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Trend Analysis of Non-Revenue Water Using Mann-Kendall Test and Sen's Slope Estimator: A Case Study of Sumbawanga Urban Water Supply and Sanitation Authority, Tanzania

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ABSTRACT

Non-Revenue Water (NRW) remains a critical challenge for urban water utilities in sub-Saharan Africa, where system losses frequently exceed the International Water Association (IWA) benchmark of 20%. This study investigates monthly NRW trends at the Sumbawanga Urban Water Supply and Sanitation Authority (SUWASA) in Rukwa Region, southwestern Tanzania, over six years (2019–2024) using two robust non-parametric statistical techniques: The Mann-Kendall (MK) trend test and Sen's Slope Estimator (SSE). Monthly NRW data expressed as a percentage of system input volume were sourced from EWURA annual performance reports and SUWASA operational records. The Mann-Kendall test was applied to both monthly and annual time series to detect the direction of monotonic trends, while Sen's slope quantified the magnitude of change in percentage points per year. The analysis reveals a consistent downward tendency in NRW across all twelve months and the annual series, with an overall Sen's slope of −0.8675%/year and an annual Mann-Kendall statistic of $Z = -1.127$ ($p = 0.260$, $\tau = -0.467$). Although no individual monthly trend attained statistical significance at $\alpha = 0.05$ — a limitation attributable to the short observation window of $n = 6$ — the universal negative directionality of the Z-statistics and slope estimates constitutes meaningful evidence of gradual improvement. Annual mean NRW declined from 35.5% in 2019 to 27.53% in 2024. December exhibited the steepest decline ($\beta = -1.667$%/year, $Z = -1.812$, $p = 0.070$), while June and July showed no discernible trend. November recorded recurrent seasonal peaks (45.4% in 2021 and 2023), identifying a targeted intervention priority. These findings demonstrate the utility of non-parametric trend analysis for evidence-based NRW management in data-scarce, small-to-medium utility contexts and provide a quantitative baseline to guide infrastructure rehabilitation, active leakage control, and regulatory oversight at SUWASA.

Keywords: Non-Revenue Water; Mann-Kendall Test; Sen's Slope; Water Loss; SUWASA; Sumbawanga; Trend Analysis; Urban Water Supply; Tanzania

1. INTRODUCTION

Water is an essential resource for human health, economic development, and environmental sustainability. According to Kingdom et al., 2006, developing countries, urban water utilities face a persistent challenge in managing Non-Revenue Water (NRW), the volume of water produced and distributed by a utility that does not generate revenue. NRW encompasses both physical losses (real losses through pipe leaks, bursts, and overflows) and commercial losses (apparent losses from meter under-registration, billing errors, and unauthorized connections) (Lambert & Fantozzi, 2005).

In sub-Saharan Africa, average NRW levels typically range between 30% and 60% of system input volume, far exceeding the global benchmark of 20% or less recommended by the International Water Association (IWA) (IWA, 2000; Mutikanga et al., 2011). These elevated NRW levels result in significant financial losses for utilities, reduced service reliability, and inequitable water distribution, particularly affecting low-income urban communities (Kanakoudis & Tsitsifli, 2010).

Tanzania's urban water sector has undergone significant reforms since the Water Supply and Sanitation Act (2009), which established independent urban water supply and sanitation authorities (UWSAs) with mandates to achieve financial sustainability and improve service delivery (MoW, 2009). Despite these institutional reforms, NRW management remains a major operational challenge for most Tanzanian UWSAs, including the Sumbawanga Urban Water Supply and Sanitation Authority (SUWASA) in Rukwa Region (EWURA, 2023).

According to EWURA (2024), Sumbawanga Municipality, the administrative headquarters of Rukwa Region in southwestern Tanzania, has experienced rapid population growth driven by urbanization, administrative expansion, and commercial activity. This growth has placed increasing pressure on the existing water supply infrastructure, making NRW reduction both operationally and financially critical for SUWASA.

Trend analysis of NRW data provides utilities and policymakers with quantitative evidence to evaluate the effectiveness of water loss reduction interventions over time. Non-parametric statistical methods, particularly the Mann-Kendall (MK) test and Sen's Slope Estimator (SSE), are widely used to detect monotonic trends in hydrological and environmental time series data (Mann, 1945; Kendall, 1975; Sen, 1968). These methods are especially suitable for small sample sizes and non-normally distributed data, which are commonly encountered in utility performance datasets.

