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ORIGINAL ARTICLE

Climate Variability and Industrial Groundwater Abstraction in a Water-Stressed Petroleum Basin: Water Demand Dynamics in Lokichar Oil Production Wells, Kenya

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Abstract

The Lokichar Basin in Turkana, northern Kenya, is a semi-arid environment marked by pronounced rainfall variability and intense competition for water resources among domestic, livestock, and oil-driven industrial demands. This study assesses long-term rainfall trends (1981–2024), aquifer characteristics, groundwater levels, and demand dynamics to evaluate resource sustainability under oilfield development. Rainfall analyses using the Rainfall Anomaly Index, Standardized Precipitation Index, and Mann-Kendall tests show marked interannual variability, with significant increases in annual and October–December rainfall and evidence of non-stationarity in seasonal precipitation. Pumping tests from 23 boreholes reveal heterogeneous transmissivity (4.17×10^{-6}–6.00×10^{-3} m^2/s) and specific yield (0.036–0.500), with high-yield zones concentrated in Nakukulas. Continuous monitoring indicates daily groundwater fluctuations linked to domestic abstraction, while simulations project extreme midday drawdowns exceeding 60 m under full-scale oil production. Estimated natural recharge (21.8–43.6 Mm^3 yr^{-1}) falls short of 2022 industrial demand (~53.0 Mm^3 yr^{-1}), exposing a recharge–demand deficit. These findings highlight the vulnerability of Lokichar aquifer to over-abstraction and emphasize the need for integrated management, regulated abstraction, enhanced monitoring, and climate-responsive planning to secure water resources and support sustainable petroleum development in this fragile semi-arid basin.

Keywords: Groundwater levels, Groundwater sustainability, Industrial water demand, Rainfall variability, Recharge levels.

1. Introduction

Water demand across the globe has been increasing at an estimated rate of 1% per year, driven by population growth, economic development, and evolving consumption patterns (United Nations, 2006). Projections indicate that global water demand will rise significantly over the next three decades, potentially reaching 6,000 km^3 annually by 2050 (Boretti and Rosa, 2019). Among the leading water-consuming sectors, agriculture ranks highest, followed by energy production, particularly in oil and gas industries where large volumes of water are essential. Oil and gas extraction processes including drilling, hydraulic fracturing, and enhanced oil recovery require millions of gallons of water. This translates to nearly nine barrels of water being injected to produce a single barrel of oil in production wells.

This significant water use results in the generation of produced water which is an oily, saline by-product that if not properly managed leads to pollution (Al-Ghouti et al., 2019). In most oil fields, produced water is partially reused, although additional fresh water is often required to sustain extraction processes (USEPA, 2015). The stress these places on local water resources has prompted countries like France to ban hydraulic fracturing due to its impact on groundwater tables (Food and Water Watch, 2012). Similar concerns have emerged globally, such as in South Africa's Karoo region, where water reallocation from communities to oil extraction has fueled social conflict (Robert and Greg, 2017).

Kenya faces significant water stress, with a per capita renewable freshwater resource of just 640 m³ (UN, 2006). This national challenge is exacerbated in arid regions like Turkana County, the location of the Lokichar Basin, where surface water is extremely limited. Here, groundwater is a critical lifeline, supporting rural populations, livestock, and essential services (Turkana County Government, 2016). It accounts for approximately 5% of the country's renewable freshwater resources (Mumma et al., 2011), and during the 2009 census, 43% of rural and 24% of urban populations reported using it as their primary source. Despite this reliance, the resource is vulnerable to strain from physical and economic scarcity (Makokha et al,2024) and the threat of over-abstraction by industries such as oil production, which could lead to dried wells, higher costs, and water quality deterioration.

In June 2018, oil production began in the Lokichar Basin under the Early Oil Pilot Scheme (EOPS), operated by Tullow Oil company. The company adopted shale fracturing technology to access hydrocarbon reserves, requiring significant volumes of water primarily sourced from groundwater. According to the Environmental and Social Impact Assessment (ESIA) report (Golder, 2020), ten boreholes were drilled within the project area to meet water demand, with plans to supplement this supply via a pipeline from Turkwel Dam which was to be realized in 2020. This heavy reliance on groundwater in a hydrologically water scarce environment raises sustainability concerns.

Water requirements for oil production in Lokichar are substantial. Between 2018 and 2020, approximately 1.46 million barrels of oil were produced, requiring an estimated 2.09 billion liters of water (Golder, 2020). Projections indicate a target of 100,000 barrels of oil per day, which would necessitate over 143 million liters of water daily that surmounts to an unsustainable abstraction rate (Makokha et al., 2024). Lokichar receives an average annual rainfall of only 121 mm, while groundwater recharge is estimated at less than 20 mm/year (Gitari et al., 2022). Over-abstraction, combined with poor recharge, could lead to groundwater depletion, declining borehole yields, and saline intrusion posing risks to both local communities and industrial sustainability.

Despite prior research identifying deep aquifers and shallow groundwater systems in Turkana, little has been done to assess the hydrological implications of large-scale groundwater abstraction for oil production. By analyzing borehole water level trends, seasonal rainfall variability, and changes in water demand before and after oil production, the study provides empirical evidence on how extractive industries can intensify groundwater stress in fragile arid basins. The Lokichar case offers a unique contribution to regional hydrogeology serving as one of the first integrated assessments of groundwater dynamics under the dual pressures of climate change and industrial development in northern Kenya. Insights from this study are intended to inform sustainable groundwater management and policy interventions in emerging petroleum industries across sub-Saharan Africa.

2. Materials and Methods

2.1. Description of the study area

The study was conducted in the Lokichar Basin, situated in Turkana County, Kenya. The basin lies between Easting 790000–820000 m and Northing 240000–270000 m (Figure 1). The research focused on boreholes located within the vicinity of Lokichar town, including those drilled by Tullow Oil Company during the Early Oil Pilot Scheme (EOPS), most of which are sited along laggas (ephemeral streams) (Turkana County Government, 2016). According to the Kenya National Bureau of Statistics (KNBS, 2010; 2020), the population of Turkana County increased from 855,399 in 2009 to 926,976 in 2019. Lokichar location experienced population growth from 23,452 in 2009 to 27,036 in 2019. The Lokichar Basin hosts the Twiga, Ngamia, and Amosing oil fields, which are Kenya's primary oil production sites and the location of the EOPS activities (Turkana County Government, 2016)

2.2. Aquifer characteristics

The aquifer in the study area comprises of alluvial (unconsolidated sedimentary) and volcanic (igneous) aquifers that provide water at varying yields. Exploratory drilling was carried out by Price (2016) in the study area at Ngamia 4, East Lokichar and Lokwii Areas. Results from pumping tests carried out on the exploratory boreholes show that high yielding boreholes (approximately 12m^3/hr) were those that encountered sandy sedimentary interflow deposits. Exploratory boreholes that intersected only the volcanic lavas were found to be low yielding (less than 1m^3/hr). The high yielding boreholes were those located along the Laggas as they acted as recharge zones during rainfall.

