Assessing the Resilience of Surface Water Bodies to Population Outbursts and Climate Fluctuations

Aakash Verma[1]*, Kunal Lende[1], Srashti Singh[2], & Anugya Shukla[3]

[1] Center for Geoinformatics, Jamsetji Tata School of Disaster Studies (JTSDS), Tata Institute of Social Sciences, Mumbai, India
[2] Civil Engineering Department, IIT Roorkee, India
[3] Center for Emerging Technologies for Sustainable Development (CETSD), IIT Jodhpur, India
*Corresponding Author's email: aakashverma50174@gmail.com

Abstract
Surface water bodies are critical components of Earth's hydrological and biogeochemical cycles, serving diverse roles in potable water supply, agriculture, biodiversity preservation, ecosystem equilibrium, and climate modulation. Their significance surpasses mere aesthetics, contributing to the robustness of ecosystems. The response of water bodies to escalating populations and changing climates remains enigmatic. The confluence of factors such as unplanned urbanization, altered rainfall trends, and excessive groundwater extraction has led to the contraction or loss of water bodies. Integrating hydrological and remote sensing data makes it feasible to dissect the patterns of the changes in water body areal extent and their intricate relations with variables like precipitation and temperature. This study scrutinizes the enduring repercussions of erratic rainfall and temperature fluctuations on surface water bodies in Madhya Pradesh, India. The research aims to unravel the intricate interplay between climatic shifts and water body dynamics by amalgamating scientific analyses with local knowledge. Insights derived from this study hold the potential to guide sustainable policies and practices, thereby mitigating the adverse consequences of climate change and bolstering the resilience of both ecosystems and societies.

Keywords Water body Extent, Change Detection, Precipitation, Temperature increase, Population explosion.

Introduction

Surface water bodies are essential components of Earth's hydrological cycle, supporting diverse human and ecological needs (Yang et al., 2021). However, rapid and unplanned urbanization in Indian cities has encroached upon and degraded natural water bodies, threatening their integrity and resilience (Pandey, 2023). The compounded effects of climate change and population growth have further exacerbated the challenges the surface water bodies are experiencing in India. India's climate is diverse, with regional variations in temperature, precipitation, and humidity. The Indian Meteorological Department (IMD) identifies four major climate zones in India: tropical wet and dry, humid subtropical, subtropical highland, and arid (Bhattacharya et al., 2023). India's precipitation patterns are characterized by high variability, with both spatial and temporal fluctuations. The IMD reports that India's average annual precipitation is 117 cm, but it varies widely from region to region. Long-term precipitation trends in India reveal a decline in rainfall over the past few decades. The IMD's State of the Climate Report 2020 indicates that India's average annual precipitation has decreased by 1.2% over the period 1951-2020. This decline is attributed to a combination of factors, including natural climate variability and human-induced climate change (sciences, 2021). India's mean temperature has increased by 0.7°C over the past century, with a more pronounced warming trend in recent decades. The IMD's State of the Climate Report 2020 indicates that India's average annual temperature has increased by 0.2°C since 1951. This warming trend is attributed to increasing greenhouse gas emissions in the atmosphere (sciences, 2021). Higher temperatures can also lead to increased evaporation and decreased runoff, which can shrink water bodies. However, climate change is also disrupting precipitation patterns, making them more erratic and unpredictable, leading to water level fluctuations. Temperature and precipitation play a critical role in the dynamics of surface water bodies.

Population growth and urbanization can lead to climatic fluctuations in cities. The expansion of urban areas can increase the concentration of heat-trapping pollutants in the atmosphere, which can lead to warming. Urban areas can also experience a heat island effect, where temperatures are higher than in surrounding rural areas. Urbanization can also alter precipitation patterns. For example, the construction of buildings and roads can reduce the amount of water that infiltrates the soil, which can lead to increased surface runoff and flooding.

This study aims to investigate the enduring repercussions of erratic rainfall and temperature fluctuations on surface water bodies in Bhopal city, Madhya Pradesh, India. Insights derived from this study hold the potential to guide sustainable policies and practices, thereby mitigating the adverse consequences of climate change.