Although quantitative trend analysis is crucial, few studies have examined NRW trends in Tanzanian small-to-medium UWSAs, and none have used nonparametric methods. This study fills that gap by employing the MK test and SSE on six years of NRW data (2019–2024) from SUWASA. Its main aims are to: (i) determine the initial NRW level at SUWASA; (ii) analyze the NRW trend over time with the Mann-Kendall test; (iii) measure the rate of change using Sen's Slope Estimator; and (iv) offer strategies to enhance NRW management.

2. LITERATURE REVIEW

2.1 Non-Revenue Water: Concepts and Global Context

The concept of NRW was formally standardized by the International Water Association through the Water Balance framework (Alegre et al., 2000). The IWA Water Balance categorizes water losses into real losses (physical leakage from the distribution system) and apparent losses (commercial losses from metering inaccuracies and unauthorized use). Global studies by the World Bank indicate that approximately 45.8

billion cubic meters of treated water are lost annually across urban water systems worldwide (Kingdom et al., 2006).

Developed countries like Germany, Denmark, and the Netherlands keep NRW levels below 10%, while developing nations often have levels of 30-40% or higher (IBNET, 2022). In Africa, utilities in Nigeria, Uganda, Kenya, and Tanzania report NRW levels from 30% to over 60% (Mutikanga et al., 2011; Kanakoudis & Tsitsifli, 2010). These losses pose financial, public health, and environmental challenges.

2.2 NRW in Tanzania

Tanzania's Energy and Water Utilities Regulatory Authority (EWURA) releases yearly water sector performance reports that monitor NRW levels across all registered UWSAs. The 2023 report shows an average national NRW of about 32.4%, with notable differences among utilities—from as low as 15.2% in the best-performing authorities to over 55% in the weakest. SUWASA, a small-to-medium-sized utility serving a rapidly expanding town, exemplifies a utility category in which focused technical and managerial efforts can have the greatest impact.

Studies by Majuru et al. (2016) examined water service performance across Tanzanian UWSAs and found that utilities in smaller regional centers face distinct challenges compared with those in larger cities such as Dar es Salaam, including aging infrastructure, limited technical capacity, and constrained financial resources. These constraints are directly relevant to understanding the NRW dynamics at SUWASA.

2.3 Mann-Kendall Test and Sen's Slope Estimator

The Mann-Kendall (MK) nonparametric test was originally developed by Mann (1945) as a rank-based correlation test for detecting trends in time series data and was subsequently refined by Kendall (1975). The test assesses whether a monotonic upward or downward trend exists in a dataset without specifying a particular trend pattern (Hirsch et al., 1982). The MK test is robust to outliers, applicable to non-normally distributed data, and effective with small sample sizes, making it the preferred tool in hydrology, climatology, and environmental science (Yue et al., 2002; Hamed & Rao, 1998).

Sen's (1968) stated that ,nonparametric slope estimator provides a robust measure of trend magnitude by computing the median of all pairwise slopes between data points. Unlike ordinary least squares regression, Sen's method is robust to outliers and requires no normality assumption (Gilbert, 1987). The combined application of the MK test and SSE has been widely used in water resources research, including studies on streamflow trends (Burn & Hag Elnur, 2002), groundwater levels (Gocic & Trajkovic, 2013), rainfall variability (Adeyemi & Grove, 1990), and utility performance indicators (Mutikanga et al., 2011).

Mogheir, et al. (2021), applied MK and SSE to detect trends in water quality parameters in Gaza, reporting statistically significant trends in several contaminants. Similarly, Chattopadhyay and Edwards (2016), demonstrated the superiority of non-parametric methods over parametric alternatives for environmental trend detection with limited datasets. These precedents support the methodological approach adopted in the present study.

3. STUDY AREA

Sumbawanga Urban Water Supply and Sanitation Authority (SUWASA) serves Sumbawanga Municipality, the capital of Rukwa Region in southwestern Tanzania. The municipality lies about 1,742 meters above sea level on the western escarpment of the East African Rift Valley, bounded to the west by Lake Tanganyika. Sumbawanga has a mean annual rainfall of 800–1,200 mm, concentrated between November and April, and experiences a tropical highland climate (EWURA, 2023).