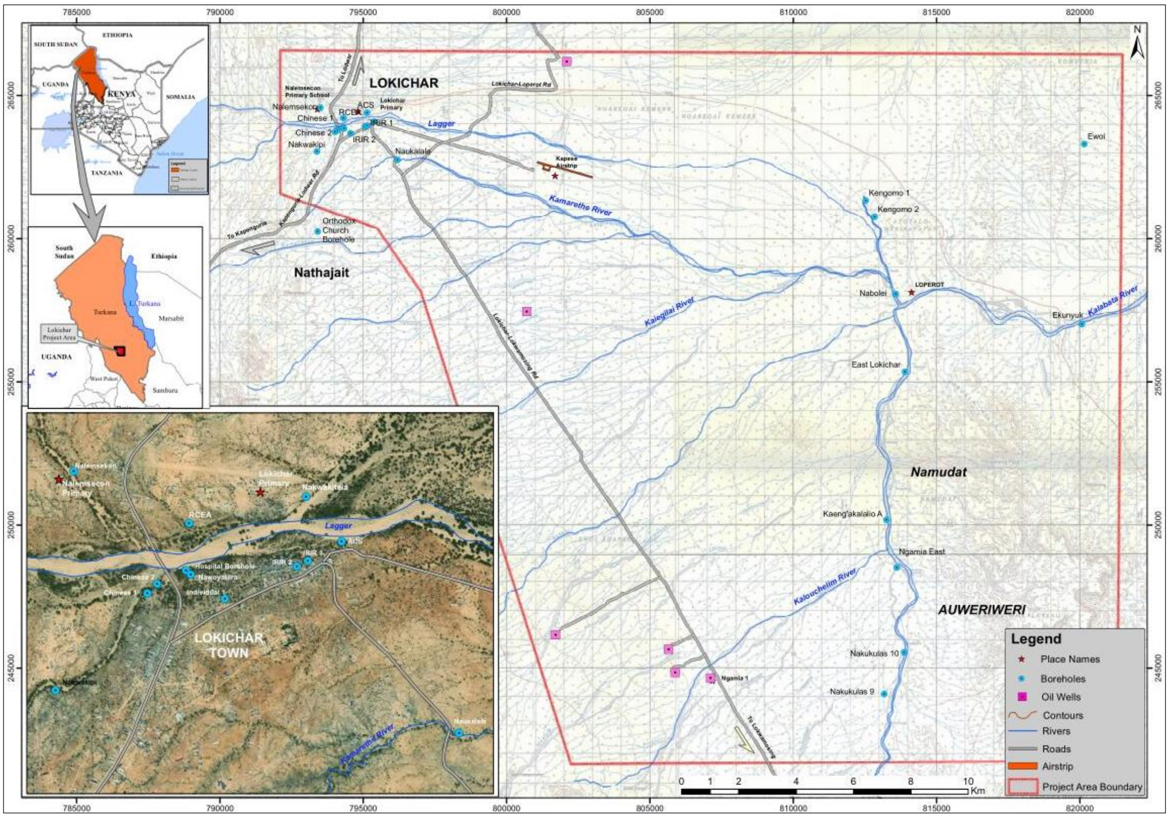

Fig. 1. Map of study area (Adapted from Gitari et al, 2022)

2.2.1. Climate

Lokichar basin is classified as an arid and semi-arid area and is characterized by warm and hot climate. The temperatures range between 20°C and 41°C with a mean of 30.5°C (Makokha et al,2024). The rainfall pattern and distribution are unpredictable and unreliable both in time and in space. The area receives an annual average rainfall of 121mm with two rainfall seasons, the long rains occurring between April and July commonly referred to as "Akiporo" and the short rains occur between October and November. The driest periods in the area are January, February and September (Gitari et al,2022). The rainfalls are brief and accompanied with violent storms thus resulting in flash floods.

2.2.2. Topography and geology

The geological framework of the Lokichar Basin is defined by a complex succession of rocks resulting from extensional rifting and subsequent infilling. The basin itself was formed by the rifting of ancient Precambrian basement rocks, which are exposed at the surface in certain areas as intensely folded gneisses and migmatites (Gitari et al., 2022). This basement is overlain by a Tertiary sequence comprising the Turkana Grits highly fractured and jointed deposits of grits, sandstones, silts, and sandy limestones derived from basement erosion as well as fluvial sedimentary deposits (sandstones and shales) and a volcanic succession of basalts and phonolites (Gitari et al., 2022; Golder, 2020). Superficial geology across the basin consists primarily of Plio-Holocene alluvium, comprising unconsolidated alluvial fan and fluvial sediments, with localized outcrops of the underlying Archaean basement and Tertiary volcanics (Golder, 2020). The predominant soil types mapped in the area are Eutric and

Calcaric regosols (Golder, 2020). The topographical features consist of plateaus, low lying plains with isolated hill ranges, minor scarps, foot slopes, footbridges and seasonal rivers (Moso, 2016).

2.2.3. Water sources

The Lokichar Basin relies on two primary water sources: surface water and groundwater (Gitari et al., 2022). Surface water is primarily available from numerous seasonal rivers, known locally as Laggas. These ephemeral streams are characterized by thick, sandy beds. During rainfall events, surface runoff flows over these Laggas, with a significant portion percolating through the sand to recharge the underlying aquifers, making them a vital medium for groundwater recharge (Golder,2020). Surface flow is short-lived, typically ceasing within a week after the rain stops. However, immediately following rainfall, water can be accessed directly from the Laggas by scooping out the sand to create small, temporary water pans. This water remains accessible for a brief period before the pans dry up (Price, 2016).

2.3. Data collection and analysis

The primary data for the analysis consisted of a long-term historical rainfall time series spanning 44 years, from 1981 to 2024. This data was obtained from the NASA Prediction of Worldwide Energy Resources (POWER) project (NASA POWER)

2.4. Rainfall trend analysis

To detect and quantify long-term trends in the rainfall data, two non-parametric statistical tests were employed: the Mann-Kendall test and Sen's Slope estimator. Mann-Kendall Test was used to statistically assess whether there was a monotonic upward or downward trend in the rainfall time series over the study period. Sen's Slope Estimator was applied to quantify the magnitude of the identified trends. The trend analysis was conducted on the annual rainfall total, as well as on the two main seasonal periods: the Long Rains (March-May, MAM) and the Short Rains (October-December, OND).

2.5. Rainfall anomaly and drought characterization

To assess rainfall variability and long-term trends, three complementary statistical methods were employed. First, the Rainfall Anomaly Index (RAI) was calculated to classify each year as extremely wet, very wet, near normal, or dry. Second, the Mann-Kendall (MK) trend test, a non-parametric method widely used in climatological studies, was applied to detect the presence of monotonic trends in the annual rainfall series without assuming a specific data distribution. Third, the Sen's slope estimator was used to quantify the magnitude of the trend identified by the MK test by calculating the median of all pairwise slopes in the time series. The MK test analyzed the monthly, seasonal and annual rainfall data and detected any significant statistical trend. Sen's slope (Q_r) determined the nature of the trend. MK test statistic (Z) was done using the mathematical relation by Bluman (2009) shown in Equation 1. The statistic S is calculated using equation 1:

$$S = \sum_{i=1}^{n-1} \sum_{j=k+1}^{n} sign(xj - xi) \qquad (1)$$

where x_i and x_j are annual rainfall values in years i and j and n is number of data points. The Z- statistic is considered and is given by the Equation 2:

$$z = \begin{cases} (s-1)/se, & s > 0 \\ 0, & s = 0 \\ (s+1)/se, & s < 0 \end{cases} \qquad (2)$$

where S_e is square root of the variance. A positive value of Z shows an upward trend while a negative value shows a downward trend. The variance is given by Equation 3:

$$var = \frac{1}{18}[n(n-18)(2n+5)] - \frac{1}{18}\sum f_t(f_t - 1)(2f_t + 5) \qquad (3)$$

where n is number of tied groups and f_t is number of data point in the i^{th} tied group.

The Mann-Kendell trend analysis was carried out in MS-Excel assuming a significance level (alpha) of 0.05.

Standardized Precipitation Index (SPI) was computed to characterize meteorological drought severity at the annual timescale. Drought events were classified based on the SPI values according to established criteria (Herrero et al., 2010).

$$SPI = \Phi^{-1}(H(x)) \qquad (4)$$

where Φ^{-1} is the inverse standard normal distribution function, *SPI* has a mean of 0 and standard deviation of 1.

The assumption of stationarity that the statistical properties of the rainfall time remain constant over time was evaluated. The results from the trend, anomaly, and stationarity analyses were synthesized to understand the overall rainfall regime of the Lokichar Basin. The identified extreme years (both wet and dry) were contextualized with documented historical climate events and their documented impacts on the region (Herrero et al., 2010; Huho and Mugalavai, 2014).

2.6. Water demand dynamics in the Lokichar Basin

Water demand in the Lokichar Basin was assessed for the years 2009, 2019, and 2022, representing the pre-oil era, the Early Oil Pilot Scheme, and the full oil field development phase, respectively. This temporal framework allows for a comparative assessment of how industrial activity influences water demand across sectors.