Materials and Methods

Study Area: In 1972, the district of Bhopal was established by separating it from the former Sehore district in Madhya Pradesh. Bhopal, serving as both the state capital and the district headquarters, boasts a diverse and distinctive landscape that includes the Bhoj wetlands, Berasia shrub forests, the Vindhya plateau, and the Narmada valley. This unique physiography significantly influences the micro-climatic variations experienced in Bhopal. Notably, the district's elevation is higher in comparison to the northern plains of India, with 427 msl. It is lies in the central part with latitude 77.12˚ & 77.35˚ east and longitude 23.15˚ & 23.45˚ north. Bhopal has 23,71,061 population as per census of India 2011. In terms of urban population percentage, Bhopal district is three times higher than the state's average. Additionally, the district's average income stands at double that of the state, and it boasts a high level of workforce participation. It is the sixteenth largest city of India and the second most populated city of Madhya Pradesh. It is also the twentieth largest urban agglomeration and one of the twenty-one fastest-growing cities in the world (Singh & Jain, 2022). Thus, urbanization and demand for water are higher in Bhopal city as compared to other cities in Madhya Pradesh.

Data Sources: Remote sensing satellite data of Landsat sensor, particularly Landsat 5, 7, and 8 images, has been obtained from USGS. The data is used for extraction of the surface water body extent from 1991 to 2021. Landsat sensor has a spatial resolution of 30 m. ERA 5 total precipitation data of 0.1° x 0.1° resolution is used to extract annual average rainfall. Further, the maximum and minimum temperature was obtained from the Bhopal district's Climate Change Action Plan (CCAP) report. Population data is obtained from the Bhopal Development Plan (BDP) 2031.

