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Integrated Management of Water Resources in India: A Computational Approach

Optimizing for Sustainability and Planning

Springer

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Foreword

Water security is a critical challenge facing India, a nation with a vast and diverse population. Traditional siloed approaches to water management are no longer sufficient. This book, *Integrated Management of Water Resources in India: A Computational Approach*, offers a compelling and timely solution. By advocating for a computational approach to *Integrated Water Resources Management (IWRM)*, the authors break new ground. Leveraging the power of computational tools, they propose a comprehensive framework that considers the complex interplay between water quantity, quality, and the social and ecological systems it sustains.

This book is not merely a theoretical exploration. It presents a practical roadmap for implementing IWRM across India's diverse landscapes. The emphasis on stakeholder engagement ensures that the solutions developed are not only technically sound, but also meet the needs of the communities most impacted by water scarcity. *Integrated Management of Water Resources in India: A Computational Approach* is a valuable resource for water resource managers, policymakers, researchers, and anyone with a stake in India's water future. By embracing a holistic and data-driven approach, this book offers a path toward a more sustainable and equitable future for all. I congratulate the editors *Akhilesh Kumar Yadav, Kanchan Yadav, and Vijay P. Singh* for bringing out this thought-provoking work. I am sure this book will be useful to graduate students, faculty, and policymakers on environmental impact and public health.

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Preface

The motivation of this volume, entitled *Integrated Management of Water Resources in India: A Computational Approach*, is mainly to present techniques to protect water resources in India. Water is the lifeblood of our nation, sustaining not only our ecosystems, but also our very existence. However, India faces a growing challenge in managing its water resources. With a vast and diverse population, coupled with the effects of climate change, ensuring water security for present and future generations requires a holistic approach. This book, *Integrated Management of Water Resources in India: A Computational Approach*, proposes a paradigm shift in how we address this critical issue. It advocates for a framework that integrates various aspects of water management, moving beyond traditional siloed approaches. This framework takes advantage of the power of computational tools to analyze complex data, model water systems, and optimize decision making. This book is an important contribution for water professionals, policymakers, researchers, and students. It presents a comprehensive overview of the challenges and opportunities in Indian water management. By exploring the potential of computational approaches, the book equips readers with the knowledge and tools needed to develop and implement integrated water resource management strategies. Throughout the book, we emphasize the importance of stakeholder engagement. Sustainable water management requires the active participation of communities, government agencies, and private entities. By fostering collaboration and utilizing the power of computational tools, we can move toward a future where water resources are managed effectively and equitably for the benefit of all.

This book presents an overview of water resources in India. The book content has been categorized into four parts. Part I gives an overview of water resources fundamental and assessment with five chapters. Part II, consisting of eleven chapters, deals with water quality assessment, monitoring, and management, while Part III consists of six chapters under the title water resources management strategies and technologies; Part IV is devoted to the advanced optimization, and efficiency in water management of six chapters.

First, we thank the Almighty for His blessings throughout this project achievement, which envisioned us successfully exploring this challenging research domain with a technique perspective. We are also sincerely thankful to Springer Nature for allowing us to publish this monogram on a contemporary research domain of modeling and simulations.

Special thanks to all who contributed to making this volume a source of knowledge and reporting the latest findings in their areas. Against the title of the proposed chapter, the total number of abstracts received was 63, of which 48 were selected for a full chapter contribution. In this book, the project accommodated only **28** chapters according to the scope of the book, which were of better quality. The authors put a lot of effort during all phases of book production, starting from writing, revising based on the comments and Springer evaluation reports, and finally checking the proofs of the chapters. The project follows a review process in which the identities of the authors and reviewers are not disclosed to avoid bias decisions. We also thank and acknowledge the Springer Nature publication team for their quick responses and for providing a proper guideline on time. Finally, we acknowledge *Jaydeep Kumar (BCAS, New Delhi, India)* and *Advocate Dinesh Chandra Gupta (High Court, Allahabad, India)* for their continuous help and support during the execution of the project.

The editors would be happy to receive any comments to further improve future editions. Comments, feedback, and suggestions for further improvement or proposals for the new chapters for next editions are welcome and should be sent directly to the volume editors.

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Part IV Advanced Optimization and Efficiency in Water Management

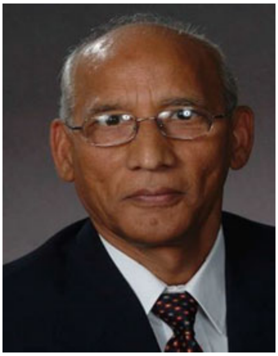
About the Editors

Akhilesh Kumar Yadav Ph.D., MIE, earned a Bachelor of Technology (B.Tech.) in Electronics and Communication Engineering from Chaudhary Charan Singh University in Meerut, India. He then obtained a Master of Technology (M.Tech.) in Environmental Engineering from Madan Mohan Malaviya Engineering College in Gorakhpur, India (affiliated with Dr. A. P. J. Abdul Kalam Technical University, Lucknow). His doctoral degree, with a research focus on air pollution, was awarded by the Indian Institute of Technology (BHU), Varanasi, India.

Dr. Yadav has served at various institutions, including the Indian Institute of Technology (Banaras Hindu University), Varanasi, India; the Indian Institute of Technology Bombay, Mumbai, India; the Bhabha Atomic Research Centre in Mumbai, India (as a research collaborator); and Chaoyang University of Technology in Taichung, Taiwan. He has authored/co-authored several research and review articles, book chapters, and edited/authored books and holds a patent.

Dr. Yadav received the Young Engineer Award from the Institution of Engineers (India) and the Young Scientist Award from VDGOOD Technology Factory, Kolkata. His research interests include air, water, and soil pollution; climate change; vulnerability; human health risk assessments; and GIS applications in environmental pollution and management. He is an active member of several reputed international professional bodies, including the IEI (Kolkata), ECI (New Delhi), AEACI (Mumbai), MSI (New Delhi), and IASTA (Mumbai).