The analysis drew on census data from the Kenya National Bureau of Statistics (KNBS) for population and livestock figures, supplemented by projections from the National Water Master Plan (2013) and revised growth rates from Tullow Oil Company (2022) to account for in-migration linked to petroleum development. A growth rate of 0.3% per annum was applied for 2009-2019. For projection to 2022, a higher rate of 3.2% per annum, as per the National Water Master Plan (2013), was used.

Livestock demand was estimated from species-specific intake rates;

Livestock Demand (l/day) = (Number of Goats × intake/goat) + (Number of Sheep × intake/sheep) + (Number of Camels × intake/camel)

Water Demand Parameters: Standard per-capita and per-unit water consumption rates were sourced from key national and local documents, including the National Water Master Plan (2013), the Ministry of Water and Irrigation (MWI) design manual, and reports from the Lokichar Water and Sanitation Company (LOKIWASCO, 2023). Domestic Demand (l/day) = Population × Per-capita water consumption rate. The spatial distribution of demand (60% concentrated in Lokichar town) was factored in based on LOKIWASCO (2023) data

Institutional Water Demand included; demand from schools, hospitals, and administrative offices. The population of school-going children was estimated as 30% of the total population. Hospital bed requirements were calculated at a rate of 0.8 beds per 1,000 persons. Demand was estimated by applying standard water consumption rates for instance; liters per student per day, liters per bed per day to the calculated beneficiary numbers.

Commercial demand was based on the number of establishments; shops and bars, which nearly doubled between 2009 and 2019.

Commercial Demand (l/day) = Number of Establishments × Average water consumption per establishment.

Industrial Water Demand: Pre-2009 Demand was assumed to be negligible since it was beginning of oil industry; Water demand for petroleum operations was calculated based on the water-to-oil ratio provided by Tullow Oil Company (2022), which specifies approximately nine barrels of water required per barrel of oil produced. This ratio was applied to projected oil production volumes for 2019 and 2022

Total demand was therefore the sum of domestic, livestock, institutional, commercial, and industrial requirements, with clear evidence that oil-related activities and rapid population growth after 2019 substantially increased pressure on the basin's limited water resources.

2.7. Borehole Selection and Monitoring

Monitoring focused on Chinese 1 and Nawoyatira boreholes, which are widely used for domestic water supply and represent the abstraction dynamics in catchment.The selection of theses monitoring boreholes was based on their spatial service coverage and relative abstraction influence within the Lokichar urban area. The Nawoyatira borehole, which supplies the largest service area and represents the highest groundwater demand, was identified as the primary monitoring point. In addition, the Chinese 1 borehole, situated within the hydraulic influence zone of Nawoyatira, was included to capture localized aquifer response. Water level measurements from these two boreholes were analyzed to detect potential temporal trends and assess spatial variability in groundwater dynamics. Additional borehole data were obtained from the Lodwar-Kerio Water and Sanitation Company (LOKIWASCO) and previous hydrogeological surveys. Borehole depths, static water levels, and abstraction records were obtained. Geographic coordinates (northing, easting, and elevation) were measured using a handheld GPS. Groundwater level data were processed in Surfer 10 software to generate potentiometric surface maps. Contours were interpolated to infer groundwater flow direction.

Hourly groundwater levels were recorded using automatic water level data loggers installed in Chinese 1 and Nawoyatira boreholes. Measurements were taken between August and September 2020, covering the daily cycles. Water levels were cross-checked manually using an electric water level dipper to validate logger readings. Hourly records were used to identify daily fluctuations in response to pumping and aquifer recovery. Extreme values (minimum and maximum depths) were documented to assess stress on the aquifer. Results were interpreted within the framework of Integrated Groundwater Resources Management (IGWRM). Findings were linked to domestic water demand, industrial abstraction scenarios (EOPS 2019–2022), and potential aquifer depletion risks.

Groundwater recharge estimates for the Lokichar Basin were derived using spatially distributed recharge coefficients reported in the Turkana County recharge assessment by Gitari (2022), which identifies recharge rates of 10–20% of mean annual rainfall for semi-arid sedimentary basins in northern Kenya. Mean annual rainfall derived from rainfall data was multiplied by these recharge coefficients to obtain a recharge Recharge volume was then computed by multiplying recharge depth by the basin surface area. Pearson correlation was done to determine the relationship between rainfall anomalies and ground water levels.

3. Results and Discussion

3.1. Rainfall data analysis

Analysis of annual rainfall in the Lokichar Basin between 1981 and 2024 reveals pronounced inter-annual variability, a defining feature of arid and semi-arid lands (ASALs). Annual totals ranged from less than 200 mm in severe drought years such as 1984, 1992–1994, 2009, 2017, and 2022 to nearly 590 mm in exceptionally wet years such as 2006, 2010, 2013, and 2019–2020. This alternating sequence of droughts and floods reflects the high sensitivity of the basin to hydroclimatic extremes.

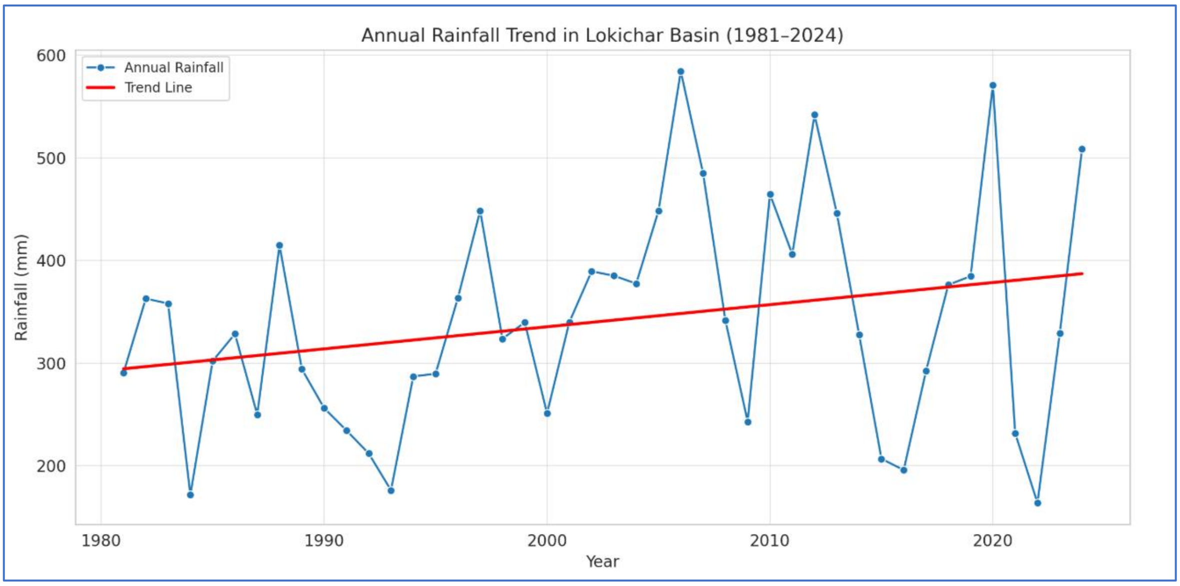

Fig. 2. Annual rainfall trend in Lokichar basin

Despite these fluctuations, the linear trend line indicates a gradual increase in rainfall, rising from an average of approximately 300 mm in the early 1980s to nearly 380–400 mm in recent years. This positive trend is consistent with regional analyses, which highlight intensifying rainfall variability rather than uniform declines across East African ASALs

(Funk et al., 2015). The persistence of recurrent droughts, however, suggests that enhanced rainfall does not necessarily translate into improved water security, given the uneven temporal and spatial distribution of precipitation.

3.2. Rainfall Anomaly Index (RAI) analysis

The Rainfall Anomaly Index (RAI) analysis for the Lokichar Basin reveals a pattern of high interannual variability, characteristic of arid and semi-arid lands (ASALs). This variability is marked by a bimodal distribution of extremes. Severe droughts (RAI < -2), as seen in years like 1984, 2000, 2009, and 2017, align with historical events that significantly impacted pastoralist livelihoods and water resources in northern Kenya (Herrero et al., 2010; Huho and Mugalavai, 2010). Conversely, extreme wet conditions (RAI > +2), such as those in 1997, 2010, and 2018, are often associated with El Niño events, which have brought both beneficial pasture growth and destructive flooding (Lyon and DeWitt, 2012).