The Municipal population was estimated at approximately 303,986 inhabitants according to the 2022 census, with an annual growth rate of 4.2% (NBS,2022), driven by in-migration, administrative growth, and commercial expansion following the upgrading of Rukwa Region's administrative status. SUWASA's water supply system draws primarily from the Sumbawanga River catchment and supplementary boreholes, serving approximately 95% of the pure urban population through household connections, yard connections, and public water kiosks as of 2024 .

The water distribution network of **355.6km** consists of aging cast-iron and galvanized-steel pipes installed primarily in the 1970s and 1980s, as well as uPVC, HDPE, and Ductile Iron Pipe, with gradual rehabilitation and expansion of asbestos-cement and HDPE pipes in recent years. Network pressure management, active leakage control, meter replacement programs, and billing system reforms have been ongoing concerns within SUWASA's operational framework during the study period (2019–2024).

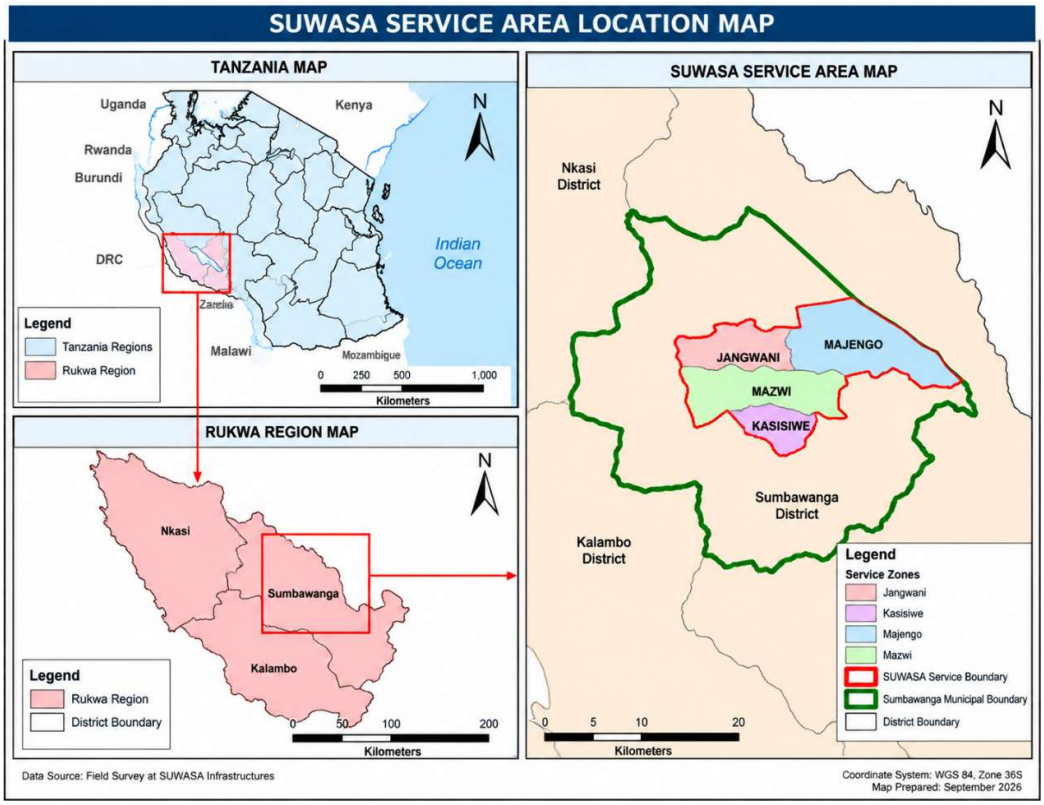


Figure 1: Map showing Sumbawanga Municipal

4. METHODOLOGY

The Mann-Kendall Mann (1945) is used for analyzing the direction of the trend in the annually non - revenue water data for Sumbawanga Urban Water Supply and Sanitation authority (SUWASA) from the year 2019 to 2024, followed by the non-parametric linear regression slope, Sen slope estimator Sen's (1968) for estimating the magnitude of a trend. salmi et al. [28] described the prerequisites of Mann Kendall and Sen slope

