

RESEARCH PAPER**OPEN ACCESS****Trend analysis of rainfall variability and its impacts on water resources in the Lake Naivasha Basin, Kenya****S. K. Tirop^{*1,2}, J. M. Kinama³, J. N. Muthama¹**¹*Wangari Maathai Institute for Peace and Environmental Studies, Department of Earth and Climate Sciences, University of Nairobi, Nairobi, Kenya*²*Department of Land Resource Management and Agricultural Technology, University of Nairobi, Nairobi, Kenya*³*Department of Plant Science and Crop Protection, University of Nairobi, Nairobi, Kenya***Key words:** Rainfall variability, Hydrological impacts, Lake Naivasha basin, Climate change, Water resources management**Received:** 17 August, 2026 **Accepted:** 27 August, 2026 **Published:** 05 September, 2026**DOI:** <https://dx.doi.org/10.12692/jbes/29.3.27-38>**ABSTRACT**

Rainfall variability is a key climatic factor influencing hydrological processes, water resource availability, ecosystem functioning, and socio-economic development. In recent decades, climate change has intensified rainfall variability, increasing the frequency and severity of floods and droughts across many regions. This study investigates long-term rainfall variability and its hydrological and environmental impacts within the Lake Naivasha Basin, Kenya, over a 35-year period. The basin supports one of Kenya's most important freshwater ecosystems and sustains floriculture, horticulture, fisheries, tourism, and wetlands of high ecological value. Rainfall data from the Kenya Meteorological Department, streamflow records from the Water Resources Authority, lake-level observations, remote sensing products, land-use datasets, and water quality records were analysed using the Mann–Kendall trend test, Sen's slope estimator, and time-series analysis to detect temporal trends and assess hydrological responses. The results indicate increasing rainfall variability, particularly in the upper catchments, with noticeable changes in the timing and magnitude of seasonal rainfall. Streamflow exhibited significant seasonal fluctuations, characterized by declining dry-season flows and shifting peak discharge periods. Lake Naivasha experienced increased water-level variability, with more frequent flooding events interspersed with periods of below-average water levels. Water quality analysis revealed increasing nutrient enrichment and sediment loading associated with agricultural runoff and shoreline development, accelerating eutrophication across several parts of the lake. These hydro-climatic changes have contributed to the degradation of riparian vegetation, wetland inundation, declining fish productivity, and increasing competition for water among agricultural, industrial, environmental, and domestic users. The study highlights the combined influence of climate variability and anthropogenic pressures on the basin's hydrological regime and emphasizes the need for integrated water resources management, strengthened hydro-meteorological monitoring, catchment restoration, sustainable abstraction practices, and climate-resilient planning to enhance the long-term sustainability of the Lake Naivasha Basin.

***Corresponding Author:** S. K. Tirop ✉ tiropskip@gmail.com

INTRODUCTION

Water resources are fundamental to ecological integrity, socio-economic development, and human well-being. Freshwater ecosystems provide essential services, including domestic water supply, agricultural production, fisheries, biodiversity conservation, and climate regulation (Mulatu *et al.*, 2014; Yongo *et al.*, 2023; Mengich *et al.*, 2024). However, these ecosystems are increasingly threatened by climate variability, land-use change, rapid population growth, and intensified human activities. In sub-Saharan Africa, these pressures are compounded by growing water demand and increasing hydro-climatic uncertainty, placing considerable stress on both water quantity and quality.

Climate variability is a major driver of hydrological change, influencing rainfall patterns, river discharge, lake levels, groundwater recharge, sediment transport, and aquatic ecosystem functioning (IPCC, 2021). In East Africa, rainfall is characterized by marked spatial and temporal variability, largely influenced by large-scale climate oscillations such as the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) (Nicholson, 2017).

These climate drivers contribute to recurrent droughts and extreme rainfall events, leading to fluctuations in water availability, declining water quality, and increased vulnerability of freshwater ecosystems.

Assessing long-term rainfall variability is therefore critical for understanding hydrological responses and informing sustainable water resources management under a changing climate.

Rainfall trend analysis provides valuable insights into shifts in precipitation regimes and their implications for watershed hydrology, ecosystem functioning, and water security. Such information is increasingly important as climate change is projected to intensify hydrological extremes and increase competition among water users.

The Lake Naivasha Basin (LNB), located in Kenya's central Rift Valley, is one of the country's most important freshwater ecosystems, supporting biodiversity as well as key economic sectors, including horticulture, floriculture, fisheries, tourism, geothermal energy, and domestic water supply. The lake receives most of its inflow from the Malewa, Gilgil, and Karati rivers, with the Malewa River contributing approximately 80% of total surface inflow. Consequently, the basin's hydrological balance is highly dependent on rainfall-driven catchment runoff and is particularly sensitive to climatic variability (Kuhn *et al.*, 2016).

Over recent decades, the basin has experienced increasing hydro-meteorological variability, including recurrent droughts, intense rainfall events, and flooding. These changes, together with expanding irrigated agriculture, increasing water abstraction, urbanization, and catchment degradation, have altered river flow regimes, caused substantial lake-level fluctuations, degraded water quality and aquatic habitats, increased sedimentation, and intensified competition among environmental, agricultural, industrial, and domestic water users.