Kanchan Yadav Ph.D., possesses expertise in research writing, data analysis, study design, and methodology. She currently holds the position of the program coordinator at Progressive Foundation, where she is responsible for overseeing and executing programs in the fields of Public Health and Education. Prior to this, she served as a research associate specializing in the utilization of microwave technology for the management of hospital waste and the purification of water while retaining precious minerals. Furthermore, she has served as the research director for a project in collaboration with the Government of India, focusing on the adherence of tuberculosis medications. She has authored numerous research pieces that have been published in peer-reviewed journals and international conference proceedings.



Vijay P. Singh Ph.D., D.Sc., D.Eng. (Hon.), Ph.D. (Hon.), P.E., P.H., Hon.D.WRE, Dist.M. ASCE, Dist.Hon. M. IWRA, Dist.F. AGGS, Hon. Member AWRA, NAE, holds Caroline and William N. Lehrer distinguished chair in Water Engineering and is the distinguished professor and the regents professor, Department of Biological and Agricultural Engineering and Zachry Department of Civil and Environmental Engineering at Texas A&M University, USA. He has been recognized for four decades of leadership in research, teaching, and service to the hydrologic and water resources engineering profession. His contribution to the state of the art has been significant in many different specialty areas, including hydrologic science and engineering, hydraulic engineering, water resources engineering, environmental engineering, irrigation science, soil and water conservation engineering, entropy-based modeling, copula-based modeling, and mathematical modeling. His extensive publications in these areas include 32 textbooks, 1425 refereed journal articles, 115 book chapters, 330 conference proceedings papers, and 72 technical reports.

For his seminal contributions, he has been honored with more than 105 national/international awards from professional organizations. As a sample, he is a recipient of the Arid Land Hydraulic Engineering Award, Ven Te Chow Award, Torrens Award, Norma Medal, Lifetime Achievement Award, and OPAL Award, all given by ASCE. He was awarded the Ray K. Linsley Award for outstanding contributions to surface water hydrology and the Founders Award of AIH. He has been awarded three honorary doctorates. He is a fellow of ASCE, AWRA, IE, ISAE, IWRS, IASWC, and IAH; and a member of AGU, IAHR, IAHS, and WASER. He is a member/fellow of 12 engineering/science academies. He is licensed as the professional engineer (PE), the professional hydrologist (PH), and the honorary diplomate, AAWRE.

Part I
Water Resources Fundamental and Assessment

Chapter 1

Exploring Climatic Dynamics in Madhya Pradesh, India Utilizing Long-Term Gridded Data (1951–2021): An Integrated Statistical and GIS Modules

Amit Kumar, Tapas Ray, and T. Mohanasundari

Abstract Climate change is a global issue resulting from numerous human activities that alter hydro-climatic factors such as temperature, precipitation, river flow, and severe weather occurrences. India has seen a notable transformation in its natural resources and agricultural industries. This chapter comprehensively examines the climatic fluctuations in Madhya Pradesh, India, from 1951 to 2021 using IMD daily gridded rainfall and temperature data. Research utilizes non-parametric statistical techniques to evaluate trends, detect abrupt change points, and investigate regional patterns in seasonal precipitation and temperature. The Mann–Kendall test (MK) and Sen's slope estimator (SS) are applied to identify the trends and magnitude and understand temporal changes in meteorological variables. Furthermore, Pettitt's test detects sudden changes in long-term data, uncovering sudden patterns alterations. The findings reveal significant fluctuations in seasonal precipitation, with a discernible upward pattern in the premonsoon season ($Z = 0.29$) with a rate of 0.02 mm annually and downward patterns in the monsoon ($Z = -0.93$), winter seasons ($Z = -0.73$) and post-monsoon ($Z = -0.76$). These results have implications for the administration of water resources and the planning of agriculture. However, the investigation uncovers a consistent increase in T_{mean}, T_{max}, and T_{min} across all seasons, with notable differences in different areas. The change point analysis identifies the year when significant changes in rainfall and temperature patterns occurred. Inverse distance weighting methods allow for examining spatial changes, revealing the geographical distribution of certain climatic variables. This chapter improves the comprehension of climatic dynamics in Madhya Pradesh, providing a constructive understanding for policy makers, researchers and practitioners engaged in climate resilience and sustainable development planning.

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Keywords Climate change · Rainfall · Temperature · Trend analysis · Change point · Spatiotemporal analysis

1.1 Introduction

The rise in atmospheric CO_2 and the resulting climate warming have recently posed a significant global concern, causing shifts in the usual climate patterns (Daniel 2022; IPCC 2014; Nadeau et al. 2022). These changes in the Earth's climate are evident through various indicators, including changes in global rainfall patterns, the frequency of extreme temperatures (Kumar et al. 2023b; Tabari 2020), and variations in ground and surface water (Shirin et al. 2023). Recent studies, such as the study conducted by Daramola (2022), have shown a rise in temperature and a reduction in moisture levels in arid regions, especially in the last several decades. Global temperatures have increased by 0.032 °C yearly during the previous 40 years, but precipitation has decreased by 0.074 mm monthly (Daramola 2022). The primary climatic factors significantly impact Earth's ecosystems, agriculture, associated industries, food security, and energy stability in many locations (Malhi et al. 2021). Climate change is causing changes in precipitation patterns, resulting in unexpected and catastrophic weather events, including floods and droughts (Kumar and Mohanasundari 2024; Stein et al. 2020). India, which is highly dependent on agriculture, has negatively impacted the pH of agricultural areas due to variations in rainfall (Thakur et al. 2019) and degradation of land (Shirin et al. 2019; Yadav et al. 2014a, b). India's economic stability is intricately linked to agricultural production, leaving millions susceptible to fluctuations in rainfall patterns (Birthal and Hazrana 2019). Various research has examined rainfall patterns in India at local and provincial stages (Kumar et al. 2010, 2023a; Machiwal et al. 2017). Recent studies show notable shifts in India's precipitation patterns, characterized by a general reduction in total precipitation and an increase in severe rainfall occurrences in certain areas (Katzenberger et al. 2021). A study of the influence of environmental change on precipitation patterns in certain areas, such as Gujarat and Uttarakhand, has shown reductions in both rainy days and average precipitation levels (Shah et al. 2023; Banerjee et al. 2020). Temperature patterns in India have been analyzed together with rainfall patterns. Research has shown rises in maximum, mean, and minimum temperatures over time (Mall et al. 2021; Ray et al. 2019; Thakur et al. 2019). Madhya Pradesh, located in central India, has shown declining patterns in both rainfall and temperature, as reported by Gupta and Mishra (2019), Sam et al. (2020), and Yadav et al. (2019). Duhan and Pandey (2013) documented a steady decrease in precipitation in Madhya Pradesh from 1901 to 2002. Fluctuating temperatures and rainfall patterns impact the hydrological system of the area, influencing precipitation trends (Madhukar et al. 2021).