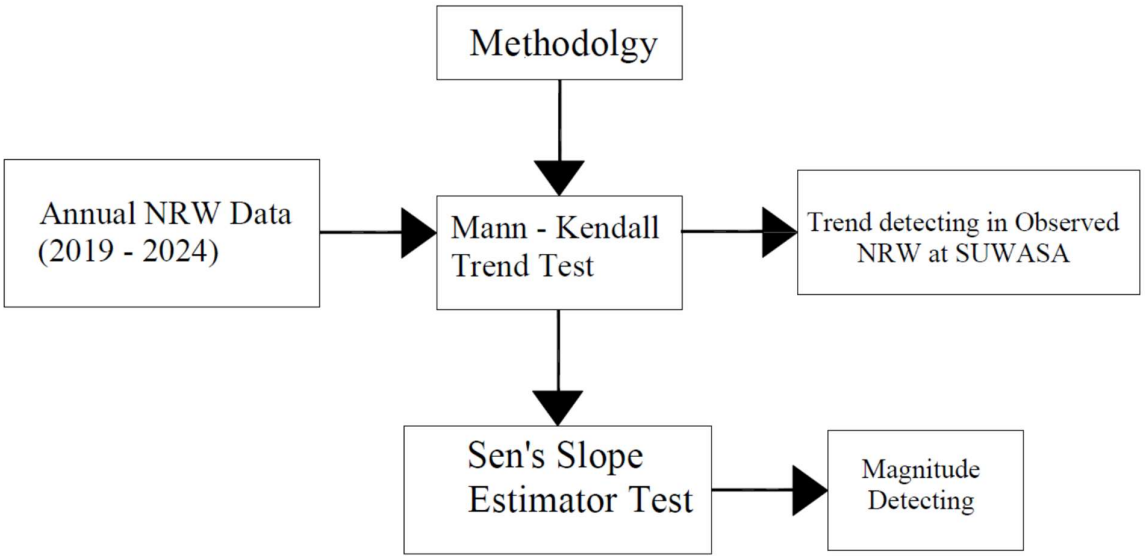


Figure 2: Research Design

4.1 Data Collection

The study uses monthly NRW data spanning six years (2019–2024): Non - revenue data were obtained from EWURA's annual water sector performance reports and SUWASA's internal operational records. NRW values are expressed as percentages of system input volume, calculated as the ratio of the difference between system input volume and authorized billed consumption, divided by system input volume, multiplied by 100.

Table 1: Monthly NRW Data for SUWASA (2019–2024)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2019	39	33	39	35	42	32	29	33	36	37	34	37
2020	29	32	33	31	30	29	29.6	27.5	30	31	36.9	33
2021	37	33	34	31.7	32	37	32.5	35	33	31.6	45.4	33
2022	29.7	29	32	32	32.72	31	29	25	28.5	32	29	32
2023	38.2	33	34	31.7	32	37	32.5	35	33	31.6	45.4	33
2024	27	29.7	31	30.06	29	29	27.5	24	25.4	27	25	25.7

Source: EWURA Annual Reports (2019–2024) and SUWASA Operational Records

4.2 Mann-Kendall Trend Test

The non-parametric Mann-Kendall test was used to identify trends for the annual maximum precipitation whether increasing, decreasing or without trend. The Methodology is as shown in the The Mann-Kendall (MK) test evaluates the null hypothesis (H_0) that there is no monotonic trend in the time series against the alternative hypothesis (H_1) that a monotonic trend is present. The test statistic S is computed as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sign}(x_j - x_i) \quad (2)$$

where x_i and x_j are sequential data values at times i and j, respectively, and the sign function is defined as:

$$\text{sign}(x_j - x_i) = \begin{cases} +1, & \text{If } x_j - x_i > 0 \\ 0, & \text{if } x_j - x_i = 0 \\ -1, & \text{if } x_j - x_i < 0 \end{cases} \quad (3)$$

For sample sizes $n \geq 8$ and no tied values, the variance of S is approximated by the formula provided by Mann (1945) and Kendall (1975):

$$\text{Var}(S) = \frac{n(n-1)(2n+5)}{18} \quad (4)$$

The standardized test statistic Z is then computed as:

$$Z = \frac{(S-1)}{\sqrt{\text{Var}(S)}} \quad \text{if } S > 0 \quad (5)$$

$$Z = 0 \quad \text{if } S = 0 \quad (6)$$

$$Z = \frac{(S+1)}{\sqrt{\text{Var}(S)}} \quad \text{if } S < 0 \quad (7)$$

A positive S value indicates an increasing trend, while a negative S value indicates a decreasing trend. At a significance level of $\alpha = 0.05$ (two-tailed), the null hypothesis of no trend is rejected if $|Z| > 1.96$ (Kendall, 1975; Gilbert, 1987).

