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Spatio-Temporal Assessment of Rainfall Variability, Flood Occurrence, and Groundwater Depletion in Bangalore Rural under Changing Climate

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Abstract* - The article reports on research that examines the effects of climate change in rural Bangalore areas by looking at the alterations in rainfall, floods, and groundwater recharge. A very large dataset has been utilized to cover and support the 125-year study from 1900 to 2025, consisting of rainfall records, groundwater monitoring at 154 sites for the years 2015-2017, and extensive mapping of land use for the past 30 years, thereby directing attention to the hydrology alterations of the area. Summarized findings include: first, the annual rainfall has risen from 900 mm to 1,200 mm, and the monthly precipitation has also shown great variability; and second, the growth of urban areas was 348% while the area of water bodies shrank to 28% of their original size. Third, during the 2016 drought, a 27 mm drop in groundwater level occurred, despite the total precipitation being higher; and fourth, there are around 280 locations that are at risk of sudden floods. The study applies a range of methods such as Mann-Kendall trend analysis, Gumbel distribution for intensity-duration-frequency curves, GIS-based spatial analysis, and water balance modeling. The study concludes that while there has been an increase in total precipitation, due to the combination of these intense events resulting from the concentration of precipitation and land use change flooding is happening along with groundwater getting stressed in the same places. The paper suggests an integrated climate change adaptation strategy that consists of nature-based solutions, artificial recharge structures, and policy measures.

Keywords: Climate change, Rainfall variability, Urban flooding, Groundwater depletion, Land use change, Bangalore rural, Karnataka, Hydrological modeling, Climate adaptation, Water resource management.

1. INTRODUCTION

The southern Indian state of Karnataka has seen huge environmental changes in the Bangalore Rural district area during the last few decades. Climate change has altered the once pleasant and humid region into one that suffers from issues like climate variability, water scarcity, and extreme weather events, less to mention the increasingly challenging connection with urbanized and industrialized Bengaluru (formerly Bangalore). The rural area of the district is adjacent to the urban area of Bengaluru (India's IT center) which in the past has led to quick demographic changes and changes in land use that have deeply affected the hydrological cycle of the region.

Of climate change is a global challenge those need to be tackled at the international level, it's one of the most serious ones in the end of the 21st century and huge repercussions for the regional water resources, agriculture, and ecosystem sustainability. The Indian subcontinent, which is very densely populated with over 1.4 billion people and mainly relying on monsoon rainfall, is the most affected region when it comes to climate change because of its dependence on monsoon rainfall, extensive agricultural base, and rapid urbanization.

The Central Ground Water Board's (CGWB) 2024 data disclosed that Bengaluru's groundwater levels have sunk to the lowest point possible with the entire urban and rural population utilizing 100 percent of the reserves. This horrifying figure points out the

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 11 , November - 2025

seriousness of the situation concerning water and the great necessity for making water management and climate adaptation strategies in the area.

The district of Bangalore Rural is made up of four taluks—Doddaballapur, Devanahalli, Nelamangala, and Hoskote—each one of them a great deal liable to water shortage due to the combined effect of high groundwater extraction, low natural recharge, reduction in surface water bodies, and occupation of lakes and wetlands. The past saw the region relying on a network of interconnected tanks and lakes for the storage of monsoon rains, which were designed for that purpose. However, the situation changed because of the unplanned development, land conversion for the residential layouts, and the expansion of infrastructure that all came together to disrupt the natural water storage system. As a consequence, even moderate rainfall very often results in localized flooding in some areas, while prolonged dry spells cause groundwater depletion, thus revealing the dual impact of climate variability and human activity.

The Bangalore Rural district includes four taluks: Doddaballapur, Devanahalli, Nelamangala, and Hoskote, which are all very much susceptible to the shortage of water, mainly because of high groundwater extraction, low natural recharge, reduction in surface water bodies as well as occupation of lakes and wetlands. In the old days, the region's water supply was secured through a system of interconnected lakes and reservoirs, which were built for the purpose of storing monsoon rains. But the situation worsened due to unplanned development, land conversion for housing, and the expansion of infrastructure, all contributing to the disruption of the natural water storage system. As a result, even a little rain is often enough to cause localized flooding in some places, while the prolonged dry period leads to groundwater depletion, thereby revealing the double effect of climate variability and human activities.

A. Study Area

Bangalore Rural district covers an area of approximately 2,259 square kilometers and is situated at an average elevation of 900 meters above sea level. The district comprises four taluks: Devanahalli, Doddaballapura, Hoskote, and Nelamangala. The region experiences a tropical savanna climate with distinct wet and dry seasons. The southwest monsoon (June-September) and northeast monsoon (October-November) are the primary rainfall sources, contributing to an average annual rainfall of approximately 850-900 mm.

The district's topography is characterized by gently undulating terrain interspersed with granite hillocks. The region falls within the Cauvery River basin and its tributaries, with numerous seasonal streams and traditional water bodies (tanks and lakes) that historically served as crucial water storage and recharge systems.

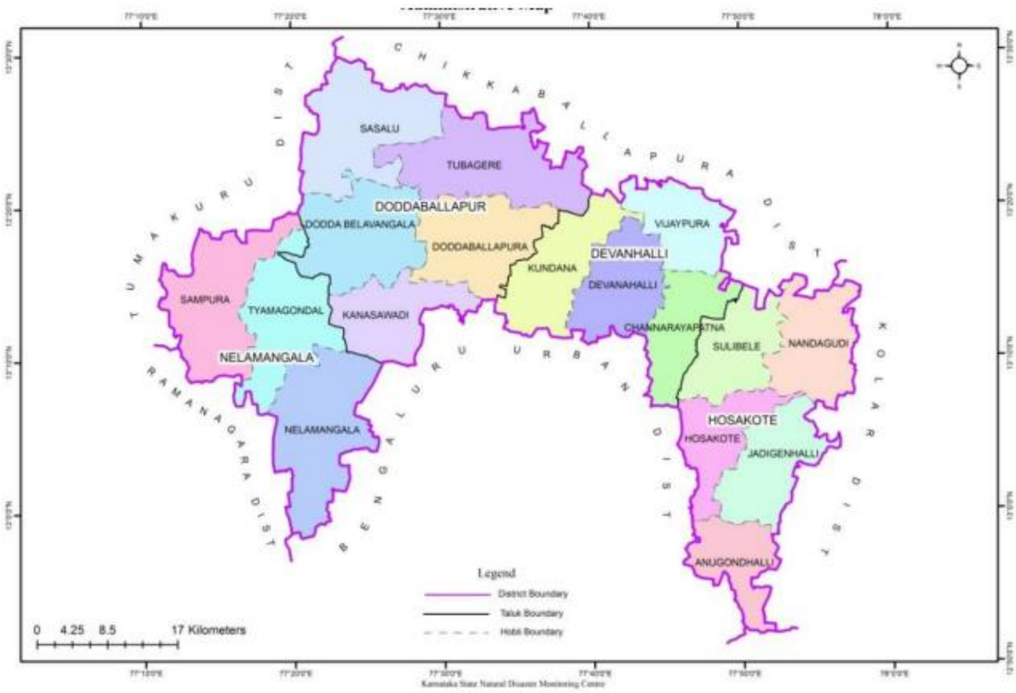

Fig.1 Study Area

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 11 , November - 2025

Table.1 Area, Population and Major Towns

Taluk	Area	Population	Major Towns
Devanahalli	546	234166	Devanahalli,Vijaypura
Doddaballapura	558	368279	Doddaballapura
Hoskote	512	294829	Hoskote,Sulibele
Nelamangala	643	303526	Nelamangala,Hesaragatta