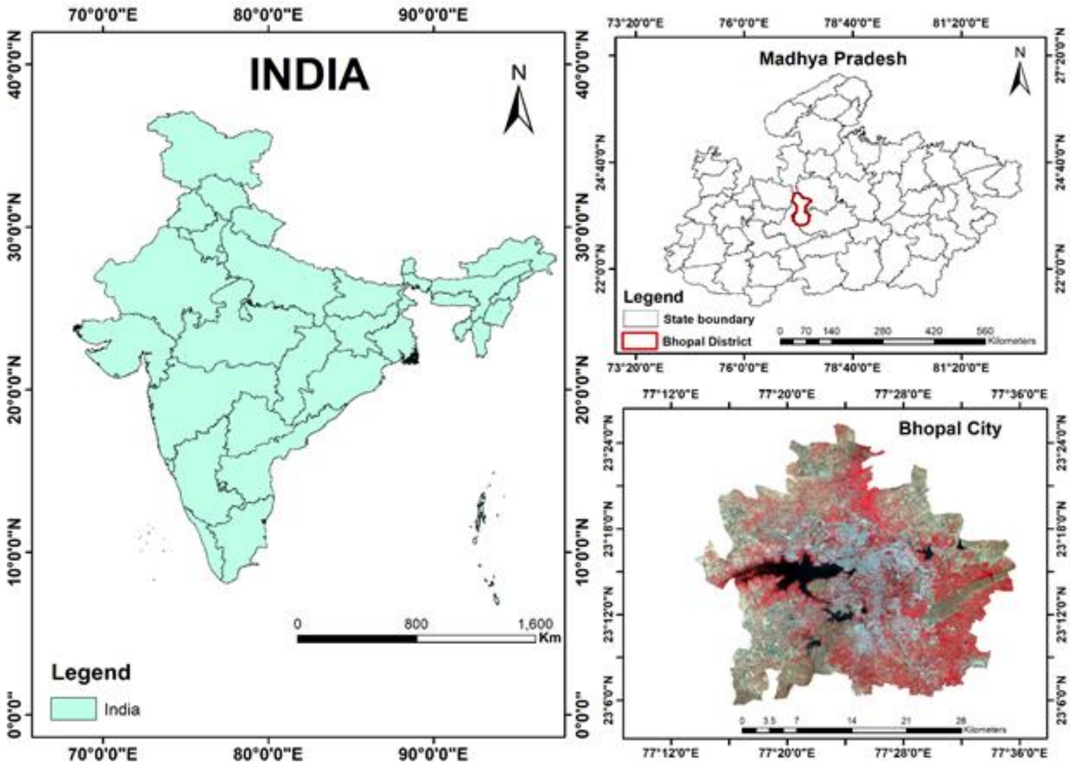

Fig. 1 *The map represents the geographical representation of Bhopal.*

Methods: Firstly, the Landsat data is used to extract the water bodies of the Bhopal Planning area in Google Earth Engine, which is a cloud-based computing platform. The Automated Water Extraction Index (AWEI) is used to compute the water body extent, and the area is calculated. ERA annual precipitation data is plotted to study the yearly fluctuations of rainfall. The mean maximum and minimum temperatures for summer (March, April, and May) and winter (December, January, and February) were analyzed. Further, changes in population, temperature, and surface water body extent are evaluated, and the relation among them is analyzed.

Surface water body areal extent extraction, using AWEI: The Automated Water Extraction Index (AWEI) is a spectral index used in remote sensing and satellite imagery analysis to detect and monitor changes in water bodies, such as lakes, rivers, and reservoirs. It aims to exploit the differences in reflectance between water and non-water surfaces to highlight the presence of water bodies (Fajar Yulianto, 2022). It was chosen for this investigation after an evaluation of numerous water indices because it produces superior results in describing the available surface water. Based on the findings of various earlier research, it was found that it is more suitable for water pixel extraction as compared to other indexes (Fajar Yulianto, 2022). AWEI has two variants, AWEI_nsh and AWEI_sh, which are used respectively for areas with "no shadow" and "shadow". AWEI_nsh is primarily used in areas where shadow effects are minimal or insignificant. It is mainly used in urban (Tri Dev

Acharya, 2018). Whereas AWEI_sh is an index that focuses on detecting water bodies while accounting for the presence of shadows, especially in areas with a lot of vegetation or complex terrain. Shadows can affect the accuracy of water body detection, as they can create variations in spectral reflectance, hence, AWEI_sh is used in such areas (Tri Dev Acharya, 2018). Bhopal Upper Lake is surrounded by hilly terrain on a considerable length of its boundary, hence, AWEI_sh is used for this study. After computing the water body boundaries, its area is calculated for each year.

Precipitation Data Analysis: ERA5-Land is a reanalysis dataset based on a surface energy model that offers higher resolution and consistent information about land characteristics over multiple decades compared to ERA5. It was created by replaying the land component of the ECMWF ERA5 climate reanalysis. The data used had a spatial resolution of 0.1 x 0.1degree. It contains post-processed data of various variables, and monthly- mean averages are pre-calculated for applications requiring quick and easy data access without the need for sub-monthly fields. Monthly-mean averages have been pre-calculated to facilitate many applications requiring easy and fast access to the data, when sub-monthly fields are not required (Europen space agency, 2019). It represents the accumulation of precipitation from the beginning to the end of a forecast period and is quantified in meters of depth.

Results

Fluctuation in surface water body extent in summer and winter: The graph (Fig 2) shows a clear decline in surface water body extent over time, both in winter and summer.

