UNIVERSITE JOSEPH KI-ZERBO

ECOLE DOCTORALEINFORMATIQUE ET CHANGEMENTS CLIMATIQUES (EDICC)

BURKINA FASO

Unité-Progrès-Justice

SPONSORED BY THE

Federal Ministry of Education and Research

MASTER`S RESEARCH PROGRAMME

SPECIALITY: INFORMATICS FOR CLIMATE CHANGE (ICC)

MASTERS' THESIS

Subject:

Numerical Assessment of Hydrodynamic Trends and Groundwater Recharge through Long Chronicle Data in the Bagré Dam, Burkina Faso: Implications for Climate Change and Dam Management Operations

Defended on 14th July 2023

by

OROWALE Triumph Prosper

Major Supervisor	Co-Supervisor
Dr. Youssouf Koussoube Laboratoire Géosciences et Environnement, UFR SVT, Université Joseph KI-ZERBO, Ouagadougou, Burkina Faso.	**Dr. Seyni Salack** Regional Thematic Coordinator: Risks and Vulnerability to Climate Extremes, WASCAL Competence Center, Ouagadougou, Burkina Faso.

Academic year: 2022 - 2023

Dedication

This research is dedicated to my parents, Isaiah Orowale and Patience Orowale.

Acknowledgment

I thank God Almighty for his mercy and for giving me the opportunity, strength, and life to begin and finish this research successfully.

This research was successful with the full support of the following great institutions and personalities.

- Federal Ministry of Education BMBF, Germany.
- WASCAL Competence Centre, Ouagadougou, Burkina-Faso.
- Director of "Ecole Doctorale Informatique et Changement Climatique" (ED-ICC), Prof. Tanga Pierre ZOUNGRANA
- Deputy Director of ED-ICC, Dr. Ousmane COULIBALY
- **Major Supervisor** -LaGE, Universite Joseph Ki-Zerbo, Ouagadougou, Burkina Faso**; Dr. Youssouf Koussoube**
- Co-supervisor, Regional Thematic Coordinator, Risks and Vulnerability to Climate Extremes, WASCAL Competence Center, Ouagadougou, Burkina Faso; **Dr. Salack Seyni**
- U.S. Geological Survey Nebraska Water Science Center in Lincoln, Nebraska; **Mr. Moussa Guira**
- Doctoral Research Programme in Climate Change and Water Resources, Université d'Abomey-Calavi, Cotonou, Benin. **Mr. Gnibga I. Yangouliba**

I also appreciate Dr. Bio Mohamadou Torou; Dr. Oyebamiji Ajibola; My family, The OROWALE' s; Engr. Caleb Olowojola; Mr. Kolade David, and my inestimable colleagues of WASCAL EDICC Batch Three (3). This list is endless, which is my debt of gratitude to the unmentioned.

Acronyms and Abbreviations

ANAM	: Agence Nationale de la Météorologie (Burkina Faso)
GWUDI	: Groundwater Under the Direct Influence (GWUDI)
SONABEL	: Societe Nationale d`Electricite du Burkina
SSA	: Singular Spectrum Analysis
PZ	: Piezometer
WL	: Window Length
WTF	: Water Table Fluctuation

List of Tables

List of Figures

Abstract

In the context of climate change and the subsequent pressure of human activities, there is abounding need to establish a clear relationship between reservoir storage, rainfall, and groundwater recharge in Bagre dam, Burkina Faso. Hydrodynamic variables collected in and around the operations of Bagré dam (e.g., evaporation, inflow, irrigation, spillage, water level, rainfall) were analysed, using the singular spectrum analysis to delineate the trends and variability over the 1993-2022 period. Additional sensitivity assessments were conducted on groundwater data between 2002 and 2022, using linear and polynomial models to predict the impact of the reservoir water level on the groundwater; Pettitt and Mann Kendall test to evaluate the significance level of the trends and a water table fluctuation and infiltration models were developed to delve into the influence of the reservoir water level and rainfall on groundwater recharge in and around the Bagré Dam. The result shows that there is an increasing trend of spillage due to increasing inflow. Evaporation trend is decreasing, and irrigation trend is increasing. Rainfall trend is decreasing from 2012, and the reservoir water level is relatively stable. The statistical indices showed strong, moderate, and very low relationship with the water level. The percentage of groundwater recharge percentage is between 25-28%, which is stable due to the constant availability of surface water. The Mann Kendall and Pettitt tests show an increasing trend and breaking points on most of the piezometer profiles. Inflows rise has affected the dam stability while spill over led to flooding downstream of the Bagre Dam. The reservoir water level is improving the groundwater recharge, which will enable agricultural practice irrespective of the seasons around the dam. These results suggest that future ground water trends and variability in and around the Bagré Dam can be predicted using the variables from dam management operations.

