



ORIGINAL RESEARCH ARTICLE

USING CLOUD-BASED APPLICATION FOR ASSESSMENT OF EXTREME THREAT  
OF CLIMATE IMPACT ON WATER RESOURCES: A CASE OF VAAL RIVER  
CATCHMENT, SOUTH AFRICA

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ABSTRACT

Climate change impact on water resources is becoming a global challenge with persistent escalation of threatening weather and changes in precipitation patterns. The study evaluates the extreme impacts of climate change in Vaal River in South Africa. The channel of Vaal River is an area with a critical water resource which supports agricultural, industrial and domestic activities. A three-decade dataset (1993-2023) of precipitation, temperature, streamflow, combined with surface water changes was engaged to examine climate impact on Vaal River water resources. Modified Normalized Difference Water Index (MNDWI) derived from Landsat-5 (1994–2012) and Landsat-8 (2013-2023) imagery on the Google Earth Platform (GEE) was also used to examine the seasonal water stress and availability. The results revealed increasing temperatures and irregular precipitation which are indications of climate altering condition resulting to decreased surface water coverage especially during dry seasons. MNDWI result records a fluctuating value indicating variations in both seasons. Further result revealed weak correlation between precipitation and streamflow, driven by anthropogenic regulations and land use. The MNDWI wet season's linear trendline showed a positive slope of 0.0046 and  $R^2$  value of 0.26 suggesting water availability over time. Similarly, polynomial trendline for the MNDWI dry season equally shows a moderate coefficient  $R^2$  value 0.38 Adaptive strategies, including Integrated Water Resource Management (IWRM) and advanced monitoring systems that will include stakeholders, planners and policy makers at all levels are recommended to mitigate these impacts. More effort should be channeled towards sustainable solutions such as tree planting, tree box filter and afforestation practices to reduce the effect of climate change on water resources.

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1.0 Introduction

Climate change is increasingly posing a significant challenge to the sustainability of global water resources. It has a variety of effects on water systems, including changes in precipitation patterns, more intense extreme weather, changes in the availability of water, and a decline in water quality (Chaturvedi et al., 2021; Xia et al., 2015). These changes threaten water security, with profound effect on ecosystems, human health survival, agricultural production and industrial activities (Raneesh, 2024; Yang et al., 2020). According to the Intergovernmental Panel on Climate Change (IPCC, 2021), heavy precipitation events have increased in frequency and intensity in many regions of the world. Conversely, areas like Southern Africa, North America, and the Mediterranean are seeing severe drought conditions and decreasing rainfall conditions (IPCC, 2021; Teweldebrihan and Dinka, 2024). This trend is indicative of more widespread disturbances to the global water cycle, which climate change is constantly changing (Bodunrin and Onyari, 2024). The hydrological cycle is becoming more intense due to rising temperatures, which causes precipitation changes to become more noticeable. Some regions are experiencing prolonged drought and increasing water scarcity, while others are getting more rainfall and even flooding (Chaturvedi et al., 2021; Xia et al., 2019).

South African's climate is influenced by its distinct location situated within the sub-tropical belt, which is encircled by an ocean on all side of the country (Dlamini *et al.*, 2023; Akanbi *et al.*, 2021; Hosea & Khalema, 2020; INR, 2019). The nation is also regarded as semi-arid region because of its diverse rainfall patterns and distribution (Botai *et al.*, 2018; Teweldebrihan and Dinka, 2024, Department of Water & Sanitation, 2018). South Africa has previously experienced sporadic droughts, and climate forecasts which suggest that such events will likely grow more regular and severe in the future (Fyna and Abiye, 2022; Schulze, 2000). This circumstance presents serious difficulties for urban water supply, agriculture, and water management (Gyamfi *et al.*, 2016).

Utilization of Remote Sensing (RS) methods, such as satellite imagery and Geographic Information Systems (GIS) is essential for tracking changes in water bodies (Cui *et al.* 2022; Bodunrin and Onyari, 2024; Dlamini *et al.*, 2023). The major benefit of using remote sensing application is that it provides a wealth of data and a variety of observations (Garajeh *et al.*, 2024; Cui *et al.*, 2022). However, the recent cloud computing platform known as (GEE) is helpful in processing and storing enormous amounts of RS images with the use of cloud storage (Wang *et al.*, 2018). GEE platform comprises of a varied range of satellites (Landsat, Sentinel, and MODIS are among the current used satellites) for temperature, precipitation, and land cover. They are also used in boundary detection, vegetation cover mapping, population and settlement detection (Akhundazadah *et al.*, 2020; Wang *et al.*, 2018; Remilekun *et al.*, 2021).

The Vaal River is among South Africa's most commercial water resources that is threatened by the adverse impact of climate change (Bodunrin and Onyari, 2024). These threats include drought, rising temperatures, and changing precipitation patterns, and it is predicted that more frequent extreme weather events will make already-existing problems with water quality and quantity worse in nearby future (Raneesh, 2024; Akanbi *et al.*, 2021). These alterations pose serious threats to the river's ecological well-being and capacity to supply sufficient, clean water for its usage in home, industrial, and agricultural processes (Chaturvedi *et al.*, 2021, Shah, 2024). Therefore, this study examined the extreme impact of climate change on Vaal River water resources situated in the North-Eastern region of South Africa. The objectives is to evaluate the effects of seasonal variations over a three-decade period utilizing the temperature and precipitation climate components.

## 2. Materials and Method

The Vaal River catchment was delineated using digitized shapefile downloaded from Google earth with the combination of satellite imagery derived from (GEE) and Quantum Geographic Information System (QGIS). The identified recording stations usually known as a permanent structure with sensor equipment or other devices used for continuous track and documentation of different environmental and hydrological factors connected with the behaviour of the catchment. It involves the use of cardinal co-ordinates from Microsoft Excel and QGIS, to identify the proximity along the Vaal River. The cloud computing platform, (GEE) was equally utilized to study the surface water changes of the Vaal River using Landsat-5 imagery featuring collection-2, Tier-1, Level-2 (TOA). The imagery was downloaded from 1993–2012 (19 year duration). Similarly, Landsat-8 (Operational Land Imager) was employed from 2013 –2024 (12years duration) featuring collection-2, Tier-1, Level-2 (TOA). These Landsat imageries was used to observe changes in surface water for three stipulated decades. Both Landsat 5 and Landsat 8 (OLI) have proven to be effective in monitoring surface water availability since inception. Modified Normalized Difference Water Index (MNDWI) was employed to examine the water level for both wet (January – March) and dry (May – July) seasons, using reflectance wavelength of the green and short- wave infrared (SWIR) bands shown in equation (1) & (2) (Remilekun *et al.* 2021). Annual precipitation and temperature data from 1993- 2023 (3 decades duration) was obtained from South African Weather Services (SAWS), while historical annual total flows of Vaal River were extracted from the Department of Water and Sanitation website (DWS/hydrology), for catchment recording station. Data derived from temperature and precipitation was analysed in Microsoft Excel where trend analysis was observed. However, normal ratio equation was utilized to account for the missing precipitation values (Haji, 2011; Chabalala *et al.*, 2019). Equation 3 displayed the formular used in accounting for missing values. Table 1 and Table 2 revealed data derived from temperature and precipitation.

$$\text{Landsat 5} = \text{MNDWI} = \frac{(P_{\text{green}} - P_{\text{SWIR}})}{(P_{\text{green}} + P_{\text{SWIR}})} = \frac{(\text{Band2} - \text{Band7})}{(\text{Band2} + \text{Band7})} \quad 1$$