Between 1981 and the mid-1990s, the basin experienced prolonged negative anomalies, with some of the lowest values (RAI < –2) recorded in 1984, 1992, and 1993, coinciding with severe droughts documented across Turkana and northern Kenya (Huho and Kosonei, 2014). This period reflects a sustained rainfall deficit that severely constrained water availability and undermined pastoral livelihoods. Conversely, from the early 2000s to 2010, a series of positive anomalies emerged, peaking in 2007–2008 and again in 2013, suggesting episodic wet years that temporarily eased water stress and likely contributed to aquifer recharge.

More recently, rainfall patterns have alternated sharply between extremes. Notable wet years were observed in 2018, 2020, and 2023 (RAI > +2), yet these were immediately followed by strong negative anomalies in 2016 and 2022, indicating intensified rainfall volatility. Out of the 44-year record, approximately half the years experienced negative anomalies, underscoring the persistent dominance of below-average rainfall. For the Lokichar Basin, such oscillations imply recurrent drought stress punctuated by short-lived wet periods. This climatic instability amplifies risks for water security, especially given rising domestic and industrial demand, and necessitates adaptive management approaches such as groundwater monitoring, artificial recharge, and drought preparedness measures (Herrero et al., 2010; Ayugi et al., 2018).

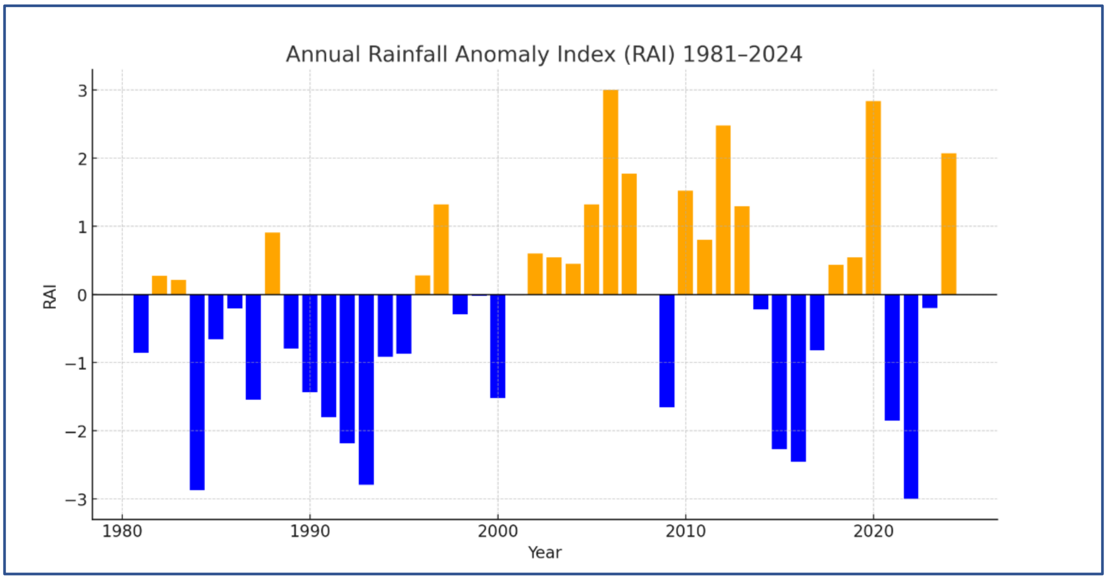

Fig. 3. Annual rainfall Anomaly index (1994-2024)

3.3. The Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (SPI) for March (1981–2024) reveals marked interannual variability in rainfall across the Lokichar Basin (Figure 4). March is a critical rainfall month for Turkana, supporting domestic water use, livestock grazing, and groundwater recharge (GoK, 2013; Opiyo et al., 2015). The SPI record oscillates frequently between wet (SPI > +1) and dry (SPI < –1) anomalies, highlighting the basin's semi-arid climate and vulnerability to rainfall extremes.

Severe droughts occurred in the early 1980s, particularly 1983–1984, when SPI values fell below –2, coinciding with the prolonged East African drought that caused widespread water shortages (Huho and Kosonei, 2014). Other notable dry periods include 1999–2000 and 2009–2011, both linked to regional ENSO-related rainfall failures (Funk et al., 2015). In contrast, wet anomalies above +1 were recorded in 1981, 1990, 2010, 2018, and 2020, suggesting episodic years of above-average rainfall that likely enhanced recharge but also increased risks of flash floods (Sifuna et al., 2019).

Of the 44 years assessed, 25% were drought years (SPI < –1) and 20% were wet years (SPI > +1), with the remainder falling within near-normal conditions. Since 2000, rainfall has shown increasing volatility, with strong wet anomalies such as 2018–2020 followed by sharp reversals into drought in 2021–2022. This intensification of rainfall variability mirrors broader climate patterns observed in Kenya's arid and semi-arid lands (Herrero et al., 2010; Ayugi et al., 2018). For the Lokichar Basin, the alternation between drought and wet extremes complicates water resource planning, placing pressure on groundwater resources already stressed by domestic demand, livestock use, and petroleum-related industrial abstraction.

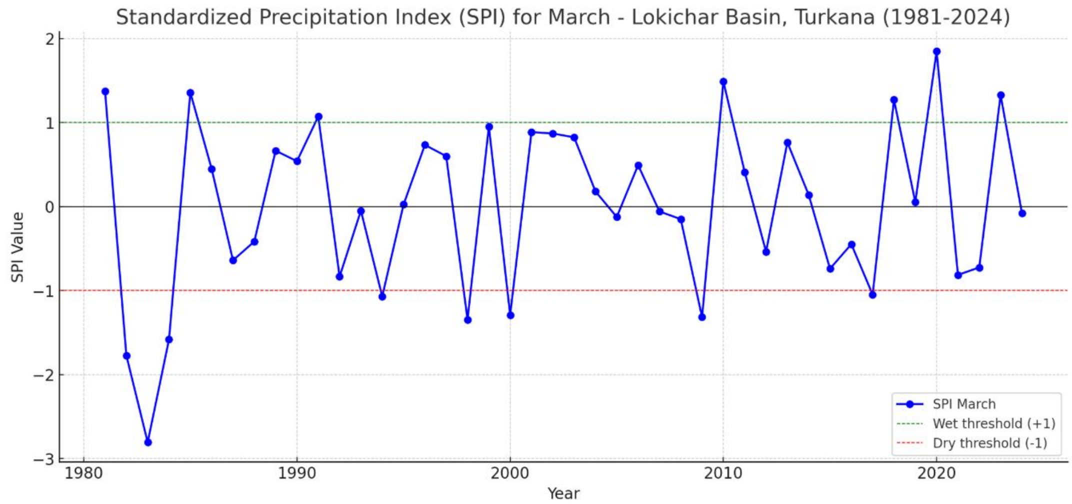

Fig. 4. SPI index of Lokichar basin

Table1. Mann Kendall and Sen's slope test for rainfall analysis

series	Mann-Kendall	Z-statistic	p-value	Sen's Slope (mm/year)	Interpretation
Ann	177	2.07	0.0385	+4.92	significant increasing trend
MAM	133	1.56	0.118	+1.83	no significant trend
OND	182	2.13	0.033	+3.95	significant increasing trend

Analysis of long-term rainfall data for the Lokichar basin in Turkana County (1981–2024) using the Mann-Kendall test reveals significant increasing trends in both annual and October–December (OND) seasonal rainfall. The annual rainfall shows a statistically significant upward trend ($p = 0.0385$) supported by a Sen's slope estimate of approximately 4.9 mm per year, indicating a steady increase in total precipitation over the 44-year period. Similarly, the OND season, which is crucial for groundwater recharge and agricultural activities in this semi-arid region, also exhibits a significant upward trend ($p = 0.033$) with a Sen's slope of about 4.0 mm per year. These findings are consistent with broader regional climate studies that show increasing rainfall variability and intensification in parts of Eastern Africa (Nicholson, 2017; Lyon and DeWitt, 2012). The observed increase in OND rainfall may positively influence water availability in

Lokichar, which is vital given the region's vulnerability to droughts (Ngigi et al., 2006).

