The Impact of climate change on Mombasa city and port activities

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ABSTRACT: The research examines the effects of climate change on Mombasa city and port by utilizing indices such as Rainfall Deciles (RD), Standardized Precipitation Index (SPI), and Reconnaissance Drought Index (RDI), while also evaluating the trends in temperature and precipitation variations. The drought indices were analyzed in Mombasa, alongside the Mann-Kendall test, to assess trends in the data from 1980 to 2024, emphasizing substantial disruptions to port throughput and infrastructure due to rising temperatures and extended droughts. Simultaneously, SPI and RDI values exhibited a correlation, demonstrating approximately analogous results throughout the entire study period. The results highlight the necessity for climate-resilient infrastructure and water management strategies to guarantee operational efficiency at Mombasa port. Future research is necessary to investigate the socioeconomic effects of climate change on Mombasa City and its port.

1- INTRODUCTION

Mombasa Port is an important commercial engine in East Africa, but it, like other coastal areas, confronts special vulnerabilities to climate change. Temperature unpredictability, rainfall extremes, and lengthy droughts are all having an increasing impact on the port, which serves as a crucial gateway for regional trade. Despite their relevance, the effects of various climate conditions on port operations, such as cargo throughput and infrastructural resilience, are understudied. This study intends to close this gap by investigating long-term climatic patterns and their operational implications for Mombasa Port."

Hassan, El-Tantawi, and Hashidu (2017), discussed the Earth's climate has persistently varied since the formation of its surface. These historical changes, imprinted on the landscape, have influenced the evolution of all life forms and provided a context for societal and economic advancements.

The Intergovernmental Panel on Climate Change (IPCC) characterizes climate change as "a change in the state of the climate that can be identified (e.g., using statistical tests) by alterations in the mean and/or the variability of its properties, and that endures for an extended duration, typically decades or longer" (IPCC, 2021). This concept includes both natural processes and anthropogenic influences, with the latter predominantly driving these changes through activities such as fossil fuel combustion and deforestation. These changes are notably accompanied by an increase in the frequency of extreme weather events, as the rise in temperature has resulted in substantial alterations in both human and natural systems, including more frequent droughts, floods, and other extreme weather phenomena, as well as rising sea levels and a reduction in biodiversity. These changes are generating unprecedented dangers for vulnerable people and communities as cited by IPCC, 2012.

In this vein, low- and middle-income countries are generally seen as more susceptible to the impacts of climate change compared to wealthier countries because of their heavy reliance on natural resources and limited ability to adapt. In Africa, the continent's low adaptive capacity is largely driven by limited financial, technological, and institutional capabilities, alongside relatively low economic development and pervasive poverty.

As a result, the accelerating effects of climate Current global trends indicate that the average global temperature has risen by approximately 1.1°C above pre-industrial levels, with projections of further increases if mitigation measures are not enhanced (IPCC, 2021). The aforementioned rise is likely to accelerate the manifestations of climate change, including temperature extremes, rainfall variations, sea level rise, and drought. These factors may introduce critical vulnerabilities to various sectors, particularly agriculture and transport, which are generally more susceptible to extreme events such as storm surges, floods, droughts, and strong winds, in contrast to gradual changes in temperature or precipitation. Transport operations are generally more susceptible to the effects of climate change compared to the infrastructure itself (Christodoulou & Demirel, 2018). Maritime transport and seaports may encounter operational disruptions and heightened costs as a result of stricter environmental regulations and the necessity for infrastructure adaptation (United Nations Office for Disaster Risk Reduction, 2021).

The United Nations Conference on Trade and Development (UNCTAD, 2023) indicates that climate change events, such as rainfall, winds, and drought, create significant vulnerabilities in maritime transportation systems. These vulnerabilities primarily affect port operations, which may experience operational disruptions and heightened costs due to stricter environmental regulations and the necessity for infrastructure adaptation.

This study will investigate the relationship between climate change incidents, including temperature, rainfall, and drought, in Mombasa. It will utilize the standardized precipitation index (SPI), developed by McKee, Doesken, and Kleist in 1993, along with the rainfall deficit index (RDI) as a meteorological drought index. The primary objectives are to monitor and assess drought characteristics, as well as to explore their patterns and impacts on Mombasa city and port activities.

2- STUDY AREA :

The coastal city of Mombasa, situated in southern Kenya (39.7°E, 4.1°S), is positioned on a coastal plain that varies in width from 4 to 6 km, as noted by Awuor, Orindi, and Adwera (2008). The region's geology, as illustrated by Embleton and Valencio (1977), has been influenced by the rifting and disintegration of the Palaeozoic Gondwana supercontinent, resulting in the formation of the Indian Ocean. Mombasa features a fringing reef coastline of Pleistocene origin, distinguished by elevated reef limestone formations. The coastal landscape comprises a mix of sandy beaches, creeks, muddy tidal flats, coral reefs, and rocky shores, as indicated by Abuodha (1992) and Oosterom (1988).

The tidal range in the creeks is significant, attaining up to 4.0 m during spring tides and 2.5 m during neap tides. Ruwa and Jaccarini (1986) asserted that freshwater and sediment from rivers contribute to the area, while wave heights outside the fringing reef can range from 1 to 3 m during the monsoon season. The seafloor descends to depths exceeding 200 m within a distance of less than 4 km from the coast (Abuodha 1992). The aforementioned natural depth is suitable for accommodating mother ships, particularly when dredging internal berths and port terminals.

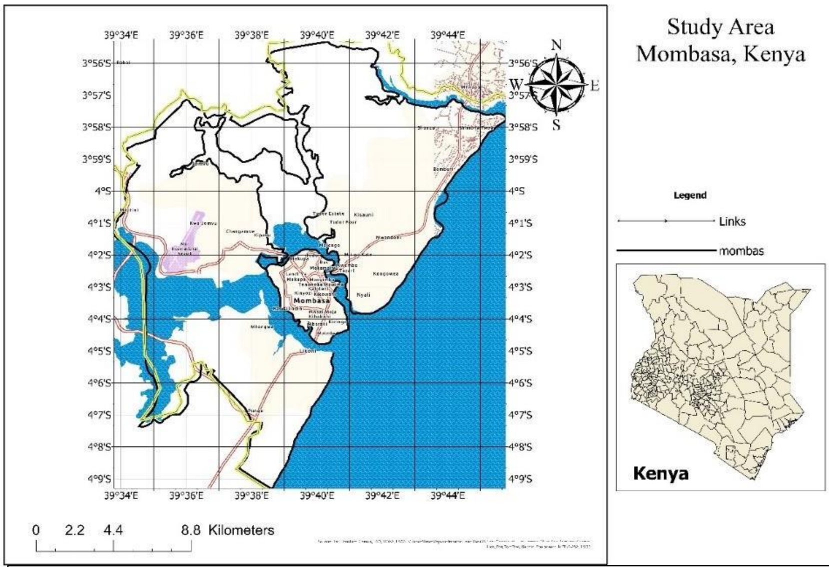

Fig., 2-1, Map of Mombasa. Created by Researcher. Based on data reterived from Kenya Marine Fisheries and Socio-Economic Development Project (KEMFSED, *https://kemfsed.org/mombasa/*)