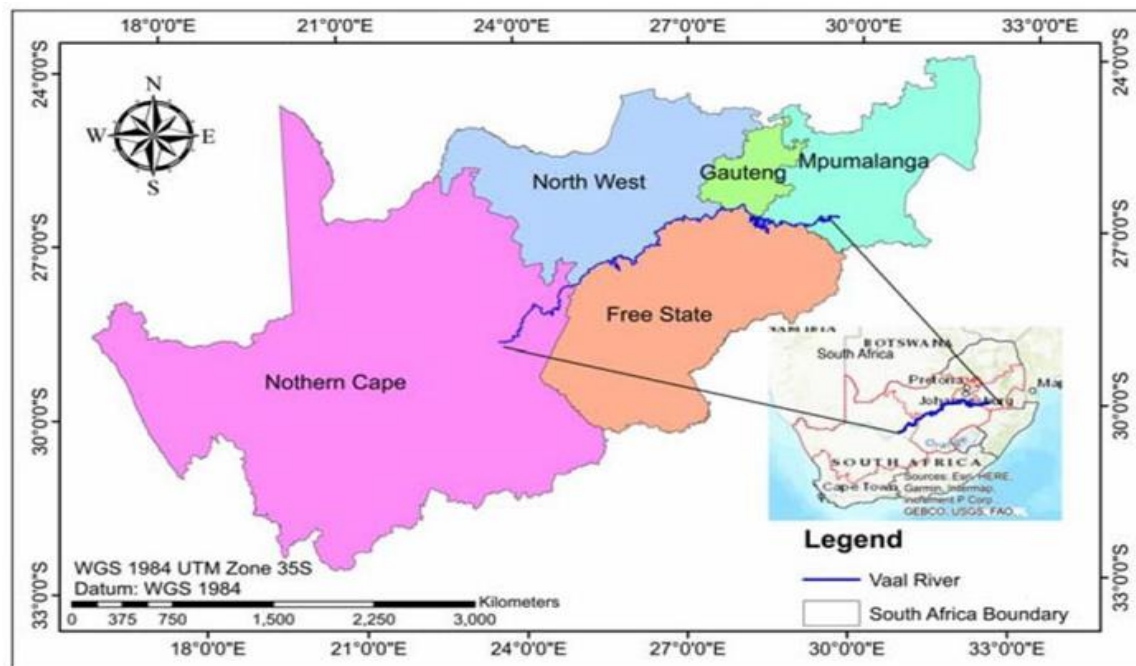
$$\text{Landsat 8} = \text{MNDWI} = \frac{(P_{\text{green}} - P_{\text{SWIR}})}{(P_{\text{green}} + P_{\text{SWIR}})} = \frac{(\text{Band3} - \text{Band7})}{(\text{Band3} + \text{Band7})} \quad 2$$

$$P_A = \frac{\sum_{i=1}^N \frac{R_A}{NR_i} \times P_i}{n}$$

where:  $P_A$  is the estimate for the ungagged station,  $P_i$  is the rainfall at the surrounding stations,  $N R_A$  is the normal annual rainfall at station A,  $N R_i$  is the normal annual rainfall at station I and  $n$  is the number of surrounding stations that data are used for estimation.

## 2.1 Study Area

The Vaal River is the largest tributary of the Orange River and is a critical water resource for South Africa traversing various climatic and geographical zones. It originates in Ermelo, in the Mpumalanga Province, west of Swaziland, and extends over approximately 1,210 km (Bodunrin and Onyari, 2024). The river forms part of the Upper, Middle, and Lower Vaal basins, each influenced by distinct climatic and anthropogenic factors (Masindi and Abiye, 2018). Figure 1 displayed the location of Vaal River within the urbanised environment.



**Figure 1:** Vaal River location (Bodunrin and Onyari, 2024)

The climate of the Vaal River in South Africa is sub-tropical dry savannah, with a pronounced seasonal rainfall pattern that peak in the summer (January to March) and an average annual evaporation rate that is much higher than its rainfall. It featured an average of 570 mm of rainfall per year; the river's watershed is primarily semi-arid. The summer months of November through January see the highest temperatures, while the winter months can have below-freezing temperatures. The average yearly temperature is approximately 15°C. (Jury, 2016; Bodunrin and Onyari, 2024). The Vaal River basin supports significant economic activities renowned to South Africa such as mining, agriculture, and industrial activities, particularly in the urbanized area of Johannesburg and Vereeniging (Masindi and Abiye, 2018; Wepener *et al.*, 2011; Haji, 2011). The Vaal River basin delineation is presented in Figure 2.

Table 1 present the annual average precipitation from recording stations along the Vaal River while Table 2 describe the annual average temperature from recording stations. The mean rainfall is relatively consistent across the study area with significant variability observed. This equally suggests average temperature increase over time within the catchment. The temperature also shows less variation in comparison to precipitation however, peaks are observed in some years. Average temperature



**Figure 2:** Vaal River delineation

**Table I:** Annual Average Precipitation from Recording Stations Along the Vaal River

Year	Barrage RWB	Potchef's Troom	Bothaville Balkfontein	Bloemloef	Leeu heuvel	Vaal River estate	Doug laspol	Mean	SD	Variance
1993	63.98	60.96	45.94	45.94	23.79	22.76	29.45	41.83	15.73	247.57
1994	46.14	38.53	21.49	21.49	22.73	18.50	20.54	27.06	9.94	98.90
1995	66.48	57.07	39.68	39.68	44.52	14.38	24.08	40.84	16.55	274.02
1996	59.77	67.50	23.56	23.56	48.26	11.41	9.68	34.82	21.73	472.07
1997	62.24	54.48	7.74	7.74	34.61	21.33	22.14	30.04	19.96	398.22
1998	57.53	59.92	2.13	2.13	37.67	13.46	22.00	27.83	22.58	510.02
1999	45.81	44.91	12.75	12.75	30.43	29.93	25.54	28.88	12.41	154.09
2000	104.62	72.78	22.18	22.18	38.88	45.13	30.38	48.02	28.17	793.53
2001	93.02	67.77	32.16	32.16	55.09	44.08	40.53	52.11	20.43	417.47
2002	51.10	52.73	25.21	25.21	46.33	32.16	24.08	36.69	11.96	143.00
2003	46.56	40.63	15.49	15.49	32.83	13.00	12.98	25.28	13.31	177.05
2004	57.73	49.94	20.04	20.04	36.43	18.92	23.26	32.34	14.82	219.51
2005	42.96	45.20	19.49	19.49	27.49	12.33	5.75	24.67	13.77	189.67
2006	85.99	62.13	36.23	36.23	61.64	29.36	34.33	49.42	19.37	375.20
2007	36.08	48.58	15.02	15.02	34.04	35.73	19.47	29.13	11.87	140.88
2008	70.79	46.03	17.93	17.93	31.99	17.33	22.55	32.08	18.52	343.09
2009	82.03	58.42	60.78	60.78	47.64	26.24	27.38	51.89	18.46	340.72
2010	77.80	58.18	62.73	62.73	46.83	33.67	27.64	52.80	16.41	269.42
2011	57.48	55.30	70.60	70.60	79.69	42.88	29.28	57.98	16.25	264.18
2012	57.34	41.07	42.30	42.30	18.71	34.85	28.40	37.85	11.30	127.80
2013	50.08	33.91	31.08	31.08	17.77	15.67	6.50	26.58	13.34	178.04
2014	61.70	43.18	44.47	44.47	36.57	26.71	19.64	39.53	12.66	160.32
2015	31.60	34.83	18.67	18.67	16.18	19.47	10.71	21.44	7.97	63.52
2016	60.66	54.34	41.07	41.07	45.65	26.33	17.20	40.90	13.98	195.37
2017	53.66	59.40	32.90	32.90	31.33	28.21	25.06	37.64	12.32	151.73
2018	44.81	38.85	34.87	34.87	23.33	12.83	15.35	29.27	11.31	127.88
2019	38.90	54.37	53.25	53.25	24.04	21.13	9.78	36.39	16.87	284.57
2020	60.41	48.33	69.37	69.37	44.39	44.25	17.59	50.53	16.79	282.03
2021	60.95	72.20	51.35	51.35	47.66	53.79	53.79	55.87	7.65	58.48
2022	72.73	69.13	46.99	33.04	50.91	31.97	32.74	48.22	15.95	254.46
2023	57.08	49.58	13.40	36.82	22.30	17.74	14.52	30.21	16.42	269.71
Mean	<b>59.94</b>	<b>52.91</b>	<b>33.25</b>	<b>33.56</b>	<b>37.41</b>	<b>26.31</b>	<b>22.66</b>			
SD	<b>16.14</b>	<b>10.63</b>	<b>18.00</b>	<b>17.48</b>	<b>13.89</b>	<b>11.23</b>	<b>9.99</b>			
Variance	<b>260.44</b>	<b>112.95</b>	<b>323.98</b>	<b>305.49</b>	<b>193.01</b>	<b>126.05</b>	<b>99.73</b>			

(Source: South African Weather Services-SAWS, 2024).