Conversely, the March–May (MAM) season rainfall showed a positive but statistically insignificant trend (p = 0.118) with a Sen's slope of 1.8 mm per year, suggesting more variability and less consistent changes during the long rains. The differential trends between OND and MAM seasons could be attributed to shifts in regional atmospheric circulations influenced by Indian Ocean Sea surface temperature anomalies and the Intertropical Convergence Zone dynamics (Sifuna et al., 2019). This seasonal variation underscores the need for tailored water resource management approaches that consider the differing rainfall dynamics throughout the year. Overall, these trend analyses highlight evolving precipitation patterns in Lokichar that could affect hydrological processes, including groundwater recharge and surface water availability, with implications for drought resilience and development planning in Turkana County.

3.4. Stationarity and non-stationarity analysis

Analysis of rainfall data (1981–2024) for the Lokichar Basin indicates non-stationarity, particularly in the annual and OND (October-November-December) seasonal records, where the Mann-Kendall test revealed significant increasing trends. This is contrasted by a non-significant positive trend in the MAM (March-April-May) season, suggesting that changes in stationarity are season-dependent.

Non-stationarity—where statistical properties like the mean change over timeis critical to recognize because many hydrological models assume stationary inputs. Using such models with trending data can lead to inaccurate predictions for water resource planning (Milly et al., 2008). The observed upward trends in Lokichar are likely driven by large-scale climatic shifts, such as changes in the migration of the Intertropical Convergence Zone or anomalies in Indian Ocean Sea surface temperatures (Hoerling et al., 2012).

Consequently, relying solely on historical records is insufficient for future water infrastructure design and management. Incorporating trend analyses into planning is essential for developing adaptation strategies that ensure a sustainable water supply and drought resilience in this semi-arid region.

3.5. Water demand dynamics

Groundwater demand in the Lokichar Basin evolved markedly between 2009, 2019, and 2022, reflecting demographic, socio-economic, and industrial changes associated with oil development (LOKIWASCO, 2023). Results indicate that the domestic water demand increased from 1.01 million liters per day in 2009 to 1.17 million liters per day in 2019, driven by a low population growth rate of 0.153% per annum (KNBS, 2010; 2019), below the national average of 2.3% (KNBS, 2019). Accelerated population growth linked to oil activities raised domestic demand to nearly 1.20 million liters per day by 2022 (Figure 5). Approximately 60% of the population resides in Lokichar town, where individual household connections dominate, contributing over 75% of total domestic consumption (Tullow Oil Company, 2022) .

Livestock water demand, primarily from goats, sheep, and camels, rose modestly from 373,000 liters per day in 2009 to 384,000 liters per day in 2022. Livestock population growth was estimated at 0.3% per annum (2009–2019) and 3.2% per annum (2019–2022), following National Water Master Plan (2013) guidelines (KNBS, 2010; KNBS, 2019).

Institutional water demand, including schools, hospitals, and administrative offices, increased from 450,000 liters per day in 2009 to 535,000 liters per day in 2022, constrained by limited facility expansion. Commercial demand, driven by shops and bars in Lokichar town, rose from 11,000 liters per day in 2009 to 21,700 liters per day in 2022, reflecting growing economic activity associated with the oil sector.

Industrial water demand, negligible prior to oil production, surged dramatically with petroleum extraction, requiring approximately nine barrels of water per barrel of oil produced (Tullow Oil Company, 2022). Demand increased from zero in 2009 to 2.86 million liters per day in 2019 and was at 143.1 million liters per day by 2022 (Figure 5) accounting for 99% of total basin water use. This unprecedented growth far exceeds national industrial water demand projections (National Water Master Plan, 2013) and dominates aggregate groundwater use, threatening access for domestic, livestock, institutional, and commercial users (Robert and Greg, 2017).

Overall, total groundwater demand increased by 168% from 2009 to 2019 and has grown to by 2,833% from 2019 to 2022. These trends underscore the urgent need for alternative water sources for oil production, enhanced water-use efficiency, and integrated water resource management to safeguard long-term water security and socio-economic well-being in the basin (Mwitari et al., 2020).

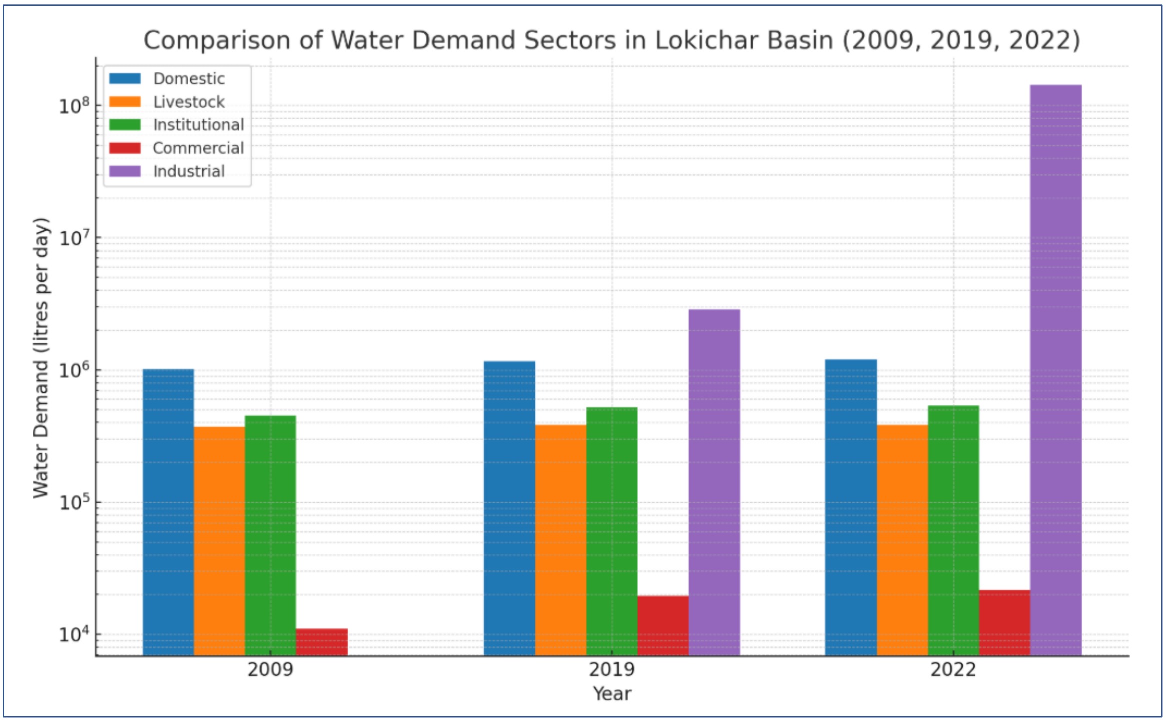

Fig. 5. Comparison of water demand sectors in Lokichar basin (2009, 2019, 2022)

3.6. Groundwater level trends

Continuous monitoring in the Lokichar Basin revealed distinct diurnal and daily groundwater fluctuations at the Chinese 1 and Nawoyatira boreholes. Hourly data showed peak water levels in the early morning (07:00 – 08:00) and late afternoon (17:00), with minima between 13:00 –15:00, reflecting overnight aquifer recovery and daytime drawdown from domestic pumping at communal water points (Chepyegon and Kamiya, 2018; Opiyo et al., 2015).

Extreme levels recorded were 3.5 m (shallowest, 15 August 2020, 07:00) and 29.0 m (deepest, 5 September 2020, 14:00) for Chinese 1, and 3.84 m and 26.60 m for Nawoyatira, highlighting the combined influence of natural recharge and abstraction patterns. Daily averages were 18.12 m for Chinese 1 and 19.50 m for Nawoyatira, showing minimal variation across the study period. This stability corresponds with the suspension of large-scale industrial abstraction during the Early Oil Pilot Scheme (Tullow Oil, 2020), indicating that domestic use alone did not significantly deplete the aquifer over short time scales, consistent with other semi-arid groundwater systems in Kenya (Maina et al., 2024).

Overall, groundwater levels in the Lokichar Basin reflect a dynamic balance between natural recharge, domestic demand, and industrial abstraction, with hourly fluctuations superimposed on stable daily averages when industrial pumping is absent.