Previous studies in the Lake Naivasha Basin have examined hydrology, water quality, ecological change, and land-use dynamics, but these aspects have generally been investigated independently. Consequently, there remains limited understanding of how long-term rainfall variability influences the basin's hydrology and how these changes cascade to affect water quality, ecosystem health, land-use dynamics, and socio-economic livelihoods within an integrated framework. Addressing this knowledge gap is essential for developing effective climate adaptation and sustainable water resource management strategies.

This study investigates rainfall variability and its implications for water resources in the Lake Naivasha Basin over the past 35 years. Specifically, the study aims to:

1. Assess long-term annual and seasonal rainfall trends and variability across the Lake Naivasha Basin.
2. Evaluate the hydrological responses to rainfall variability, including changes in river discharge and lake water levels.
3. Examine the implications of rainfall variability for water quality, land-use dynamics, and aquatic ecosystem health.

By integrating climatic, hydrological, ecological, and land-use information, this study provides an assessment of the impacts of rainfall variability on the Lake Naivasha Basin. The findings will improve understanding of climate–water interactions and provide evidence to support adaptive water resource management, ecosystem conservation, and climate-resilient policy development in Kenya and freshwater basins facing hydro-climatic challenges.

MATERIALS AND METHODS

Study area

Location and physiography

The study was conducted in the Lake Naivasha Basin (LNB), located in Kenya's Central Rift Valley (approximately 0°45'–0°55'S and 36°15'–36°30'E) (Fig. 1). Covering about 3,400 km², the basin experiences a bimodal rainfall regime, with long rains (March–May) and short rains (October–December), receiving 600–1,200 mm of annual precipitation, largely influenced by the surrounding Aberdare highlands. The basin is drained primarily by the Malewa and Gilgil rivers, which feed Lake Naivasha, a freshwater lake of significant ecological and socio-economic importance. Major land uses include irrigated horticulture and floriculture, livestock grazing, and domestic water abstraction.

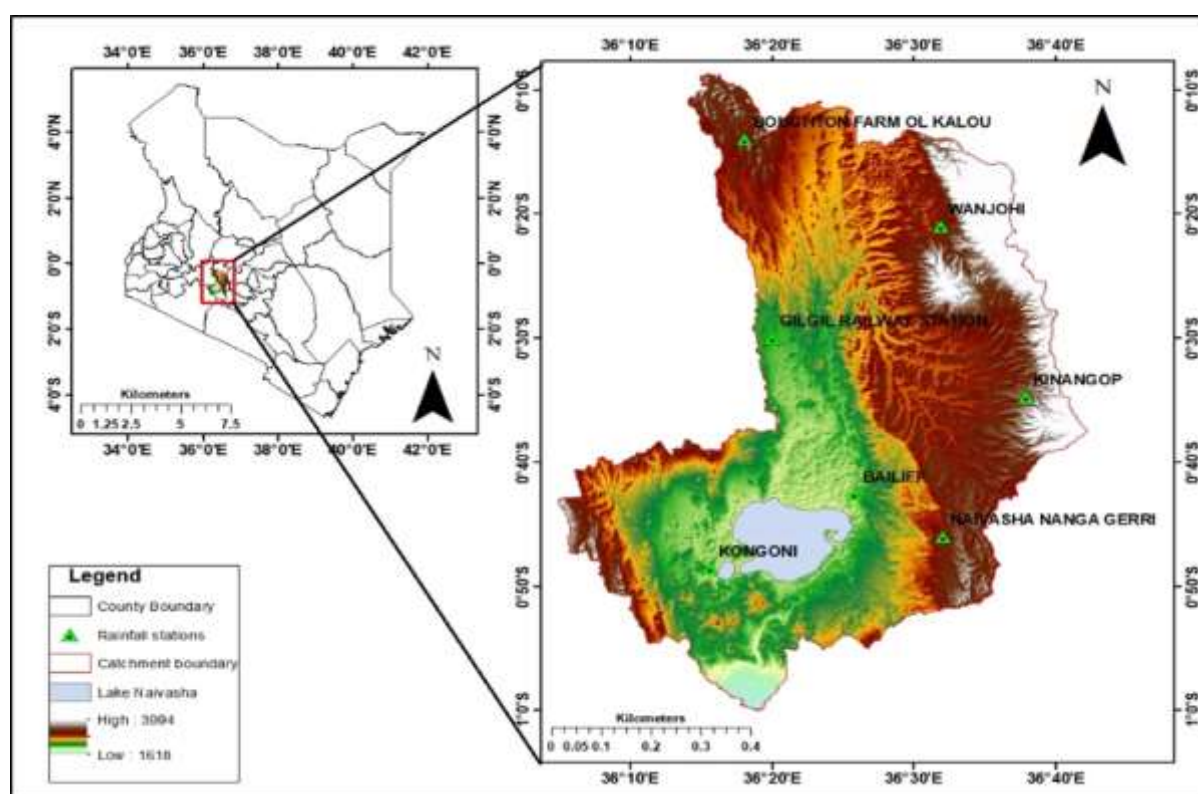


Fig. 1. Map of Lake Naivasha Basin, and its location in Kenya

The basin exhibits a pronounced elevation gradient, ranging from approximately 1,890 m above mean sea level (a.m.s.l.) around Lake Naivasha to 3,990 m a.m.s.l. on the eastern slopes of the Aberdare

Mountains. This topographic variation strongly influences rainfall distribution, temperature, vegetation, and hydrological processes across the catchment (Fig. 2).