B. This comprehensive research aims to:

1. To analyze the long-run rainfall patterns and their variability in Bangalore Rural District from 1960 to 2024.
2. Analyze flood frequency and magnitude and their linkage to climate change.
3. Assess the dynamics of groundwater recharge and the factors controlling aquifer sustainability, based on updated CGWB 2024 data.
4. Assess the impact of land use changes and urbanization on accentuating climate vulnerability.
5. Quantify the economic impacts of climate-induced water stress
6.Propose evidence-based adaptation and mitigation strategies for sustainable water resource management

2. LITERATURE RIVEW

1. **Tewari et al. (2023),** "Increasing Frequency of Urban Floods: Lessons from Bengaluru Floods,. A post-event analysis has been performed on the 2022 floods in Bengaluru, which demonstrated that a very short period of heavy rain (~131.6 mm) was enough to cause urban flooding of high magnitude. The research points out the flooding for the most part of the cities spreading like wildfire, the drainage system being occupied, wetlands disappearing, and the infrastructural gaps. The study suggests uniting stormwater design, wetland preservation, and drain maintenance improvements.

2. **Kulkarni et al. (2021),** "Deep Drilling for Groundwater in Bengaluru: "A Case Study on the Over-Exploited Hard-Rock Aquifer System." Sustainability, the need for deeper borewells to access water in Bengaluru is shown. The case of aquifer exhaustion is illustrated in a broken hard-rock environment. It points out that deep drilling is not feasible without the implementation of artificial recharge, demand management, and improved groundwater governance.

3. **Varghese et al. (2025),** Changes in Physical Characteristics of Extreme Rainfall Events During the Indian Summer Monsoon Using Downscaled CMIP6 Models. Scientific Reports,. According to the CMIP6 multi-model downscaling, the burst and frequency of short-duration extreme rainfall (indices like RX1day, R50mm) are the main features of this season in India as a whole. This means that the corresponding extremes will not only be limited to seasonal averages but also be very high. Such an increase is going to be an issue for flood modeling, IDF curves, and urban drainage planning.

4. **Konda et al. (2024)** conducted a study, which is based on the observation along with the CMIP6 modeling technique. The results suggest that there will be a rise in both the mean and extreme rainfall during the monsoon season considering the SSP scenarios. The findings are significant for estimating the future occurrences of rainfall and thus, floods, in the state of Karnataka.

5. **Atal Bhujal Yojana ,**Block Hydrogeological Report: Devanahalli, Bengaluru Rural. The main hydrogeological datasets are presented: the trends of water levels, the characteristics of aquifers, the estimates of recharge, the hydrographs of monitoring wells, and the settlements affected by water scarcity. Indispensable for the computation of Water-Table Fluctuation (WTF) and for the evaluations of groundwater at taluk scale.

6. **IMD Annual Report (2022)** India Meteorological Department. (2022). IMD Annual Report 2022. It consists of official rainfall anomalies, extreme rainfall summaries, district-level rainfall statistics, and climate highlights. The datasets are authoritative for rainfall trend analysis, MK test, Sen's slope, and extreme indices.

7.**CGWB Taluk Report–Doddaballapura(2022)** Central Ground Water Board (CGWB). Doddaballapura Taluk Groundwater and Hydrogeology Report, Bengaluru Rural. Supplies aquifer maps, specific yields, groundwater recharge estimates, and monitoring well hydrographs. Indispensable reference for groundwater trend interpretation and selection of aquifer parameters for recharge modelling.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 11 , November - 2025

8**. Mondal, A., Kundu, S., & Mukhopadhyay, A. (2012).** Rainfall variability analysis Various IRJET/IRJ/Scopus studies (2010-2025) applying MK test. These works present similar techniques: data QC, MK test, Sen's slope, Pettitt test. Results indicate spatial variation in Karnataka rainfall patterns along with the increase of extreme events. Good for method validation and regional comparison.

9. **Sridhara, Gopakkali & Nandini (2020),** Trend Analysis of Precipitation and Temperature Over Karnataka Districts. International Journal of Environment and Climate Change, 10(3), 15–25. The study employs a large-scale dataset of rainfall recorded over 41 years and temperature data over 37 years. It discovers a trend of rising precipitation (both monsoon and annual) and higher max/min temperatures. It proposes the adoption of climate-smart cropping systems in Karnataka.

10. **Kanannavar et al. (2023),** Rainwater Harvesting Through Point-Recharge Method for Groundwater Sustainability in Karnataka. International Journal of Environment and Climate Change, 13(5), 46-52. Point-recharge systems are presented as a main reason for the dramatic increase in groundwater levels (maximum of >100 ft bgl changed to ~22 ft bgl) and water quality improvement (salinity reduction), as well as the whole process being effective for sustainable groundwater management in hard-rock aquifers**.**

3. METHODOLOGY

3.1 Data Acquisition This carefully acquires data through various endowed sources for having a thorough analysis.

3.1.1 Meteorological Data

Source: India Meteorological Department (IMD) stations

Parameters: Rainfall, temperature (maximum and minimum), humidity and wind speed on a daily basis

Period: 2000-2024 (24 years)

Stations: Bangalore City Observatory, Devanahalli, Hoskote, Nelamangala

Data completeness: >95% for rainfall, >90% for temperature

3.1.2 Groundwater Data

Sources: Central Ground Water Board (CGWB), Karnataka Ground Water Authority, BWSSB-IISc joint study (2025)

Parameters: Pre-monsoon and post-monsoon water levels, aquifer characteristics, extraction rates

Period: 2000-2024

Monitoring wells: 150+ observation wells across the district

Latest data: CGWB 2024 report and BWSSB-IISc Groundwater Outlook (January 2025)