**Table 2:** Annual Average Temperature from Recording Stations Along the Vaal River

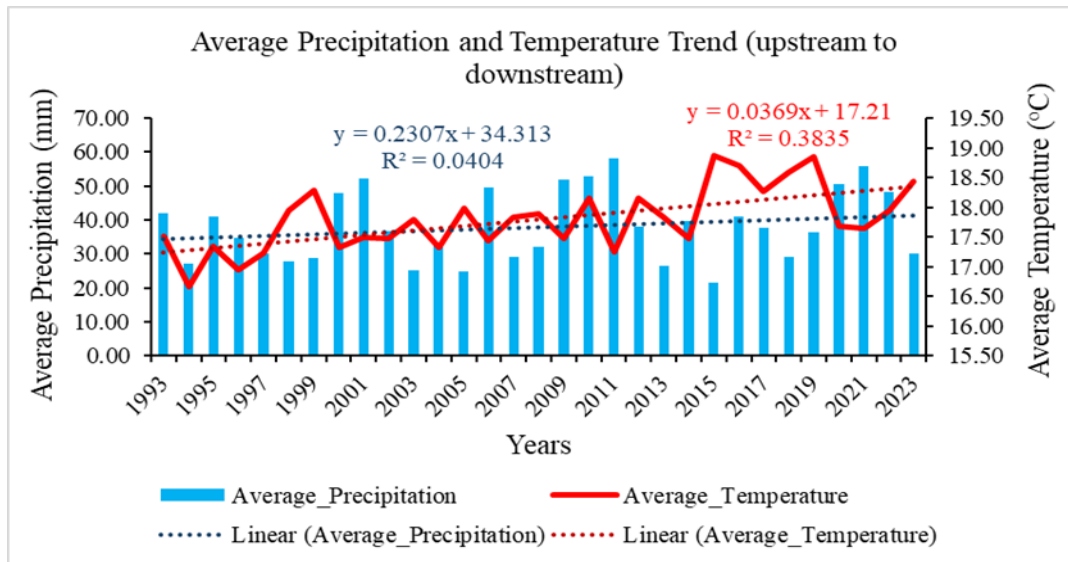
Year	Secunda	Verneengine	Portchel Stroom	Klerksdorp	Bothaville Balkfontein	Bloemhot	Postmas burg	Mean	SD	Varia nce
1993	15.97	16.70	17.77	17.41	18.20	18.37	18.15	17.51	0.82	0.68
1994	15.28	16.34	16.68	16.50	16.55	17.57	17.77	16.67	0.77	0.59
1995	15.94	16.99	17.72	17.22	17.29	18.34	17.96	17.35	0.72	0.52
1996	15.58	16.22	17.06	17.12	17.40	17.45	17.86	16.95	0.73	0.53
1997	15.70	16.37	17.69	17.26	17.63	17.88	18.07	17.23	0.81	0.65
1998	16.75	17.30	17.96	18.73	17.89	18.31	18.74	17.95	0.68	0.46
1999	16.65	17.64	18.81	18.78	18.42	18.83	18.83	18.28	0.78	0.60
2000	15.43	16.87	17.65	18.88	17.44	17.67	17.36	17.33	0.96	0.92
2001	16.27	17.28	18.64	17.92	17.24	17.72	17.38	17.49	0.67	0.45
2002	16.48	17.53	17.34	17.01	17.81	18.56	17.58	17.47	0.60	0.36
2003	17.28	17.55	18.57	17.14	18.07	18.49	17.46	17.79	0.54	0.29
2004	17.15	15.38	17.90	16.23	18.68	18.22	17.66	17.32	1.08	1.16
2005	19.37	16.97	17.63	16.57	19.06	18.73	17.55	17.98	1.00	1.00
2006	16.04	16.65	18.37	17.64	19.02	17.50	16.80	17.43	0.96	0.92
2007	16.44	17.29	17.98	18.25	19.08	18.12	17.62	17.83	0.77	0.59
2008	16.73	17.25	18.07	18.50	17.82	18.71	18.15	17.89	0.65	0.42
2009	16.47	16.94	17.88	17.79	16.03	18.69	18.55	17.48	0.95	0.90
2010	17.26	17.43	18.38	17.98	18.22	18.95	18.89	18.16	0.61	0.37
2011	16.59	16.56	17.29	17.29	17.72	17.70	17.64	17.26	0.46	0.21
2012	17.05	16.71	18.98	18.88	18.32	18.35	18.77	18.15	0.84	0.71
2013	16.94	16.97	18.89	18.98	16.98	18.59	17.54	17.84	0.88	0.77
2014	16.02	15.90	17.67	18.78	18.02	18.58	17.40	17.48	1.06	1.13
2015	17.16	17.85	18.66	19.70	18.98	20.13	19.63	18.87	0.99	0.98
2016	17.08	17.47	18.85	19.79	19.36	19.53	18.79	18.70	0.96	0.93
2017	16.64	17.30	18.40	18.90	18.15	18.34	20.13	18.27	1.03	1.07
2018	17.00	17.44	18.80	19.13	18.41	18.27	21.05	18.58	1.22	1.48
2019	17.45	18.00	19.14	19.53	18.88	19.37	19.58	18.85	0.76	0.58
2020	16.84	17.16	17.89	17.95	17.65	18.06	18.23	17.68	0.47	0.22
2021	16.85	17.04	18.41	18.18	17.56	17.95	17.48	17.64	0.53	0.29
2022	17.03	17.27	17.89	18.23	18.13	17.87	19.18	17.94	0.65	0.42
2023	17.04	17.91	18.66	18.87	18.63	18.98	19.01	18.44	0.67	0.44
<b>Mean</b>	<b>16.66</b>	<b>17.04</b>	<b>18.12</b>	<b>18.10</b>	<b>18.02</b>	<b>18.38</b>	<b>18.28</b>			
<b>SD</b>	<b>0.75</b>	<b>0.58</b>	<b>0.60</b>	<b>0.65</b>	<b>0.76</b>	<b>0.60</b>	<b>0.63</b>			
<b>Varia nce</b>	<b>0.57</b>	<b>0.34</b>	<b>0.36</b>	<b>0.60</b>	<b>0.57</b>	<b>0.37</b>	<b>0.86</b>			

(Source: South African Weather Services-SAWS, 2024).

### 3. Results and Discussion

A statistical analysis of the mean, standard deviation, and variance indicated the volatility of the stream flow in the Vaal River given the hydrological trend analysis. The mean rainfall is relatively consistent across the study area. However, some variability is observed. The upstream Barrage-RVB and Potchefstroom stations have a higher means of 59.94 mm and 52.91 mm respectively, in comparison to the downstream Douglas-POL station with 22.66 mm. The streamflow analysis implies that some stations receive more consistent and substantial rainfall than other stations illustrating changes in water availability per season. This result also aligned with the study of Garajeh *et al.*, (2024); Assiri *et al.*, (2024) and Mwelwa *et al.*, (2024) where streamflow varies across stations indicating water presence variation per time. The condition is likely influenced by localized climatic conditions as depicted by Chabalala *et al.*, (2019, and Pham Phuoc, (2014) and Jury, (2016). However, the variance shows a similar trend with the standard deviation, being higher upstream and reducing downstream, suggesting rainfall patterns are more predictable downstream.

