam watershed in southwest of Iran. The model used basic input data such as DEM, land use, soil maps and climate data. The study calibrated and validated the model using data from the catchment of Maroon Dam. Sediment yield was estimated using the Modified Universal Soil Loss Equation.

Similarly, another study conducted by (Ty Sok et al., 2020) used the SWAT model to evaluate the water balance components and sediment erosion yield in the Mekong River Basin. The model was validated against hydrological and sediment stations along the Mekong mainstream. The study resulted in a soil erosion map to identify and prioritize critical erosion-prone areas and a sediment loading map to support management strategies in the region. These findings can provide a baseline for sustainable watershed management planning. In the similar way, (Ndomba and Griensven, 2011) conducted a study to test the capability of the SWAT model to estimate sediment yield was assessed in three distinct case studies in eastern Africa, including Koka Reservoir Catchment in Ethiopia, Nyumba Ya Mungu Reservoir Sub-catchment in Tanzania, and Simiyu River Catchment in Tanzania. Their findings suggested that the SWAT model could be a reliable tool for catchment sedimentation management in the tropics.

In this study (Devraj Chalise et al., 2019) used the IntErO model to estimate sediment yield and maximum outflow from the Sarada river basin. The study found that the river basin is in a degraded state and needs soil conservation measures. The IntErO model was effective in assessing soil loss in the area and can be applied to similar river basins in Nepal. The study's outcomes can assist policymakers in developing soil and water conservation guidelines. Similarly, by (Sanjay K. Jain et al., 2003) assesses sediment yield for Satluj River in the western Himalayan region using two approaches: suspended sediment load and discharge relationship, and empirical relationship based on geographical parameters. The first approach is used for larger basins, while the second approach is used for a smaller intermediate basin. The empirical relationship is revised to incorporate basin parameters, resulting in a good correlation between computed and observed sediment yield. Another study conducted by (Webb et al. 2001) investigated three techniques for estimating sediment yield in small drainage basins in the Grand Canyon. These included a regression equation, an empirical relation, and a new method that combined flood-frequency analysis with sediment-rating curves. The study found that simpler methods were as accurate as more complex ones for estimating sediment yield on a regional scale. However, the flood-frequency technique showed potential for estimating stream flow-sediment yield, especially in areas with local stream flow data available. This technique relies on some untested assumptions, but further testing in areas with known sediment yields may improve its accuracy.

According to research study conducted by (Adeniyi Ganiyu Adeogun et al., 2018) the study used a calibrated hydrologic model (SWAT) interfaced with GIS was used to assess the effectiveness of different sediment management methods in a 12,992 km^2 watershed in Nigeria. The study found that reforestation, vegetative filter strips, and stone bunds reduced sediment yield by up to 65.6%, 63.4%, and 12%, respectively, and were also cost-effective. The study suggests that hydrological models like SWAT can be useful in developing water resource management strategies and evaluating the cost and benefits of adopting best management practices, particularly for controlling sediment in erosion-prone watersheds. The study provides valuable information for policy makers.

Additionally, another research study conducted by (G.D. Betrie et al., 2011) aims to use the SWAT model to predict sediment transport in the Upper Blue Nile under four different Best Management Practice (BMP) scenarios. The model accurately simulated sediment concentrations for existing conditions, but some physical processes were not well represented. However, implementing BMPs, including filter strips, stone bunds, and reforestation, reduced sediment yields in both sub-basins and basin outlets, producing positive effects.

Similarly, the research by (Michael J. White and Jeff G. Arnold., 2009) aims to develop a field-scale Vegetative Filter Strip (VFS) sub-model for the Soil and Water Assessment Tool (SWAT). A new method was created to retain sediments and nutrients in VFSs (vegetative filter strips) and a runoff retention model was adapted for field-scale use. High-resolution topographical data and multipath flow accumulation were used to evaluate flow concentration through hypothetical VFSs. The VFS model has two sections, one for low flow densities and another for treating more concentrated flow. This model was incorporated into SWAT (Soil and Water Assessment Tool) and verified for its functionality, which improves the ability of SWAT to assess the effectiveness of VFSs at the watershed scale.

Additionally, the study conducted by (Tesema et al., 2020) developed a watershed model and estimated sediment yield for the Kesem Dam watershed in Ethiopia, and evaluated the effect of management options on sediment reduction. They used the SWAT model to simulate sediment yield and develop management options, and identified areas with high sediment yields. The mean annual sediment yield was estimated to be 11.43 t/ha/yr, and implementing management options reduced it by 80%. These findings can help reduce sediment loadings and promote sustainable watershed management in similar areas. According to research study conducted by (Youssef Brouziyne et al., 2017) applied manual calibration and sensitivity analysis techniques using the SWAT model in a semi-arid watershed in North-western Morocco. The study aimed to analyze the sensitivity of the model to watershed-specific input parameters and develop a detailed methodology for manual calibration and validation in a semi-arid context. Sensitivity analysis identified 4 out of 12 input parameters that significantly influenced the flow components of the watershed. The calibrated and validated SWAT model showed satisfactory performance with good goodness-of-fit indicators, including NSE values above 0.5, R2 values exceeding 0.7, and PBIAS lower than 25%. The study concluded that the calibrated and validated SWAT model accurately represented the hydrologic processes in the watershed and can be used for assessing current and future conditions and evaluating management practices.