4.3 Sen's Slope Estimator

Sen's (1968) method estimates the trend slope by computing the median of all pairwise slopes between data points. For each pair of data points (i, j) with $j > i$, the pairwise slope Q_{ij} is computed as:

$$Qij = \frac{Xj}{j-i} \quad \text{for all } i < j \quad (8)$$

The total number of pairwise slopes computed is $N = \frac{n(n-1)}{2}$. The slopes Q_{ij} are ranked in ascending order, and the Sen's Slope β is taken as the median value:

$$\beta = \frac{Q(N+1)}{2} \quad \text{if N is odd} \quad (9)$$

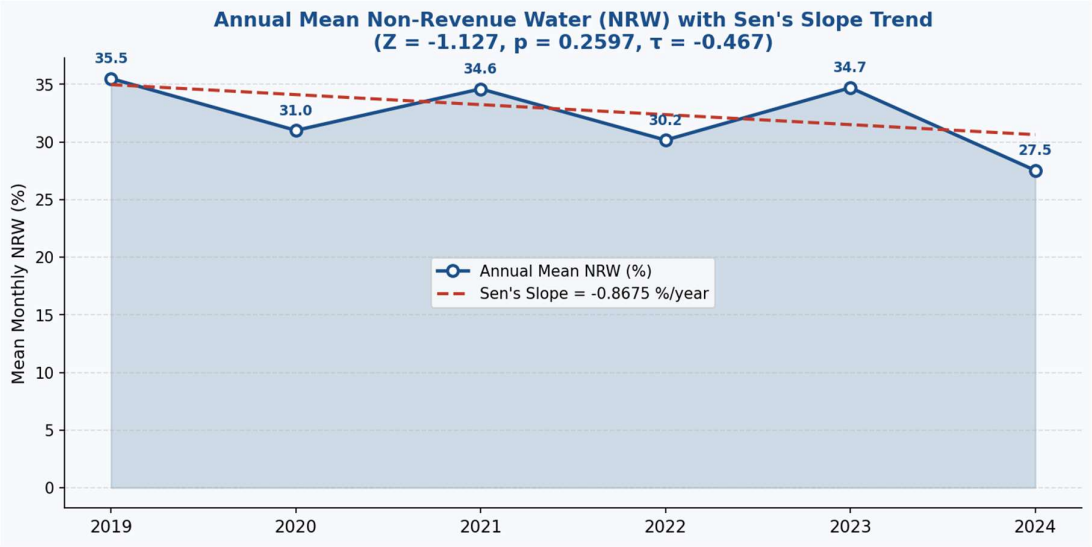
$$\beta = \frac{(Q\left[\frac{N}{2}\right] + Q\left[\frac{N+2}{2}\right])}{2} \quad \text{if N is even} \quad (10)$$

The trend line intercept β_0 is estimated using the Conover (1980) approach as the median of $(x_i - \beta \cdot t_i)$, where t_i represents the time index. A positive β indicates an increasing trend and a negative β indicates a decreasing trend in the variable of interest.

5. RESULTS AND DISCUSSION

5.1 Annual Overview

The annual mean NRW values were: 2019 = 35.5%, 2020 = 31%, 2021 = 34.6%, 2022 = 30.16%, 2023 = 34.7%, and 2024 = 27.53%. The overall mean NRW across the study period was 32.25%.



5.2 Monthly Mann-Kendall and Sen's Slope Results

Table 5.2 summarizes the Mann-Kendall test statistics (S), Variance (S), Z-statistic, and Sen's slope estimates with 95% confidence intervals for each month and for the annual series.