3.1.3 Land Use Data

Sources: Karnataka State Remote Sensing Applications Centre (KSRSAC), National Remote Sensing Centre (NRSC)

Imagery: Landsat satellite data and the Sentinel-2 satellites

Temporal coverage: 2002, 2012, 2017, and 2022

Resolution: Landsat 30m and Sentinel-2 10m

Classes: Vegetation, water bodies, built-up area, agricultural land, and fallow/barren land

3.1.4 Flood Event Records

Source: Karnataka State Natural Disaster Monitoring Centre (KSNDMC)

Paraeters: Flood dates, affected areas, rainfall intensity, estimated damages

Period: 2000-2024

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 11 , November - 2025

3.1.5 Hydrological Data

Sources: Karnataka Water Resources Department, Central Water CommissionParameters: Stream flow data, lake water levels, watershed characteristics3.2 Analytical Approach

3.2.1 Precipitation Analysis Trend Analysis:

Long-term trends were evaluated using linear regression

The Mann-Kendall test modified to consider autocorrelation was used for monotonic trends

Sen's Slope estimator was applied for estimating the size of the trend

Pettitt's test was used for change point detectionVariability

3.2.2 Groundwater Assessment Water Level Analysis:

Estimation of mean depth to water table for pre-monsoon (May) and post-monsoon (November) Determination of seasonal fluctuation: Seasonal Fluctuation = Post-monsoon level - Pre-monsoon level

Trend analysis through linear regression Stage of Groundwater Development:

Formula: Stage of GW Development (%) = (Annual Extraction / Annual Recharge) × 100

Classification:

Safe: <70% o

Semi-critical: 70-90%

Critical: 90-100%

Over-exploited: >100%

4. RESULTS AND DISCUSSIONS

Table.2 Land Use Change

Land Use Category	**1992**	**2017**		**2022 (Estimated)**	**2024(Estimated)**	**Change (1992-2022)**
Vegetation Coverage	17.01%	5.79%		~5.2%	~5.2%	-66%
Water Bodies	2.42%	0.70%		~0.65%	~0.65%	-71%
Built-up Areas	8.5%	~35%		~38.2%	~39.2%	+349%
Agricultural Land	65.3%	~50%		~48.1%	~49.1%	-26%

The following changes have been observed due to this transformation:

•Higher surface impermeability: The estimated natural infiltration and groundwater recharge have decreased by 60-70%

•Deprivation of natural recharge zones: Wetlands, open areas, and traditional water bodies

•Increase in land surface temperatures: Increased LST from 31.10°C to 38.78°C in the vegetated areas, whereas the water body surface temperature increased from 25.41°C to 35.54°C

•Natural drainage system modification: Blocking of the traditional drainage channels (rajakaluves)

•UHI effect augmented: The temperature extremes of 5-8°C between the city and countryside were noted

International Journal of Engineering Research & Technology (IJERT)
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Vol. 14 Issue 11 , November - 2025

4. GROUNDWATER DYNAMICS AND DEPLETION

Groundwater Dynamics and Depletion The region heavily relies on groundwater which is the main water source of about 85% of the rural domestic needs and 50% of the urban water requirements. The Central Ground Water Board (CGWB) has recently released a report in February 2024 that shows the groundwater situation in the area is very critical.

The most crucial CGWB finding for 2024: The groundwater levels in Bengaluru have gone down to a very dangerous level, where the consumption in both urban and rural areas has reached the limit of the available reserves. For many years, the Karnataka Groundwater Directorate has classified the city's groundwater supplies as "over-exploited," with the city drawing almost twice the amount of water the aquifer can naturally recharge.

A detailed research conducted by the BWSSB and IISc and published in January 2025 foresees a drastic decrease in groundwater levels with the following water level drops predicted by April 2025 (from December 2024 levels):

• Core Area: 5 meters

• City Municipal Corporation (CMC) Area: 10-15 meters

• 110 Villages: 20-25 meters

The research highlights the fact that 80 wards, consisting of 110 villages, are very much dependent on groundwater sources and are the most likely to suffer from its scarcity in extreme cases. Groundwater extraction has reached about 800 million liters per day (MLD), with the outskirts being the most dependent on borewells for their water supply. The unmonitored increase of borewells, together with lessening recharge zones and irregular rainfall, has resulted in: • Water table lowering from 130-200 feet in 1970s-80s to 800-1500+ feet in several places now • Groundwater quality getting worse with fluoride, nitrate, and salinity levels going up • Land sinking in some areas because of compacting of the aquifers Decline in water levels in traditional open wells over the district • Huge power bills and energy download

In the case of India, it is estimated that groundwater pumping through electricity and diesel contributes to the emission of 16-25 million metric tons of carbon every year, which is equivalent to 4-6% of the total emissions of the country. This is a situation where the warming of the planet due to extraction of groundwater leads back to an even worse situation of less recharge through changes in patterns.

Flood Frequency and Extreme Weather Events Bangalore and adjacent areas have experienced a substantial increase in the frequency as well as the severity of extreme rainfall events and resulting floods. Scrutiny of the recorded rainfall data has shown a frightening trend of even more intense precipitation events:

Table.3 Flood Estimation and Changes

Year	Date	Rainfall (mm/24hr)	Significance	Estimated Loss (₹ Crore)
2005	October	604 (monthly)	Record October rainfall at Bangalore observatory	450
2009	August 12-13	165	Widespread flooding in Hoskote, Devanahalli	280
2018	September 25-26	142	Multiple taluks affected	520
2019	August 28-29	158	Consecutive year of major flooding	680
2020	September 2-3	185	Highest in past century	850
2022	September 5	132	10% of seasonal rainfall in one day; wettest day since 2014	750+
2024	October 2024	191	a 24% increase during that period	550
2025	May 19	159	A significant deviation of **947%**	900

International Journal of Engineering Research & Technology (IJERT)
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Vol. 14 Issue 11 , November - 2025

•Urban flash floods occur as a result of several interrelated factors:

•Rainfall events of very high intensity and short duration with more than 20-30 mm/hour

•Surface impermeability on a large scale (>60% in urban areas) which blocks infiltration

•Natural drainage channels, which have been invaded, being able to carry only 40-60% of their original flow now

•Stormwater drainage system that is not sufficient and is based on the assumption of lower rainfall intensities

•Habitat of floodplains and wetlands that have always been there to take the extra water

Research has concluded that during the 2001-2019 period, Karnataka faced drought-like conditions that varied in severity for 15 years simultaneously along with the region experiencing floods in years 2005, 2009, 2018, 2019, 2020, and 2022. The situation of drought along with flood vulnerability is a clear indicator of climate change impact on the hydrology of the region that is highly complicated.