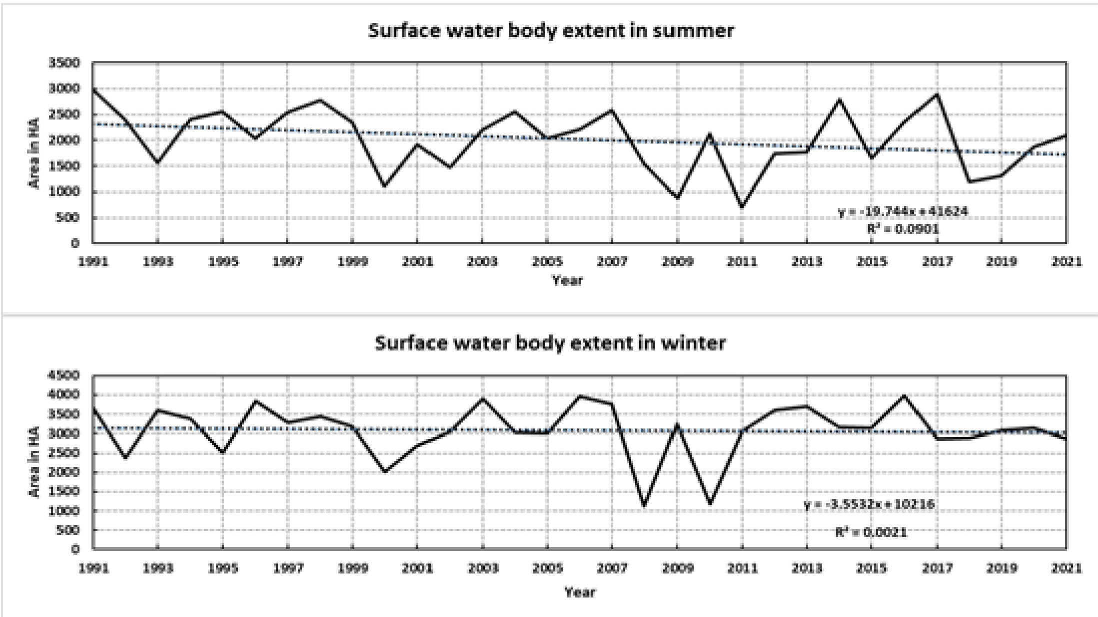

Fig. 2 Water body extent over the period. (a) In summer (b) In winter.

The winter water body extent decreased from 3656 hectares in 1991 to approximately 2862 hectares in 2021. The summer water body extent decreased from 2988 hectares in 1991 to around 2080 hectares in 2021. Whereas 2008 and 2010 depict the lowest surface water area in the city in the past 30 years in both seasons, i.e., winter and summer. The results depict that the surface water body extent is reduced in summer than in winter. This is because evaporation rates are higher in the summer months. Also, the rate of decline in surface water body extent has been accelerating in recent years due to global warming.

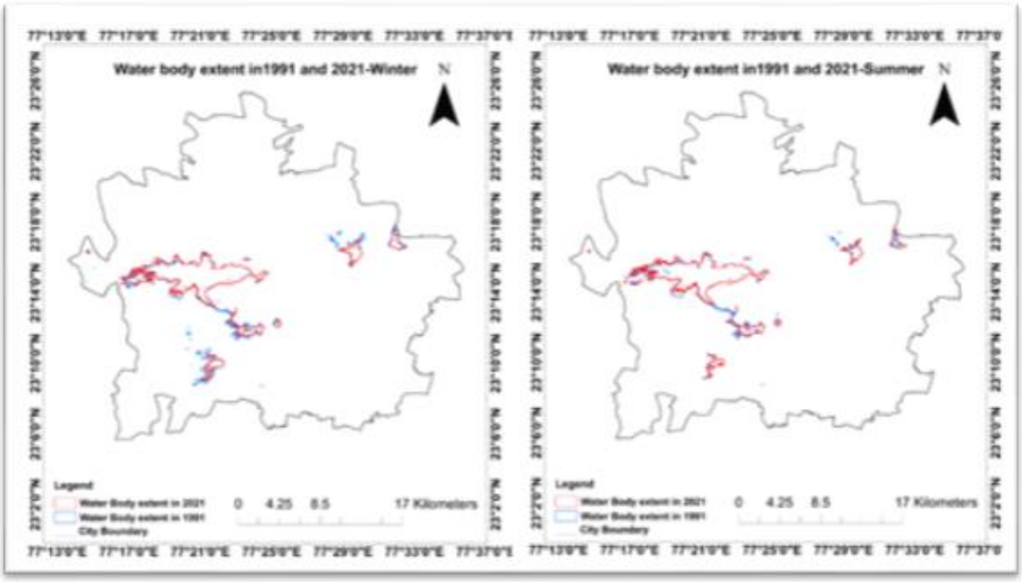

Fig. 37 Water body extent in summer and winter from 1991-2021.

Figure 3 shows the water body extent in Bhopal Planning area, India, in 1991 and 2021, during both winter and summer. A significant decrease in the water body area can be seen in Fig 3, in 1991 and 2021, during both winter and summer. The water body extent in 1991 is shown in blue, and the water body extent in 2021 is shown in red. The results depict that 899 Ha of the area in summer and 794 Ha in winter were reduced between 1991 and 2021. The study also revealed that the average area over 30 years in summer is around 2017.8 ha and 3088 ha in winter. This difference is mainly attributed to the monsoon season between summer and winter, which fills the brim of surface water bodies.