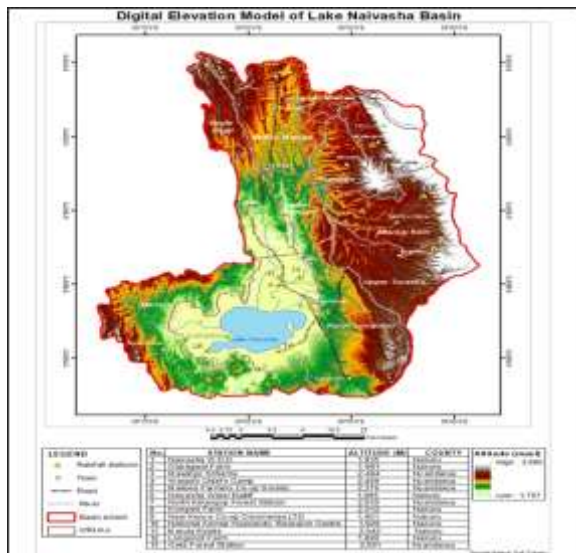


Fig. 2. The Lake Naivasha basin showing the topography (m MSL), the rainfall stations, and the WRUAs location (Source: Kenya Soil Survey)

Climate

The Lake Naivasha Basin has a bimodal rainfall regime influenced by the Intertropical Convergence Zone (ITCZ), with the long rains occurring from March to May (MAM) and the short rains from October to December (OND). Annual rainfall varies from about 500–700 mm in the lowland areas around the lake to approximately 1,525 mm in the upper Aberdare catchments due to orographic effects. Mean daily temperatures range from 8°C to 30°C, while high annual evaporation (1,700–2,200 mm) contributes substantially to water loss from Lake Naivasha (Fig. 3).

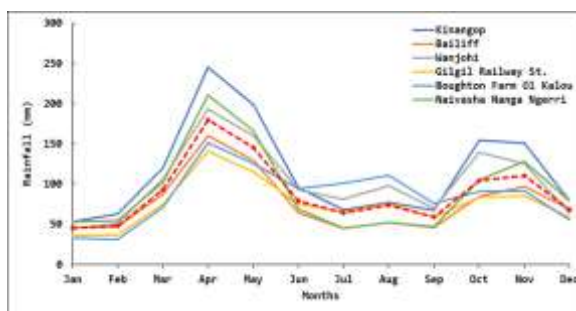


Fig. 3. Mean monthly rainfall distribution for selected stations over Lake Naivasha basin

Hydrology

Lake Naivasha is primarily fed by the Malewa, Gilgil, and Karati rivers, with the Malewa River contributing

about 80% of surface inflow, the Gilgil River about 18%, and the seasonal Karati River providing additional inflow during wet periods. Groundwater recharge contributes an estimated 15% of the lake's total inflow. As a closed-basin lake with no surface outlet, Lake Naivasha loses water mainly through evaporation, making its water balance highly sensitive to rainfall variability, water abstraction, and land-use changes within the catchment.

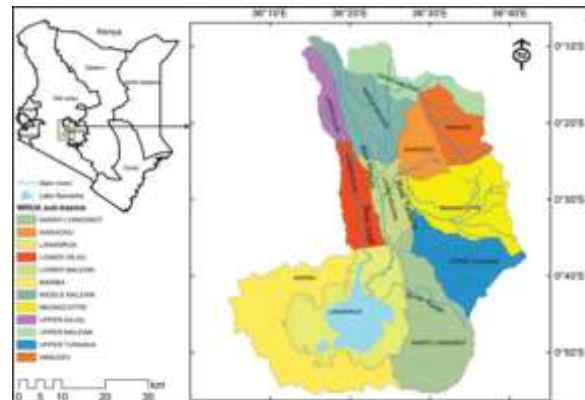


Fig. 4. A map of Lake Naivasha basin showing its hydrology and local water resources management units. Source: (Ogada *et al.*, 2017)

Land use and socio-economic characteristics

The Lake Naivasha Basin is one of Kenya's most intensively utilized freshwater catchments, supporting irrigated horticulture and floriculture, fisheries, livestock production, tourism, geothermal energy, and domestic and industrial water supply. The basin also contains ecologically important wetlands, riparian forests, and protected habitats that provide biodiversity conservation, groundwater recharge, flood regulation, and water purification services. However, rapid agricultural expansion, urbanization, deforestation, wetland encroachment, pollution, and increasing water abstraction have degraded these ecosystems and intensified competition among agricultural, environmental, industrial, and domestic water users.

Water resources management

Water resources in the basin are managed through integrated catchment initiatives led by the Imarisha Naivasha Programme, abstraction regulation by the Water Resources Authority (WRA), and

infrastructure projects such as the Turasha Dam. Despite these interventions, increasing water demand, declining water quality, land-use change, illegal riparian encroachment, and climate variability continue to pose significant management challenges.

Data sources

The study integrated meteorological, hydrological, remote sensing, land-use, and socio-economic datasets covering 1990–2023. Daily rainfall and temperature data were obtained from the Kenya Meteorological Department (KMD) and complemented with CHIRPS rainfall data. River discharge, lake water levels, and groundwater records were acquired from the Water Resources Authority (WRA). Land-use and vegetation information were derived from Landsat, Sentinel, and digital elevation datasets, while socio-economic data, including water abstraction, population growth, and irrigation statistics, were obtained from the Kenya National Bureau of Statistics (KNBS), Nakuru County Government, Naivasha Water and Sewerage Company, and other government agencies.