Mombasa County is located along the coastline strip in a hot tropical environment, influenced by monsoon winds. The region endures persistently elevated temperatures and humidity levels of approximately 80%. The mean annual temperature in Mombasa is 30℃, with a minimum average of 21.3℃ (Government of Kenya 2021). January is the warmest month, averaging 30℃, while July is the coldest. Rainfall in Mombasa exhibits seasonal variation, characterized by pronounced long and short rainy intervals. The area experiences an annual average rainfall of 1,260 mm. The prolonged rains, linked to the South-Eastern monsoon winds, generally transpire from April to June, yielding an average precipitation of 1,040 mm, as demonstrated in (Mombasa County 2021). The short rains, associated with the relatively dry Northeastern monsoon winds, occur from late October to December, averaging 240mm of precipitation. The county's overall annual rainfall averages 640 mm, as indicated by Awuor, Orindi, and Adwera (2008). Similar to other regions in the country, Mombasa, Kenya, has observed an increase in temperatures.

McGranahan, Balk, and Anderson (2007) highlighted that many coastal communities in developing nations are ill-prepared for the effects of climate change, including rising sea levels, variations in temperature and precipitation, and significant storm occurrences. Similarly, Nicholls et al. (2008) emphasized the vulnerability of these communities to such climatic impacts.. These cities frequently undergo swift, unregulated expansion, high population density, and overburdened infrastructure, all of which intensify their susceptibility to climate-related occurrences. Mombasa, Kenya's second-largest city, is especially susceptible due to its geographical position and the existence of significant harbours that constitute the region's primary seaport. Musingi, Kithiia, and Wambua (1999) elucidated that elevated sea levels can result in flooding, erosion, intensified storm surges, temperature variations, increased precipitation, and saltwater intrusion, impacting not only Kenya but also its adjacent landlocked nations, including Uganda, Rwanda, and Burundi.

Awuor, Orindi, and Adwera (2008) asserted that disruptions to Mombasa Port resulting from catastrophic climate events may precipitate both direct and indirect economic consequences throughout Kenya and across East and Central Africa. Despite considerable dangers, few coastal communities have undergone thorough evaluations on their possible climate impacts, a concern echoed by other port cities globally as cited by (Nicholls et al., 2008a; Bicknell, Dodman, & Satterthwaite, 2009). The intensity of these impacts will fluctuate based on local variables such as terrain, geology, and anthropogenic activities like groundwater extraction, which can influence water levels and sediment availability.

Mombasa city, like other coastal cities, confronts substantial climate change challenges in the form of rising sea levels, rainfall, and temperature. Mombasa has experienced major socio-environmental changes over the 40-year period from 1981 to 2024, which have influenced climate impact estimates at the port. Rapid urbanization and industrialization have not only increased population density and changed land use, but they have also added new features such as the urban heat island effect, which can raise local temperatures. (UN-HABITAT 2011; Ngare et al. 2022) proposed that high population density and unplanned settlements in low-lying coastal zones increase vulnerability to flooding and sea-level rise, affecting both infrastructure and urban population resilience. According to (Abuodha 1992; Hanson et al. 2009), industrial development near Mombasa port, combined with emissions from increased transportation and infrastructure construction, has had an impact on air quality, perhaps impacting precipitation patterns.

Socio-environmental changes add to variability in observed climate data, highlighting the importance of taking into account both anthropogenic changes and evolving climate measurement standards when assessing long-term trends. Addressing these characteristics allows the study to better account for localized consequences, hence improving the robustness of climate impact assessments on Mombasa port, as highlighted by (UN-HABITAT 2011; Garschagen and Kraas 2011). As a result, as observed by (Awuor, Orindi, and Adwera, 2008), if catastrophic weather occurrences disrupted its international harbour, the ramifications would be felt throughout the region, emphasizing its economic importance to neighboring landlocked countries. From a climatological standpoint, Mombasa was subjected to a variety of climatic conditions, as well as the frequency of extreme events such as droughts and changes in precipitation and temperature patterns.

3- DATA AND METHODS

A historical analysis spanning from 1981 to 2024 was performed to investigate climate variability in the coastal region of Kenya, particularly in Mombasa County. The research location is situated just south of the equator, at a latitude of -4°S and a longitude of 39°E. Climate variability data were obtained from ECMWF Reanalysis v5 (ERA5). The ECMWF Reanalysis (ERA5) data is exceptionally dependable for studying the climate impact of Mombasa on the city and port operations. It offers high-quality, hourly climate data with a geographical resolution of around 31 km, facilitating extensive investigation of localized phenomena (ECMWF, 2023). Covering the period from 1950 to the present, ERA5 provides consistency and historical depth, essential for trend research. The four-dimensional variation (4D-Var) data assimilation system consolidates observations from several sources, improving accuracy and consistency (Hersbach et al., 2020). ERA5 is extensively utilized in climate research, affirming its reliability for this work.

This dataset included both rainfall and temperature records for the area, which were subjected to time series analysis to identify anomalies and trends, for this objective A simple linear regression analysis, commonly referred to as the least squares method, was employed to identify trends in climatic data over a specified period across all the study area. This approach is fundamental for describing and analyzing changes in climate parameters as claimed by (Houghton et al. 2001; Hassan, El-Tantawi, and Hashidu 2017).

The Mann-Kendall (M-K) test (Gilbert, 1987; Kendall, 1975; MANN, 1945) is a prevalent non-parametric statistical method employed to assess trends in temperature and rainfall time series data. It is especially effective at identifying monotonic increasing or decreasing trends in datasets without supposing any particular distribution (non-parametric). This test is utilized when the data fails to satisfy the assumptions necessary for parametric tests, such as normal distribution or linearity, rendering it suitable for environmental variables like temperature, precipitation, and river flow data.

The Mann-Kendall test assesses the consistency of data value trends across time by comparing pairs of data points.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \tag{1}$$

Whereas:

- S : is the Mann-Kendall statistic.
- n: is the number of data points.
- xj and xi are the data values at time points j and i, respectively.
- Sgn (xj−xi) is the sign function, which returns +1, 0, or -1 depending on whether the difference (xj−xi) is positive, zero, or negative.