Finally, research study conducted by (Kati L. White et al., 2005) implemented the SWAT watershed model in the Beaver Reservoir Watershed of Northwest Arkansas. The objectives included detailed calibration and application of a multisite and multivariable SWAT model, sensitivity analysis, and calibration/validation at three sites for various parameters. Relative sensitivity analysis was used to identify successful model calibration and validation. The study aimed to provide information on calibration and validation of multisite, multivariable SWAT models to assist watershed management goals by reducing uncertainty and increasing user confidence in the model's predictive abilities.

2.3 Groundwater dynamics due to climate change

Global groundwater dynamics undergo significant changes due to alterations in surface runoff, land use, and land cover (LULC). Human activities, such as urbanization, deforestation, agricultural expansion, and industrialization, lead to substantial modifications in LULC patterns, impacting surface runoff properties. These changes reduce rainfall infiltration into the soil while increasing surface runoff, ultimately influencing groundwater availability and recharge rates (Shi et al., 2007). In regions like Shenzhen, rapid urbanization over the past two decades has resulted in a decline in agriculture and an increase in urban land, adversely affecting water environments. Urbanization exacerbates water shortages, flood risks, and water pollution. The complex interactions between social and ecological factors, including land use, soil texture, prior soil moisture, and rainfall intensity, influence runoff. Simulation models, such as the SCS model applied to the Buji River Basin, predict increased runoff, higher flood peak discharge, and shorter runoff confluence periods due to urbanization, raising the likelihood of flood disasters (Shi et al., 2007). Another study by (Tam and Nga, 2018) assessed the impact of urban development on Hanoi City's groundwater by analyzing changes in land use and escalating groundwater abstraction due to urban population growth. The investigation employed a coupled hydrological simulation, integrating rainfall-runoff and groundwater flow with WetSpa and MODFLOW codes, utilizing comprehensive spatial and temporal data. Results indicated that rainfall infiltration accounted for 53.6% of groundwater recharge, followed by 31% from seepage in rivers and lakes, and 15.4% from leakage in municipal water supply and sewerage networks. The study emphasizes extensive groundwater abstraction as the primary driver of declining groundwater levels, with urban impervious area expansion contributing minimally to reduced groundwater recharge. On other study by (Naik et al., 2008) focuses on Solapur, a rapidly growing city in central India, assessing the impact of urbanization on its groundwater regime and addressing water management challenges up to 2020. Contrary to conventional assumptions of decreased recharge due to urbanization, the research reveals a rise in groundwater recharge, correlating with the city's increasing water demand and supply efforts. While groundwater levels have increased within the main city area, there is a general decline outside due to heightened groundwater utilization for irrigation, and localized groundwater quality deterioration is observed, particularly in dugwells.

Likewise, the study conducted by (Minnig et al., 2018) addresses the critical importance of managing groundwater, the world's primary fresh water reserve, amid urbanization impacts. Focusing on a northern Switzerland urban site, water budget calculations reveal a significant positive correlation between urban area expansion and groundwater recharge rates. The increase in recharge rates, influenced by land transformation and water main leakages, emphasizes the need for a deeper understanding of urban groundwater recharge changes to foster sustainable water management in urban areas. This study by (Rashid et al., 2017) explores how rapid urbanization in Muzaffarabad city is negatively impacting water resources, the environment, and public health. Based on 20 in-depth interviews conducted in 2015 with local authorities, political activists, and residents, the research highlights the pollution of rivers Jhelum and Neelum by the local population. This pollution results in a shortage of clean water and an increased risk of viral diseases, emphasizing the urgent need for adopting sustainable urban development practices to address these issues. Lastly, urbanization's effects on urban flooding were studied, revealing positive linear relationships between surface runoff rate/river outflow rate and impervious surface area (ISA %). Urbanization accelerates the time to peak discharge during incidents and increases peak discharge, expanding areas vulnerable to flash floods and flooding due to ongoing urbanization (Feng et al., 2021).

2.4 Rainfall simulator in water resources research

Rainfall simulators have been used successfully in research on many aspects of water resources. Adams et al. (2005) performed an analysis of surface runoff generation source by using large-scale rainfall simulator experiments. They used field experiments results to calibrate the hydrological model and interpret the runoff mechanisms. Arnaez et al. (2007) used a rainfall simulator to compare runoff and sediment production under distinct rainfall intensities in a vineyard plantation in Spain. It has been shown in prior studies that rainfall simulators should have the ability to produce controlled and reproducible artificial rainfall which represents natural conditions at a given location. Rainfall simulators were proven as a useful tool in representing the natural rainfall events with fast data acquisition and controllable spatio-temporal variability of intensity, duration and kinetic energy.

A cost-effective portable rainfall simulator has been developed for a 5 m^2 plot, allowing easy field transport and assembly for experimental replicates for understanding the runoff losses in agricultural areas (Boulange et al., 2019). The research conducted by (Vahabi and Nikkami, 2008) in the Taleghan watershed, Iran, used a rainfall simulator and soil erosion plots to evaluate the impact of soil factors on sediment yield. Results showed strong correlations between sediment yield and vegetation cover for various rainfall intensities, highlighting the value of simulation approaches in comprehending intricate soil erosion processes. A study on modification of rainfall simulator by (Macedo et al., 2021) used an automated PI control system for a rotating simulator, manipulating the shutter disc's rotation to mimic diverse rainfall patterns. An electronic control system, tied to a micro SD memory card, facilitates user input for desired rainfall patterns. The modified simulator, with an intuitive