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Investigating the Impact of Climate Change on Water Resources in Jozini Municipality, South Africa

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Abstract
Declining water supplies and significant water quality degradation threaten South Africa's water resources. Climate change has exacerbated this situation and poses a major challenge to the country's natural resources and people. The impacts of climate change on water resources are felt most acutely in rural areas, large cities, and metropolitan areas, where water scarcity is a growing problem. This study aims to examine the impacts of climate variability on water resources in Jozini municipality and identify feasible mitigation measures for adequate water security and management. The study focuses on the effect of climate change on dam water levels in the Jozini area, using precipitation and temperature variability as parameters. Traditional and machine-learning techniques were used to analyse the data collected in this study. The results of this study show that rainfall and temperature variations due to climate change affect the water levels of dams in Jozini, South Africa. This has serious implications for the rural population in the Jozini area, which is already vulnerable to poverty, weak infrastructure, and overdependence on climate-sensitive resources. The study highlights the urgent need for viable remedies and feasible mitigation measures to promote adequate water security and management in Jozini and other parts of South Africa. To build resilience in South Africa's water crisis, it is critical to understand the factors that hinder or facilitate local adaptation strategies. This study helps to identify feasible climate change adaptation measures and promote appropriate water security and management in Jozini. While resilience-enhancing factors can lead to and mobilise climate action, institutions and mechanisms must be robust to achieve policy goals.

Keywords: *Climate Change, Jozini Dam, Precipitation, Temperature, Water Security*

1.0. Introduction

South Africa has recently faced water scarcity issues due to inconsistent rainfall patterns (Petersen et al. 2020; Adam 2020; Zwart, Mishra, and Dembélé 2018). Botai, Botai, and Adeola (2018) predict that the annual rainfall will be around 450 millimetres. Compounded by high potential evaporation rates (PET) and limited water reaching river systems and dams (Jovanovic et al. 2015), extreme weather events frequently surpass precipitation, leading to a null value in many cases. Climate change's chilling impact has resulted in severe weather fluctuations, causing droughts and long periods without rainfall in certain regions (Orimoloye, Ololade, and Belle 2021; Ndlovu and Demlie 2020). Consequently, water shortages have become widespread, affecting drinking water supply and agricultural needs. These challenges have also hindered the nation's economic growth. McDonald et al. (2011) predict that by 2050, between 50 and 100 million people will face water shortages, indicating the severity of the problem. Climate change in South Africa poses significant risks to natural resources and the human population (DeTombe 2015). Freshwater supplies are in danger, and if not adequately addressed, a complex socio-economic disaster may ensue. The increasing demand for scarce water resources may lead to conflicts among various economic sectors, households, and communities. Despite advancements made since 1994, a considerable portion of the population still lacks access to clean drinking water. Certain provinces, notably Eastern Cape, KwaZulu-Natal, Limpopo, and Northwest, struggle to provide basic water services (Eales 2011). Issues like topography, water stress, and a lack of surface water hinder progress in these areas. Delays in water delivery often occur due to the high cost of building new water supply systems, leading to technical problems within the existing infrastructure and denying users' access to drinkable water. The backlog of infrastructure development in Limpopo and Mpumalanga further exacerbates water scarcity challenges (Petersen et al. 2020; Adam 2020). Proper attention and investment in water supply facilities are crucial to alleviate water scarcity concerns in these regions.

Figure 1 below illustrates the classification of South African rivers according to their average flow. However, it was found that 146 of South Africa's 565 rivers have very low flows, while 105 rivers have low flows, and 88 rivers show moderately low flows, based on the National Integrated Water Information System of the Department of Water and Sanitation (DWS). It is noted that 60 % of the country's rivers are overused. According to the Organization for Economic Cooperation and Development, only one-third of major rivers are healthy, and one-quarter of river ecosystems are seriously threatened in the country (Reynolds and Wier 2016). It may not be immediately apparent where the impacts of overexploitation will surface, but "exploitation of aquatic ecosystems and the organisms (including people) that depend on them for lives" will be "the ultimate losers" (Connor 2015). The Western Cape is the worst-affected province. During the January/ February season of 2018, the standard dam levels were 20 % in the Breede-Gouritz basin for the winter months and 35 % in the Berg-Olifants catchment. Over 80 % of the rivers in the two catchments have been exploited. This is not an exclusive problem in the Western Cape. A voluntary water restriction program similar to that imposed in Cape Town has caused dam levels in the Eastern Cape to drop (Otto et al. 2018). About half of the rivers in KwaZulu-main Natal's catchment (Pongola Mtamvuna), where the dam levels are around 52 % (or quite low for this time of year), are similarly overused.