Comprehending the spatiotemporal flexibility of temperature and rainfall is critical to understanding the consequences of regional climate change. This chapter analyzed the evolving temperature and precipitation patterns in the study area using

IMD long-term data from 1951 to 2021. One of the key objectives of this chapter is to detect specific transition points in rainfall and temperature within the region. By pinpointing these transition points, the research aims to highlight critical variations in the climatic conditions of this study region. The findings of this chapter will provide valuable insights into how the region is responding to the impacts of environmental change. Assessing spatio-temporal changes in temperature and rainfall in this region will enable researchers and policy makers better to understand the region's approach of the region to environmental change. This knowledge will facilitate an evaluation of the potential consequences of the shifting patterns of rainfall and temperature in vital industries like agriculture and water supplies. Additionally, this helps create effective measures to mitigate climate change in the area.

1.2 Methodology

1.2.1 Study Area

The study area comprises Madhya Pradesh, which is 308,252 km^2 and accounts for 9.38% of the total area. Located between 21°03′ to 26°52′ N and 78°02′ to 82°48 E (Fig. 1.1), this region has a sub-tropical climate characterised by distinct monsoon, winter, and summer seasons. Madhya Pradesh can be divided into four biogeographical zones: low-lying regions around Gwalior, Satpura ranges, Vindhyan mountains, and the Malwa plateau. The annual average monsoon precipitation is 1194 mm; however, it varies in different places. Changing rainfall patterns make accessing water difficult, affecting agricultural and ecological stability (Kumar et al. 2024). Significant rivers like Narmada, Ken, and Son rely on rainfall, which is essential for water supplies and agriculture. The Narmada River is the boundary between the Satpura and Vindhyan mountain ranges. The Satpura range is characterized by thick forests and heights that reach 1350 m, with an average maximum temperature of 34.6 °C. Temperature and rainfall interact significantly to impact the microclimate of Madhya Pradesh.

1.2.2 Data Acquisition

The gridded data for daily rainfall and temperature with a spatial resolution of $0.25^\circ \times 0.25^\circ$ and $1^\circ \times 1^\circ$ respectively, were obtained from the Indian Meteorological Department (IMD) (https://www.imdpune.gov.in/). The data covers a time of 71 years, from 1951 to 2021. The current research used daily maximum and lowest temperatures from 26 grid points and rainfall from 439 grid points to cover the study area. This method has been widespread in numerous hydroclimatological investigations to assess rainfall, temperature patterns, and trends (Kumar et al. 2023a). The data from

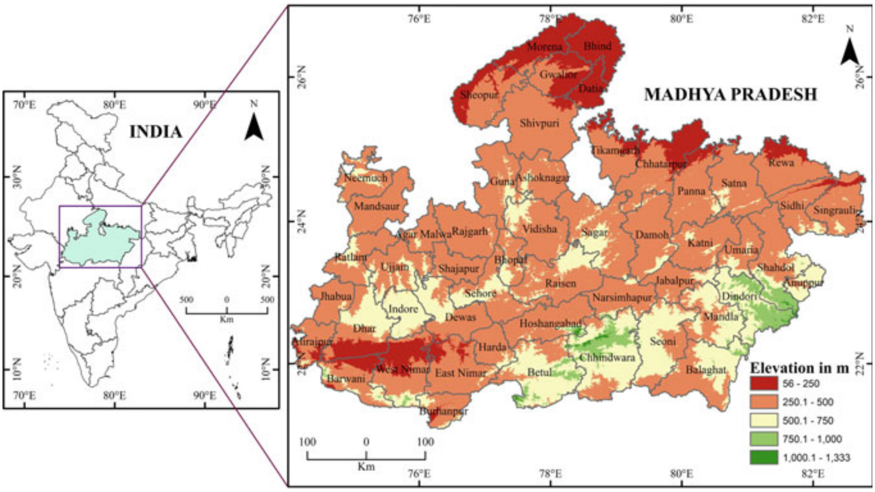

Fig. 1.1 Study area map

each year are divided into four distinct seasons: The four seasons in this region are as follows: Monsoon (J-J-A-S), premonsoon (M-A-M), Post-monsoon (O-N), and winter (D-J-F).

1.2.3 Methods

Examining data patterns necessitates parametric and nonparametric methodologies (Fig. 1.2), providing a thorough and resilient study (Shree and Kumar 2018). The study analyzed the trends and magnitude of rainfall and temperature using the Mann–Kendall (MK) test and the Sen slope (SS) estimator. The researchers used the Pettitt test to detect the abrupt discontinuities of temperature and precipitation data by examining the fluctuations from 1951 to 2021. The IDW interpolation method was employed to illustrate the temporal and spatial distribution of temperature and precipitation patterns in Madhya Pradesh. Descriptive statistical analysis was performed using MS Excel, trend and change point analysis was performed using MATLAB R2023a, and GIS analysis was performed using ArcGIS 10.8.