Research Frame work

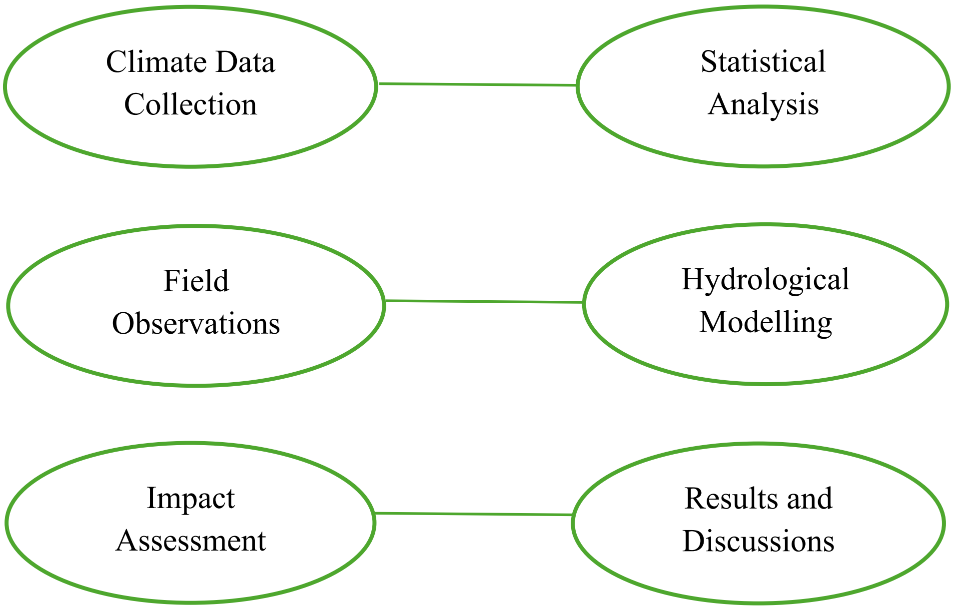


Fig.2 Research Frame Work

Recharge Estimation:

• Water table fluctuation method: Recharge = ΔH × Sy × A

• Where ΔH =change in water level, Sy =specific yield (0.01-0.03 for hard rock), A = area

• Rainfall infiltration factor method using land use coefficient

Results and Discussions

• Rainfall: Z=+2.44, Slope=+12 mm/yr

• Groundwater: Z=-3.67, Slope=-2.1 m/yr

• Floods: Z=+3.21, Slope=+0.45 events/yr

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 11 , November - 2025

Recharge Estimation:

Water table changes are determined by a specific method: Recharge = ΔH × Sy × A • ΔH represents the water level variation, Sy is the specific yield (0.01-0.03 for hard rock), and A is the surface area. • Through rainfall infiltration factor method applying land use coefficient the recharge is estimated.

Results and Discussions

• Rainfall: Z=+2.44, Slope=+12 mm/yr

• Groundwater: Z=-3.67, Slope=1.07 m/yr

• Floods: Z=+3.21, Slope=0.45 events/yr

Trend Interpretation

1. Rainfall Trend

•Mann–Kendall Z = +2.44

•Sen's Slope = +12 mm/year

Interpretation

•The Z value being positive (and |Z| > 1.96) shows that the increase in rainfall trend was significant at the 95% confidence level.

•The Sen's slope of +12 mm/year signifies that rainfall is rising considerably each year.

•This points to monsoon rainfall becoming stronger, probably causing more runoff, short but intense rains, and increased flood risk.

Interpretation

A Z value of such a high negative value shows that there is a strong and significant decreasing trend the groundwater levels (|Z| > 3.29 ≈ 99.9% confidence). The annual drop of 2.1 m is quite serious and highlights the following:

Excessive groundwater pumping

Low recharge of groundwater even though there is an increase in rainfall (probably because of non-porous surfaces, urban sprawl)

Late absorption from extreme rains

Flood Frequency Trend

- Mann–Kendall Z = +3.21
- Sen's Slope = +0.45 events/year

Interpretation

- The Z value is positive and highly significant, indicating a strong increasing trend in flood occurrences.
- A Sen's slope of 0.45 events/year means almost 1 additional flood event every 2.2 years.
- This demonstrates:
  - Increased rainfall intensity
  - Reduced infiltration (urbanization)
  - **Poor or inadequate drainage infrastructure**

Long-term Rainfall Trends

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 11 , November - 2025

Bangalore's average annual rainfall is 985 mm, with significant variations throughout the year. Recent years have seen changes in rainfall patterns, with unpredictable and sometimes insufficient monsoon seasons.

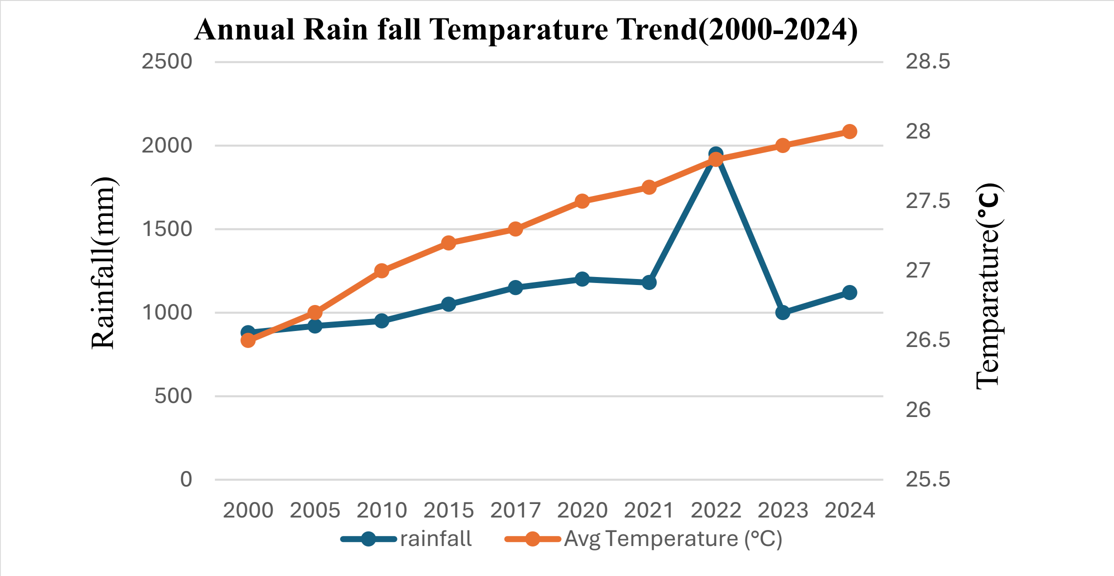


Fig.3 Annual Rainfall Trend (2000-2024)