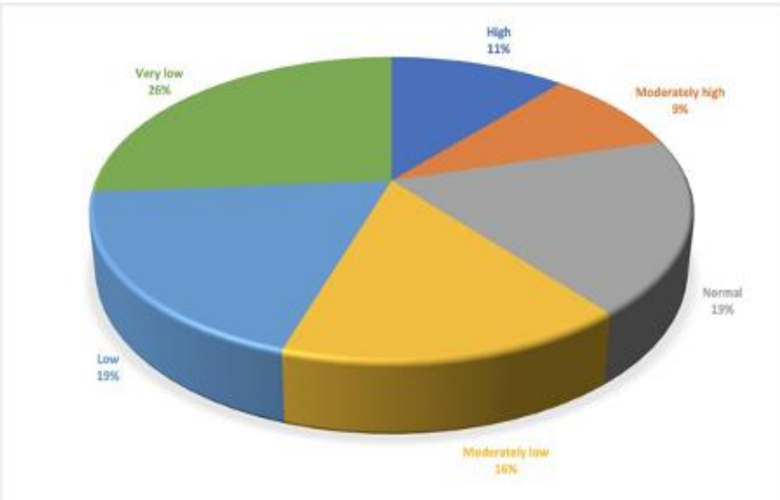


Figure 1: Rivers in South Africa categorised by average flows (adapted from (Donnenfeld, Hedden, and Crookes 2018))

Temperature, precipitation, and biomass are critical climatological metrics to assess climate change variability (Shako 2015). The diverse array of climate examination and investigation devices is truly remarkable. In this particular study's context, the focus is on two climate elements: temperature and precipitation. Temperature plays a pivotal role in determining climate change variability and can be assessed or reconstructed for the earth's surface and the sea surface temperatures. Monitoring temperature fluctuations is crucial in understanding climate patterns and their implications. On the other hand, precipitation, encompassing rain, snowfall, and other falling precipitation, offers another valuable measure of climate variability. Beyond mere rainfall or snowfall, precipitation analysis can also consider factors such as humidity, water balance, and water quality, as highlighted by (Shako 2015). By delving into temperature and precipitation variations, researchers can gain insights into the ever-changing climate patterns and their potential impacts on various ecosystems and human activities. These climatological metrics serve as essential tools for studying and comprehending the complex dynamics of climate change, ultimately aiding in developing strategies to address and mitigate its consequences.

Surface water accessibility is expected to change due to climate variability, primarily due to high precipitation variability (Change 2014) and potential evapotranspiration due to increased temperatures and global warming (Kingston et al. 2009; Seneviratne et al. 2010). In addition, other conditions, such as reductions in snow and ice storage (Huss 2011), can have significant impacts. Variations in agricultural land use, responsible for high global water consumption, are also expected to affect freshwater systems (Fluixá-Sanmartín et al. 2018). These changes are expected to affect both hydrological activities in the basin and irrigation demand. In addition, demographic changes, socio-economic conditions, and technological advances, including a country's population increase, changes in land use, or the use of dams, have a considerable effect on water demand and distribution. The interplay of all these elements is likely to shift the stability between water demand and supply and, consequently, directly affect the water in the reservoir. This impact refers not only to the amount of water stored but also to the distribution of this water over time, which, as previously mentioned, has a significant impact on the dam's safety (Fluixá-Sanmartín et al. 2018). In investigating the effect of climate variability on dam water levels, the uncertainties to climatological and hydrological estimates must be included in the evaluation. In this scenario, the parameters considered to model water resource exploitations are additionally subjected to uncertainty assessment. Moreover, non-climatic drivers that impact each variable of the water balance calculation (variation in land use, adjustment of reservoir use rules, etc.) can be valid and should be considered in the assessment. This is because these factors can affect any attribute of the water balance. However, this technique may be impractical due to the large volume of data, the amount of work required, and the various key determinants required. Therefore, it should only be considered when the complexity of the system, accessibility of data, and duration of study allow it (Fluixá-Sanmartín et al. 2018).