1.2.4 MK Test

It is a statistical technique that identifies trends or monotonic patterns in time series data (Kumar et al. 2023b; Singla et al. 2022). Equation 1.1 was used to calculate MK statistics.

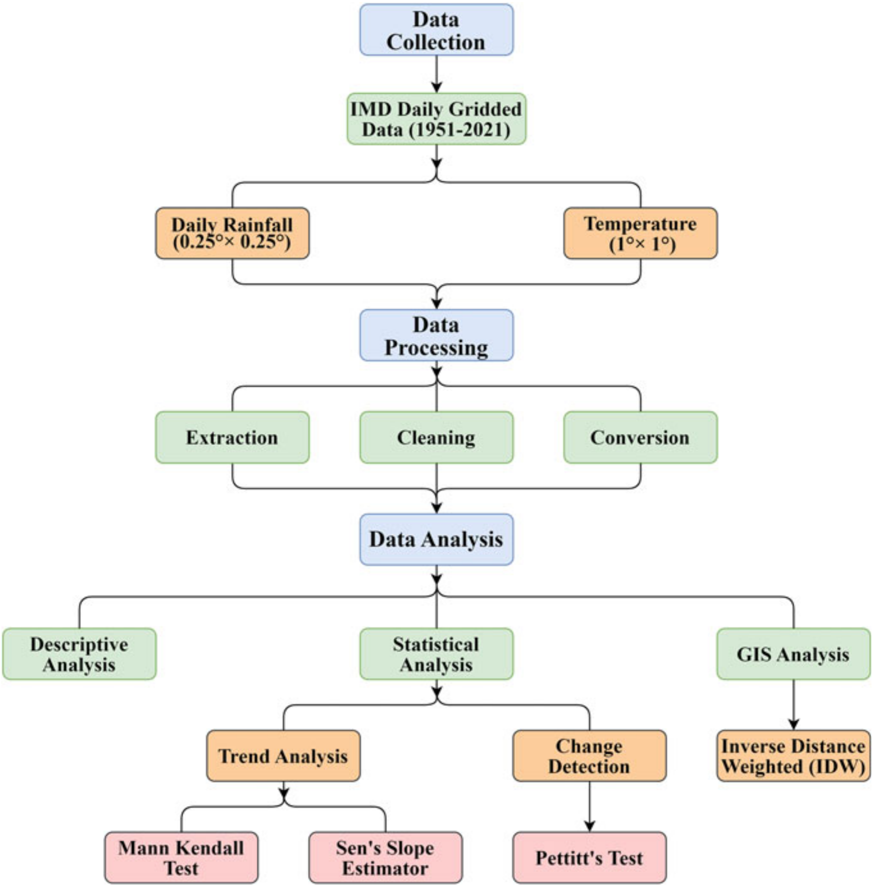

Fig. 1.2 Methodology flowchart

$$S = \sum_{j=1}^{n-1} \sum_{i=j+1}^{n} sig(x_i - x_j) \tag{1.1}$$

The normal distribution S is denoted by the mean, n represents the number of observations (≥ 10), and x_j signifies the jth observation. The sign function sig () is defined as follows: sig (α) = 1 if $\alpha > 0$; sig (α) = 0 otherwise; and sig (α) = -1 if $\alpha \leq 0$. Equation 1.2 is used to calculate the variance of *S*.

$$var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{K} p_i(p_i - 1)(2p_i + 5)}{18} \tag{1.2}$$

The number of connected groups with similar values is n, and the number of data points in the ith linked group is t_i. Equation 1.3 shows the MK statistics accurately.

$$Z_s = \begin{bmatrix} \frac{S-1}{\sqrt{var(S)}}, ifS > o \\ 0, ifS = 0 \\ \frac{S+1}{\sqrt{var(S)}}, ifS < 0 \end{bmatrix} \tag{1.3}$$

Positive Z_S values indicate a rising trend, while negative Z_S numbers indicate a falling trend.

1.2.5 Sen's Slope (SS) Estimator

It identified the magnitude of the trend slope in a dataset, including N data pairs (Sen, 1968). Like basic linear regression, this method computes the slope of the median between two separate variables (independent and dependent). The slope is calculated using Eq. 1.4.

$$Q_i = \frac{t_j - t_k}{j - k} \text{ For } i = 1, 2, 3 \ldots, \text{ N} \tag{1.4}$$

Given a time series data set with values t_j and t_k at time j and k, respectively, whereas $j > k$, the steps to calculate the Sen's slope estimator involve and calculated using Eq. 1.5.

$$Q_{med} = \begin{bmatrix} Q_{\frac{N+1}{2}}, ifNisodd \\ \frac{Q_{\frac{N}{2}} + Q_{\frac{N+2}{2}}}{2}, ifNiseven \end{bmatrix} \tag{1.5}$$

where, if $Q_{med} < 0$, shows a descending trend.

$Q_{med} > 0$, shows an ascending trend.

Pettitt test

It identifies abrupt changes or breakpoints in a time series dataset (Pettitt 1979), indicating a significant shift in the data values (Dhorde and Zarenistanak 2013; Kang and Yusof 2012). The stages associated with performing the Pettitt test are as follows:

The first stage includes calculating the U_K statistic using Eq. 1.6.

$$U_k = 2\sum_{i=0}^{n} p_i - k(n+1) \tag{1.6}$$

The variable P_i represents the position of the *ith* observation in the time series data when the values $x_1, x_2, x_3, x_4 \ldots\ldots x_{n-1}, x_n$ are ordered in the increasing sequence. The statistical change point test should, therefore, be defined as follows (Eq. 1.7):

$$K_n = max|U_k| \tag{1.7}$$

When U_k in a data set experiences the highest value of K, the transition point will occur. Equation 1.8 was used to get the crucial value.

$$K_\alpha = \left[-1n\alpha\left(n^3 + n^2\right)/6\right]^{1/2} \tag{1.8}$$

where α is the degree of significance and n is the number of observations that define the critical value.