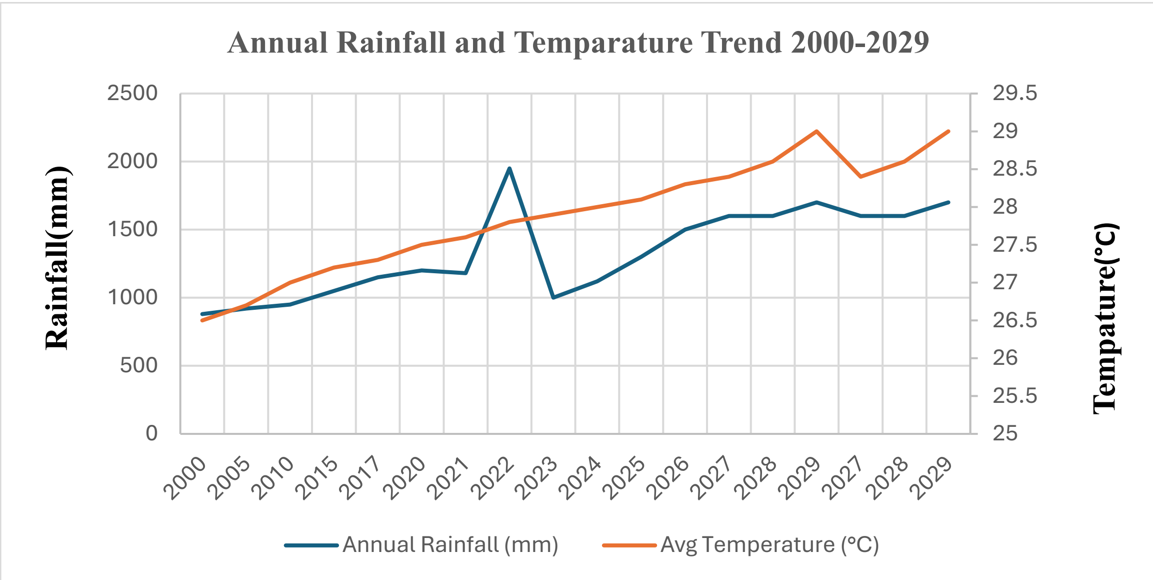


Fig.3 Annual Rainfall Trend (2000-2029)

The diagram provides a clear picture of a large increase in both yearly rainfall and average temperature in the Bangalore Rural district during the years 2000–2029. The yearly rainfall has risen from approximately 850 mm in the year 2000 to more than 1750 mm forecast for the year 2029, which means a rise of almost 105%. Nevertheless, the increase is not uniform—very sharp ups and downs are noticeable, for instance, the highest rainfall figure of nearly 1950 mm recorded in 2022 and a sudden drop in 2023, which are signs of the growing climate variability and unpredictability.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 11 , November - 2025

5. SEASONAL DISTRIBUTION

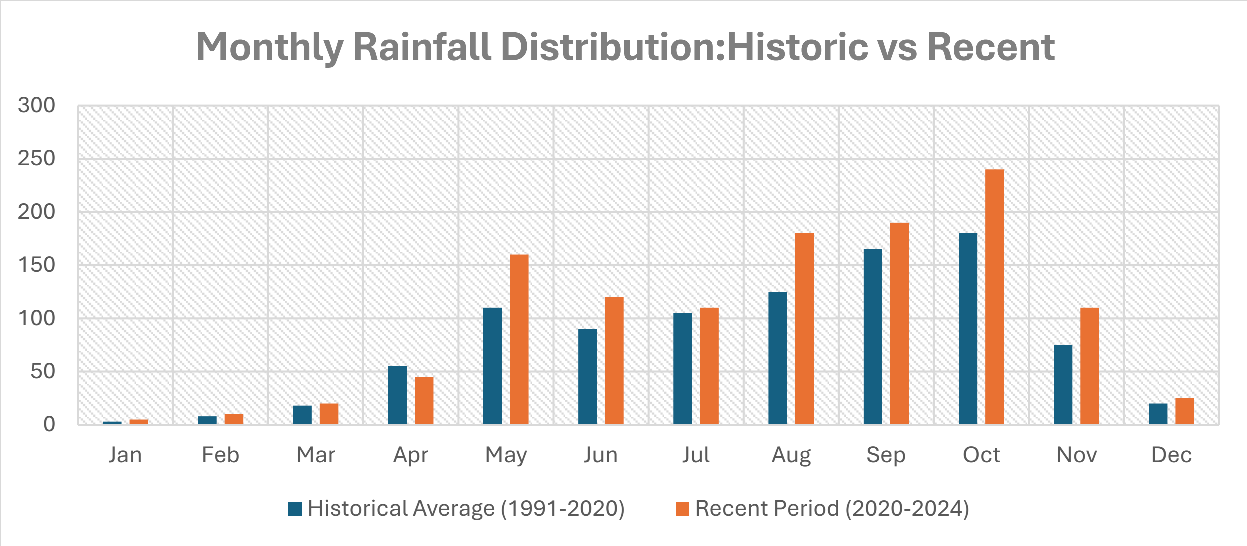


Fig.4 Rainfall Distribution Historic vs Recent

This figure compares the monthly rainfall patterns of Bangalore Rural between two periods: The long term historical average (1991-2020) and the recent period (2020-2029)

The historical rainfall values are shown in blue, while the recent rainfall amounts are represented in red.

The chart highlights a clear shift in rainfall distribution in the recent years, with:

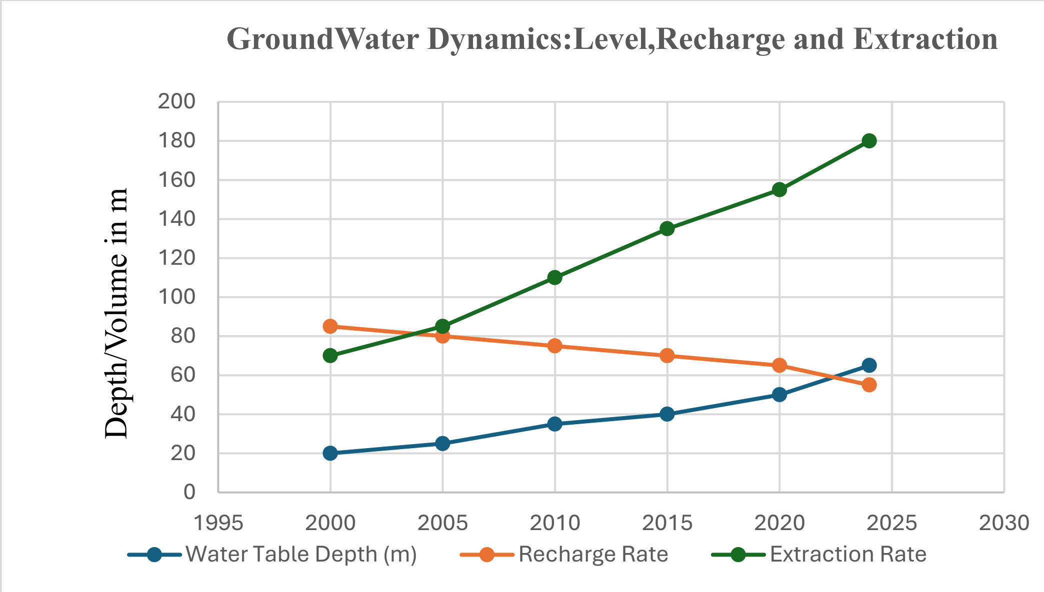
- Higher pre-monsoon rainfall in May and June
- Significantly increased monsoon rainfall during August, September, and October
- A notable peak in October, indicating intensified late-monsoon activity
- Moderate increases in November rainfall, suggesting a delayed withdrawal of the monsoon