Data quality control

All datasets underwent quality control to identify missing values, outliers, and inconsistencies. Missing rainfall observations (<10%) were estimated using the Normal Ratio Method and Inverse Distance Weighting (IDW). Homogeneity was evaluated using the Pettitt, Buishand Range, and Standard Normal Homogeneity (SNHT) tests, while serial correlation was assessed using lag-1 autocorrelation and the Ljung–Box test. Where necessary, Trend-Free Pre-Whitening (TFPW) was applied before trend analysis. Daily data were aggregated into monthly, seasonal, and annual series, and spatial datasets were standardized to a common 0.05° resolution.

Rainfall variability and trend analysis

Rainfall variability was assessed using descriptive statistics, including the mean, standard deviation, coefficient of variation (CV), seasonal totals, and the Rainfall Anomaly Index (RAI).

Spatial rainfall patterns were mapped using Ordinary Kriging and Inverse Distance Weighting (IDW). Temporal trends in rainfall, river discharge, and lake water levels were analysed using the non-parametric Mann–Kendall test, while Sen's slope estimator quantified trend magnitude. Analyses were performed for annual rainfall and the long-rain (March–May) and short-rain (October–December) seasons at a 95% confidence level.

Hydrological and spatial analysis

Hydrological responses were evaluated using river discharge, lake water levels, and groundwater observations. Pearson and Spearman correlation, regression, and cross-correlation analyses were used to examine relationships and response lags between rainfall and hydrological variables. Catchment water balance was assessed using:

$$P - ET - Q = \Delta S$$

where P is precipitation, ET is evapotranspiration, Q is surface runoff, and ΔS represents changes in surface and groundwater storage.

GIS and remote sensing techniques were used to assess rainfall distribution, land-use change, vegetation dynamics, wetland extent, and lake surface fluctuations, with spatial overlay analyses examining interactions among climate, hydrology, land use, and ecosystem condition.

Statistical analysis and uncertainty assessment

Statistical analyses were conducted in R 4.3.2 using the trend, Kendall, hydroTSM, ggplot2, and tidyverse packages. Spatial analyses were performed in ArcGIS 10.8 and QGIS 3.28, with supplementary analyses in SPSS 28. Uncertainty was evaluated using 1,000 bootstrap resamples, Root Mean Square Error (RMSE) comparisons between station and CHIRPS rainfall data, and sensitivity analyses based on $\pm 10\%$ rainfall perturbations.

Ethical considerations

Meteorological and hydrological data were obtained with permission from the Kenya Meteorological

Department and the Water Resources Authority. All data were processed and reported in accordance with institutional requirements and the FAIR (Findable, Accessible, Interoperable, and Reusable) data principles.

RESULTS AND DISCUSSION

Rainfall temporal variability patterns and trends

The Mann–Kendall (MK) test indicated predominantly non-significant trends in annual rainfall across the Lake Naivasha Basin ($Z < 1.2, p >$

0.05). Most stations exhibited slight declining trends, while Nyandarua and Gilgil recorded weak positive trends ($Z = 0.9–1.4$), suggesting localized increases in rainfall. Sen's slope estimates ranged from -3.2 to $+2.8 \text{ mm yr}^{-1}$, indicating low-magnitude and spatially variable rainfall changes over the 1990–2023 period (Table 1, Fig. 5, 6 & 7).

Longonot recorded a weak, non-significant declining trend in annual rainfall ($Z = -1.11, p = 0.27$), with a Sen's slope of -3.2 mm yr^{-1} , indicating a gradual decrease over the study period.

Table 1. Mann–Kendall (MK) test statistics and Sen's slope estimates for annual rainfall trends in the Lake Naivasha Basin (1990–2023).

Station	Mean annual rainfall (mm)	MK Z-statistic	p-value	Sen's Slope ($\text{mm}\cdot\text{yr}^{-1}$)	Trend direction
Naivasha	812	-0.94	0.35	-2.6	Decreasing
Gilgil	967	+1.22	0.22	+1.8	Increasing
Nyandarua	1023	+1.44	0.15	+2.4	Increasing