The **Z-value** of the test, which indicates the significance of the trend, is calculated to determine the presence of a trend. A positive Z indicates an upward trend, while a negative Z suggests a downward trend. The Z-value is calculated using the following equation:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\operatorname{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\operatorname{Var}(S)}} & \text{if } S < 0 \end{cases} \tag{2}$$

Where:

- S is the Mann-Kendall statistic, calculated from the sum of differences between data points.
- Var(S) is the variance of S, which accounts for the possible ties in the data (i.e., data points that are equal).

The variance Var(S) is calculated using the following equation:

$$\operatorname{Var}(S) = \frac{n(n-1)(2n+5) - \sum t_i(t_i - 1)(2t_i + 5)}{18} \tag{3}$$

Whereas:

- n is the number of data points.
- ti is the number of tied groups (i.e., repeated values in the dataset).

Interpretation of Z-value:

- If **Z > 0**, it indicates an **upward trend**.
- If **Z < 0**, it indicates a **downward trend**.
- If **Z = 0**, no significant trend is detected.

The Z-value is subsequently compared to a critical value from the standard normal distribution to ascertain the significance level, typically at 95% confidence, which corresponds to a Z-value of ±1.96. If the Z-value is beyond this range, the null hypothesis (absence of trend) is rejected, indicating the presence of a significant trend (either upward or downward). To assess the severity of meteorological drought, datasets encompassing 44 years of monthly precipitation and temperature records from Mombasa meteorological stations were employed. This analysis enabled the calculation of three separate drought indices: the RD index, which categorizes years as dry or wet based on annual total precipitation; the Standardized Precipitation Index (SPI) assessed at various temporal scales, specifically over 3, 6, and 12 months (SPI-3, SPI-6, and SPI-12); and the Reconnaissance Drought Index (RDI). The indices were calculated using the DrinC program, a tool specifically developed for computing SPI and other drought indicators. Concerning the Standardized Precipitation Index (SPI) that solely takes into account precipitation data: The Standardized Precipitation Index (SPI) quantitatively measures the divergence of precipitation from its historical average, adjusted for standard deviation. The mean and standard deviation are calculated using historical data.

The SPI is determined by the formula: SPI = (P - P*) / σ_P, where P denotes the recorded precipitation, P* signifies the long-term mean precipitation, and σ_P represents the standard deviation of precipitation.

This study calculates the Standardized Precipitation Index (SPI) at three distinct timescales: short-term (3 months), medium-term (6 months), and long-term (12 months). This index is frequently utilized for water supply management, assessing long-term hydrological health, and informing decisions in sectors such as urban planning and large-scale water management. This adaptability allows the SPI to swiftly signal the emergence of drought conditions and improve the assessment of drought intensity, hence enabling comparisons across diverse geographical areas with differing climatic circumstances. It is important to acknowledge that SPI calculations rely exclusively on precipitation data. Drought intensities are classified according to SPI values, as indicated in table (3-1) (McKee, Doesken, and Kleist 1993).

Table (3-1), The classification of the SPI & RDI values

SPI and RDI values	The classification
2.00 or more	Extremely wet
1.50 to 1.99	Very wet
1.00 to 1.49	Moderately wet
+0.99 to -0.99	around normal
-1.00 to -1.49	Moderately dry
-1.50 to -1.99	Severely dry
-2.00 or less	Extremely dry

The researcher based on (McKee, Doesken, and Kleist 1993)

Gibbs and Maher (1967) noted that rainfall deciles are simple to utilize, and the influences of temperature and other factors are not considered in drought evaluations. Historical data is segmented into ten equal intervals (deciles), and drought is classified according to the decile ranking. The initial decile signifies extreme drought, the second denotes severe drought, the third indicates moderate drought, and the fourth implies mild drought, whilst deciles 5 and 6 are regarded as normal conditions; values over the sixth decile are categorized as wet years.

The Reconnaissance Drought Index (RDI), formulated by Tsakiris and Vangelis (2005), utilizes a streamlined water balance equation that incorporates precipitation and potential evapotranspiration. The incorporation of evapotranspiration, in conjunction with rainfall, offers a more precise measurement of water deficits, hence improving the accuracy of drought severity assessments. The World Meteorological Organization and Global Water Partnership (2016) issued detailed rules about drought indicators and indices. The severity of drought, defined by certain criteria of the RDI, is categorized into seven classifications as illustrated in table (3-1).

The computation of the RDI entails multiple processes, principally centered on ascertaining the ratio of actual precipitation to projected evapotranspiration over a designated timeframe. The fundamental equation for RDI, referred to as the Initial RDI (α_RDI), is expressed as follows:

Initial RDI (α-RDI)

$$\alpha\text{-RDI} = \frac{\sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} PET_i} \quad (4)$$

Where:

- α-RDI is the initial value of the RDI over a specified period.
- P_i represents the precipitation in the i-th month.
- PET_i represents the potential evapotranspiration in the i-th month.
- n is the number of months over which the RDI is calculated.

4- RESULTS AND DISCUSSION

The nonparametric Mann-Kendall test is employed to identify the trend illustrated in Figure 4-1. This test indicates whether the trend is increasing (positive) or decreasing (negative). The analysis quantifies the annual rate of temperature increase for Mombasa city's mean maximum temperatures from 1981 to 2024, yielding a 95th percentile value of 28.74°C. The graph displays an orange line indicating the annual mean maximum temperature, accompanied by a blue dashed line that represents the linear trend. The x-axis represents the year, and the y-axis represents temperature measured in degrees Celsius.