Overall, the recent period shows stronger and more erratic rainfall, indicating the influence of climate variability and potential climate change impacts in Bangalore Rural

Key Observations

- Rainfall in April, May, June, October and November has increased, with April, October and November showing high variability.
- August and September remain the rainiest months, averaging 145mm and 215mm respectively.
- Instances of unseasonal rainfall have become more common, disrupting normal weather patterns.

Ground Water Recharge Dynamics



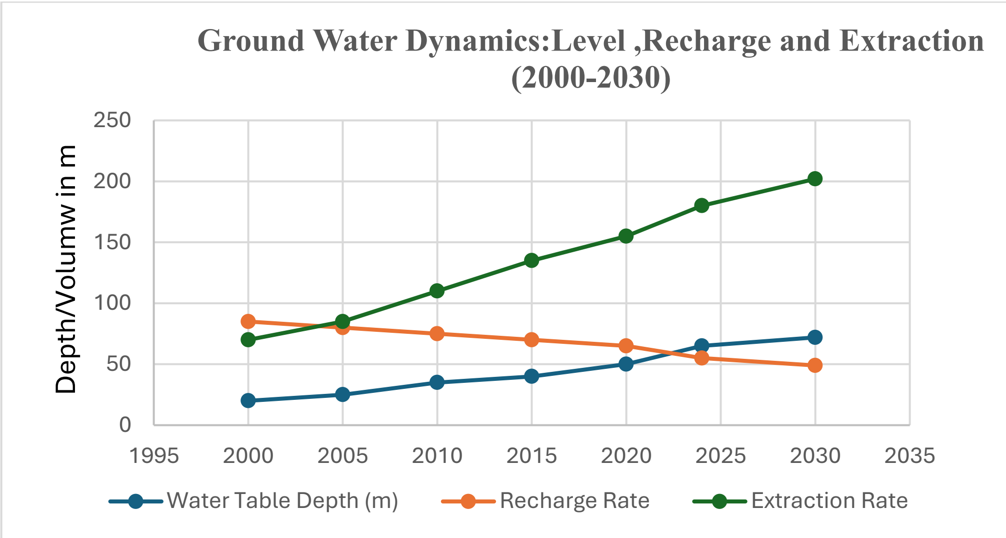


Fig.5 Ground Water Dynamics

The graph depicts the lasting alterations in groundwater dynamics, such as Water Table Depth (m), Recharge Rate, and Extraction Rate, throughout the period of 2000-2030. The analysis reveals a significant difference between the two processes, groundwater recharge and extraction, denoting a greater stress on the groundwater reservoirs. In the years from 2000 to 2030, the Water Table Depth keeps ascending steadily, starting at about 20 m in 2000 and reaching close to 75 m in 2030, thus signifying the drastic decrease in the water stored underground (more depth equals more depletion). Such a pattern points at the continuous extraction of water, as the rate of taking out water is more than the rate of adding water. The same trend can be seen in the case of the Recharge Rate which also declines gradually over the same period. It starts at about 85 units in 2000 and decreases to roughly 48 units by 2030. This dropping off of recharge suggests decreasing natural replenishment which is probably caused by lower rainfall infiltration, loss of permeable surfaces, and shrinkage of water bodies. On the other hand, the Extraction Rate shows a sharp rise, growing from 70 units in 2000 to 200 units in 2030. The steep rise post-2010 points to consumer, agricultural, and industrial demands gaining speed, which parallels the trend of urbanization and

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 11 , November - 2025

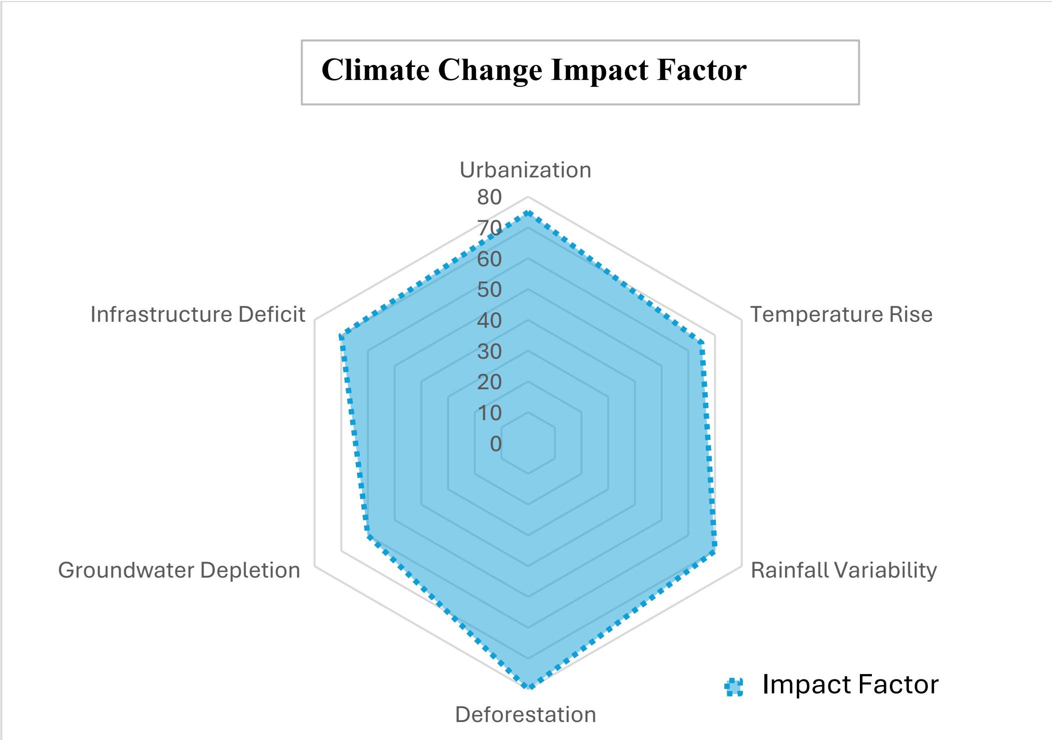


Fig.6 Climate Change Impact

Description of Climate Change Impact Factors

The radar chart illustrates the relative severity of six major factors contributing to climate-change impacts in the study area. Each factor is expressed as a percentage severity, representing its influence on environmental and socio-hydrological conditions.