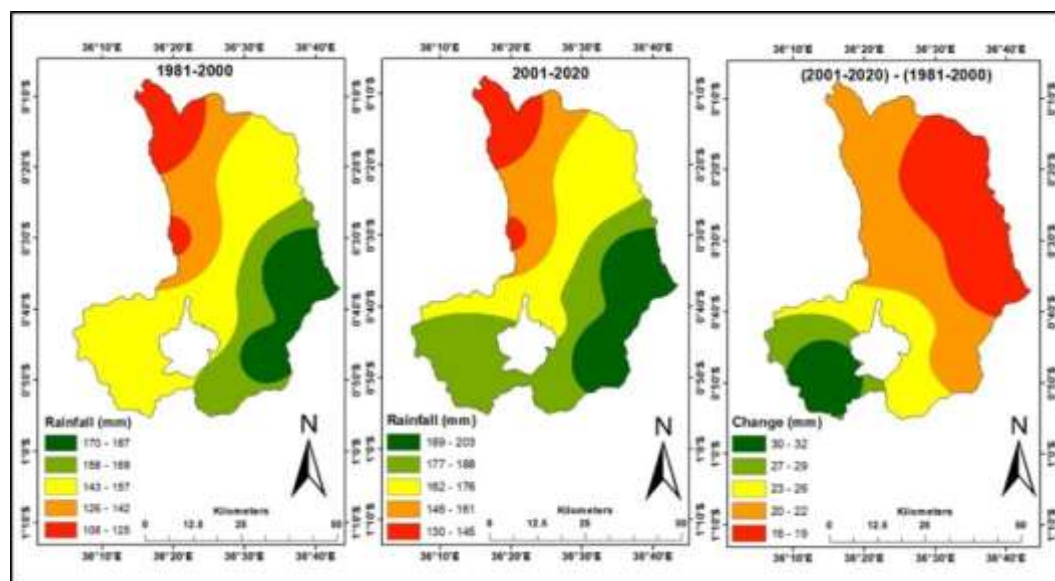


Fig. 5. The mean seasonal rainfall over the Lake Naivasha Basin during the March–April–May season of (a) 1981–2000, (b) 2001–2020, and (c) is the seasonal change between (a) and (b)

Seasonal Mann–Kendall analysis revealed contrasting rainfall patterns. The long rains (March–May; MAM) generally exhibited weak declining trends ($Z = -1.4$ to $-1.8, p > 0.10$), whereas the short rains (October–December; OND) showed increasing trends ($Z = 1.5–2.3, p < 0.10$), consistent with regional observations linking

enhanced OND rainfall to Indian Ocean Dipole (IOD) variability (Wainwright *et al.*, 2019). These findings indicate that rainfall seasonality is changing more markedly than annual rainfall totals, with potential implications for agricultural water availability, reservoir recharge, and water resources management.

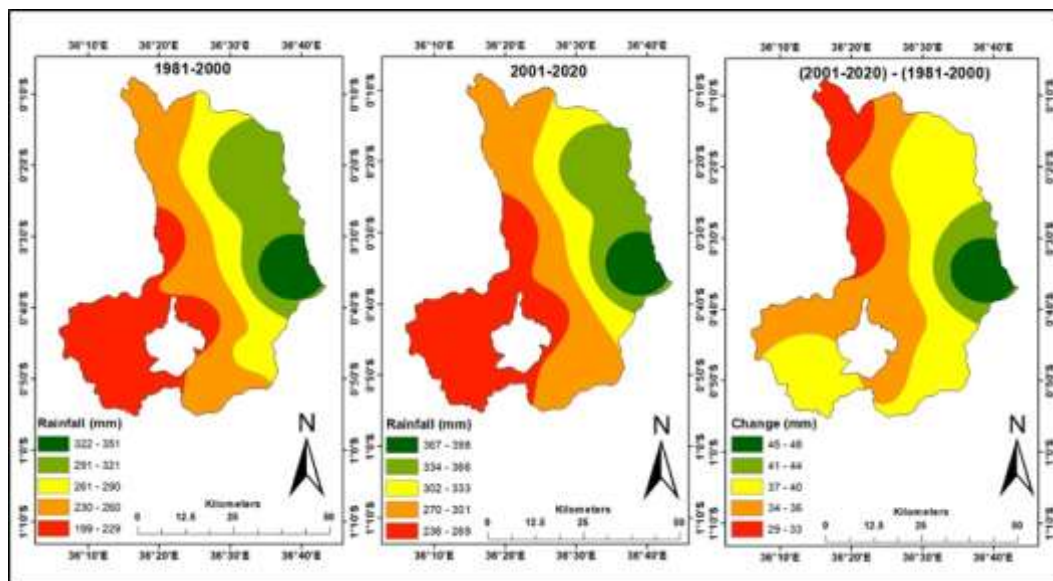


Fig. 6. Mean seasonal rainfall over the Lake Naivasha Basin during the September–October–November (SON) season for (a) 1981–2000, (b) 2001–2020, and (c) the difference between the two periods

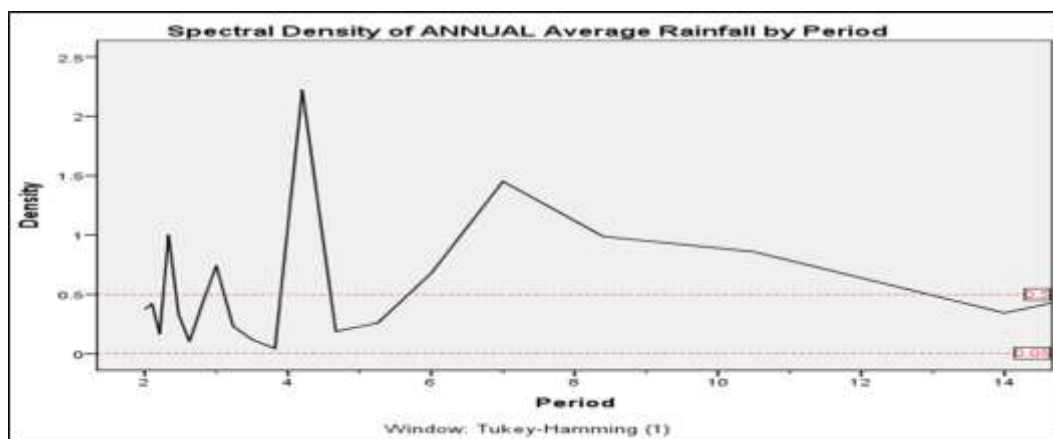


Fig. 7. Spectral analysis of total annual rainfall during the March–May (MAM) season in the Lake Naivasha Basin (1981–2022)