Coefficient of Variation (CV)

The present chapter used the CV to assess the extent to which each data point deviated from the mean regarding temperature and precipitation variability. An increased CV value signifies more significant variability (Kumar et al. 2023a, 2023b). The CV was computed using Eq. 1.9.

$$CV = \frac{\sigma}{\mu} \times 100 \tag{1.9}$$

where $\mu =$ mean; $\sigma =$ standard deviation.

A CV is categorised as high (> 30%), moderate (20–30%), and low (<20%) (Bharath et al. 2023; Sarkar et al. 2021).

Inverse Distance Weighted (IDW)

In order to demonstrate the spatio-temporal pattern of temperature and rainfall in Madhya Pradesh, we computed the mean temperature for each grid. Subsequently, the collected data were used to generate a cartographic representation that illustrates the spatial arrangement of temperature and precipitation distribution patterns. The spatiotemporal maps were generated using the Interpolation method (IDW). The method assumes that close data points are comparable regardless of distance (Kumar et al. 2023a, b, c).

1.3 Results and Discussion

Analyzing climatic variability, detecting trends and assessing regional distribution is essential to gain deep insights into the implications of environmental change and improving infrastructure and resource planning. Meteorological data are an essential source of knowledge to understand these alterations. Detecting trends in long-term data without imagining component distributions is a major benefit of nonparametric tests in climate research. Weather factors such as temperature, precipitation, wind speed, and humidity can be measured in various sizes with these tests. Examining the spatial distribution is essential to understanding local alterations in climatic variables and their historical changes (Ampofo et al., 2023).

1.3.1 Temporal Trend Analysis

Rainfall

Table 1.1 summarizes the study area's seasonal temperature and rainfall patterns of the study area for 71 years (1951–2021). The CV for monsoon, pre-monsoon, post-monsoon, and winter season rainfall are 82.40, 17.39, 84.44, and 79.25, respectively (Table 1.1a). It changes a lot during the winter, post-monsoon, and premonsoon seasons, but not as much during the monsoon season. This conclusion supports other studies conducted by Shree and Kumar (2018), Chandniha et al. (2017), Kumar et al. (2023a), and Warwade et al. (2018), highlighting the region's susceptibility to droughts and floods, as noted by Pandey and Ramasastri (2001). The chapter used the MK and SS tests to demonstrate a slight rise in premonsoon precipitation and a decline in monsoon, postmonsoon, and winter (Fig. 1.3a). The monsoon exhibits a statistically insignificant annual reduction of −0.977 mm, with a Z-score of −0.933, raising concerns about water shortages during this crucial season. On the other hand, a little increase ($Z = 0.288$) in pre-monsoon rainfall indicates some advantages for agricultural and industrial water resources. The decreasing trends in winter and postmonsoon rainfall trends of −0.067 mm and −0.116 mm per year, respectively, provide difficulties in recharging groundwater and maintaining river and reservoir levels. The results are consistent with previous research conducted by Chandniha et al. (2017), Kumar et al. (2023a), Warwade et al. (2018) and Shree and Kumar (2018), highlighting the susceptibility of the area to floods and droughts as highlighted by Pandey and Ramasastri (2001).

Table 1.1: Statistical results of seasonal rainfall, $T_{mean,}$ $T_{max,}$ T_{min} in Madhya Pradesh (5% significance level).

Mean temperature (T_{mean})

The premonsoon season of T_{mean} exhibits moderate variability ($CV = 2.29$), with a non-significant positive trend ($Z = 1.052$, annual magnitude = 0.005 °C). The monsoon season shows lower variability ($CV = 1.73$) with a similar trend ($Z = 1.092$, annual magnitude = 0.003 °C) (Table 1.1b). On the contrary, the post-monsoon season shows a significant increasing trend ($Z = 3.594$, annual magnitude = 0.018 °C) and higher variability ($CV = 3.47$), while winter also shows considerable variability ($CV = 3.23$). Despite a weaker result of the MK test ($Z = 0.149$), the SS estimator supports a positive trend (0.050 °C annually). All seasons show warming trends (Fig. 1.3b), aiding in adaptation strategies to climate change.

Maximum Temperature (T_{max})

The CV shows moderate to high variability in T_{max} across all seasons: Premonsoon ($CV = 2.37$), Monsoon ($CV = 3.50$), Postmonsoon ($CV = 3.38$), and Winter ($CV = 3.77$) (Table 1.1c). The MK and SS analysis shows increasing trends in T_{max} throughout all seasons. Pre-monsoon has a notable trend ($Z = 1.241$, change: 0.009 °C/yr), while Monsoon, Post-Monsoon, and Winter have less pronounced trends. Although there is some variation, all seasons in Madhya Pradesh consistently

Table 1.1 Statistical results of seasonal rainfall, T_{mean}, T_{max}, T_{min} in Madhya Pradesh (5% significance level)

Season	CV	Z-Stat	Q-Stat	P-value	Trend
Rainfall (a)					
Pre-monsoon	82.40	0.288	0.018	0.773	Increasing
Monsoon	17.39	−0.933	−0.977	0.351	Decreasing
Post-monsoon	84.44	−0.764	−0.116	0.445	Decreasing
Winter	79.25	−0.735	−0.067	0.462	Decreasing
T_{mean} (b)					
Pre-monsoon	2.29	1.052	0.005	0.293	Increasing
Monsoon	1.73	1.092	0.003	0.275	Increasing
Post-monsoon	3.47	3.594	0.018	3.26e−04	Increasing
Winter	3.23	0.149	0.050	0.882	Increasing
T_{max} (c)					
Pre-monsoon	2.37	1.241	0.009	0.215	Increasing
Monsoon	3.50	1.449	0.011	0.148	Increasing
Post-monsoon	3.38	0.834	0.007	0.404	Increasing
Winter	3.77	0.074	0	0.941	Increasing
T_{min} (d)					
Pre-monsoon	17.49	2.422	0.026	0.015	Increasing
Monsoon	5.88	0.551	0.002	0.582	Increasing
Post-monsoon	20.38	3.891	0.033	9.96e-05	Increasing
Winter	37.20	2.750	0.018	0.006	Increasing

increase T_{max} (Fig. 1.3c), indicating a long-term warming trend with significant consequences for industries susceptible to climate change.