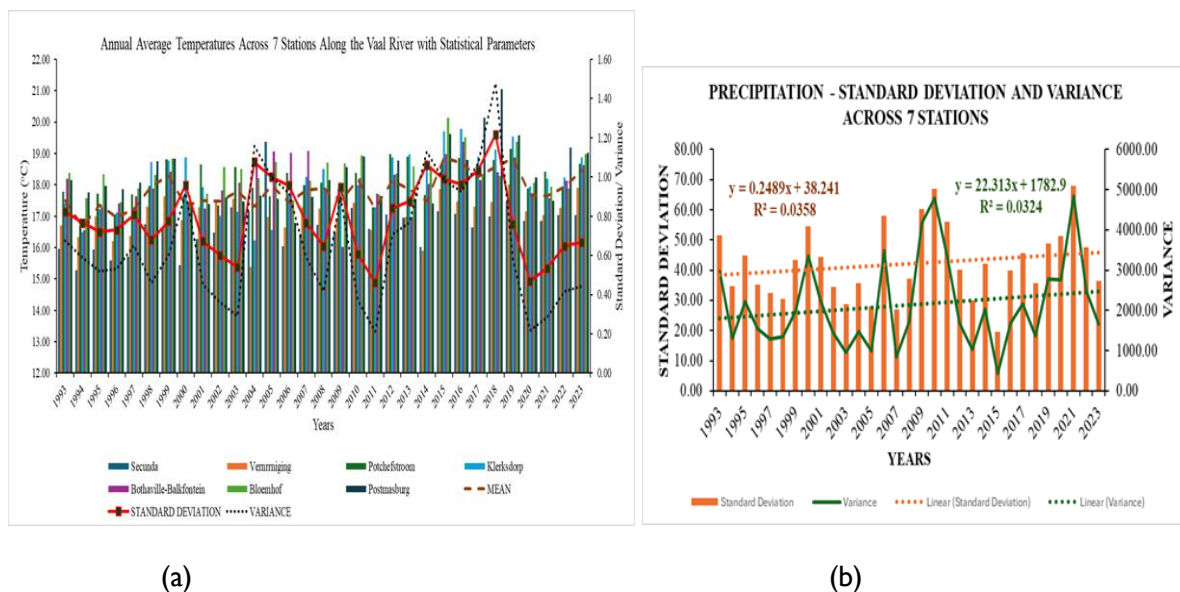
The linear regression line for precipitation illustrates increase in the precipitation pattern over the years ( $y = 0.2307$ ). signalling significant inter-annual variability with peaks in 2001, 2006, 2009, 2010, and 2011 and notable declines in 2005, and 2015. Between 2019 – 2023, the trend was discreetly increasing after the dip in 2018, Figure 3. The linear regression for temperature displayed an upward trend ( $y = 0.0369$ ), indicating a moderate correlation. This equally suggests average temperature increase over time within the catchment. Although the temperature shows less variation in comparison to precipitation, peaks are observed in 2015, 2019, and 2023, contrastingly hollows that occur in 1994, 1996, 2011, and 2014. The recent years, 2019 – 2023, remain consistently high indicating possible warming trends as depicted by Jury, (2016) and Chabalala *et al.*, (2019).



**Figure 3:** Trend Analysis of Average Annual Precipitation and Temperature.

Precipitation and temperature relationship showed a consistent increase independently from each other, (Figure 4a & 4b). Similarly, 1998, 1999 and 2015 have low precipitation but contrasting temperatures indicating possible changes on precipitation variability outlined also by Merolla (2011); Olabanji *et al.*, (2020). The years 2010 – 2011 indicate high precipitation coinciding with moderate temperatures. The weak correlation testing between precipitation and streamflow revealed that there is no significant relationship between the two variables indicating the dominance of other factors impacting streamflow along with temperature.

Figure 4 (b) revealed gradual rising of both standard deviation and variance trend lines, indicating a minor upward trend in variability. This implies that precipitation variability recorded some growth in some of the years. For instance, 2003, 2008 and 2017 reported significant rise in standard deviation and variance. The linear correlation relationship  $R^2$  showed a weak value however, with an increasing trend suggesting that precipitation is gradually getting more erratic across stations in the region. Although, there is no significant change in the average rainfall but, the distribution and consistency showed unpredictable. This result is consistent with studies by Kusangaya *et al.*, 2014; Van-Rooyen *et al.*, 2018, who identified rising temperatures and irregular precipitation as key indicators of climate stress on water systems.

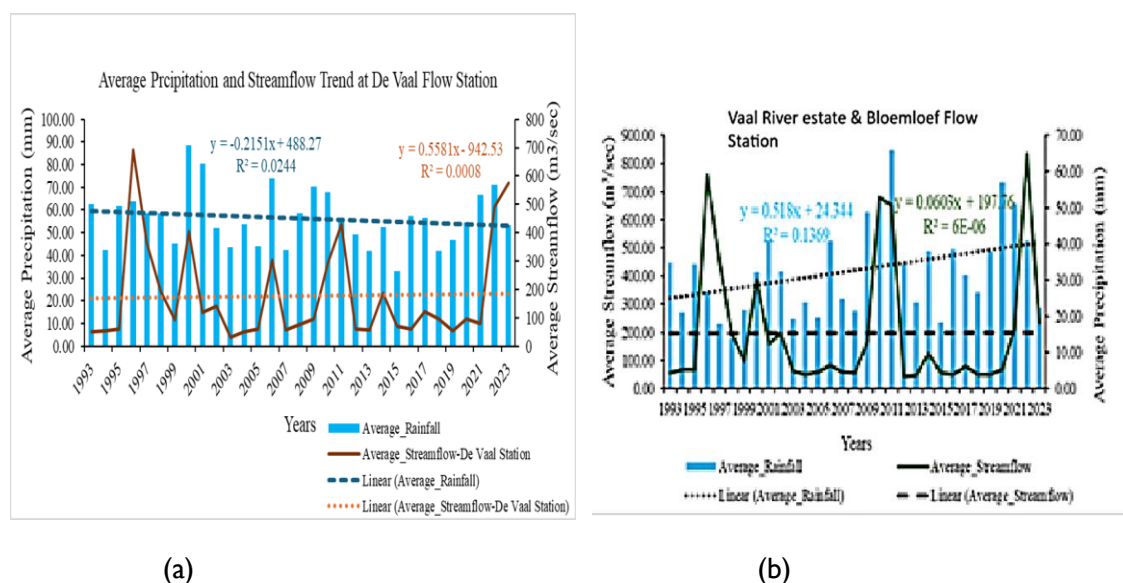


**Figure 4:** a) Mean monthly average temperature across all stations b) Mean annual precipitation across all stations 1993- 2023.

### 3.1 Trend Analysis of Precipitation, Temperature and Streamflow

The temperature and streamflow trend displayed a notable variability over the three decades, the statistical analysis of temperature pattern revealed significant fluctuation across the study period indicating possible

streamflow variations with inferences of climate variability on water availability. The red line shows the dispersion, or annual variance, in temperatures across all stations. Significant peaks coincide with increases in global warming which occur between 2015 and 2019 (Akanbi *et al.*, 2021; Masindi & Abiye, 2018; Kusangaya *et al.*, 2014). The variance and standard deviation lines from 2003, 2010–2011, and 2015–2017. Notable peaks, suggesting localized or regional climate anomalies. However, 2020–2023 recorded moderated standard deviation indicating stable temperature lately. The region's climate is changing, with occasional extremes, as seen by rising mean temperatures and greater variability in some years. Higher fluctuation and sudden shifts in variance are indicators of unpredictable temperature patterns that may affect water resources, agriculture, and human comfort. The findings of this study, which are related to earlier research on the Vaal River, show that the extreme climatic impact causes streamflow fluctuation (Akanbi *et al.*, 2021; Masindi & Abiye, 2018; Okoye *et al.*, 2022). Figure 5 (a & b) revealed trend analysis of streamflow and precipitation of two recording station which also indicate very weak correlation



**Figure 5:** Trend analysis of streamflow and precipitation in a) De Vaal and b) Bloemloef Station

### 3.2 Modified Normalized Difference Water Index (MNDWI)

The investigation of the MNDWI data offers additional information about the effects of climate change on the Vaal River's water resources presented in Table 3. MNDWI values for wet and dry seasons displayed consistent variations throughout the study period with value ranging from 0.08 to -0.12. The wet season's MNDWI value was often greater than the dry season's, indicating that there was more water present during wet periods due to heavy rainfall that overflowed the water body level. Additionally, there are records of lower values during the dry season, which indicates substantial water stress and shrinkages. This phenomenon can be ascribed to the impact of rising temperatures on river flow. The MNDWI wet season's linear trendline showed a positive slope of 0.0046 and  $R^2$  value of 0.26 suggesting water availability over time.