3.7. Groundwater flow direction

Borehole monitoring data within the Lokichar Basin is scarce, and the few available records present limitations for groundwater flow direction analysis. This is primarily because most monitoring wells are also utilized for water supply, making it difficult to obtain accurate pumping records (Mbugua et al, 2022). The flow direction analysis revealed that groundwater in the Lokichar Basin flows predominantly eastwards (Figure 7), a pattern that closely aligns with the northeastward trend reported by Gaye and Tindimugaya (2018).

Understanding the groundwater flow direction is critical for effective water resources management in petroleum development areas such as Lokichar, where abstraction patterns, potential contamination pathways, and aquifer recharge zones are directly influenced by subsurface hydraulic gradients.

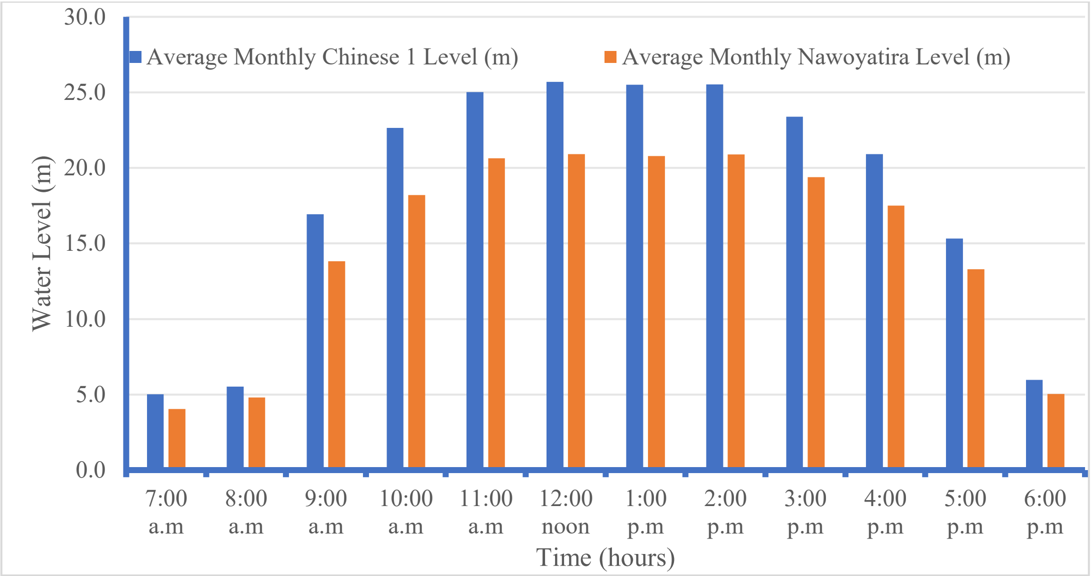

Fig. 6. Average monthly groundwater levels in Chinese1 and Nawayatira borehole

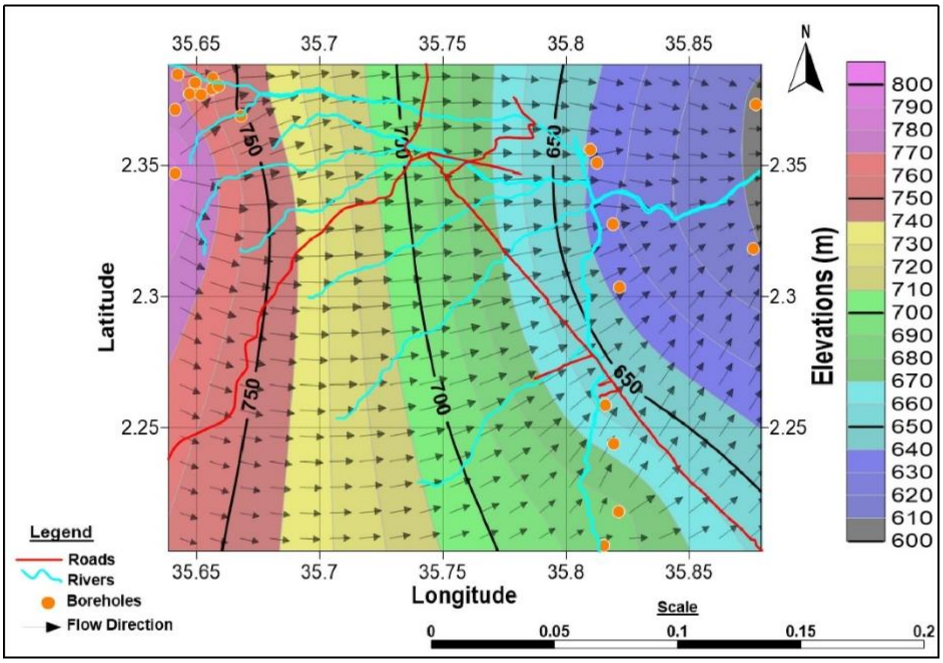

Fig. 7. Groundwater flow direction in the study area

3.8. Radius of influence and aquifer characteristics

Pumping test results from 23 boreholes in the Lokichar Basin showed wide variation in aquifer properties. Most boreholes (n = 13) had moderate transmissivity values of about 1.26×10^{-3} m²/s and a specific yield of 0.21, giving an estimated radius of influence of about 787 m under normal conditions and up to 2,572 m in sensitivity analyses. The Nakukulas 9 and 10 boreholes exhibited the highest transmissivity (6.00×10^{-3} m²/s) with influence zones extending to 5,612 m, indicating highly permeable aquifer zones. In contrast, Kaeng'akalalio A and Ekunyuk had very low transmissivity ($<10^{-5}$ m²/s), producing limited influence zones below 100 m. These results highlight the heterogeneous nature of the aquifer system across the basin.

High transmissivity and large influence zones cluster in the Nakukulas area, likely reflecting coarse alluvial deposits or fractured volcanic rocks. Eastern fringe boreholes, in contrast, are characterized by finer sediments or poorly fractured units that restrict flow. Specific yield values (0.036–0.500) further indicate strong heterogeneity in aquifer storage, ranging from confined to unconfined systems. These values are consistent with East African sedimentary basins, where lithologic variation and fracture density control aquifer productivity (Gaye and Tindimugaya, 2018). High-yield zones, such as Nakukulas, are critical for meeting industrial water demand (Tullow Oil, 2019), whereas low-yield boreholes highlight areas vulnerable to rapid depletion (Gaye and Tindimugaya, 2018).

Demand data are from LOKIWASCO (2023), KNBS (2010; 2019), and Tullow Oil Company (2022), with drawdown simulations based on (Gaye and Tindimugaya, 2018) aquifer parameters. Industrial abstraction for oil production increased from 0 ML/day in 2009 to 2.86 ML/day in 2019, and is projected at 143.1 ML/day by 2022, accounting for > 99% of total demand. Corresponding drawdowns rise from ~14 m (2019) to > 60 m (2022), reflecting the strong sensitivity of the interconnected aquifer system to large-scale pumping. Without alternative water sources like Turkwel Dam pipeline or integrated groundwater management (Golder, 2020), such abstraction risks aquifer depletion and reduced community water access in this semi-arid petroleum basin.

From a management perspective, large radii of influence increase the potential for well interference, necessitating regulated abstraction to prevent drawdown and quality decline (Golder, 2020). Sensitivity analyses also show radius estimates are highly dependent on S_y, underscoring the need for detailed site characterization. Estimations of the 2019 industrial water demand already indicated a pronounced drawdowns of about 11–14 m midday with a forecasted drawdowns exceeding 60 m in 2022. Such depth reductions could threaten well performance but risk hitting pump-intake zones, increasing pumping costs, and potentially depleting local groundwater reserves.

3.9. Industrial water demand impact on groundwater levels

Simulation of the 2019 EOPS industrial water demand indicated substantial midday drawdown in both boreholes, particularly at 13:00 when peak abstraction occurred. For Chinese 1, water levels dropped from 25.50 m to 39.47 m, while Nawoyatira declined from 20.78 m to 32.16 m (Figure 8). These results demonstrate the significant short-term stress imposed by high-volume withdrawals, which reduce aquifer pressure and increase pumping costs (Buddemeier, 2010).