Minimum Temperature (T_{min})

The CV shows different levels of fluctuation of T_{min} throughout the seasons (Table 1.1d). The premonsoon has a coefficient of variation of 17.49, while the monsoon has a coefficient of variation of 5.88. The postmonsoon season has a CV of 20.38, whereas the winter season has a CV of 37.20, showing significant fluctuation. The MK test and SS analysis validate increasing minimum temperature trends throughout all seasons. The premonsoon is seeing a notable rise with a Z value of 2.422 and a temperature change of 0.026 °C each year. The monsoon at $Z = 0.551$ shows a diminishing yet ascending pattern with a temperature change of 0.002° C. The postmonsoon and winter seasons show notable upward tendencies, with the postmonsoon having a Z value of 3.891 and a temperature change of 0.033 °C and winter having a Z value of 2.750 and a temperature change of 0.018 °C. The data highlights the increasing temperature trend in Madhya Pradesh (Fig. 1.3d), which affects many industries that face climate change problems.

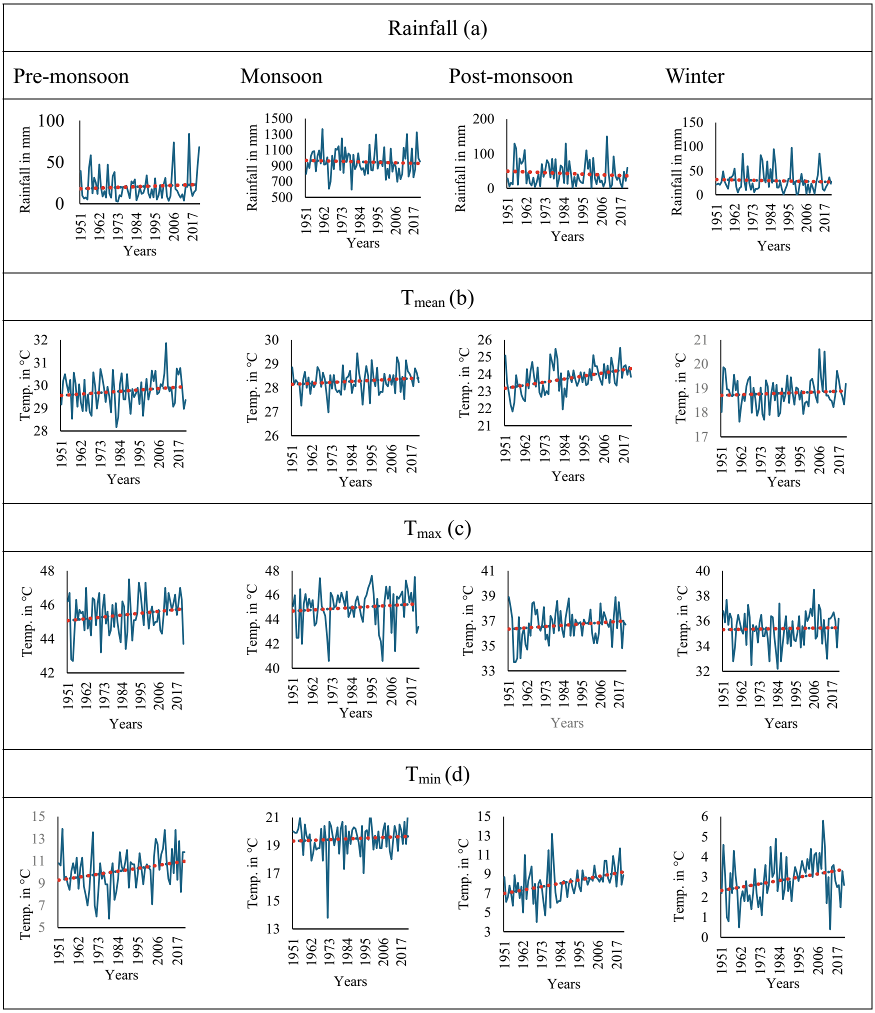

Fig. 1.3 Trends in seasonal rainfall, T_{mean}, T_{max}, T_{min} of Madhya Pradesh

Our results are consistent with previous research in the Central West and Central India. Kundu et al. (2017) noted a decrease in monsoon, annual, winter, and post-monsoon precipitation from 1901 to 2011, although seeing an opposite increase in premonsoon precipitation. Kumar et al. (2010) noticed a yearly and monsoonal rainfall reduction for 135 years (1871–2005) but found an increase in premonsoonal precipitation. Devi et al. (2020) also documented a decline in rainfall patterns in Madhya Pradesh. Duhan and Pandey (2013), Shukla and Khare (2013), and Shukla et al. (2017) observed notable increases in annual average temperatures, including T_{mean}, T_{max}, and T_{min}. Devi et al. (2020) noted increasing trends in T_{mean}, T_{max}, and T_{min} in Central India between 1971 and 2015. Kundu et al. (2017) observed a steady rise in both T_{max}, and T_{min} over 105 years (1901–2005), with the most notable increases occurring in the winter and post-monsoon periods. Singla et al. (2022) observed a steady rise in both T_{max}, and T_{min} in Northwestern India since 1970. The results align with previous studies by Dubey et al. (2022), Kumar et al. (2023b), Pal and Al-Tabbaa (2010), and Radhakrishnan et al. (2017), which reported increasing temperatures in different parts of India. Consistent patterns highlight the importance of comprehending and dealing with variations in precipitation and temperature for successful climate adaptation and mitigation initiatives.