Similarly, polynomial trend line for the MNDWI dry season equally shows a moderate degree of fit to the trend with coefficient  $R^2$  value 0.38 as shown in Figure 6. Water presence fluctuation across the study period is shown by the chosen year trend of MNDWI. The trend analysis of the yearly MNDWI value over the Vaal River recorded varying values that could be attributed to the effects of climate variability as well as variations in surface water. This outcome aligned with previous studies on fluctuating values caused by climate factors (Botai *et al.*, (2018); Cui *et al.*, (2022); Yang *et al.*, (2021); Peterson *et al.*, (2017). However, less negative indices are shown in the Landsat-5 data for 1993, 1998, and 2007, indicating more water presence. Similarly, the Landsat-8 output for 2014, 2019, and 2023 shows a sharp decrease especially in 2019, hence reduced water presence dominates recent years from 2020–2023.

**Table 3: MNDWI Output for 30-Year Study Period - Wet Season**

Year	Season	Data	Range	Mean-Band 2(L5)/ 3(L8)	Mean-Band 7	MNDWI- wet	
1993	Wet Mar)	(Jan- 1993- 2012)	Landsat 5	-0.263 0.4393	12734.36	15040.48	-0.08
1995			-0.227 0.5037	12416.83	14618.14	-0.08	
1997			-0.289 0.2605	11003.47	12478.04	-0.06	
1998			-0.276 0.2455	12656.35	13343.74	-0.03	
2001			-0.224 0.547	13540.35	12815.85	0.03	
2007			-0.241 0.1902	11836.83	13466.16	-0.06	
2008			-0.206 0.1902	13900.97	13635.66	0.01	
2014	wet Mar)	(Jan- 2013- 2023)	Landsat 8	-0.278 0.3912	14408.21	14267.39	0.00
2015			-0.262 0.4013	12570.73	13756.27	-0.05	
2016			-0.285 0.3897	13398.34	15341.64	-0.07	
2017			-0.236 0.2	13729.75	13755.35	0.00	
2018			-0.172 0.5523	16660.48	14911.23	0.06	
2019			-0.247 0.215	11655.11	13840.72	-0.09	
2020			-0.242 0.1896	13133.99	13489.97	-0.01	
2021			-0.184 0.287	12196.94	12564.52	-0.01	
2022			-0.176 0.207	12065.55	12357.42	-0.01	
2023			-0.217 0.4663	13042.10	13313.41	-0.01	

**MNDWI Output for 30-Year Study Period - Dry Season.**

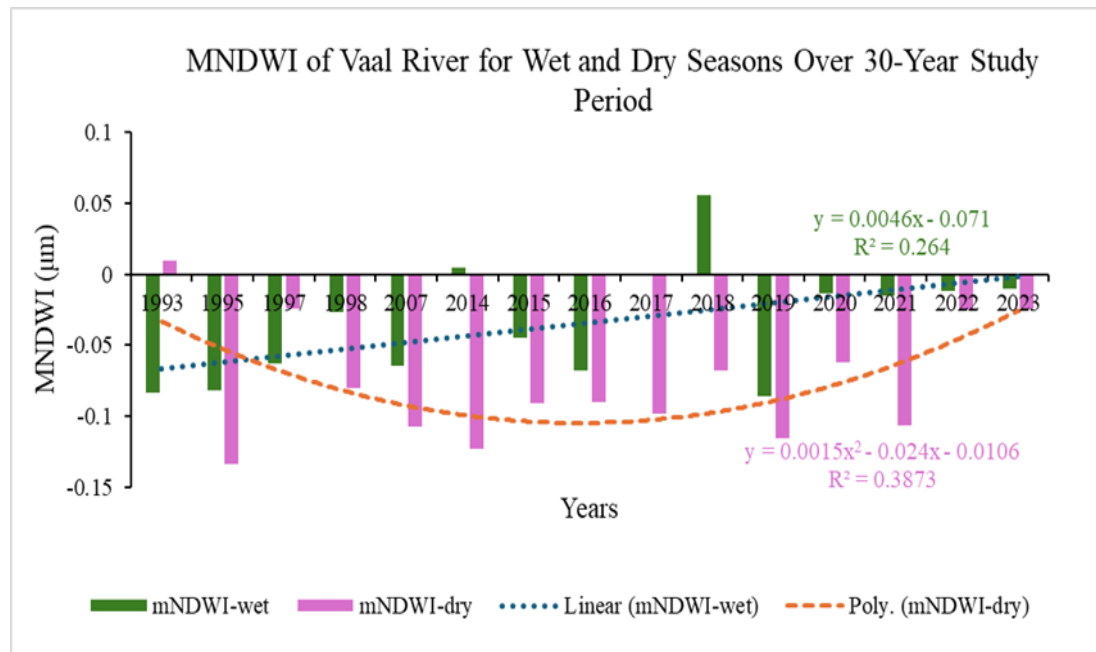
Year	Season	Data	Range	Mean-Band 2(L5)/ 3(L8)	Mean-Band 7	MNDWI- wet	
1993	Dry (May-Jul)	Landsat 5 (1993-2012)	-0.26	0.684	13900.97	13635.66	0.01
1994			-0.237	0.2774	11362.02	14020.44	-0.10
1995			-0.27	0.2415	11176.40	14614.56	-0.13
1997			-0.243	0.363	12436.26	13346.93	-0.04
1998			-0.252	0.2289	14023.81	14730.29	-0.02
2004			-0.218	0.2451	12285.56	14425.95	-0.08
2006			-0.262	0.1159	11299.31	13965.71	-0.12
2007	Dry (May-Jul)	Landsat 8 (2013-2023)	-0.244	0.2162	11334.42	13367.03	-0.08
2008			-0.27	0.1695	11617.07	14412.21	-0.11
2009			-0.228	0.2216	12786.83	13853.82	-0.01
2014			-0.268	0.2029	10447.41	13828.34	-0.14
2015			-0.29	0.2089	10662.95	13642.83	-0.12
2016			-0.284	0.1255	12374.70	14855.08	-0.09
2017			-0.286	0.3519	12014.70	14398.08	-0.09
2018			-0.239	0.2172	11211.60	13646.35	-0.10
2019			-0.271	0.2054	12003.61	13756.39	-0.07
2020			-0.26	0.2272	10332.69	13034.96	-0.12
2021			-0.269	0.228	11924.68	13503.83	-0.06
2022			-0.257	0.2012	104412.62	12894.20	-0.11
2023			-0.279	0.202	12878.24	13540.92	-0.03

### 3.3 Correlation between MNDWI, Temperature and Precipitation

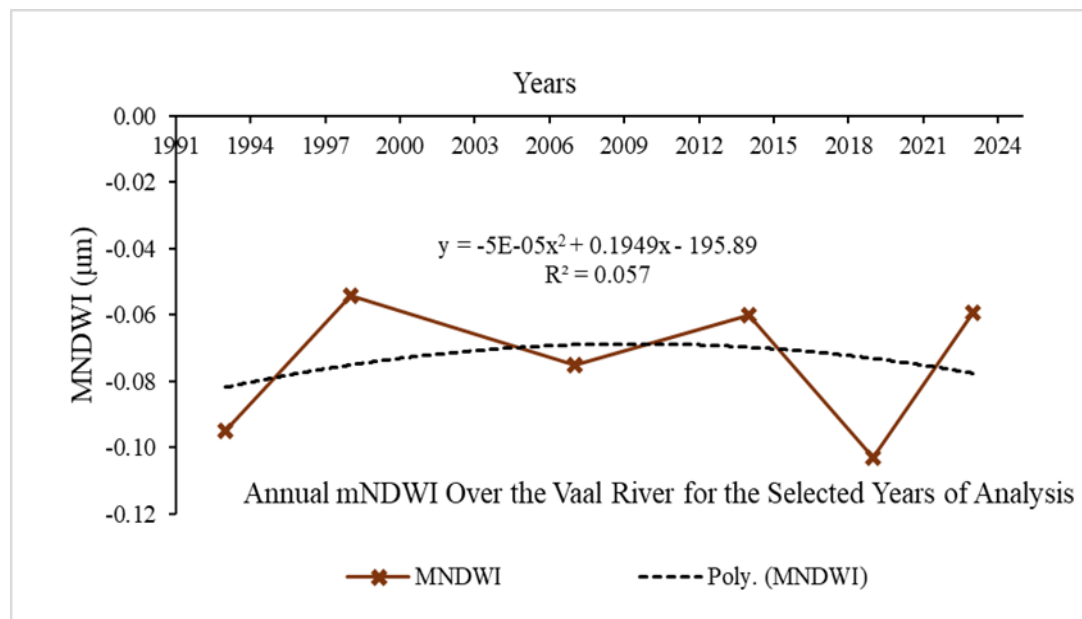
The outcome of MNDWI in the wet season varies between positive and negative values, indicating periods of water presence and water stress, Figure 7. The MNDWI during the dry season consistently displays negative values, indicating a reduction in the amount of available water. However, MNDWI exhibits a more noticeable fall during the dry seasons, which could result from the combined effects of climate induced factors such as higher evaporation, decreased inflows as well as human-induced water abstractions (Enriquez, 2022; Zhang et al., 2014). As anticipated, wet seasons consistently have higher water presence than dry seasons. The difference was more noticeable between 2010 and 2019, suggesting that the dry seasons throughout that decade, Vaal River might have witness severe water stress. Higher precipitation or surface water retention is probably correlated with higher MNDWI values. Similarly, the dry season MNDWI values correlates with temperature changes, as increased temperature further reduces the value during the dry seasons. However, higher temperature is also noted to worsen water stress in the Vaal River, likely due to cumulative evaporation and



reduced water flows. The clear evidence of variability, with significant fluctuations over the year highlights the sensitivity of the Vaal River system to climate induced changes.