To this end, this study aims to provide an empirical evidence-based understanding of how climate change, particularly temperature and precipitation changes, impacts the Jozini municipality's water resources, focusing on the crucial Jozini Dam. The primary objective is to investigate the effect of climate variability, specifically changes in temperature and precipitation, on the water levels and overall water availability in the Jozini Dam. The knowledge gained from this study will be invaluable in devising effective measures to safeguard water availability and ensure the sustainable development and resilience of the region's water resources in the face of a changing climate.

3.0. Materials and Method

This section describes the study region, data source, and methodology, including the data visualisation techniques (boxplot visualisation and pairwise linear connection analysis) used to analyse the data collected.

3.1. Location, Physiography and Climate of Study Area

Jozini is an administrative region in the Umkhanyakude district of KwaZulu-Natal, South Africa, located at 27° 25' 59" south latitude and 32° 4' 0" east longitude (Figure 2). It is the most populous part of the Umkhanyakude district. The Jozini region is 250 m (820.21 ft) above sea level and is characterised by dry winters, wet summers and recurrent floods. Summer temperatures range from 23° to 27°C, while winter temperatures range from 16° to 21°C. The Lebombo Mountains are located in a moisture belt that receives an average of 600 to 800 mm of yearly rainfall. The waters of the Pongola are dammed by the Ingwavuma and Usuthu rivers, resulting in a heavily flooded region and inundation of the plains during the flood. A system of seasonal streams drains the escarpments and cliffs of the adjacent mountains that are part of the local mountain range. Some of these streams contain pools that remain open throughout the year. The Shemula system receives a significant portion of its water from the Pongola River, a major source. The Jozini water treatment plant is currently operating at its maximum capacity, and the city of Jozini draws its water from this plant (Hattingh 2021).

Figure 2. Map of Jozini Municipality (Source: Jozini Municipality (2022))

3.2. Variable Description, Sources and Analysis

3.2.1. Variable Description and Sources

The reservoir level (Dam lev) was measured in a million cubic meters (MCUM), temperature (Temp) in degrees Celsius (°C), and precipitation (Prep) in millimetres (mm). Dam level was used as the dependent variable for trend and empirical analyses, while the other two variables were used as exogenous variables. The South African Meteorological Service (SAWS) was the temperature and precipitation data source from 2010 to 2021. The primary data sources are the Jozini Dam level, local temperature, and local rainfall from 2010 to 2021. Jozini Dam level data for 2010 to 2020 were collected from the KwaZulu Natal Province Department of Water & Sanitation (DWS), Water Resources Support. Analytical models have been employed to assess the impact of these climate variability factors. One aspect of the analysis involves examining the relationship between temperature and dam levels over an extended period, providing insights into any potential correlation or lack thereof. Additionally, the study analyses the association between precipitation patterns and dam levels, determining if there is a linear connection between the two variables.