1.3.2 Change Point Analysis

Identifying sudden changes in climate historical data is crucial to revealing abrupt changes in trends. Identification of change points uses several techniques, and this chapter used Pettitt's test to find sudden breaking points within the temperature and rainfall data in the study area. The Pettitt test detected abrupt changes in seasonal temperature and rainfall trends (Fig. 1.4).

Rainfall

The outcomes of Pettitt's test for rainfall are graphically represented in Fig. 1.4a. The results of the Pettitt test show 1955, 1998, 1987, and 1986 for all seasons of rainfall, according to the data. These transition points indicate the years when significant changes in rainfall patterns occurred, signalling modifications in the corresponding seasons.

Mean Temperature (T_{mean})

The test successfully identified abrupt changes in the seasonal T_{mean} trends (Fig. 1.4b). The analysis revealed the breaking points for 1998, 2007, 1987, and 1959 for all seasons, respectively. These identified change points signify pivotal moments when substantial changes occurred in the average temperature patterns, indicating noteworthy alterations in the respective seasons.

Maximum Temperature (T_{max})

Based on the findings, 2008, 1990, 1963, and 1966 were identified as change points for all seasons (Fig. 1.4c). These points denote significant shifts in the T_{max} patterns, indicating alterations within the corresponding seasons.

Minimum Temperature (T_{min})

The analysis revealed change points in 2003, 1960, 2008, and 1995 for all seasons, respectively (Fig. 1.4d). These change points indicate the years when significant changes occurred in the T_{min} patterns, signifying notable alterations in the corresponding seasons.

Research results underscore significant alterations in rainfall and temperature during specific time intervals. Similar investigations have been conducted in different

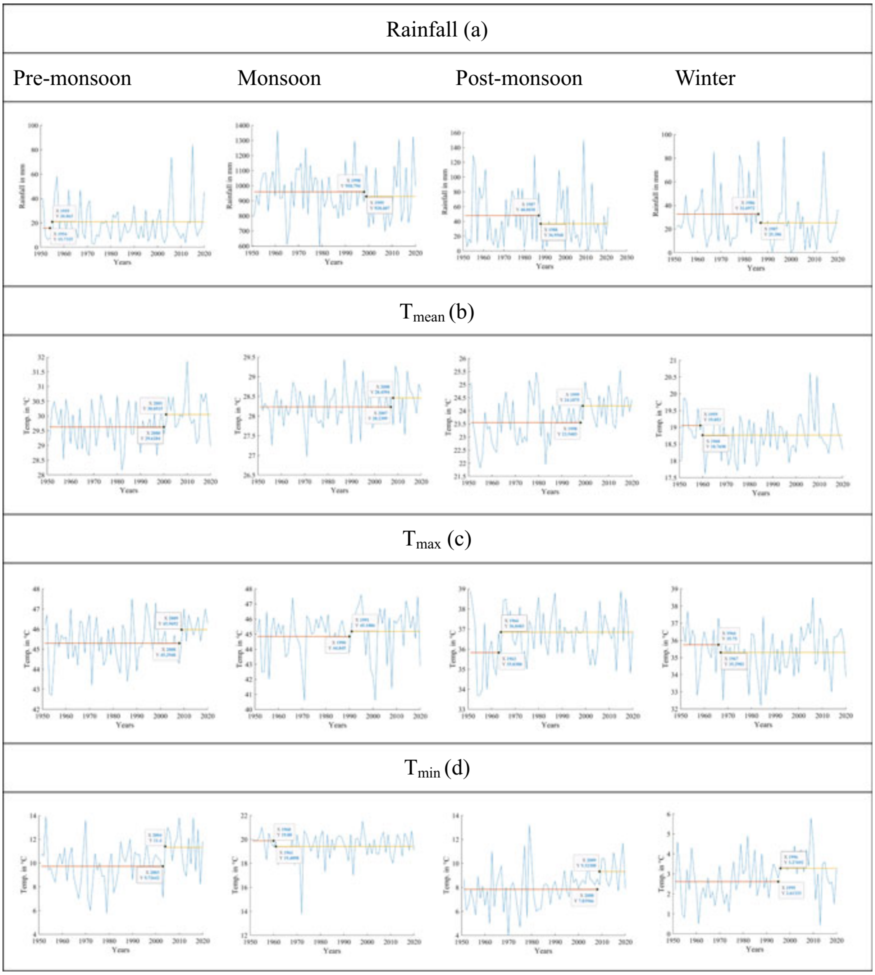

Fig. 1.4 Change point results of seasonal rainfall, T_{mean}, T_{max}, T_{min}

geographical areas to pinpoint notable transition points in climate variables. For instance, Zarenistanak et al. (2014) found a significant transition in Iran's climate in 1973. Kumar et al. (2023a, b, c) identified abrupt changes in annual rainfall trends at three stations in India: 2004, 1998, and 1991. These findings highlight the dynamic nature of climatic conditions and their implications for ecosystems and human activities. In their study, Shukla et al. (2017) found 1963 to be the critical moment when the T_{mean} data, covering 1901–2005, significantly changed the study area. Chandole and Joshi (2023) observed a favourable pattern in the T_{min}, with a consistent change occurring in two specified districts of Gujarat after 1986. Zarenistanak et al. (2014) identified significant changes in temperature patterns throughout the 1980s and 1990s. These investigations in several areas enhance our understanding of the intricacies of climate change with its temporal expressions.