**Figure 6:** MNDWI correlation (wet and dry season)

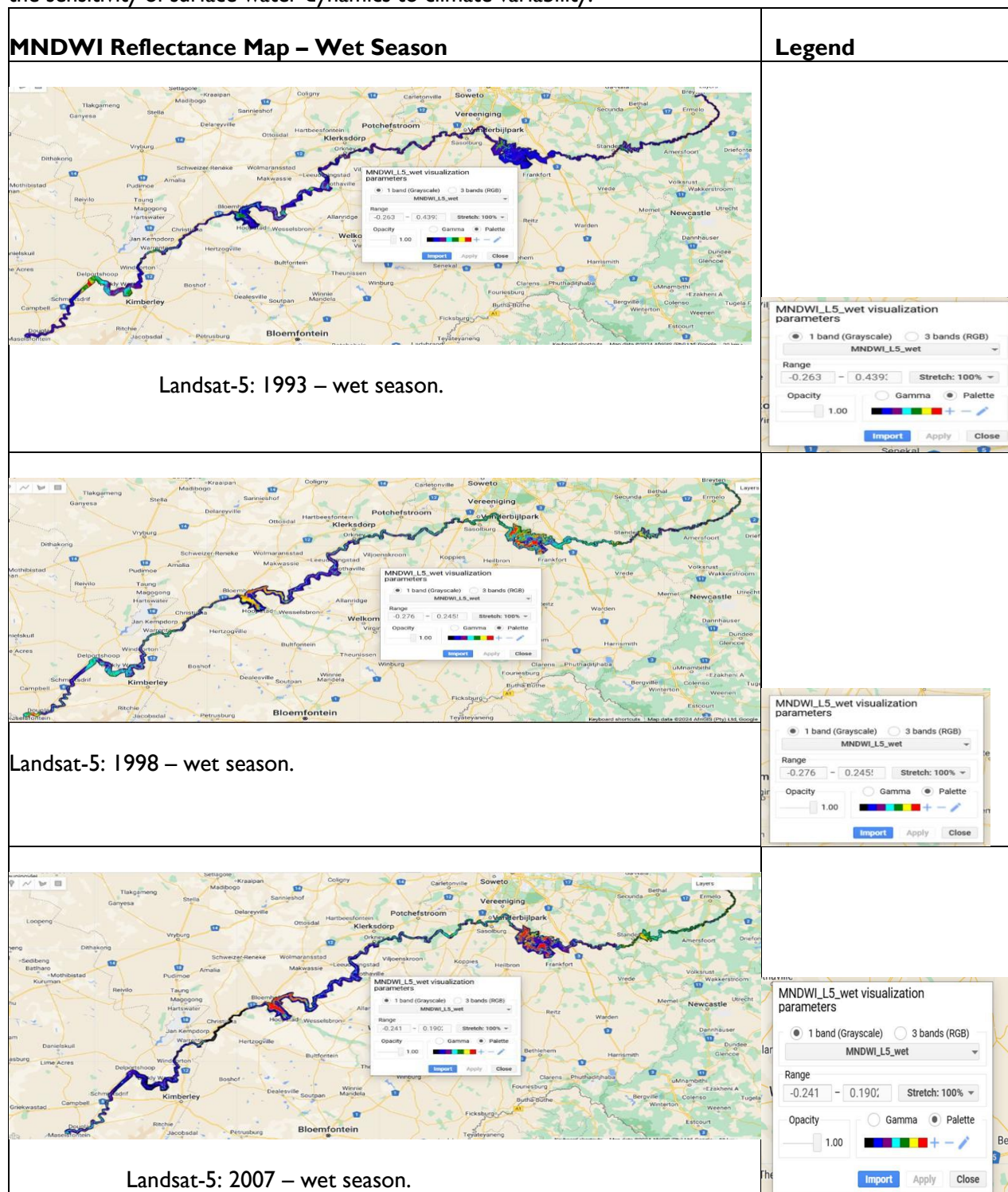


**Figure 7:** MNDWI Performance on Vaal River

The dry season low values indicate that surface water availability was substantially decreased particularly from the year 2000 to 2010. However, the most significant decline of water presence was witnessed in 2014 and 2019 with value range of (-0.12), indicating widespread shrinkage and water stress, due to increased temperatures, reduced precipitation and increased water extraction. This report aligned with the study of Chabalala *et al.*, (2019) and Akhundzadah *et al.*, (2020), who confirmed with temporal correlation that high temperatures during the wet season correlate with less positive values due to accelerated evaporation and increased water stress.

The mapping of MNDWI in the Vaal River basin aided in providing more insight into water shrinkage and stress over the study period using both Landsat 5 and Landsat 8 (OLI). The distribution and dynamics of surface water along the river are spatially revealed by the mapping Figure 8 (a & b). The span value ranges from positive to negative outcome indicates fluctuating water availability. The key observations in the maps are indicative of the water body having positive MNDWI values or showing areas with significant moisture content aligning with previous studies of (Kaplan, 2020; Bhaga *et al.*, 2021; Botai *et al.*, 2018; Zhang *et al.*, 2014). From the map, areas with blue / purple background are areas with strong water presence indicating water availability

in the Vaal River. Wet season have more record of blue / purple background with significant evidence in 2009, while other wet season such as 1998, 2007, 2014 and 2019 displayed fluctuation in water presence. Reduction in blue background areas or changes to other colours are signals of water stress and shrinkage. The yellow / red background represents sparse or no water suggesting water stress usually caused by climate change. It is observed that the wet season MNDWI exhibits a strong dependence on precipitation than the dry season MNDWI, demonstrating rainfall critical role in replenishing water bodies during the wet season as depicted by Mpanyaro *et al.*, (2024); Zhang *et al.*, (2020). The dry season MNDWI correlates with temperature changes, as increased temperatures further reduce the MNDWI values during the dry seasons. This reflects reduced water availability and increased evaporation during low rainfall seasons Figure 8(a & b). Dry season mapping reports more of yellow and red background indicating sparse and shrinkage however, significant evidence was noticed in 2023 reflecting increasing climate impact on surface water availability. The outcome of this study aligned with studies by Wang *et al.*, (2018) and Banda *et al.*, (2024) who utilized remote sensing to demonstrate the sensitivity of surface water dynamics to climate variability.