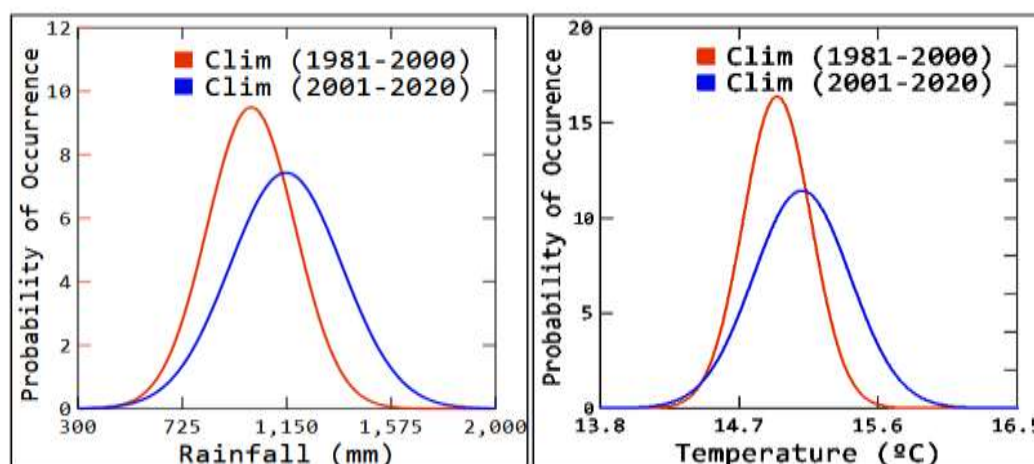


Fig. 8. Spatial distribution of (a) annual rainfall and (b) mean annual temperature for the period 1981–2020, illustrating climate patterns and shifts across different climatic periods in the Lake Naivasha Basin

Rainfall variability and long-term trends

Analysis of rainfall records (1981–2022) revealed marked inter-annual and seasonal variability across the Lake Naivasha Basin (Fig. 8). Annual rainfall ranged from approximately 620 mm in dry years (e.g., 2000 and 2009) to about 1,180 mm in wet years (e.g., 1997 and 2018). The long rains (March–May; MAM) contributed approximately 55–60% of annual rainfall, while the short rains (October–December; OND) accounted for 30–35%. Annual rainfall exhibited moderate variability, with coefficients of variation ranging from 18% to 25%, reflecting alternating wet and dry cycles associated with the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) (Nicholson, 2017; Owiti *et al.*, 2011).

The Mann–Kendall test indicated predominantly non-significant trends in annual rainfall across the basin ($Z < 1.2, p > 0.05$). Sen's slope estimates ranged from -3.2 to $+2.8$ mm yr⁻¹, indicating only minor long-term changes in annual rainfall. However, seasonal analyses revealed contrasting patterns: the long rains (MAM) showed weak declining trends ($Z = -1.4$ to -1.8), whereas the short rains (OND) exhibited increasing trends ($Z = 1.5$ – $2.3, p < 0.10$), consistent with reports of strengthening short rains in East Africa (Wainwright *et al.*, 2019). These findings suggest that rainfall seasonality is changing more noticeably than total annual rainfall, with potential implications for agriculture, groundwater recharge, and reservoir inflows.

Spatial distribution of rainfall

Spatial interpolation using Ordinary Kriging showed that rainfall is highest ($>1,000$ mm yr⁻¹) in the elevated northern and eastern catchments and decreases towards the lower southern and western areas surrounding Lake Naivasha (<800 mm yr⁻¹). Trend maps indicate weak rainfall declines around the lake and modest increases in the upper catchment, reflecting the combined influence of topography and land-use change, including expanding irrigated agriculture and urbanization.

Streamflow variability and trends

Streamflow records from the Malewa and Gilgil rivers (1990–2023) showed substantial temporal variability associated with rainfall fluctuations, catchment changes, and increasing water abstraction. The Malewa River, the major contributor to Lake Naivasha inflows, recorded mean annual discharges of 12.5 – 35.8 m³ s⁻¹, while the Gilgil River ranged from 3.5 – 9.2 m³ s⁻¹. Peak flows occurred mainly during the long rains (April–May), with secondary peaks during the short rains (November). Prolonged low-flow periods in 1999–2001, 2008–2010, and 2016–2017 coincided with drought conditions and were further influenced by increased irrigation abstraction, catchment degradation, and reduced baseflow contributions.

The Mann–Kendall analysis revealed significant declining trends in annual streamflow for both the Malewa ($Z = -2.3, p < 0.05$) and Gilgil ($Z = -2.0, p < 0.05$) rivers. Sen's slope estimates indicated declines of approximately -0.28 m³ s⁻¹ yr⁻¹ for Malewa and -0.23 m³ s⁻¹ yr⁻¹ for Gilgil, corresponding to an overall reduction of approximately 15–25% in mean annual discharge during the study period (Table 2, 3). Seasonal analysis showed stronger declines during dry periods (January–February and June–September), suggesting reduced baseflow availability and increasing vulnerability of the basin's water balance. These trends are consistent with previous studies linking declining Lake Naivasha inflows to catchment degradation, groundwater abstraction, and changing hydro-climatic conditions (Becht and Harper, 2002; Ondieki *et al.*, 2020).