3.2.2. Data Visualisation and Analysis

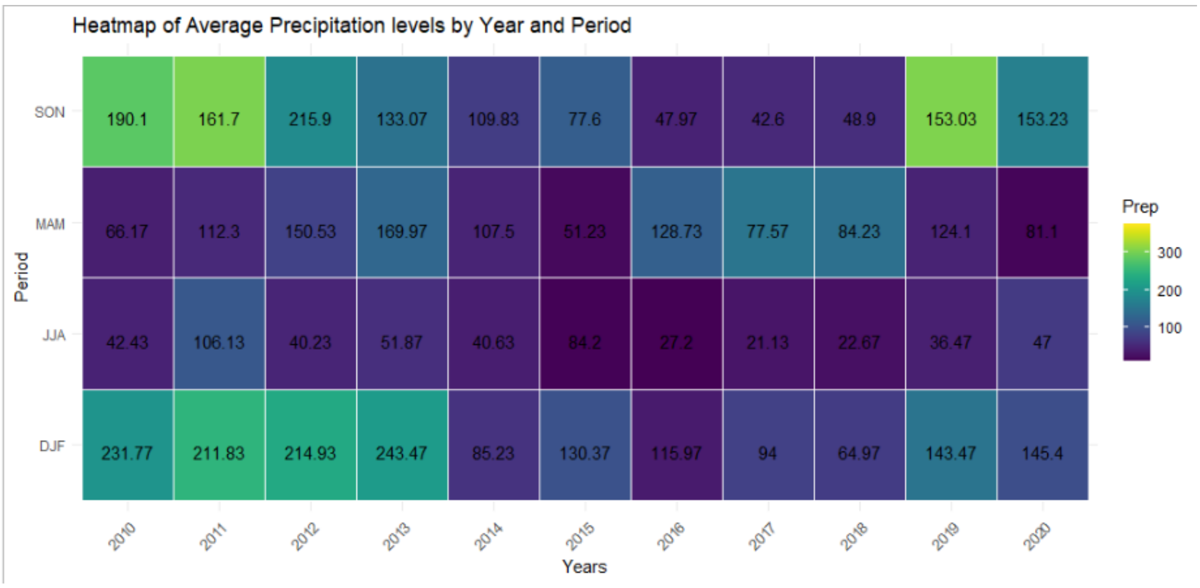
The distribution of data over the study period was determined using boxplot visualisation and pairwise linear connection analysis as part of our analysis. R Software for Statistical Computing version 4.1.2 was used to create the visualisations (Core Team, 2019). Boxplots are useful for locating information that may be hidden in the dataset and allow for comparison between different variables, as previously argued by Williamson, Parker, and Kendrick (1989). The boxplot visualisation technique has also been used because of its ability to divide the data set into quartiles, display the median, lower quartile, and upper quartile, and provide intuitive insights into the data distribution. This method is useful for detecting outliers and fluctuations in the data set. Summer (December, January, and February), winter (June, July, and August), spring (September, October, and November), and fall (March, April, and May) were used for the visualisation. The interquartile range is represented as a rectangle or box. The black line dividing the box in two represents the median. The interquartile range or "whisker" is the range between the minimum and maximum values (IQR 1.5 * IQR). The upper and lower whiskers indicate values above and below the IQR, respectively (within 1.5 times the IQR, above and below the 75th and 25th percentiles, respectively). After using boxplots to determine how the data set was distributed over the three 10-year periods, we used pairwise linear relationship analysis to examine the linear relationship between dam level, our main variable of interest, and the other two independent variables, temperature and precipitation.

3.0 Results and Discussion

3.1. Visualising Seasonal Fluctuations in Precipitation, Temperature, and Dam Level in Jozini

Figure 3a above depicts rainfall over the Jozini area within ten years. The visualisation shows a fluctuating trend with periods of high and low precipitation over the years. This observation reveals that the lowest precipitation is recorded in the winter season. This can also be attributed to decreased earth's surface temperature, as seen in Figure 3b. When the temperature decreases, the amount of evaporation decreases, resulting in a decrease in total precipitation. Between 2010 and 2011, the data show months of high precipitation; this was also observed in 2013. However, after 2013, precipitation decreased and fluctuated in the lower range. Following a decrease in rainfall, Monyela (2017) studied a two-year drought in South Africa during the summers of 2014/2015 and 2015/2016, and the events between 2014 and 2016 would directly affect dam levels, especially in subsequent years. Normally, the rainy season begins in October and lasts until April, but this area is reportedly constantly dry due to frequent drought [23]. In addition, the low rainfall has implications for the supply and demand value chain. Lanyi (2018) noted that to compensate for low water levels, the Cooperative Scientific Program by Breen and Heeg recommended a flow regime to imitate the endemic flows of the Pongola River, which flow at 2 cubic metres per second in winter and 600 to 800 cubic metres per second in summer. Using Figure 3b above, it was found that, as expected, the temperature was higher during summer and lowest during winter. In spring and autumn, the temperature was average. However, the latter showed higher variability compared to the other three seasons. Interestingly, except for summer and spring, the winter and autumn seasons in 2020 showed a remarkable decrease in temperature values compared to the previous 6 years. In the Jozini region, the historical distribution of the monthly average temperature ranges from 18 to 27 °C. Based on the visual representation, the data collected throughout the study show a weak but increasing trend in the average temperature measured in most months in all four seasons (Fig. 3b). The notable increase in temperature suggests that the season currently experiencing drought may face much greater problems in the future. In seasons when the temperature increases more during the rainy months, the Jozini region can expect a decrease in rainfall during these months. Similar to temperature, precipitation has also increased during most rainy months, as shown in the visualisation, but there was a notable decrease in 2017 and 2018 compared to previous years. It is important to note that temperature variations from one season to the next were more stable in seasons JJA and DJF than in seasons MAM and SON.