Climate change is leading to more erratic rainfall patterns and increased temperatures, both of which can contribute to water body shrinkage. Population growth and urbanization also lead to increased demand for water, which can lead to lowered water levels and reduced extent of water bodies. This is concerning because it suggests that the problem is getting worse. The decline in surface water body extent over time can be attributed to several factors, including climate change, population growth, urbanization and its induced effects. The decrease in surface water body extent has a number of negative consequences. Water bodies provide a number of important ecological services, such as water filtration, flood control, and habitat for wildlife.

Inter-annual variation of temperatures and annual precipitation **:** Figure 4 (a) represents the mean maximum temperature in summers from the year 1991 to 2021. A significant increase in the mean maximum temperature is observed from 1991 to 2021. Over 30 years, the maximum temperature has been increased from 36.8°C to 40.54°C. Fig 4 (b) represents the mean minimum winter temperature from 1991 to 2021. From 1991 to 2021, a slight increase in mean minimum temperature was observed. This is possibly due to the adverse impact of climate change and global warming.

Figure 5 represents the total precipitation in millimetres from 1991 to 2021. The x-axis of the graph represents the years, and the y-axis represents the rainfall in millimetres. The variations in rainfall patterns could be seen through the study, where the peaks and valleys depict the increase and decrease of rainfall in a particular year. Overall, there has been a slight increase in rainfall patterns in Bhopal city over the past 30 years. The results show that the city's highest rainfall was received in 2006 and 2013, whereas the lowest rainfall was observed in 1992, 2008, and 2014.While comparing yearly precipitation data and yearly water body extent, it is observed that precipitation has increased, and water body areal extent has decreased over time. The probable reason for this is attributed to hydrological imbalance. Hydrological imbalance means the imbalance in the inflow and outflow of water. In this case, the amount of evaporation from the water body is more than precipitation, which caused the water body extent to decrease. The mean maximum and minimum temperature values in summer and winter, respectively, show that the temperature has significantly increased, due to which evaporation has also notably increased.

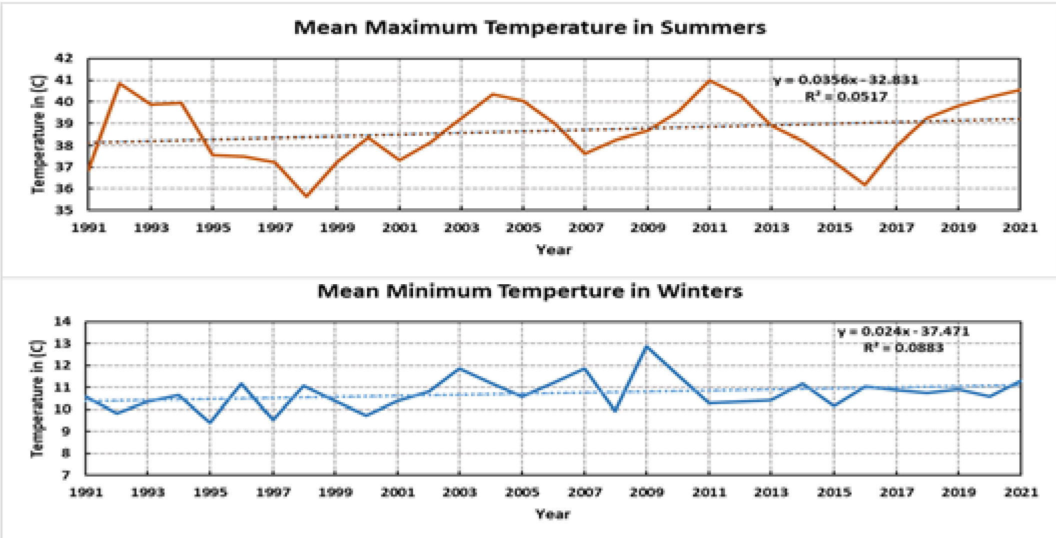

Fig. 8 Mean temperature from 1991-2021. (Top) Mean maximum temperature in summer. (Down) Mean minimum temperature in winter.