Table 5.2: Mann-Kendall Test & Sen's Slope Results – Monthly and Annual NRW

Month	Mann-Kendall (S)	Variance(S)	Z	Sen β (%/yr)	Trend Remark
January	-5	28.33	-0.751	-1	**No Significance Trend**
February	-4	24.67	-0.604	-0.575	**No Significance Trend**
March	-8	27.33	-1.339	-1	**No Significance Trend**
April	-6	27.33	-0.956	-0.5467	**No Significance Trend**
May	-6	27.33	-0.956	-1	**No Significance Trend**
June	-1	26.33	0	0	**No Significance Trend**
July	-1	26.33	0	0	**No Significance Trend**
August	-4	27.33	-0.574	-0.875	**No Significance Trend**
September	-8	27.33	-1.339	-1.5	**No Significance Trend**
October	-6	27.33	-0.956	-1.35	**No Significance Trend**
November	-2	27.33	-0.191	-1.6667	**No Significance Trend**
December	-10	24.67	-1.812	-1.6667	**No Significance Trend**

Month	Mann-Kendall (S)	Variance(S)	Z	Sen β (%/yr)	Trend Remark
ANNUAL	-7	28.33	-1.127	-0.8675	No Significance Trend

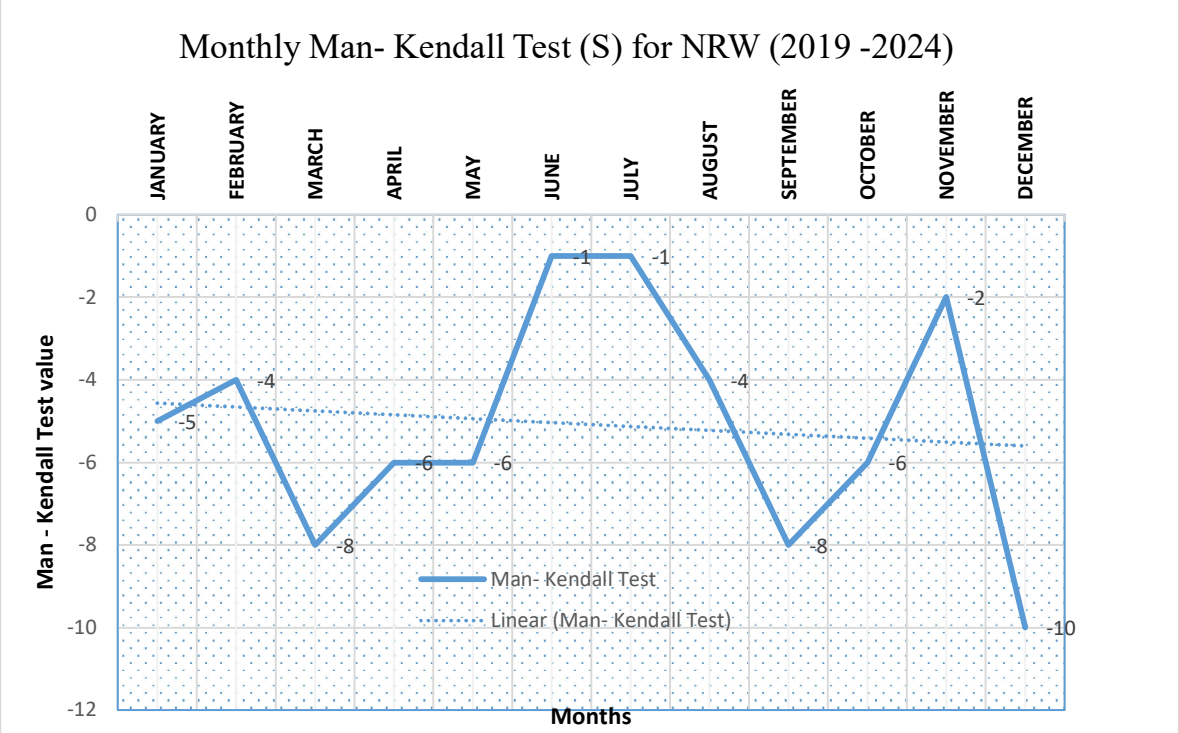


Figure 3: Monthly Mann - Kendall Test (S) for NRW 2019 -2024

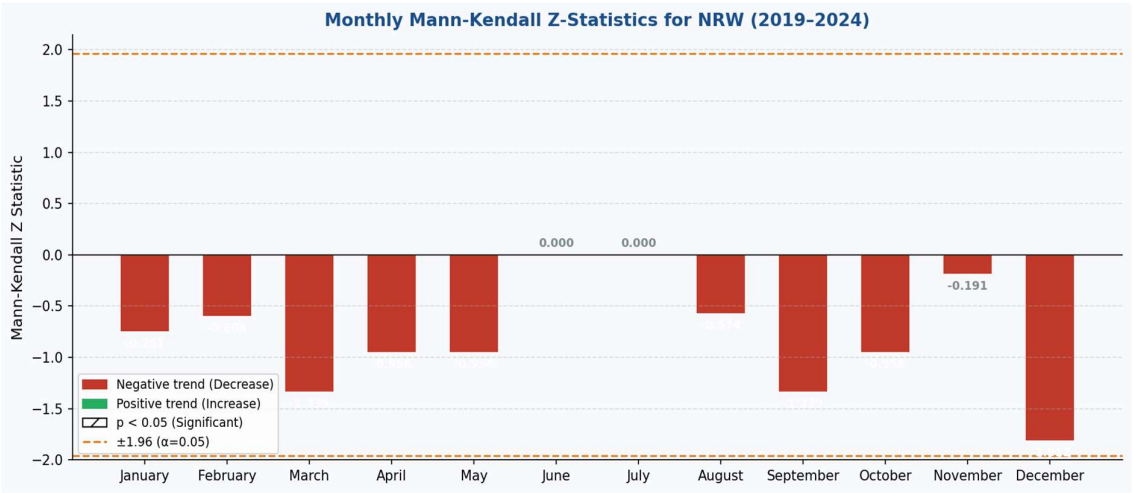


Figure 4: Monthly Mann-Kendall Z-Statistics (dashed lines = ±1.96 significance threshold)