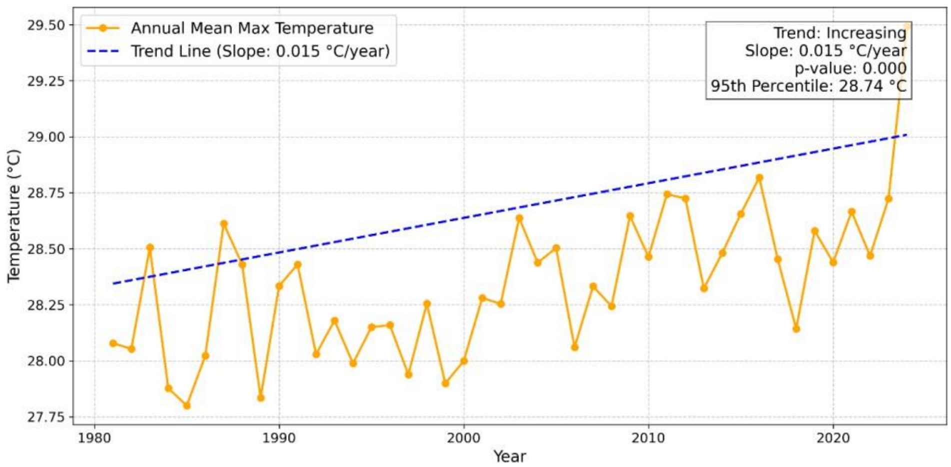

Figure (4-1), Annual Mean Maximum temperature at 95th Percentile from (1980-2023)

Evaluating the trend in long-term temperature series is a fundamental prerequisite in climatological study to demonstrate that temporal variations in the data are only attributable to meteorological and climatic fluctuations. The M-K test is employed to assess the validity of the subsequent hypothesis:

- H_0 (Null Hypothesis): There is no upward trend in the yearly mean maximum temperature data at the 95th percentile.
- H_1 (Alternative Hypothesis): An upward trend exists in the annual mean maximum temperature data at the 95th percentile.

The graph (4-1) indicates a 95th percentile value of 28.74 °C, with a reported p-value of 0.000, suggesting that the observed trend is statistically significant and not attributable to random variation. The graph indicates a positive slope of 0.015 °C/year, consistently reflecting a warming trend throughout the analyzed period. This indicates that recent temperatures are increasingly attaining higher extremes. The p-value (< 0.001) confirms the statistical significance of the warming trend, highlighting the reliability of the observed upward temperature trend and indicating that this trend is unlikely to occur by chance. Based on the p-value and the positive slope, the null hypothesis (H_0) would be rejected, while the alternative hypothesis (H_1) would be accepted, signifying a statistically significant upward trend in the annual mean maximum temperatures.

The 2020 report from the Mombasa County Government states that since the early 1960s, Kenya, especially Mombasa County, has experienced a warming trend characterized by significant increases in both daytime and nighttime temperatures. Minimum temperatures in Mombasa have generally risen by roughly 0.7°C to 2.0°C, while maximum temperatures have grown by about 0.2°C to 1.3°C, with fluctuations based on the season and region. Projections indicate that average surface temperatures in Kenya might rise by 1°C to 1.5°C by 2030, with possible increases of up to 5°C by the 2090s. The prevailing trend of rising temperatures is expected to persist across all seasons nationwide, including Mombasa County, resulting in changes to weather patterns and increased climate unpredictability.

Table 4-1 presents the descriptive statistical analysis of mean monthly precipitation for the study area, Mombasa. The monthly precipitation mean varies, with a maximum of 7.05 mm in May, designating it as the wettest month, and a minimum of 0.55 mm in February, categorizing it as the driest month. The analysis of precipitation variability in Mombasa reveals significant insights into rainfall distribution patterns, emphasizing the Standard Deviation (StD) and the Coefficient of Variation (CV). The StD quantifies the distribution of rainfall over various months, whereas the CV evaluates the relative variability, providing insights into the consistency and fluctuation of rainfall throughout the year. The standard deviation values reflect the dispersion of precipitation data for each month, with the highest standard deviation observed in May (13.59 mm), indicating considerable variability in rainfall amounts for that month. The data indicates that the months listed exhibit medium standard deviation values, ranging from approximately 2.31 to 5.04 mm. July: 3.15 mm; August: 2.46 mm; September: 2.41 mm; October: 5.04 mm; November: 4.43 mm; June: 4.36 mm. These months demonstrate moderate variability in precipitation, positioned between the extremes of May (13.59 mm) and February (1.28 mm). This indicates that rainfall patterns during these months exhibit relative stability, yet remain susceptible to fluctuations. In contrast, February exhibits one of the lowest standard deviations (1.28 mm), signifying a more consistent pattern of lower precipitation. The coefficient of variation indicates that January exhibits a notably high value of 246.17%, signifying considerable relative variability in relation to its mean. Conversely, August exhibits a lower coefficient of variation (114.93%), suggesting greater consistency in its rainfall patterns compared to the mean.

Table 4-1 Descriptive statistics of mean monthly rainfall of Mombasa (1981-2024)

	Mean	Std	Min	max	median	count	Q1	Q3	Cv
Jan	0.79	1.95	0.00	43.93	0.32	1364.00	0.10	0.75	246.17
Feb	0.55	1.28	0.00	23.56	0.19	1243.00	0.07	0.57	231.34
Mar	1.99	2.66	0.00	25.70	1.04	1364.00	0.28	2.70	133.37
Apr	5.33	7.37	0.00	125.91	3.41	1320.00	1.98	6.08	138.34
May	7.05	13.59	0.00	262.06	3.62	1364.00	1.68	7.95	192.60
Jun	3.39	4.36	0.00	50.30	2.41	1320.00	1.14	3.91	128.47
Jul	2.67	3.15	0.00	35.47	2.00	1364.00	1.11	3.27	117.91
Aug	2.14	2.46	0.00	39.70	1.68	1341.00	0.89	2.70	114.93
Sep	1.90	2.41	0.00	29.50	1.48	1290.00	0.59	2.36	126.97
Oct	2.64	5.04	0.00	71.58	1.48	1333.00	0.60	2.68	191.17
Nov	2.69	4.43	0.00	84.59	1.65	1290.00	0.91	2.84	164.70
Dec	1.90	2.31	0.00	23.00	1.18	1333.00	0.52	2.32	121.46

Researcher analysis based on data retrieved from ERA5

According to Gibbs and Maher (1967), rainfall deciles (RD) exclusively employ precipitation data to assess meteorological drought. In the specified research region of Mombasa, classification of Annual Rainfall Deciles (RD) Rainfall deciles are a statistical instrument employed to classify rainfall distribution into ten equal segments, each denoting 10% of the overall data set. This method evaluates whether the rainfall during a specific period is below, near, or above normal levels by categorizing the sorted rainfall data into deciles. Applying this method to the Monthly Mean Precipitation (mm) presented in table (4-2) revealed that Mombasa experiences approximately four months of drought annually, while normal and wet months occur for three and four months, respectively.

Table (4-2) Decile Category of Mombasa Monthly Mean Precipitation (mm)

Month	Mean Precipitation (mm)	Decile Category
January	0.791576	0.1- dry
February	0.553176	0.1 - dry
March	1.991745	0.4 - normal
April	5.328394	0.9 - wet
May	7.053666	0.9 - wet
June	3.393500	0.9 - wet
July	2.667544	0.7 - wet
August	2.144076	0.5 - normal
September	1.899248	0.3 - dry
October	2.638582	0.6 - normal
November	2.689829	0.8 - wet
December	1.898927	0.2 - dry

Researcher based on (Gibbs and Maher 1967)

Although, that the drought, normal and wet months according to the classification are equally four months for each, it is noticeable as shown in table (4-3) that the normal years were predominated with the percentage of 50%, followed by dry year with the percentage of 29%, and final the wet years with the percentage of 20%.