3.10. The 2022 industrial demand scenario

The Turkwel Dam is being constructed by government to help meet the water demand, if not completed, meeting oil production water requirements would necessitate approximately 300 high-yield boreholes (20 m³/hr each). Under such conditions, extreme midday drawdowns would be: Chinese 1 levels fall from 14.71 m at 07:00 to 74.74 m at 13:00 before partially recovering to 17.48 m at 17:00, while Nawoyatira drop from 11.80 m to 60.90 m at 13:00 before rising to 14.77 m by 17:00 (Figure 9). These fluctuations far exceed typical daily variations and suggest unsustainable stress on the aquifer system if industrial abstraction is resumed without supplementary water sources.

3.11. Linking Rainfall Variability to Groundwater Level Trends

The Rainfall Anomaly Index (RAI) and Standardized Precipitation Index (SPI) analyses reveal that Lokichar Basin experiences pronounced hydroclimatic variability, with multi-year droughts; 2000, 2009, 2017 and episodic wet years; 1997, 2010, 2018 (Figure 10). Periods of sustained negative anomalies correspond to reduced recharge potential in the basin's lagga-fed alluvial aquifers, thereby lowering baseline groundwater levels (Nicholson, 2017). Conversely, positive anomalies during wet years can enhance shallow aquifer recharge, though high-intensity rainfall and elevated evapotranspiration limit infiltration efficiency (Funk et al., 2015; Lyon and DeWitt, 2012).

The interaction between climatic variability and abstraction pressure is critical: during dry anomaly periods, even moderate pumping for domestic use can produce significant drawdowns, whereas in wet anomaly years, industrial-scale pumping as projected for full oil production in 2022 could offset recharge gains and drive extreme midday drawdowns (>60 m). These findings highlight the compounded vulnerability of groundwater resources in arid petroleum basins, where rainfall variability and anthropogenic demand act synergistically to shape water availability (Golder, 2020).

The calculated correlation coefficients show a moderate inverse relationship between groundwater levels and rainfall anomalies, with groundwater depth correlating negatively with both RAI (r =–0.55) and SPI (r =–0.60). This indicates that groundwater levels tend to decline during years of negative rainfall anomalies (dry periods) and recover during years of positive anomalies (wet periods). In contrast, the rainfall anomaly indices themselves exhibit a strong positive correlation (RAI–SPI, r=+0.90), demonstrating their consistency in representing temporal rainfall variability in the basin. Collectively, these relationships suggest that groundwater in the Lokichar Basin responds sensitively to interannual fluctuations in rainfall, reinforcing the role of climatic variability as a primary control on recharge dynamics.

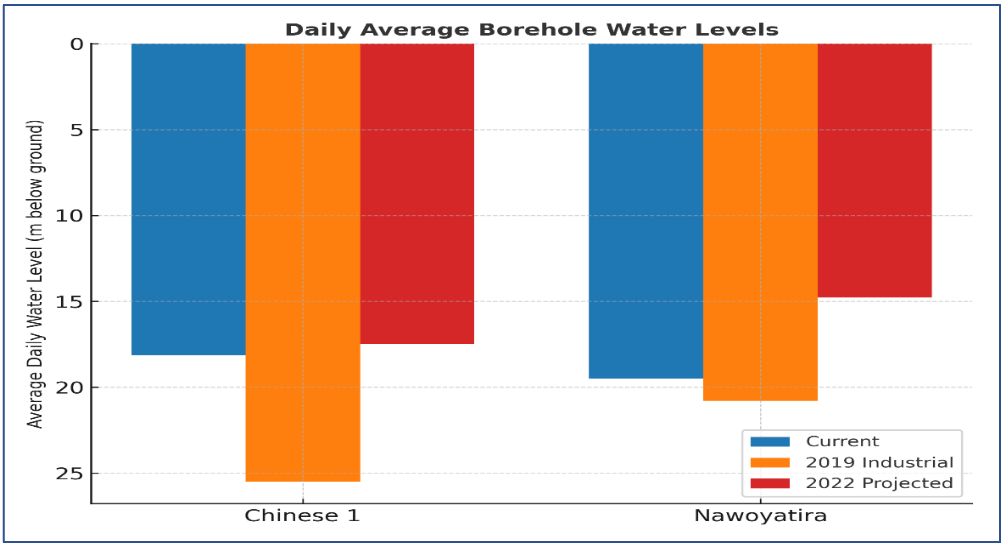

Fig. 8. Average daily water level (meters below ground)-sensitivity analysis

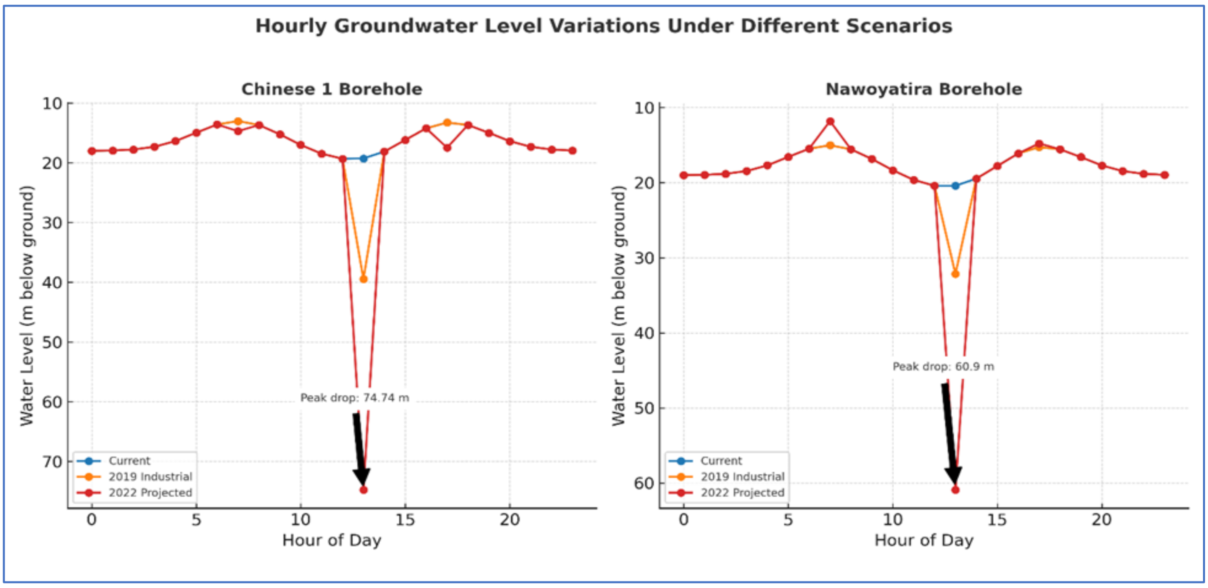

Fig. 9. Hourly groundwater level simulations under different scenarios

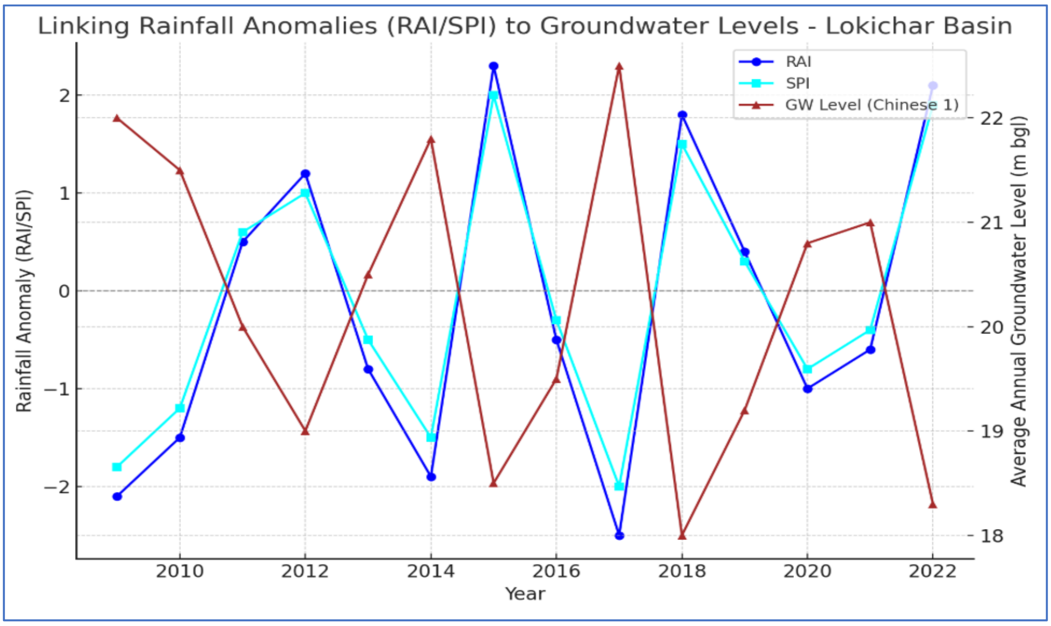

Fig. 10. Linking Rainfall Anomalies (RAI/SPI) to groundwater levels in Lokichar Basin