Figure 3a: Jozini catchment area precipitation seasonal distribution



* Note: (Summer: December, January and February (DJF); Autumn: March, April and May (MAM); Winter: June, July and August (JJA); Spring: September, October and November (SON))

Figure 3b: Jozini catchment area temperature seasonal distribution

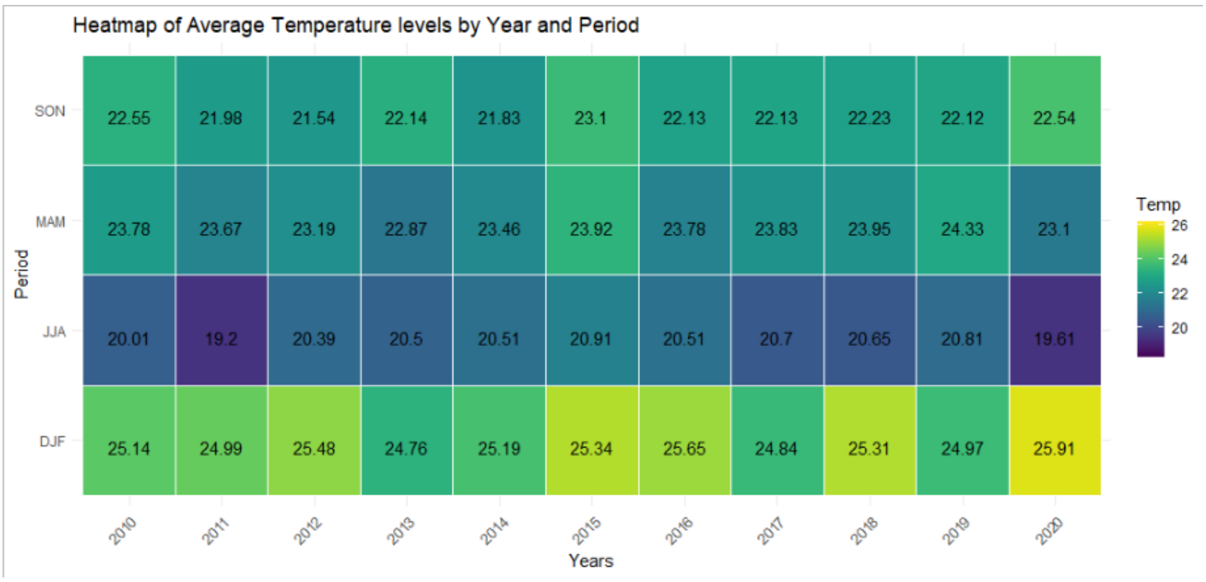
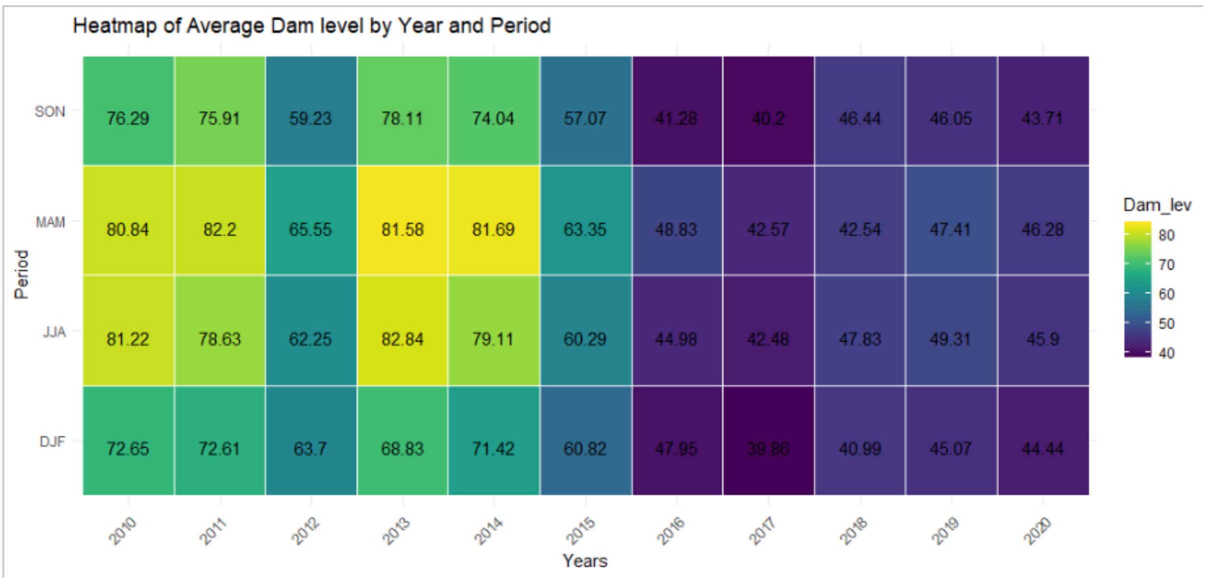