Table (4-3), Rainfall deciles in Mombasa (affected years)

Range of dry deciles rainfall (0.1-0.3)	Range of normal deciles rainfall (0.4-0.7)	Range of wet deciles rainfall (0.8-1.0)	**Annual Rainfall Deciles classification in Mombasa**	
1991, 1993, 1996, 2003, 2004, 2008, 2009, 2011, 2012, 2016, 2021, 2022, 2024,	1981,1983, 1984, 1985, 1986, 987, 1988, 1989, 1990, 1995, 1999, 2000, 2001, 2002, 2005, 2007, 2010, 2013, 2014, 2015, 2018, 2023	1982, 1992, 1994, 1997, 1998, 2006, 2017, 2019, 2020	0.1	775.980
			0.2	824.454
			0.3	847.310
			0.4	924.212
			0.5	966.620
			0.6	1020.992
			0.7	1092.164
			0.8	1185.162
			0.9 – 1.0	1283.45
13 years, 29%	22 years, 50%	9 years, 20%		

The dry decile conditions may result in crop failures, thereby diminishing food availability and farmers' income. The data presented above outlines the years affected in Mombasa. Crop yield from Mombasa and its surrounding areas may decline due to drought, subsequently impacting the volume of dry bulk commodities, particularly grain, exported through the port of Mombasa. This may result in a direct impact, such as a reduction in port throughput, particularly concerning grain bulk, and an indirect threat to the volume of exports from Kenya to other nations.

Wet deciles rainfall significantly impacts Mombasa port, an essential maritime hub that supports commerce for Kenya and the wider East African region. The inland transportation networks link the port to other landlocked nations and areas in East Africa. These networks, comprising roads and railways, are susceptible to high rainfall events, especially as a significant volume of transit cargo is conveyed by road, which may adversely impact seaport productivity and regional trade.

The Standardized Precipitation Index (SPI) is commonly employed because of its simplicity and versatility. The design aimed to quantify deficiencies in rainfall across various timescales. The variability in SPI scales enables the analysis of various drought types. A 1- or 3-month Standardized Precipitation Index (SPI) is typically utilized to evaluate meteorological droughts. A 1- to 6-month SPI is employed to investigate agricultural droughts, while longer timescales, ranging from 6 to 12 months or more, are applied in the analysis of hydrological droughts. Figure (4-2) depicts the progression of SPI across annual, 3-month, 6-month, and 12-month scales, demonstrating that drought frequency decreases inversely as the timescale increases linearly.

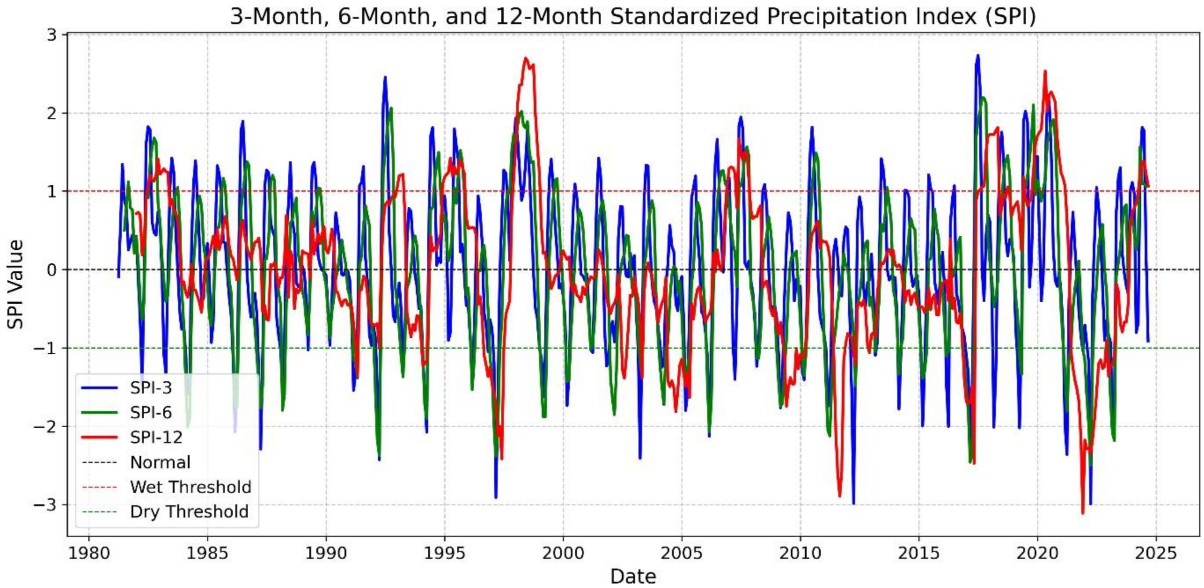

Figure (4-2): Drought classification based on Standardized Precipitation Index (SPI)

The SPI on a three-month time scale (Blue Line) illustrates short-term precipitation trends, with the SPI-3 often falling below critical drought thresholds (-1, -2, and -3), signifying the occurrence of frequent and severe drought events. The rapid fluctuations underscore the variability in short-term precipitation, which can impact seasonal agricultural practices and immediate water resource management. The SPI on a six-month basis (Green Line) serves as a medium-term index, indicating that the SPI-6 experiences infrequent yet significant declines below the drought thresholds (-1). This suggests that certain drought conditions may initiate and endure beyond a single season, potentially impacting extended agricultural cycles and the management of water reservoirs. Meanwhile, the SPI over a twelve-month period (Red Line) indicates long-term trends, with the fluctuations of the SPI-12 being significant as they suggest persistent patterns in precipitation. Intermittent declines beneath the drought thresholds in this index signify substantial, extended drought durations.