1.4 Spatial Change Analysis

This chapter used interpolation methods to evaluate changes in rainfall and temperature using the spatial change analysis approach. Pettitt's test used the yearly rainfall, T_{mean}, T_{max}, and T_{min} data to compare seasonal changes, using the base year as a reference. The elongated time-series data were divided into 2 separate parts: 1951–1998 and 1999–2021 for rainfall, 1951–2004 and 2005–2021 for T_{mean}, 1951–2020 and 2011–2011 for T_{max}, and 1951–1999 and 2021 for T_{min}, offering valuable insights into spatial and temporal trends. Figures 1.5 and 1.6 provide IDW maps showing the seasonal distribution of rainfall and temperature in Madhya Pradesh, allowing for comparison. These maps provide valuable information on spatial and temporal precipitation and temperature fluctuations in various regions within the state.

Rainfall

This chapter analyzes seasonal precipitation patterns in Madhya Pradesh, India, explicitly emphasizing changes after 1998. Premonsoon rainfall considerably rises in central and northern regions, but monsoon rainfall falls after 1998, particularly in places with above 1000 mm of rainfall. During the winter and post-monsoon seasons,

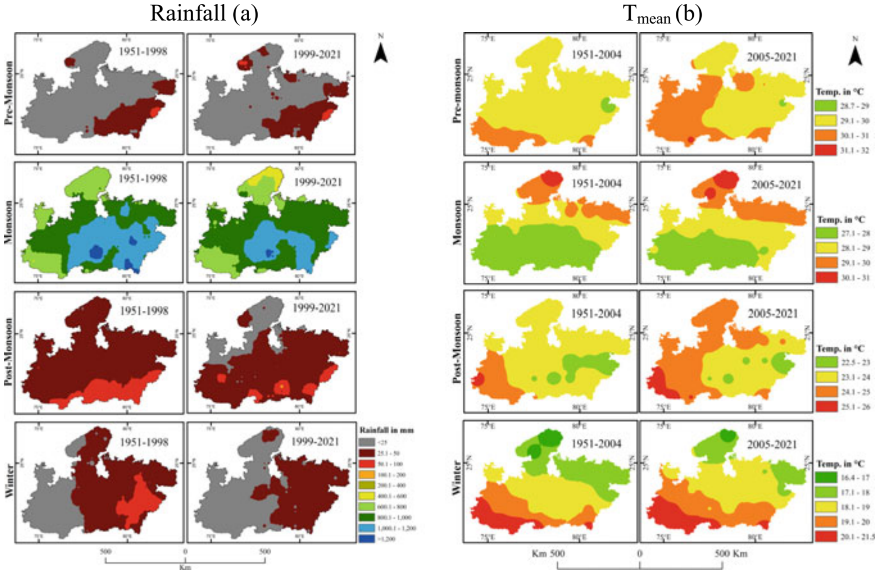

Fig. 1.5 Spatiotemporal distribution maps of seasonal rainfall and T_{mean}

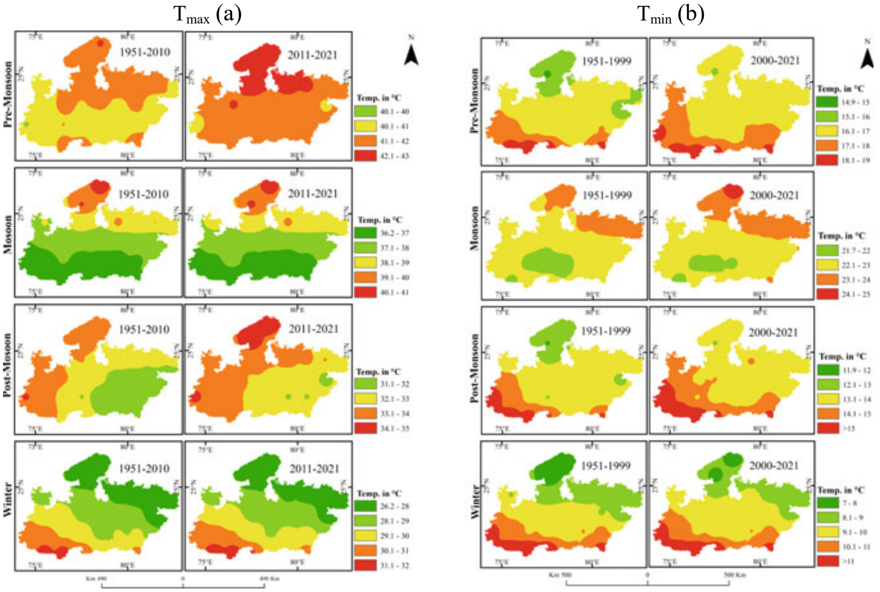

Fig. 1.6 Spatiotemporal distribution maps of seasonal T_{max} and T_{min}

there has been a decrease in rainfall patterns. Areas receiving less rainfall (<25 mm) have increased, while those receiving more than 50 mm have decreased since 1998. The research uses statistical tests to analyze rainfall patterns, focusing on the spatial and temporal distribution in different seasons (Fig. 1.5a).

Mean Temperature (T_{mean})

The regional distribution of seasonal T_{mean} in Madhya Pradesh is shown in Fig. 1.5b. This data suggests that there has been a substantial temporal variation in the T_{mean}. Before 2004, the mean temperature ranged from 29–30 °C. After 2004, it shifted to 30–31 °C throughout the monsoon and premonsoon seasons, with decreases in places below 28 °C and rises in areas over 28 °C. After the monsoon season, there were notable changes with decreases in places with temperatures of 23–24 °C and increases in regions with temperatures of 24–26 °C. Winters saw changes, with reductions in places below 18 °C and increases in areas above 19 °C after 2004. The results highlight notable changes in the climate of Madhya Pradesh after 2004, which require a deeper examination of the root causes. It is essential to understand climate patterns and their effects on agriculture, water resources, and public health.

Maximum Temperature (T_{max})

The geographical distribution of seasonal T_{max} in Madhya Pradesh is presented in Fig. 1.6a. After 2010, significant changes have been seen, especially during the pre- and post-monsoon periods. Before the monsoon season, the T_{max} notably rises in regions ranging from 41–43 °C. After the monsoon season, areas with temperatures