Key words: Dam Management Operations; Hydrodynamic Trends & Variability; Groundwater Recharge; Bagré Dam, Burkina Faso

Résumé

Dans le contexte du changement climatique et de la pression subséquente des activités humaines, il est nécessaire d'établir une relation claire entre le stockage du réservoir, la pluviométrie et la recharge des eaux souterraines dans le barrage de Bagré, au Burkina Faso. Les variables hydrodynamiques recueillies dans et autour des opérations du barrage de Bagré (par exemple, l'évaporation, le débit entrant, l'irrigation, le déversement, le niveau d'eau, les précipitations) ont été analysées, en utilisant l'analyse du spectre singulier pour délimiter les tendances et la variabilité au cours de la période 1993-2022. Des évaluations de sensibilité supplémentaires ont été menées en utilisant des modèles linéaires et polynomiaux pour prédire l'impact du niveau d'eau du réservoir sur les eaux souterraines ; les tests de Pettitt et de Mann Kendall pour évaluer le niveau de signification des tendances et une fluctuation de la nappe phréatique et des modèles d'infiltration ont été développés pour étudier l'influence du niveau d'eau du réservoir et des précipitations sur la recharge des eaux souterraines à l'intérieur et autour du barrage de Bagré. Les résultats montrent qu'il y a une tendance à l'augmentation des déversements en raison de l'augmentation du débit entrant. La tendance de l'évaporation est à la baisse et celle de l'irrigation à la hausse. La tendance des précipitations est en baisse depuis 2012, et le niveau d'eau du réservoir est relativement stable. Les indices statistiques ont montré une relation forte, modérée et très faible avec le niveau d'eau. Le pourcentage de recharge des eaux souterraines se situe entre 25 et 28 %, ce qui est stable en raison de la disponibilité constante des eaux de surface. Les tests de Mann Kendall et de Pettitt montrent une tendance à l'augmentation et des points de rupture sur la plupart des profils piézométriques. L'augmentation des débits a affecté la stabilité du barrage, tandis que les débordements ont entraîné des inondations en aval du barrage de Bagre. Le niveau d'eau du réservoir améliore la recharge de la nappe phréatique, ce qui permettra de pratiquer l'agriculture indépendamment des saisons autour du barrage. Ces résultats suggèrent que les tendances et la variabilité futures des eaux souterraines dans et autour du barrage de Bagré peuvent être prédites en utilisant les variables des opérations de gestion du barrage.

Mots clés : Opérations de gestion du barrage ; tendances et variabilité hydrodynamiques ; recharge des eaux souterraines ; barrage de Bagré, Burkina Faso

INTRODUCTION

A dam is a structure constructed over a massively flowing stream to control the movement of water. Generally, a dam is meant to supply water for municipal and industrial use, human and animal consumption, hydroelectric generation, and irrigation. Furthermore, it is used to store large amount of water, control flooding, and serve as groundwater recharge. Since dam construction serves a tremendous purpose for the human community, the design and construction of a dam are expected to create a stable structure that will last a very long time (Oladunjoye, 2017). The management of water resources in a dam depends heavily on an understanding of the processes and timescales by which above- and below-ground water resources interact and are refilled (Geris, 2022).