3.12. Recharge versus demand

Based on the Turkana County recharge map (Gitari, 2022), which estimates recharge rates of 10–20% of rainfall in the Lokichar Basin, the mean annual rainfall of 121 mm yr⁻¹ over an area of ~1,800 km² translates to a recharge depth of 12.1–24.2 mm yr⁻¹, equivalent to volume of 21.78–43.56 Mm³ yr⁻¹. In 2019, total groundwater demand was ~1.81 Mm³ yr⁻¹, well within this range. However, the 2022 full-production scenario implies a demand of ~53.0 Mm³ yr⁻¹, exceeding the upper-bound recharge by ~9.4 Mm³ yr⁻¹ (≈122% of the upper bound; 243% of the lower bound) (Figure 11).

This imbalance implies that under full-scale oil production, groundwater abstraction would exceed the basin's natural recharge capacity, leading to progressive aquifer depletion and a shift toward the mining of non-renewable (fossil) groundwater reserves (Mumma et al., 2011; Gitari, 2022). Such overexploitation is likely to manifest through declining water tables, reduced borehole yields, and potential drying of shallow wells, ultimately altering the local hydrogeological balance and increasing the risk of saline intrusion and water quality deterioration as deeper, mineralized zones are accessed (Golder, 2020). The long-term outcome would be a sustained reduction in groundwater storage, with adverse consequences for both environmental integrity and socio-economic resilience. From a social equity perspective, the disproportionate allocation of groundwater to industrial extraction poses serious challenges to domestic and pastoral water security, particularly in arid areas where groundwater serves as the primary source of supply (Makokha et al,2024; Turkana County Government, 2016). As water levels decline, rural communities reliant on hand-pumped boreholes would experience higher access costs, reduced reliability, and extended collection times. This competition between industrial and domestic users may exacerbate existing inequalities in resource distribution and intensify vulnerability among marginalized pastoral households, for whom water availability is critical to livelihood stability. Without robust governance mechanisms, effective abstraction controls, and equitable allocation frameworks, large-scale industrial use risks transferring the burden of scarcity to local populations—undermining social welfare and threatening the long-term sustainability of the Lokichar aquifer system.

3.13. Limitations of study

The use of projected groundwater demand and drawdown data introduces uncertainty in assessing the sustainability of abstraction in the Lokichar Basin. Industrial water use estimates, particularly those for oil production, are based on future projections that may not fully capture operational variability, regulatory constraints, or delays (Tullow Oil, 2022). Consequently, the forecasted 2022 demand of 143.1 ML day⁻¹ may either over- or underestimate actual abstraction.

Model sensitivity to aquifer parameters from Gaye and Tindimugaya (2018)—especially transmissivity and specific yield—further limits reliability, as these values were derived from limited tests and may not represent the heterogeneous alluvial and fractured systems of the basin.

The simulations also assume a homogeneous, isotropic aquifer and constant recharge, overlooking localized faulting, inter-aquifer flow, and variable storage conditions that could alter actual drawdown responses. In addition, discrepancies among data sources (LOKIWASCO, 2023; KNBS, 2010; 2019; Tullow Oil, 2022) may introduce inconsistencies when integrated for analysis. These limitations highlight the need for continuous groundwater monitoring, periodic aquifer testing, and model recalibration using observed abstraction and water-level data. Strengthening data quality and representation will improve confidence in future groundwater projections and ensure that management decisions reflect the basin's true hydrogeological behaviour.

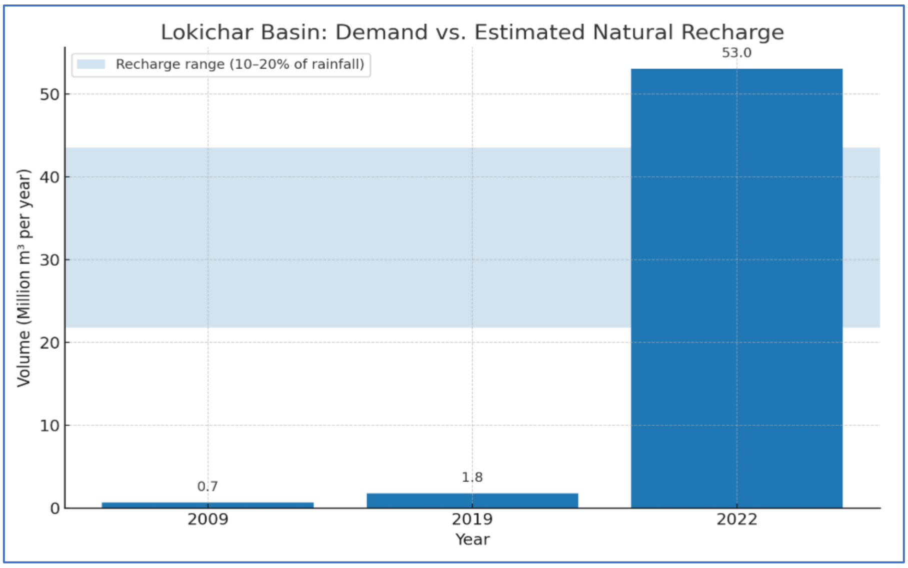

Fig. 11. Demand versus estimated natural recharge in Lokichar Basin

4. Conclusions

This study reveals a critical and unsustainable trajectory for water resources in the Lokichar Basin, driven by the convergence of inherent climatic variability and unprecedented industrial demand. The analysis of rainfall from 1981 to 2024 confirms the high hydroclimatic variability characteristic of arid and semi-arid lands, with no long-term trend sufficient to mitigate water scarcity. Crucially, the projected groundwater demand for full-scale petroleum production, estimated at approximately 53.0 $Mm^3\ yr^{-1}$, far exceeds the estimated annual recharge potential of the aquifer (21.78–43.56 $Mm^3\ yr^{-1}$). This significant recharge-demand gap indicates that reliance on groundwater alone for industrial operations would constitute aquifer mining, leading to unsustainable depletion.

The dominance of industrial use, which surged to over 99% of total demand by 2022, fundamentally alters the basin's water dynamics. Hydrological simulations demonstrate that this level of abstraction would cause extreme drawdowns exceeding 60 meters, far surpassing natural fluctuations and threatening the functionality of wells, increasing pumping costs, and potentially compromising water quality. The aquifer's vulnerability is compounded by rainfall variability; periodic droughts diminish recharge precisely when the system is under greatest stress, creating a compound risk that amplifies water insecurity.

Therefore, the current path of groundwater-dependent development is untenable. The findings underscore an urgent imperative for a paradigm shift in water resource management. Ensuring long-term water security for all sectors requires immediate and decisive action, primarily through the diversification of water sources. The development of alternative supplies, such as the proposed Turkwel Dam pipeline, is essential to offset industrial demand. Furthermore, the implementation of a robust, integrated water resource management (IWRM) framework is critical. This must include stringent regulatory controls on abstraction, enhanced continuous monitoring of aquifer health, and proactive drought preparedness plans. Without these interventions, the escalating conflict between industrial water needs and the preservation of community water access and ecological integrity will intensify, jeopardizing the socio-economic stability of the region.

5. Acknowledgements

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6. Conflict of Interest

The authors declare that there is no conflict of interest.

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