Figure 3c: Jozini catchment area dam level seasonal distribution



3.2. Analysing the Impact of Temperature and Precipitation on Dam Levels through Pairwise Trend Analysis

The data presented in Figure 4a suggests a linear relationship between the levels of dams and the amount of rainfall in the Jozini region. However, the strength of this association is not very strong, as indicated by the Pearson correlation coefficient of 0.814, which was not statistically significant at the 5% level. In contrast, Figure 4b shows a graphic investigation that reveals no obvious linear link between temperature and dam levels over the next ten years until 2020. This is supported by a Pearson correlation coefficient of -0.127 and a p-value of 0.148, which refutes the null hypothesis of a deteriorating link between these two variables. Based on the statistical findings, it can be concluded that higher amounts of rainfall positively correlate with dam levels in the region. However, it is essential to recognise that these visualisations provide valuable insights into the linear relationship between rainfall and dam levels in the Pongola Area. This illustrates the variation in water levels within the Jozini Dam over 10 years as a function of precipitation. It is generally observed that the level of the Jozini Dam tends to rise in conjunction with an increase in precipitation. This connection was also demonstrated by Figure 4a, which showcases the association between dam-level changes and precipitation trends during the same period. The data suggests that the dam's level increases proportionally with rainfall. However, there are instances where particularly heavy rainfall does not result in a noticeable rise in water levels. Hydrologists attribute this to excessive rainfall in regions with small catchments, affecting dam levels and impacting ecosystems and communities reliant on this water source. Low rainfall has also impacted dam levels, posing challenges to the local communities and ecosystems in Jozini. Further empirical investigation is necessary to determine the potential link between these variables. Figure 4c reveals a non-linear connection between temperature and precipitation during the decade spanning from 2010 to 2020. This suggests that changes in rainfall are not strictly proportional to changes in temperature, as the precipitation fluctuates based on the specific temperature range and the individual year.

Apart from the immediate effects on dam levels and water availability, the construction of dams and climate change have introduced other consequences. These include releasing greenhouse gases, destroying carbon sinks in wetlands and oceans, depletion of nutrients in ecosystems, habitat destruction, rising sea levels, wastewater treatment issues, and the displacement of economically disadvantaged communities. Interestingly, Donnenfeld, Hedden, and Crookes (2018) have also identified a pattern similar to the one observed in this study.