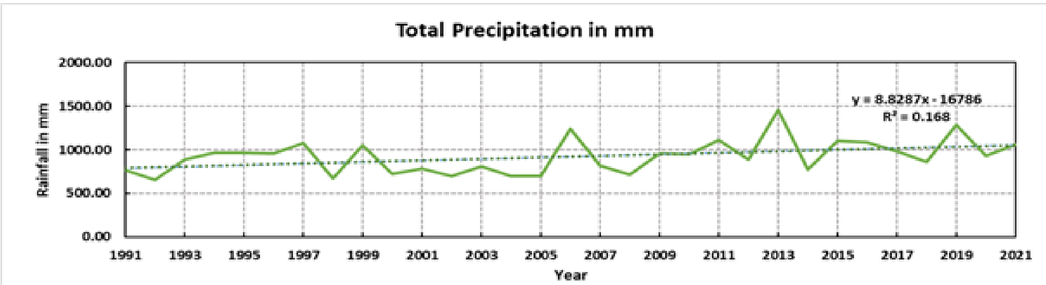

Fig. 9 Mean annual rainfall.

Relation between Population and Temperature: The population growth in lakhs from 1951 to 2021 is shown in the Fig 6. Figures 4 (a) and 4 (b) depict the mean maximum temperature in summers and the mean minimum temperature in winters.

In 1991, the population was about 11 lakhs, and the mean maximum temperature was about 36.8°C. In 2001, the population increased to about 14 lakhs, and the mean maximum temperature also increased to about 37.2°C. In 2011, the population increased to about 18 lakhs, and the mean max temperature increased to 41°C. The population grew to about 23 lakhs in 2021, and the mean maximum temperature increased to 40.5°C. Based on the decade's data from 1991 to 2021, a positive correlation is observed between the temperature and population. This resulted from urbanization, pollution, and other environmental and social factors. As the population increases, more housing facilities are built to accommodate them, resulting in the expansion of urban land, which causes an increase in land surface temperature and alteration of the natural drainage system of a city.

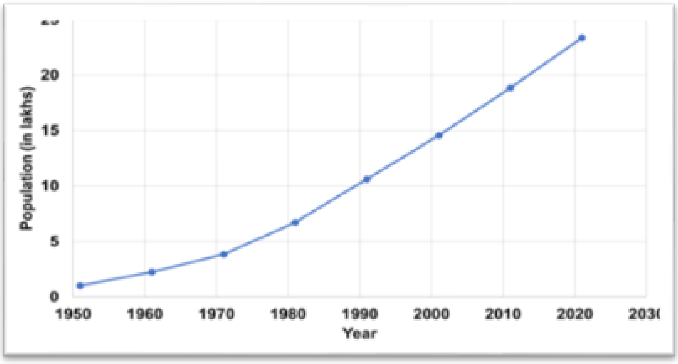

Fig. 10 Variation of the population of Bhopal since 1951.

Discussion

An increase in temperatures significantly impacts the change in water body area in both winter and summer. However, in recent years, both the winter and summer temperatures in the state have been increasing, leading to increased water evaporation from the water bodies. As a result, the water levels have been decreasing, especially in shallow water bodies. (Bhattacharya et al., 2023). A study conducted in Madhya Pradesh, India, found that the state's total area of water bodies decreased by 10% between 1991 and 2018 (Sharma, 2021). The impact of temperature variation on the water body area is likely to be exacerbated by other factors, such as population growth and urbanization. It is important to note that the impact of temperature variation on the water body area is likely to vary depending on several factors, including the size and depth of the water body, the surrounding landscape, and the local climate. However, warmer temperatures are expected to decrease water body area, especially in small and shallow water bodies.

Conclusions

Surface water bodies are under constant threat due to climate change, population growth, and urbanization. This study shed light on the complex interplay between temperature, precipitation, population expansion, and their profound impact on water body extent in Bhopal. Climate change, driven by human activity, is causing temperatures to rise and precipitation patterns to change. These changes directly impact surface water bodies, making them more vulnerable to shrinkage. In particular, increased evaporation rates in the summer months are leading to a decline in water levels. This study highlights the importance of holistic approaches to address the decline in water body extent in Madhya Pradesh. Efforts should include sustainable urban planning, the preservation of green spaces, water conservation practices, and measures to combat climate change. Moreover, this research emphasizes the need for informed policies and practices that safeguard surface water bodies. Integrating scientific analyses with local knowledge can provide valuable insights for developing strategies to protect and restore these critical natural assets.

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