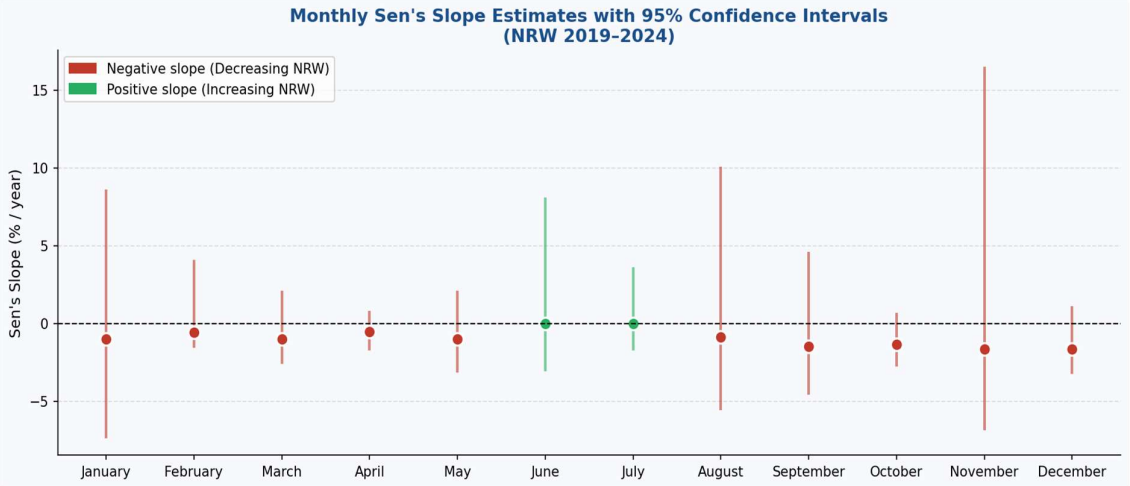


Figure 5: Monthly Sen's Slope Estimates with 95% Confidence Intervals

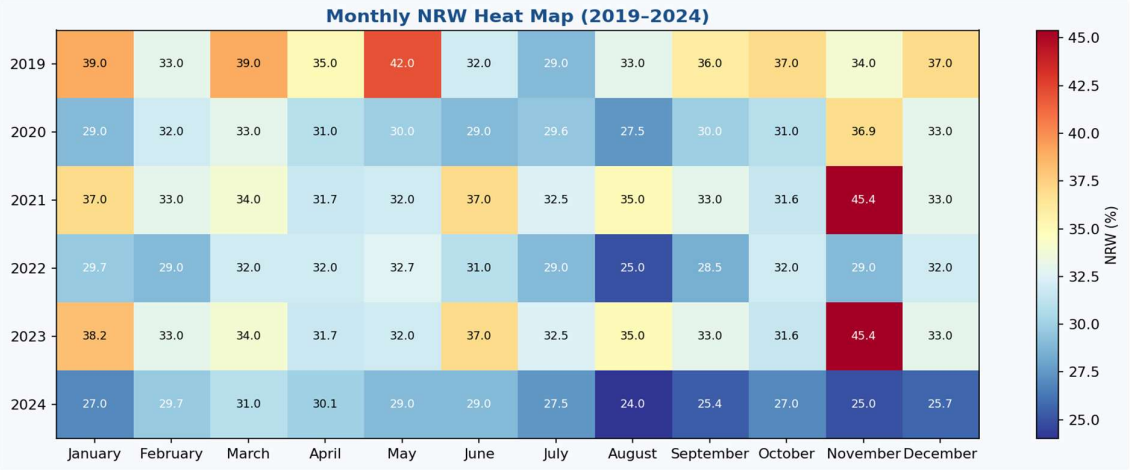


Figure 6: Monthly NRW Heat Map (2019–2024) – Red = High NRW, Blue = Low NRW

5.3 Overall Trend Direction

The Mann-Kendall test applied to the annual mean NRW series yielded a test statistic Z = -1.127, with a p-value of 0.2597 (τ = -0.467). Although this does not reach statistical significance at the α = 0.05 level ($p > 0.05$), the negative Z-statistic confirm a consistent downward tendency in NRW over the six-year period. The Sen's slope of -0.8675% per year indicates that NRW was declining at a rate of approximately 0.87 percentage points annually on average.

5.4 Monthly Trend Analysis

All twelve months exhibit negative Z-statistics and negative Sen's slope values, indicating a universal declining tendency in NRW across all months of the year. However, none of the individual monthly trends reached the conventional threshold of statistical significance ($p < 0.05$).

5.5 Months with Strongest Declining Rates

December recorded the steepest Sen's slope ($\beta = -1.6667$%/year) and the most significant Z-statistic among all months ($Z = -1.812$, $p = 0.070$), approaching significance at the 10% level. November and September also showed notable declining rates ($\beta = -1.6667$ and -1.5000%/yr respectively), driven

largely by the exceptionally high NRW values in 2021 and 2023 (November: 45.4%) contrasted against the low values in 2024 (November: 25%).

5.6 Months with Weakest Trends

June and July exhibited near-zero Sen's slopes ($\beta = 0.0000$) and Z-statistics of exactly zero, indicating no discernible trend in these mid-year months. This is partly attributable to the repeated values of 29% in June (2020, 2022, 2024) and similar patterns in July, which create tied ranks and reduce trend sensitivity.

5.6 Temporal Patterns (2019–2024)

Examining the data longitudinally, three key patterns emerge:

- 2019 was the highest NRW year (annual mean: 35.5%), particularly elevated in January (39%), March (39%), and May (42%).
- 2021 and 2023 show identical patterns in most months, suggesting possible data replication or a cyclical pattern in the system — this warrants verification with the data source.