Figure 4a

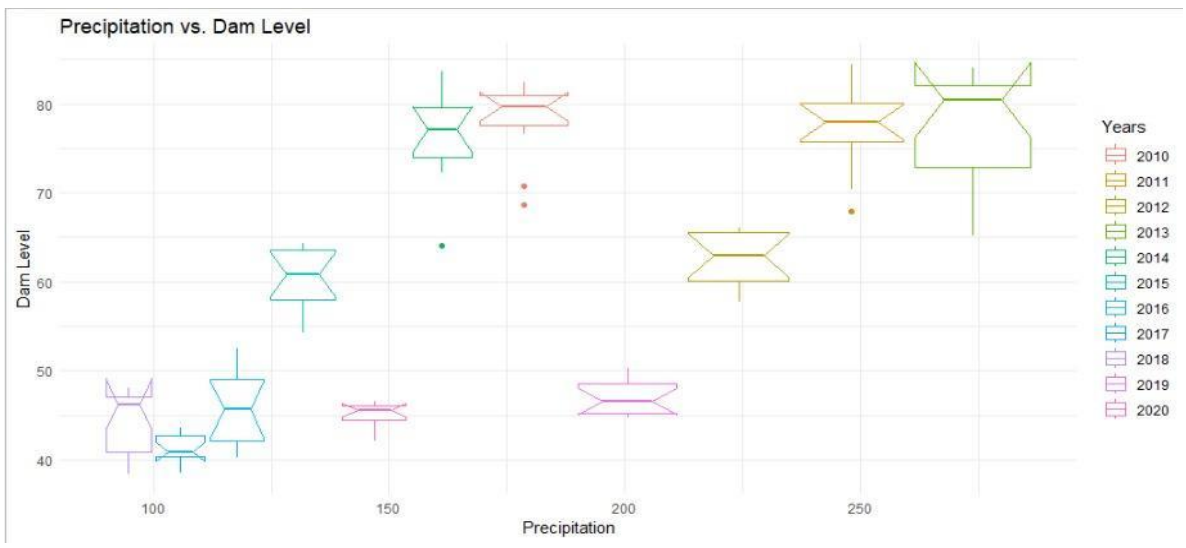


Figure 4a: Precipitation vs Dam level

The figure shows a positive relationship between precipitation and dam levels. This means that as rainfall increases, also the Jozini dam level increases, and the opposite is true. This is also an indication of the fact that increased rainfall results in more water supply in the dam. The analysis also shows some outliers across most years in the data. For example, in 2013, there was an outlier data point with low dam level and high precipitation and an outlier with a high dam level and low rainfall. This implies the possibility of other factors influencing the relationship between these two variables, which inter alia may include leakage, evaporation, and water usage, among others.

Figure 4b

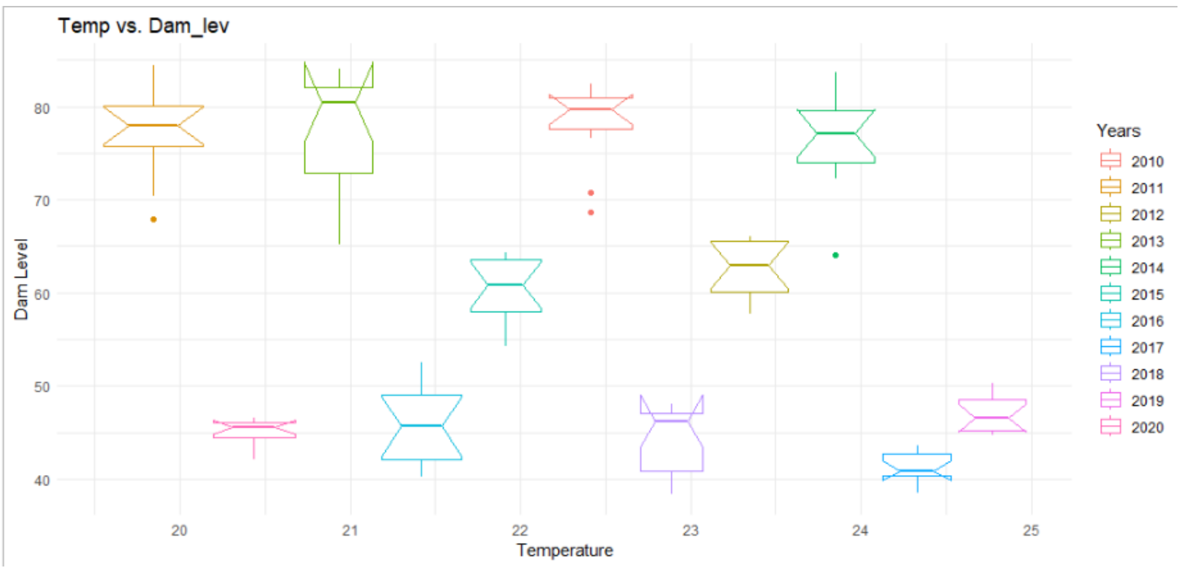


Figure 4b: Effect of temperature on dam level and precipitation.

The analysis shows an inverse correlation between temperature and the Jozini dam level from 2010 to 2020. The analysis reveals that dam level is a decreasing function of temperature. This implies that increasing temperature levels results in more evaporation, which affects the Jozini dam's water levels.