Long-term drought conditions significantly affect large-scale water resource planning, ecological sustainability, and agricultural planning over extended periods. According to the guidelines established by McKee et al. for drought classifications utilizing the Standardized Precipitation Index (SPI), an analysis of the SPI-3, SPI-6, and SPI-12 charts for Mombasa can facilitate the identification and categorization of drought intensity across the recorded years. The classifications entail analyzing the SPI values as they surpass designated thresholds:

- **Mild Drought**: SPI between 0 and -0.99; **Moderate Drought**: SPI between -1.0 and -1.49; **Severe Drought**: SPI between -1.5 and -1.99, and **Extreme Drought**: SPI at or below -2.0 The

SPI on a three-month time scale indicated The data frequently fluctuates above and below the ±1 threshold, indicating numerous short-term extreme events throughout the study period. Droughts occur intermittently, particularly evident around 1983, 1997, and the recent years approaching 2025. Wet periods are also frequent but brief, with notable instances around 1988, 1995, and 2010. The negative trend in SPI-3 is a critical factor affecting agriculture, as it serves as a limiting factor for maize crop yields, which is cultivated in Mombasa and exported from its port.

The seasonality of rainfall in Mombasa correlates with drought frequency across different scales. SPI-6 drought events occur less frequently but are more prolonged compared to SPI-3. This pattern is particularly evident during the mid-1990s and mid-2010s. Conversely, wet periods are infrequent yet last longer, as observed in the late 1980s and early 2000s. The SPI-6 drought events are less frequent yet more prolonged compared to SPI-3, particularly evident during the mid-1990s and mid-2010s. Conversely, wet periods occur less frequently but endure for longer durations, as observed in the late 1980s and early 2000s. Consequently, the SPI-12 exhibited lower frequency on longer time scales during the 1980s, while droughts were noted in the mid to late 1990s and mid-2010s, with an increase in drought events from 2012 to 2024. In contrast, extended wet periods were observed in the late 1980s and early 1990s. In conclusion, as noted by McKee, Doesken, and Kleist (1993), a drought incident is characterized by a consistently negative SPI that reaches an intensity of -1.0 or lower. The graph indicates a significant increase in the frequency of oscillation from 2010 to 2024. Notably, there is a redundancy during periods when dry seasons surpassed the extreme drought threshold of -2. This phenomenon may adversely impact the Mombasa coastal area, which depends on healthy mangroves and other ecosystems that are vulnerable to prolonged dry periods. This could impact fisheries and the protection of coastal areas from storms.

The standardized RDI values were similar in nature to SPI values and can be compared to it directly explained by similar climate characteristics.

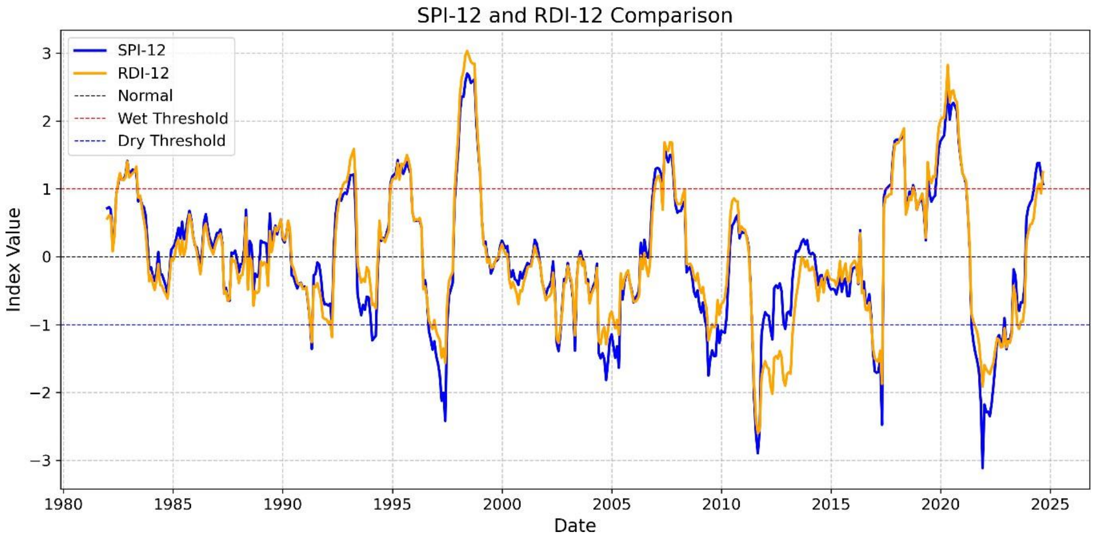

Figure (4-4) , SPI-RDI-12 months for hydrological drought

Figure 4-4 presents a comparison of two drought indices covering the period from 1980 to approximately 2025: the 12-month Standardized Precipitation Index (SPI-12) and the 12-month Reconnaissance Drought Index (RDI-12). These indices provide insights into extended drought conditions, with the SPI focusing solely on precipitation anomalies, whereas the RDI incorporates both precipitation and potential evapotranspiration (PET). Correlation The SPI and RDI exhibited a comparable pattern, underscoring that precipitation is a vital component of both indices. However, some anomalies are obvious, attributable to the inclusion of PET in the RDI-12 calculations. The discrepancies are especially pronounced during periods of substantial temperature variations, which affect PET but not precipitation directly. Both indices surpass their specified dry and wet thresholds numerous times throughout the study period. Notable periods of drought (values below the blue dotted line) and precipitation (values above the red dotted line) are apparent in both indexes, illustrating their effectiveness in detecting extremes. Both indices demonstrate a significant peak in 2020, indicating an extraordinarily wet period, followed by a large reduction in drought conditions by the mid-2020s. This rapid change may indicate increasingly unpredictable weather patterns, potentially reflective of climate change impacts. The drought indices demonstrated a substantial correlation between the RDI and SPI on a 12-point scale.

The reduction in precipitation and increasing temperatures due to recent climate change affect drought occurrences in the study region, especially from 2010 to 2024, potentially hurting Mombasa, which currently has water scarcity (World Bank Group 2021). Moreover, extended drought conditions will exacerbate this issue. Reduced precipitation leads to a decline in the replenishment of local water sources, necessitating the city's growing dependence on external water supplies.

Extended dry spells may affect Mombasa's urban infrastructure, leading to increased stress on the city's energy systems due to elevated demand. Ports function as energy-intensive centers that rely heavily on efficient energy utilization to maintain productivity, as noted by Brinkmann (2011). Acciaro, Ghiara, and Cusano (2013) indicated that ports rely on cranes, container handlers, forklifts, and conveyor belts, all of which require significant energy consumption. These enable the loading and unloading of ships, the movement of containers, and the management of cargo within the port area. Insufficient or unstable energy supply leads to reduced activities, resulting in delays and decreased port productivity, which negatively affects Mombasa port throughput.

Irrigation schemes exist in Mombasa (Kikuchi et al. 2019); nonetheless, dry decile rainfall can deplete water resources, limiting farmers' ability to irrigate crops and consequently heightening agricultural losses.