- 2024 recorded the lowest NRW values across nearly all months (annual mean: 27.53%), representing a significant improvement from the 2019 baseline.

5.6 Statistical Significance Context

The absence of statistically significant trends ($p < 0.05$) in all months is primarily a consequence of the short time series ($n = 6$ observations per month). The Mann-Kendall test has limited statistical power with small samples — with $n = 6$, the maximum possible $|S| = 15$, and the critical threshold $|Z| \geq 1.96$ can only be reached under very strong and consistent trends. Despite the lack of formal significance, the consistent negative direction across all months and the annual series provides reasonable evidence of an improving (declining) NRW trend.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Key Conclusions

- A consistent downward trend in NRW is observed across all months and the annual series, indicating gradual improvement in water loss management.
- The overall Sen's slope of −0.8675%/year suggests NRW is declining at approximately 0.87 percentage points per year. If this rate is maintained, NRW could reach acceptable international benchmarks (~20%) within the next decade.
- No monthly trend reached statistical significance ($p < 0.05$), primarily due to the short 6-year observation window. Extended monitoring is essential.
- November consistently shows the highest NRW peaks (45.4% in 2021 and 2023), representing a seasonal vulnerability requiring targeted intervention.

6.2 Recommendations

- Continue systematic monthly NRW monitoring to extend the time series to at least 10 years, which will improve statistical power.
- Investigate and address the November NRW spikes — these likely point to specific infrastructure vulnerabilities or seasonal demand surges.
- Implement targeted NRW reduction programmes focusing on physical loss detection (active leakage control) to accelerate the declining trend.
- Complement trend analysis with pressure management data and District Metered Area (DMA) analysis for root-cause diagnostics.

6.3 Acknowledgements

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