Figure 4c

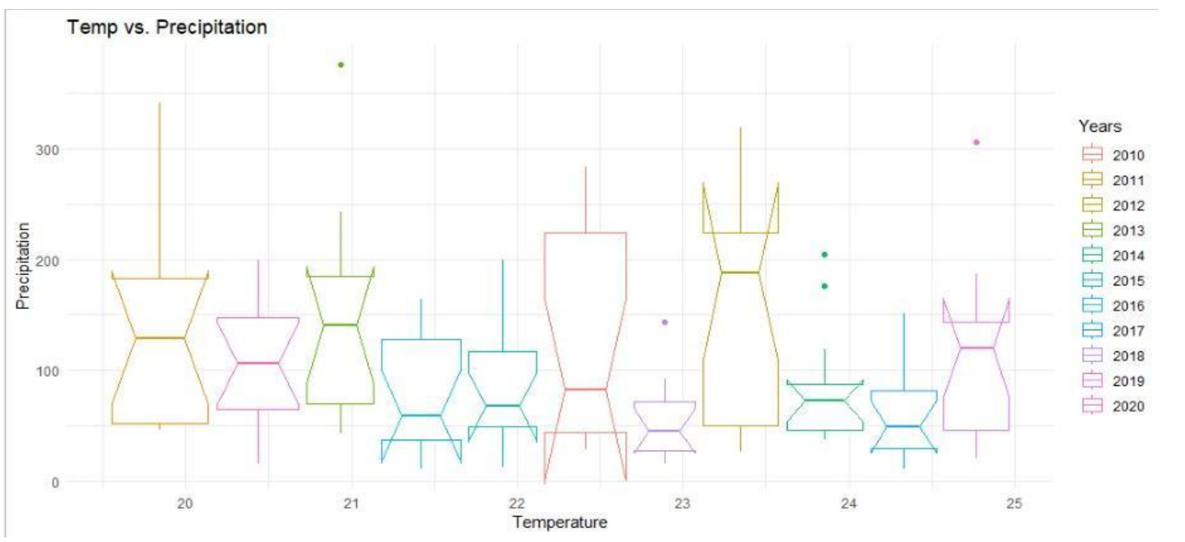


Figure 4c. Relationship between precipitation and temperature.
The analysis presents a nonlinear relationship between the duo of temperature and precipitation over the 10 years between 2010 to 2020. This indicates that rainfall does not necessarily increase or decrease proportionally with prevailing temperature levels, as the former varies per the temperature range and year. The figure also reveals some interesting patterns in the data points across the 11 years. For instance, rainfall tends to increase when the temperature range lies between 20 °C and 25 °C, and when the latter range above 30 °C or below 20 °C, rainfall tends to be lower. This implies an optimal temperature range for precipitation, such that very high temperatures tend to affect the water cycle in the Jozini area.

This study showed that temperature and precipitation are key climate parameters that directly influence the hydrological cycle and, consequently, the water levels in the dam. Rising temperatures can increase evaporation rates, which may exacerbate water scarcity issues. On the other hand, changes in precipitation patterns can directly impact the inflow into the dam, affecting its water levels and overall storage capacity. Understanding the effects of climate change on the Jozini Dam and its water resources is crucial for making informed decisions in water management, conservation efforts, and adaptation strategies. The results of this investigation will offer valuable insights into the vulnerability of the region's water supply to climate change and will aid in developing sustainable and resilient approaches to address these challenges. Moreover, by establishing the connection between climate variability and water resources, this study contributes to the broader scientific understanding of climate change's impact on local hydrological systems. The findings will be relevant not only to Jozini but also to similar regions facing similar climate-related water resource challenges worldwide. The results will also serve as a foundation for further investigations into the broader implications of climate change on regional water supplies and ecosystems.

4.0. Conclusion

This investigation reveals that climate variability impacts the water level of Jozini Dam in contrasting ways, with temperature showing a generally negative effect and precipitation exhibiting a positive influence. As a result, the water level in the Jozini Dam Reservoir and the availability of drinking-quality water in the Jozini area from 2010 to 2020 are positively and negatively affected. For precipitation, increasing temperature leads to higher evaporation rates, which might reduce the Jozini Dam's water level. Conversely, long-term river discharge due to increased water inflow into the dam also contributes to declining water levels in the reservoir. This combined effect highlights the urgency of developing an adaptation strategy to address climate change's negative impact on the delicate ecosystem of the Jozini area. With projected declines in inaccessible water resources and a rise in water demand due to agricultural activities and other development plans, the need for an adaptation strategy becomes even more apparent. This strategy must tackle the challenges of water scarcity and ensure the continuity of future water supply in the Jozini region. Developing models specific to a dam system is crucial for exploring future scenarios, assessing their implications, and identifying knowledge and data gaps. This approach supports a more holistic management strategy considering different meteorological and socio-economic conditions, influencing water quantity and availability. It is important to acknowledge the significance of this research in guiding policymakers, water resource managers, and stakeholders in formulating effective strategies to ensure the long-term availability and sustainability of water resources in the Jozini municipality. Further investigation is needed to better understand these variables' complex interactions and long-term implications for the region's water resources and ecosystems, and determine whether direct changes in precipitation, runoff, discharge, and groundwater flow are the main drivers behind decreases in water flow through major rivers and the water level of dams. Understanding these factors will be essential for implementing effective measures to address the challenges of climate change and ensure the sustainable management of water resources in the Jozini area.

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