The data analysis reveals a persistent rise in temperature alongside variations in rainfall patterns. The Standardized Precipitation Index (SPI) and Rainfall Deficit Index (RDI) indicate a trend towards drought in Mombasa, linked to climate change. This situation presents a considerable challenge to sustainable agriculture and, subsequently, the export of agricultural products via the Mombasa port, especially crops like maize grown in the region. Erratic rainfall, increasing temperatures, soil salinization, and rising sea levels collectively disrupt crop yields and supply chains, resulting in a decline in agricultural exports via the Port of Mombasa.

The agricultural crops is crucial for supplying export commodities that pass via the Port of Mombasa, including agronomic crops such as tea, coffee, maize, horticulture items, and various cash crops from Kenya and neighboring counties (Food and Agriculture Organization 2020). Maize is mostly produced in Kenya's Rift Valley and Western areas, with notable production along the coastline near Mombasa (Government of Kenya 2021). Maize is one of the crops and an exported item within Kenya's agricultural exports, cultivated in Mombasa. The effects of climate change in Mombasa, marked by unpredictable rainfall, increasing temperatures, and severe weather phenomena, pose a substantial risk to agricultural yields, especially maize cultivation in Mombasa coastal areas. Consequently, any reduction in maize production may impact the export capacity at the grain bulk terminal in Mombasa port, as noted by Kogo, Kumar, and Koech (2021). The Intergovernmental Panel on Climate Change indicated in 2021 that this circumstance impacts export quantities and overall port operations. Kogo, Kumar, and Koech (2021) showed that a decline in local maize yields due to climate stress directly results in decreased export quantities, as domestic consumption needs and commercial demands compete for a limited supply. This diminishes the throughput at the Port of Mombasa, consequently affecting revenue for port operations and national income (KPA, 2019).

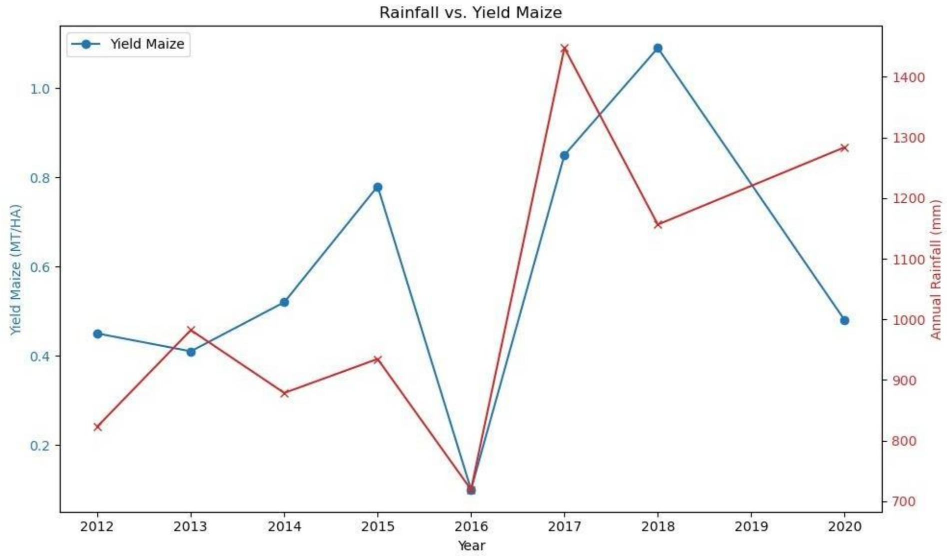

Figure (4-5) : The correlation between maize yield and rainfall in Mombasa

Figure 4-5 illustrates a correlation coefficient of 0.61 between maize yield and rainfall in Mombasa. The relationship between annual rainfall and maize yield in Mombasa from 2012 to 2020 is moderately strong and positive, indicating that increased rainfall is generally associated with improved maize yields, although this correlation is influenced by other agronomic and environmental factors. The decrease in yield from 2014 to 2015, followed by a substantial increase in 2017 corresponding with heightened precipitation levels, is significant. This is followed by a notable reduction in 2018, a year marked by diminished precipitation. This suggests that an increase in rainfall typically correlates with a rise in maize production; however, other factors may also influence this relationship. A decrease in agricultural productivity leads to a reduction in the volume of goods available for export. The Port of Mombasa, primarily engaged in the export of agricultural products, experiences a direct reduction in cargo volumes, consequently leading to a decrease in overall throughput. The decline affects the quantity of agricultural exports and the demand for related shipping supplies and services, including bulk vessels and storage silos. Reduced throughput in certain years may lead to decreased activity and financial strain on Mombasa port. The reliability of grain shipments from Mombasa can affect Kenya's trade relationships and its standing in international markets. Significant fluctuations in throughput can impact contractual obligations and trading agreements.

5- CONCLUSION

This study investigates Mombasa; nevertheless, similar climate change concerns affect other East African coastal cities, such as Dar es Salaam in Tanzania and Lamu in Kenya. These cities demonstrate susceptibility to rising sea levels, temperature variations, and unpredictable rainfall patterns, which threaten the resilience of coastal and port cities, thereby exacerbating the sustainability challenges of port activities, particularly in nations reliant on raw material exports, including agronomic crops most impacted by climate instability and change, as exemplified by Kenya and its port of Mombasa. In this context, Mubenga-Tshitaka et al. (2023) demonstrate that climate-induced droughts in East Africa negatively impact crop yields, a significant concern for Kenya's agricultural sector.

Mombasa, essential for regional trade, is at risk from rising temperatures and sea-level increases, which may disrupt logistical efficiency, as indicated by Thiault et al. (2019). Implementing region-wide strategies to address these issues may enhance shared adaptation pathways and strengthen infrastructure resilience in climate-sensitive areas (Daron 2014).

Mombasa, as a coastal city, may experience exacerbated climate-related challenges, including flooding and rising sea levels, compounded by erratic temperature fluctuations, so affecting port operations and urban development. The city, largely identified as a port city, experiences challenges in segregating city and port operations; thus, there is an integration between the two, mutually influencing one another. The increasing trend in annual mean maximum temperatures is associated with detrimental impacts on urban and port operations and infrastructure, as the rise in mean maximum temperatures may intensify the urban heat of Mombasa Island, where urban areas become markedly warmer than their surroundings, especially given Mombasa's consistently high humidity levels. Procedures and precautions must be implemented, considering the months with considerable variability, including April, March, November, August, and February, as Mombasa city, particularly the port, may be affected by these fluctuating events, given that port operations are highly susceptible to weather conditions.