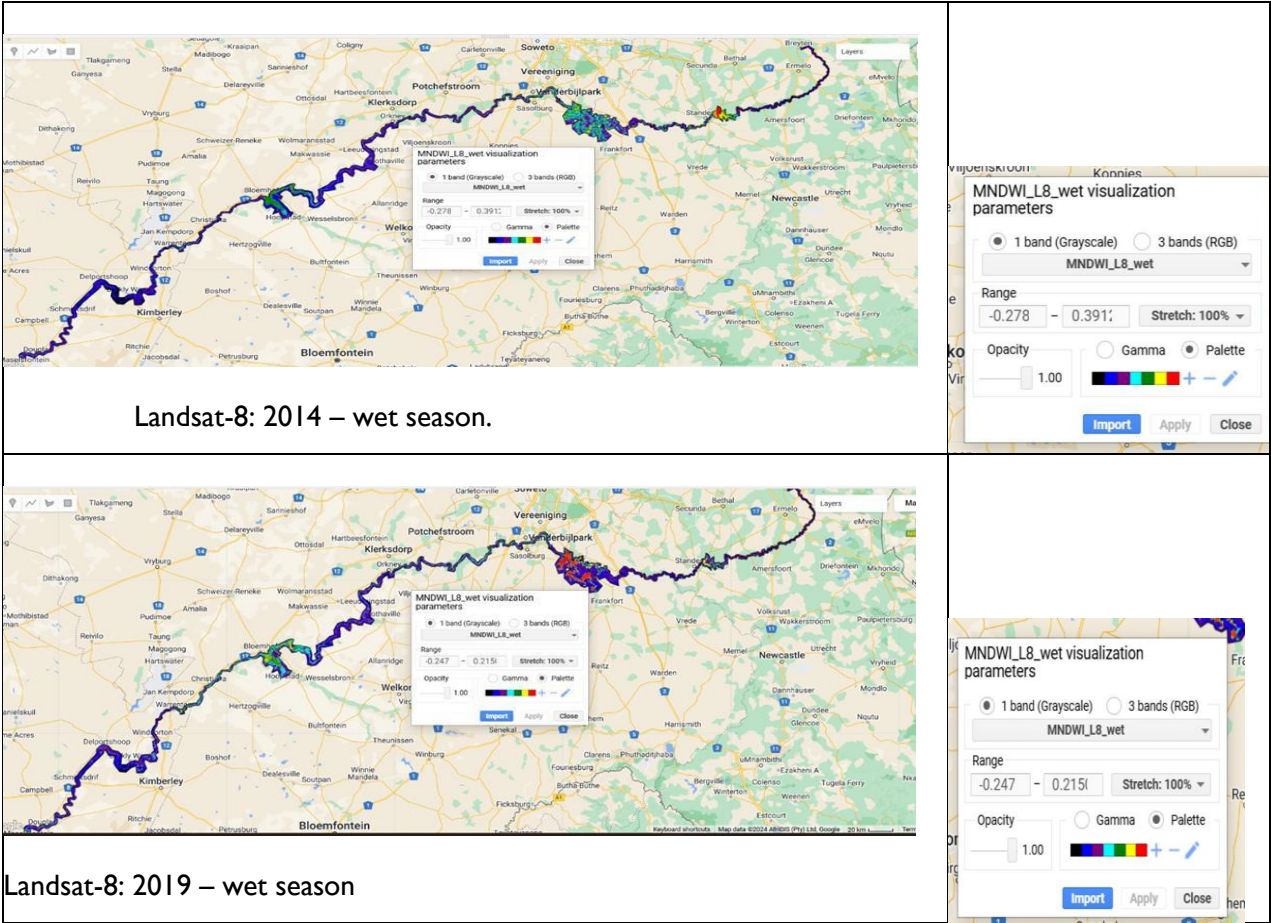
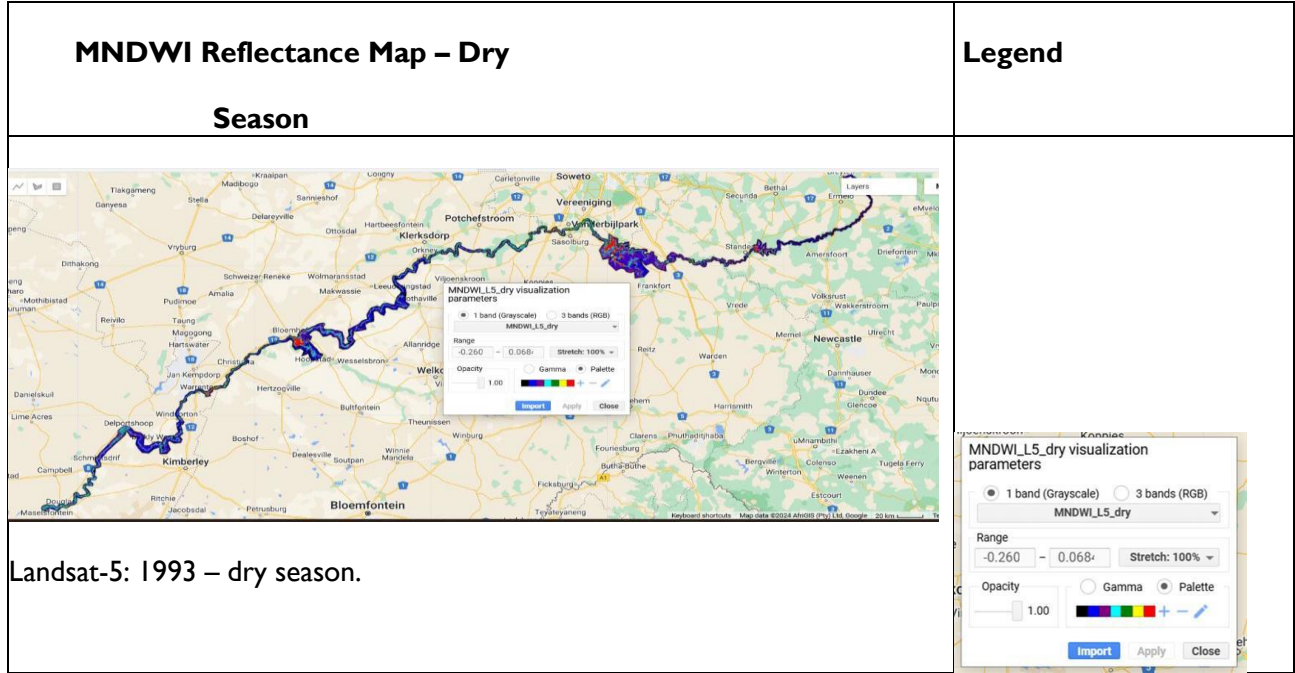
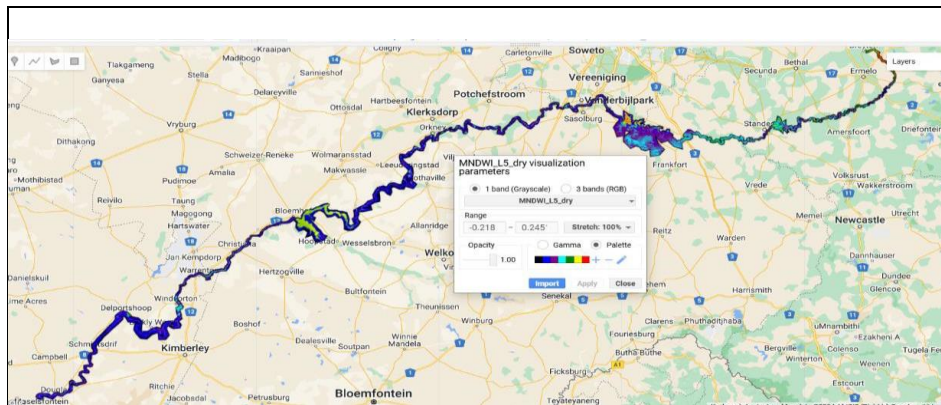


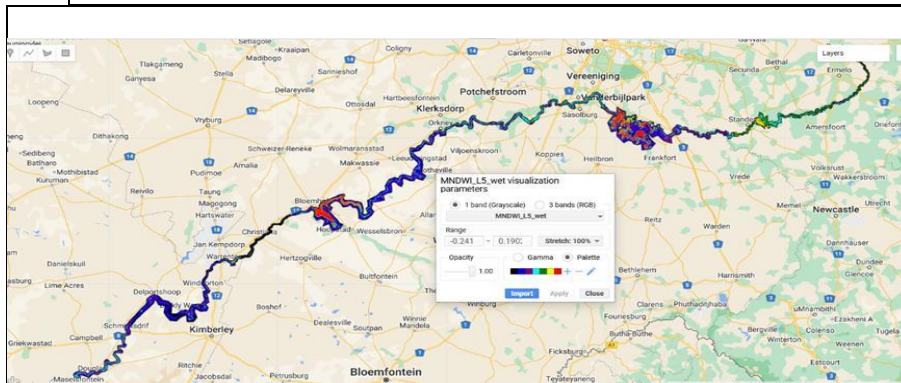
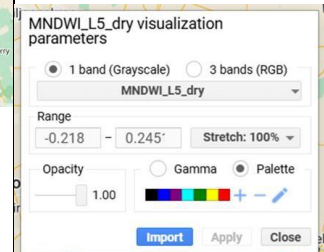
Figure 8a: MNDWI for selected years (wet season)