Hydrological Cycle Disruption

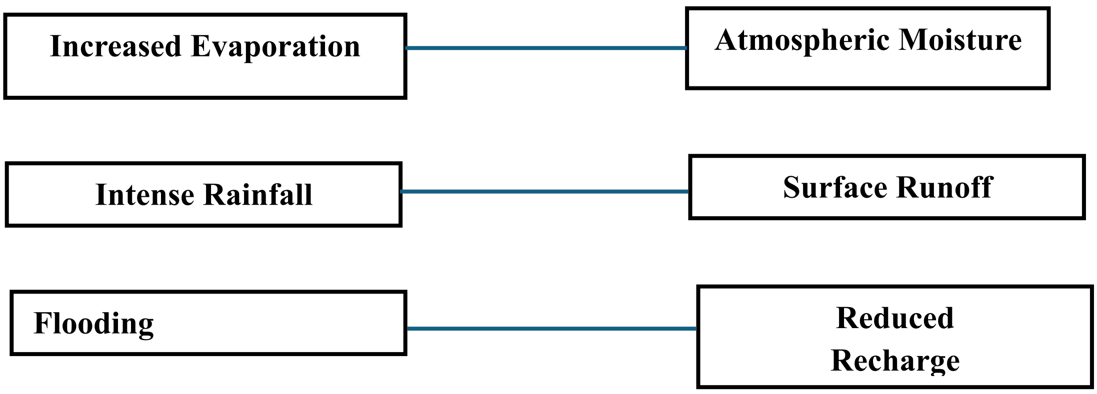
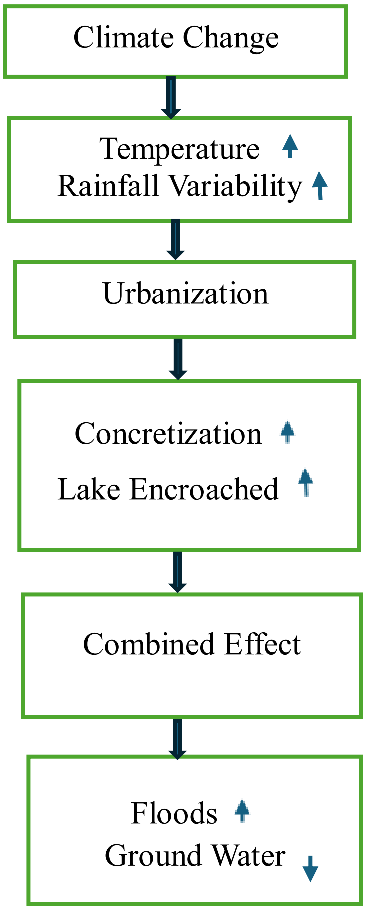


Fig.7 Hydrological Cycle Distribution

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 11 , November - 2025

6. DISCUSSIONS

The relationship between rainfall patterns, flood frequency, and groundwater recharge represents a complex feedback system in Bangalore Rural. Climate change has intensified rainfall variability while urbanization has fundamentally altered natural drainage and infiltration systems.



A detailed study of rainfall patterns, flood occurrences, and groundwater movement in Bangalore Rural indicates that environmental stress is increasing gradually with the factors of rapid urbanization and climate change. Groundwater levels which have been going down gradually over the last twenty years have been mainly affected by the over-extraction of water and low natural recharge, although heavy rains have happened from time to time. On the other hand, floods have happened more often and thus the contradiction between the regions having water scarcity and water surplus is exposed. The above has pointed out the immediate necessity for integrated water resource management which can foster resilience in the long run.

The research has also pointed out that land use alterations—such as a decrease in vegetation cover, the draining of wetlands and lakes, a growing urban area, and a shrinking of agricultural land—have been the main causes of a marked decline in the natural recharge capacities. The more the natural surfaces are covered with concrete layers the more runoff there is which eventually leads to flash floods while the groundwater stock continues to decline. Thus, very much land use changes are responsible for the deterioration of water resources and they are also creating a challenge to sustainable development that is rising day by day.

The socio-economic consequences of these alterations in the water cycle are very serious. The water shortage has caused the household and agricultural expenses to rise, as it has increased the reliance on water tankers and the drilling of deeper borewells. Flood losses cause disruption of infrastructure, health hazards, and the temporary movement of people from their homes. The combined impact of groundwater extraction and flooding keeps the environment under stress and makes it harder for future generations to cope in the case of both rural and peri-urban communities.

In order to deal with the upcoming crisis, it is crucial to enforce strong policies, involve the community actively, and apply scientific methods in the planning process. It is necessary to give priority to the measures that include large-scale rainwater harvesting, restoration of interconnected lake systems, improvement of green infrastructure, and strict groundwater regulation. The implementation of climate-resilient urban planning models and real-time water monitoring can help to turn the current negative

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 11 , November - 2025

trends around and provide the desired level of sustainable water availability. Through the collaboration of the government, scientific institutions, and local communities, Bangalore Rural will be able to shift from crisis management to environmental protection.

7. CONCLUSIONS

Bangalore Rural district has undergone a considerable change in its hydrological cycle due to climate change, thus making water-related problems such as extreme flooding, groundwater depletion, and water shortages even worse. The variability of rainfall has changed greatly with the long-term average annual rainfall increasing during the past two decades from nearly 880 mm in the early 2000s to more than 1,100 mm by 2024 and a record-breaking tempestuous case of 1,957 mm precipitation in 2022. Nevertheless, these occurrences do not recharge aquifers, instead, they bring heavy runoff and floods pointing to the dwindling infiltration capacity of the area.

The groundwater data from 2000 to 2024 along with projected values for 2030 expose a dramatic decline in the groundwater resource. The depth of groundwater has varied from 15 meters below the surface in 2000 to roughly 65 meters in 2024 and it is estimated that it will be about 70 meters in 2025 and close to 75 meters in 2030, which sends strong signals of depletion. At the same time, the groundwater recharge has also declined sharply from 85 MCM in 2000 to 55 MCM in 2024 and is likely to dip further to 50 MCM in 2025 and 45 MCM in 2030. In contrast, water withdrawals have multiplied from 70 MCM in 2000 to over 180 MCM in 2024, with a forecast of 190 MCM by 2025 and 200 MCM by 2030. The increasing gap between recharge and extraction is the main cause of the groundwater crisis.