The decline in streamflow is more pronounced during dry seasons, indicating reduced baseflow contributions possibly linked to deforestation and groundwater abstraction in the upper basin (Becht and Harper, 2002; Harper *et al.*, 2001).

Streamflow variability and rainfall–streamflow relationships

Annual streamflow in the Malewa and Gilgil rivers exhibited substantial interannual variability

throughout the study period. Mann–Kendall analysis showed no statistically significant trends in annual discharge ($p > 0.05$), although significant changes were observed in specific flow characteristics, including low flows, high flows, median flows, and baseflow conditions.

Monthly analyses indicated declining discharge during some dry-season months, suggesting increasing seasonal water stress despite relatively stable annual flow totals.

Correlation analysis demonstrated a strong positive relationship between annual rainfall and river discharge, with Pearson correlation coefficients ranging from 0.62 to 0.74 ($p < 0.01$), confirming rainfall as the primary climatic control of streamflow

variability. However, the rainfall–streamflow relationship weakened during recent decades, indicating increasing influence from non-climatic factors. Cross-correlation analysis showed an average lag of approximately one month between rainfall and streamflow response, reflecting the influence of soil moisture conditions, infiltration, groundwater recharge, and subsurface flow processes.

The weakening coupling between rainfall and discharge suggests that changes in land use, water abstraction, and catchment condition are modifying natural rainfall–runoff processes. Increasing irrigation demand, groundwater extraction, catchment degradation, and reduced infiltration capacity may therefore contribute to declining dry-season flows and reduced effective water availability.

Table 2. Mann–Kendall and Sen’s slope results for annual streamflow (1990–2023)

Station	Mean annual flow ($\text{m}^3\cdot\text{s}^{-1}$)	MK Z-statistic	p-value	Sen’s Slope ($\text{m}^3\cdot\text{s}^{-1}\cdot\text{yr}^{-1}$)	Trend direction	Significance
Malewa	24.3	-2.31	0.02	-0.28	Decreasing	Significant
Gilgil	6.4	-2.04	0.04	-0.23	Decreasing	Significant

Table 3. Annual streamflow trends for the Malewa River (1990–2023) with Sen’s slope lines showing decreasing flow magnitude

River	Period	Mann–Kendall (MK)	Sen's slope	Interpretation
Malewa River	1990–2023	No significant trend ($p > 0.05$)	Not reported	Annual discharge fluctuated considerably but showed no statistically significant long-term increase or decrease.
Gilgil River		No significant trend ($p > 0.05$)	—	Decreasing flows during some dry-season months, but these did not translate into a significant annual trend

Implications for water resources sustainability

Changes in rainfall seasonality and streamflow dynamics have important implications for water security in the Lake Naivasha Basin. Although annual rainfall totals have shown limited long-term change, increasing rainfall variability, intense storm events, and prolonged dry periods may alter groundwater recharge, increase surface runoff, and accelerate erosion. These changes could reduce the reliability of seasonal water availability despite relatively stable annual precipitation.

Reduced and more variable inflows affect Lake Naivasha’s hydrological balance, environmental

flows, and water quality. Lower inflow volumes reduce the lake’s capacity to dilute nutrients and pollutants, increasing risks of eutrophication, algal blooms, and ecosystem degradation. These impacts directly affect fisheries, biodiversity, tourism, irrigated agriculture, and domestic water supply.

Improving basin resilience requires strengthened Integrated Water Resources Management (IWRM), including improved regulation of surface and groundwater abstraction, catchment restoration, protection of riparian ecosystems, enhanced monitoring, and adoption of climate adaptation measures such as water-efficient irrigation, rainwater

harvesting, wastewater reuse, and drought preparedness.

Lake water levels and land–water interactions (1981–2022)

Lake Naivasha water levels exhibited substantial interannual variability, with a notable rise after 2010. Elevated lake levels resulted in extensive flooding of riparian areas, agricultural land, infrastructure, and settlements, particularly along the northern shoreline. Satellite observations indicated expansion of the lake surface area during high-water periods, resulting in approximately 34.4 km² of terrestrial land inundation between 2008 and 2020.

Changes in lake extent influenced riparian vegetation, wetland dynamics, sediment transport, and shoreline stability. Hydrological fluctuations also affected ecosystem productivity, with lake surface variation reported to influence fisheries production and revenue. Meanwhile, increasing nutrient loading, sediment inputs, agricultural runoff, and shoreline disturbance have contributed to declining water quality and increased ecological vulnerability.

The findings indicate that rainfall variability alone does not fully explain hydrological changes within the Lake Naivasha Basin. While rainfall trends were generally weak and non-significant, changes in streamflow characteristics and lake dynamics demonstrate increasing influence from anthropogenic pressures.

Hydrological responses have likely been modified by expansion of irrigated agriculture, groundwater abstraction, deforestation, wetland degradation, and urban development. These pressures alter infiltration, runoff generation, groundwater recharge, and evapotranspiration processes, causing increasing divergence between climatic inputs and hydrological responses. Similar impacts of abstraction and land-use change on basin hydrology have been reported by McCartney *et al.* (2010).

Catchment degradation further amplifies climate impacts by reducing infiltration capacity, increasing

runoff and erosion, and weakening dry-season baseflows. Reduced inflows also affect lake water quality by limiting pollutant dilution and increasing nutrient concentrations, turbidity, and electrical conductivity, thereby accelerating eutrophication and habitat degradation.