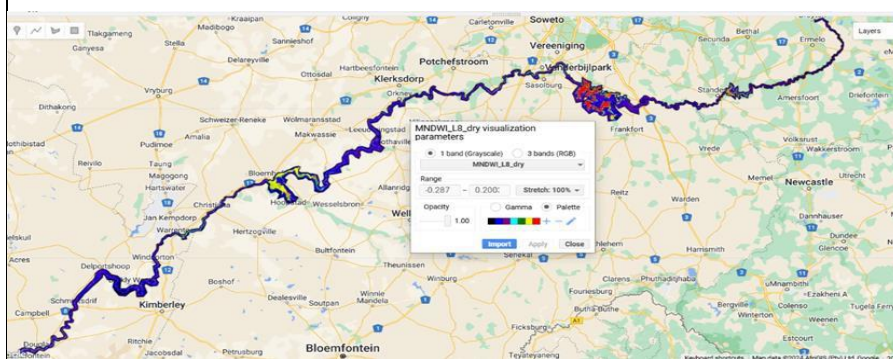
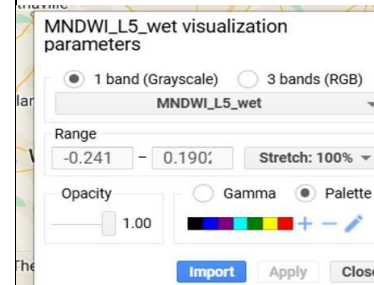




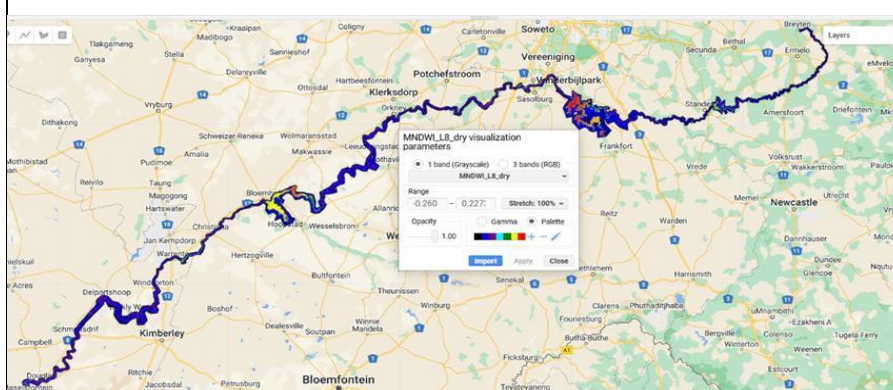
Landsat-5: 1998 – dry season.



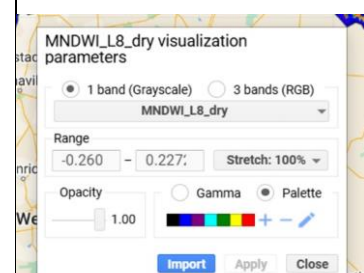
Landsat-5: 2007 – dry season.



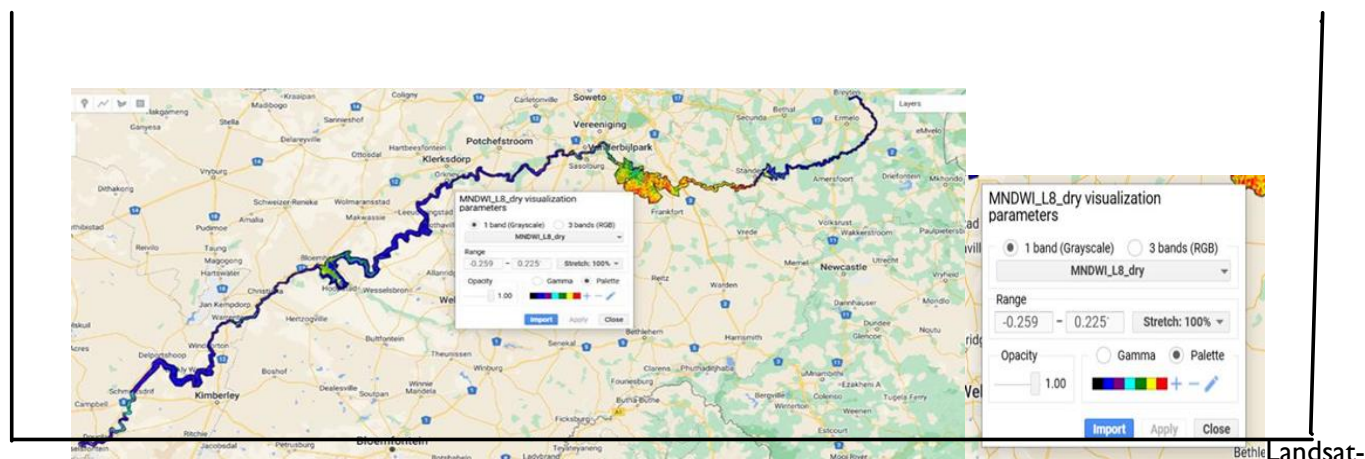
Landsat-8: 2014 – dry season.



Landsat-8: 2019 – dry season.







8: 2023 – dry season.

**Figure 8b:** MNDWI for selected years (dry season)

Significant climatic change impact was found in the Vaal River basin throughout a thirty-year period, as evidenced by changes in temperature, precipitation, and streamflow variability that affected water resources both geographically and temporally. Higher altitude regions had lower climates and more reliable precipitation, based on data gathered upstream, downstream regions, which are defined by lower altitudes, had higher temperatures and less predictable precipitation. The outcome from MNDWI revealed seasonal variations in the water surface area, with noticeable drops in water availability especially during dry season resulting from combined impacts of evaporation, rising temperatures, and decreased inflows. These findings aligned with the report of climate change on the hydrological cycle, consistent with studies by Kusangaya *et al.*, (2014) and Van-Rooyen *et al.*, (2018), where increasing temperatures and uneven precipitation was confirmed as key indicators of climate stress on water systems. Significant variations across the study years demonstrated the variability of precipitation patterns, following periods of high rainfall contributing a major impact on the availability of water resources. Water availability is uneven throughout the basin as a result of this fluctuation. Significant variations between wet and dry seasons were equally found when streamflow report was examined using recording stations connected with precipitation data. The weak relationship recorded on streamflow analysis can also be attributed to human interventions impacting on the surface water aside from climate effects. The outcome of streamflow variability correlates with studies by Wang *et al.*, (2018) and Akhundzadah, *et al.*, (2020) who utilized remote sensing to demonstrate the sensitivity of streamflow dynamics to climate variability.

#### 4. Conclusion

This study highlights the significant impact of climate change on the water resources of the Vaal River basin using combined consequences of rising temperatures, erratic precipitation patterns, and streamflow effects. Notable patterns across the three-decade study period demonstrate the catchment's vulnerability to climate change. The investigation showed decreased water availability during dry seasons and an increased trend in temperatures, which was especially noticeable downstream intensifying water scarcity. Trends in precipitation showed notable interannual fluctuation, with rainy years increasing water availability within the Vaal River channel. Additionally, the MNDWI analysis offers a temporal and spatial perspective for comprehending surface dynamics. It displayed seasonal variations, with inconsistent recovery during the wet season, which is hampered by rising temperatures, and decreases in water bodies during the dry season. Variability in intensity indicates that certain parts reflect water more strongly than others. The findings are consistent with regional and international studies, highlighting the urgent need for flexible water management techniques. IVRM strategy, entails equitable water allocation through effective maximization of its use to balance the demands of household, industrial, and agricultural applications while maintaining environmental flow releases. Additional effort should be channeled towards sustainable remedies that will support the reduction of climate change effect on water resources while further research is proposed using high-resolution satellite imagery from Sentinel imagery and Landsat 8 (OLI) to improve the understanding and clarity of water stressors in the catchment.

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