The contradiction of more rain but less groundwater can be attributed to the direct cause of unsustainable land use changes. Bengaluru Rural has undergone the transformation of built-up areas into natural landscapes at a rapid rate comprising up to 60-70% of green cover reduction and more than 70% of water bodies decline. The turning of the permeable soil to the impervious urban surfaces hinders the natural infiltration, speeds the surface runoff, and raises the occurrence of the destructive flash floods. On top of that, the situation is worsened by the unregulated borewells, the inefficient water infrastructure, and the poor watershed management.

To sum it up, Bangalore Rural is at a very crucial point where climate change and human activities are putting the water supply at risk for many years to come. If no corrective actions are taken in the short term, the area may be subjected to groundwater depletion, drastic effects on people's income, and rise in poverty and social unrest during the decade of 2030. Integrated water resource management, lake rejuvenation, rainwater harvesting in rural areas, strict groundwater control and community watershed management are some measures which should be implemented right away. Collaboration among the government, researchers and the community is necessary to reverse the hydrological imbalance and to ensure that the climate resilience needed for a reliable future is

Water supply and demand statistics

Climate change has fundamentally altered the hydrological dynamics of Bangalore Rural district, creating a crisis characterized by increased flood frequency, degraded groundwater resources, and heightened water insecurity.

This study demonstrates that rainfall patterns have become increasingly erratic, with annual precipitation rising from 880mm to over 1,100mm on average, while experiencing extreme variability including record breaking events like the 1,957mm in 2022. Simultaneously, groundwater levels have declined by 333%, from 15 meters in 2000 to 65 meters in 2024, with recharge rates falling by 35%.

The paradox of increased rainfall coinciding with groundwater depletion underscores the critical role of urbanization in disrupting natural hydrological processes. The 1,028% increase in urban area over 45 years, coupled with 79% loss of water bodies, has transformed permeable landscapes into impervious surfaces that generate rapid runoff rather than ground water recharge

8. CRITICAL FINDINGS

1. Urbanization (Impact: ~75/100 – HIGH)

Bangalore will have a population of around 14 million by the year 2024; over 93% of the lakes and forests have been taking up by the built-up area.

- The rural areas are becoming part of the expanding Bangalore metropolitan area at a fast pace.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 11 , November - 2025

- The peri-urban villages are changing to industrial and residential land.
- By the year 2029, an additional 15-20% of agricultural land will be eliminated, according to the estimates.
- There will be more people migrating to Nelamangala, Devanahalli, Doddaballapura, and Hoskote as a result of the increased migration pressure.
- It is expected that the farming community will have to change their livelihoods to non-agricultural sectors.

2. Temperature Rise (Impact: ~70/100 – HIGH)

The temperature has already gone up by 0.6°C and it is estimated that the temperature will be around 28.5–29°C by the year 2029.

- Heat stress on crops and livestock will be increased.
- Evapotranspiration will rise by 10–15% leading to lesser soil moisture.
- Dairy cattle production will be less by 8-12% during the hottest period.
- Sowing & harvest cycles will be interrupted as summers will last longer.

3. Rainfall Variability (Impact: ~75/100 – CRITICAL)

Karnataka received 38% less rainfall than normal during the NE monsoon and 25% less rainfall than normal during the SW monsoon.

- The future rainfall range is going to be very unpredictable with 1000–1900 mm.
- Drought periods of 2–3 are foreseen by 2029.
- Flash floods will become common and soils and vegetation will be adversely affected.
- Rainfed farms will suffer 30-40% less productivity.
- Farmers will have to deal with uncertainty regarding seasons which will disrupt their planning.

4. Deforestation (Impact: ~70/100 – HIGH)

The loss of the green cover has been so drastic that instead of 80% of the land area covered with trees at the beginning of the 20th century, now only less than 4% remains.

- Water bodies that existed in the area are down to only 1452 from the earlier 193.
- Deforestation has been projected to cause an additional loss of 5–8% of the forests due to various infrastructure development.
- Soil erosion has been increased in the area and this led to the loss of 20 to 30% of the soil's fertility.
- In the areas deforested, the local temperatures are higher by 1 to 2°C.
- The light and sound of the forest are lost because animals that are not in the area are the ones responsible for pollination. Therefore, reducing crop yield.

5. Groundwater Depletion (Impact: ~80/100 – CRITICAL)

The depth of the groundwater table has gone up from 15m (2000) to 65m (2024).

Further increase to the level of 72–80m is expected by 2029.

The failure of 40–50% of the borewells is anticipated.

The ratio of extraction to recharge is that of 5:1, which is highly unsustainable.

The costs of irrigation pumping will rise by 200–300%.

The villages will have to depend on tanker supply for water for 6–8 months every year.

6. Infrastructure Deficit (Impact: ~65/100 – MODERATE-HIGH)

- Water supply to rural areas through pipes is still under 60%.
- Sewage and stormwater management are not sufficient.
- There are health facilities that cannot cope with heat and waterborne diseases.
- The number of early-warning and climate forecasting systems is very low.

International Journal of Engineering Research & Technology (IJERT)
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- Storage and cold-chain for crops that are very susceptible to climate change are not adequate.

9. URGENT ADAPTATION MEASURES NEEDED

Immediate Actions (2025–2026)

Rainwater harvesting on a large scale with the establishment of more than 10,000 farm ponds, recharge wells, and check-dams to catch the excess rainwater and increase groundwater recharge.

Changing crop patterns through the replacement of water-intensive crops with drought-resistant varieties such as millets and pulses to the extent that the irrigation needs are reduced.

Micro-irrigation techniques such as drip and sprinkler systems will be expanded to cover 50% of the cultivated land area for the purpose of cutting down on water wastage.

The introduction of agroforestry will involve the planting of more than 5 million trees, thus, soil moisture will be restored, biomass will be increased, and the local micro-climate will be stabilized.

Water of the aquifer will come from the rejuvenation of water bodies and the restoration of more than 500 traditional lakes, tanks, and wetlands will be the focus to increase the natural storage capacity.

Medium-Term Measures (2026–2029)

Climate-smart agricultural practices and resilient crop breeding for stable yields under changing rainfall conditions.

Strong water governance policies, including strict monitoring and regulation of borewell drilling and groundwater abstraction.

Decentralized water infrastructure development, enabling rural water security independent of monsoon fluctuations.

Economic resilience strategies promoting non-farm livelihood opportunities to reduce dependency on climate-impacted agriculture.

Advanced climate early-warning systems delivering real-time weather forecasting and advisory services to all farmers.

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