- **Implications of temperature increasing and drought events on Mombasa port activities and Infrastructure:**

In highly populated and industrialized areas, such as port cities like Mombasa, rising temperatures can cause what is known as a "heat island" effect. Given that Mombasa experiences severe humidity of approximately 80%, which exacerbates heat stress on individuals, increased temperatures may reduce the efficiency of cargo-handling operations (KPA, 2019). Furthermore, as the IPCC (2018) showed, that substantial temperature fluctuations may adversely affect labor productivity, especially when workers encounter elevated heat levels, which present health risks and diminish operational efficiency. Elevated temperatures coupled with high humidity hinder the body's thermoregulatory mechanisms through sweat evaporation, resulting in discomfort and heightened susceptibility to heat-related ailments, such as heat exhaustion or heat stroke. This phenomenon undoubtedly detrimentally influences employee productivity in Mombasa port or any sector within the warm city.

The frequency of heatwaves and changes in wind patterns are both predicted to increase as global temperatures rise. More stringent scheduling and more cooling or reefer container capacity are necessary for cargo operations involving temperature-sensitive items (e.g., medications, perishables) due to the increased spoilage risks (FAO, 2020). According to Kogo, Kumar, and Koech (2021), these extra precautions could cause berthing and vessel turning delays.

The impact of rising temperatures on construction materials, particularly concrete, imposes additional stress on port infrastructure. Repeated thermal expansion and contraction may induce micro-cracks in pavements and mooring points, ultimately compromising load-bearing capacity. Long-term structural degradation increases the necessity for more regular inspections, repairs, and possible retrofitting measures. Elevated temperatures heighten the risk of equipment overheating, especially in heavy machinery like cranes, forklifts, and conveyor systems. Increased ambient temperatures compel cooling systems, hydraulic circuits, and lubrication systems to operate with greater intensity, thereby expediting wear and tear. As a result, operators are required to enhance the frequency of maintenance and component replacement, resulting in elevated operational costs (KPA, 2019).

Cooling and energy distribution systems are essential for port operations, providing power to refrigerated storage areas, vessel loading equipment, and administrative buildings (FAO,2020). Increased temperatures elevate the demand for air conditioning and refrigeration, thereby imposing further strain on electrical grids. Insufficient power supply or system overloads may result in intermittent shutdowns that hinder port operations.

Drought can put pressure on local water resources that are essential for these activities, which could cause prices to rise or water rationing to be enforced. As a result, cities in Kenya confront considerable problems with water availability, which has a negative impact on port activities due to the necessity of freshwater for the cleaning and maintenance of containers, ships, and other port infrastructure (The World Bank Group, 2021). For instance, rationing and the continuation of reliance on private sources of water are consequences of Mombasa's present water shortage, which is half of what the city needs. To begin, shipping schedules and port efficiency might be affected by more costly repairs and lengthier downtime for vessels due to a lack of freshwater opportunities. Freshwater is essential for many processes, including sluicing docks, handling aggregates and grains, and running ballast water treatment systems. As freshwater becomes increasingly scarce, costs could rise, rendering some activities economically unsustainable.

Moreover, drought and rising temperatures have an impact on goods and commodities handled in Mombasa port because changes in exported volumes can disrupt port operational rhythms, resulting in underutilization of cargo handling capacities, especially since agriculture crops such as tea, coffee, and maize are primarily exported from Mombasa and will undoubtedly be adversely affected by freshwater scarcity in their production locations. This could lead to a decrease in port traffic, jeopardizing their economic viability. Or, conversely, abrupt increases in demand for shipping other items, especially main dry bulk cargo, due to deterioration in crop productivity during drought seasons that lead to unforeseen congestion in the port.

In arid and semi-arid regions Drought may have an impact on energy generation in regions that rely substantially on hydropower, such as Ethiopia (83%), Uganda (75%), Sudan (65%), and Kenya (27%), according to UNEP (2023). As a result, power outages will have an impact on port operations, which require a high and stable power supply. While drought resilience management exists at several governance levels, it is frequently insufficient to save lives, emphasizing the need to better synchronize and harmonize sectoral drought preparedness and emergency responses, (Mombasa County, 2021).
Chandler services, which provide crucial provisions such as food, water, and technical supplies to ships, may also be affected. Both wet and dry conditions may interrupt delivery schedules and enhance the difficulties of loading products during heavy rains. Drought conditions frequently create parched environments, increasing the risk of fires. Ports that carry flammable chemicals, such as liquid petroleum bulk at Kipevu Oil Terminal (KOT) in Mombasa, are more vulnerable during droughts, as the surrounding flora, infrastructure, and commodities may become more prone to ignition.
To counteract the effects of climate change on Mombasa port, climate-resilient infrastructure such as modernized port terminal planning, superstructure, infrastructure, and sophisticated drainage systems should be implemented. Enhanced water recycling for operational purposes, as well as predictive analytics for extreme weather interruptions, are also crucial. These initiatives will ensure the long-term viability of Mombasa as an East African trading hub.

FUTURE RESEARCH:

Subsequent research ought to assess the enduring economic effects of climate variability on Mombasa's port throughput, concentrating on trade interruptions and revenue deficits. Examining the function of renewable energy in alleviating operational hazards is essential. Furthermore, examining governance frameworks for the incorporation of climate adaptation into port design will facilitate sustainable operations. Assessing the effects of climate change on Mombasa port through a multidisciplinary approach that incorporates advanced data collection techniques, Artificial Intelligence predictive modelling, and stakeholder engagement, along with integrated modelling frameworks that connect climatological, hydrological, and infrastructural variables, would enable a comprehensive understanding of how sea-level rise, storm surges, and rising temperatures collectively impact port operations. Future studies utilizing remote sensing and geospatial approaches, including satellite images and geographic information system (GIS) mapping, may provide essential tools for monitoring coastal erosion, land-use changes, and vulnerabilities in port infrastructure over time. These technologies can deliver high- resolution data that elucidate spatiotemporal patterns of floods or erosion, facilitating proactive strategies for port resilience. Simultaneously, multi-port comparative analyses could elucidate the distinctions in Mombasa's vulnerabilities relative to other prominent African or global ports, emphasizing context-specific remedies and collective adaptation best practices. Research on socio-economic factors analyzing trade flow fluctuations, labor productivity, and insurance expenses across various climate scenarios would clarify the extent of danger to Mombasa's economic output. Combining quantitative measurements, such as variations in cargo handling volumes or insurance premiums, with qualitative inputs from stakeholders, including port authorities, local communities, and industrial partners, can produce more comprehensive and contextually relevant findings.

Furthermore, studies must be conducted to determine the impact of rising temperatures, especially heatwaves, on the port's physical infrastructure, including its roads, trains, and storage facilities.

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