Lake level fluctuations create additional socio-economic challenges. High water levels have resulted in flooding of farms, settlements, infrastructure, and riparian habitats, while reduced dry-season inflows increase competition among agricultural, industrial, domestic, and ecological water users. Sustainable management therefore requires addressing both climate variability and human-induced pressures through integrated catchment planning.

CONCLUSION

This study demonstrates that rainfall variability in the Lake Naivasha Basin has increased over recent decades, although long-term annual rainfall trends remain weak and largely non-significant. In contrast, hydrological responses show increasing variability, particularly in seasonal streamflow behaviour and lake-level fluctuations, indicating that human activities are becoming important drivers of basin hydrological change.

The weakening relationship between rainfall and streamflow highlights the influence of land-use change, groundwater abstraction, catchment degradation, and increasing water demand on water availability. These pressures have contributed to altered flow regimes, declining ecosystem resilience, and increased vulnerability of water-dependent livelihoods.

Lake level variability has significantly affected shoreline dynamics, riparian ecosystems, infrastructure, agriculture, and fisheries, demonstrating the close link between hydrological processes and socio-economic outcomes. Effective management of the basin requires integrated approaches that combine climate adaptation, catchment conservation, sustainable abstraction, and ecosystem protection.

RECOMMENDATIONS

1. Expand hydro-meteorological monitoring networks to improve long-term assessment of rainfall, streamflow, groundwater, and water quality trends.
2. Strengthen regulation and enforcement of surface and groundwater abstraction permits, particularly for irrigation activities.
3. Restore degraded upper catchments through reforestation, riparian rehabilitation, and wetland conservation to improve infiltration and sustain environmental flows.
4. Integrate remote sensing and GIS approaches into routine monitoring of land-use change, lake dynamics, vegetation condition, and hydrological variability.
5. Improve flood and drought preparedness through early warning systems, climate-informed infrastructure planning, and water storage strategies.
6. Promote stakeholder-based Integrated Water Resources Management (IWRM) to balance agricultural, industrial, domestic, and ecological water needs.
7. Incorporate future climate projections into basin planning while promoting efficient irrigation technologies, water reuse, rainwater harvesting, and demand management.

Together, these measures provide a framework for enhancing climate resilience, protecting ecosystem services, and sustaining the ecological and socio-economic value of the Lake Naivasha Basin under increasing hydro-climatic and anthropogenic pressures.

REFERENCES

- Becht R, Harper DM.** 2002. Towards an understanding of human impact upon the hydrology of Lake Naivasha, Kenya. *Hydrobiologia* **488**(1), 1–11. DOI: 10.1023/A:1023395616716
- Harper DM, Mavuti KM, Muchiri SM.** 2001. Ecology and management of Lake Naivasha, Kenya, in relation to climatic and anthropogenic influences. *Hydrobiologia* **458**, 11–23.

Intergovernmental Panel on Climate Change (IPCC). 2021. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press.

Intergovernmental Panel on Climate Change. 2022. *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press.

Kuhn A, Britz W, Kyalo Willy D, van Oel PR. 2016. Simulating the viability of water institutions under volatile rainfall conditions—The case of the Lake Naivasha Basin. *Environmental Modelling & Software* **75**, 373–387.

McCartney M, King J, Cheesman J. 2010. *Environmental Flows and Water Management in Lake Naivasha Basin.* International Water Management Institute.

Mengich BM, Karanja AM, Ogendi GM, Morara GN. 2024. Effects of surface area and water level variability on fisheries production in Lake Naivasha, Kenya. *Journal of the Kenya National Commission for UNESCO* **4**(2).

Mulatu DW, van der Veen A, van Oel PR. 2014. Farm households' preferences for collective and individual actions to improve water-related ecosystem services: The Lake Naivasha basin, Kenya. *Ecosystem Services* **7**, 22–33.

Nicholson SE. 2017. Climate and climatic variability of rainfall over eastern Africa. *Journal of Arid Environments* **139**, 4–20. DOI: 10.1016/j.jaridenv.2016.12.006

Ogada JO, Krhoda GO, van der Veen A, Marani M, van Oel PR. 2017. Managing resources through stakeholder networks: Collaborative water governance for Lake Naivasha basin, Kenya. *Water International* **42**(3), 271–290.

Ondieki CM, Home PG, Mutua BM, Gathenya JM. 2020. Impact of climate variability and land use on hydrological processes in the Lake Naivasha Basin, Kenya. *Water* **12(3)**, 854.
DOI: 10.3390/w12030854

Owiti Z, Ogallo LA, Mutemi J. 2011. Linkages between ENSO, Indian Ocean Dipole and rainfall variability over Eastern Africa. *International Journal of Climatology* **31(4)**, 505–517.

Wainwright CM, Marsham JH, Keane RJ, Rowell DP, Finney DL, Black E, Allan RP. 2019. ‘Eastern African Paradox’ rainfall decline due to shorter not less intense Long Rains. *npj Climate and Atmospheric Science* **2**, 34.

Yongo E, Agembe SW, Manyala JO, Mutethya E. 2023. Assessment of the current trophic state and water quality of Lake Naivasha, Kenya, using multivariate techniques. *Lakes and Reservoirs: Science, Policy and Management for Sustainable Use* **28(1)**, e12432. DOI: 10.1111/lre.12432