Hydroclimatic trends and variability play a critical role in shaping the stability of dams, which are vital infrastructure assets for water resource management and flood control. Understanding the impact of hydrological factors on dam stability is of paramount importance for ensuring its long-term functionality and safety. Various hydrological parameters have a significant influence on the stability of an embankment dam. Rainfall and upstream inflow events will provide opportunities for consistent availability of surface water in a dam, which will enable the productive operation of the dam. Precipitated seepage zones in the bedrock and discontinuities in the structure itself are other factors that pose a threat to the integrity of a dam (Felix, 2000). In Burkina Faso dams structure usually fail every year during the raining season (DGIH, 2010).

Climate change is expected to significantly impact river basins and water supply systems in West Africa (Eccles et al., 2019; Liersch et al., 2020). The trend of hydrological variables in the dam can be used to analyse the impact of climate change. These events are in response to climate change. By regulating reservoirs, the serious problem of hydrological extremes can be mitigated and controlled. Climate change will increase the risk of flooding at the end of the twenty first century (Yun et al., 2021). The stability of the dam is based on the impact of climate change on the hydrological events that occur at the dam.

Groundwater, surface water, and saltwater resources are under several threats from environmental pollution, climate change, and negative human activities. Groundwater is the primary source of water supply for both urban and rural inhabitants, as well as for businesses and agriculture. Groundwater recharge is the main hydrological parameter that determines the availability and sustainability of groundwater resources among several parameters of the water cycle. (Ali et al., 2017). In Burkina Faso, groundwater abstracted through boreholes and wells accounts for about 60% of the total drinking water supply in rural areas (DGH, 2001).

Cities in the main basin such as Tamale in Ghana and Ouagadougou in Burkina Faso also rely heavily on groundwater sources for their residential water supplies (HAPs, 2006). Based on available data and reasonable assumptions (Martin et al., 2005), it is estimated that about 44% of the total population in the Volta basin depends on groundwater for their water needs. To meet the demands of industry, home water supply, agriculture, and ecosystems, groundwater dependence is still increasing (Wada et al., 2010; Green et al., 2011; Taylor et al., 2013).

The water inside a dam can cause surrounding groundwater levels to rise (Killian et al., 2019). The direct effect of dams on groundwater is expected to be upstream and downstream. Although the effect of the dams on the basins far from them diminishes with time, it is seen that the water level within the dams' basins rises dramatically and then maintains a steady level. (ÇELİK, 2018).

Problem Statement

In the context of climate change, there is a need to increase our understanding on the factors influencing groundwater recharge and dam stability in the Bagre Dam.

Despite the recurring need to analyse hydroclimatic trend events on dam stability and establish a clear correlation between reservoir storage and rainfall on groundwater recharge, there is a significant lack of research regarding the specific influence that determines groundwater recharge and hydrological trends on the stability of Bagre Dam. The challenge lies in examining the issue of infiltration and seepage rate, specifically in relation to recharging the groundwater that passes through the dam. Several factors contribute to this challenge, including the geotechnical region, construction techniques, geologic faults, and climate change. These factors result in water from the surface percolating into the dam's groundwater, creating a significant concern.

Although the importance of hydroclimatic variables in determining dam stability is acknowledged, there is a lack of comprehensive understanding regarding the impact of hydrological variable trends on dam stability, the need to analyse a concrete relationship between reservoir surface water and rainfall on groundwater recharge in the dam. As a result, there is still a lack of knowledge on the complexity and variability of the interactions between rainfall, soil water flow, and groundwater recharge (Al-Gamal, 2020 and Dey et al., 2020). The influence of climate variables on groundwater is poorly understood (Dey et al., 2020).

An essential part of a watershed's water cycle is the surface water to groundwater interaction. The management of water resources and the preservation of ecological systems in dry regions are both impacted by the water balance and material exchange, which support the surface water and groundwater ecosystem fundamental processes (Sophocleous, 2002; Lambs; and Kalbus, 2006). It is obvious that topography, geology, landform conditions, climate, and human activities regulate the surface and groundwater interaction because its dynamic mechanism and ecological effects in arid places are so complicated. Wang et al., (2018) discovered that groundwater transformation could be controlled by geologic and lithological structures. The demand for dams for the purpose of water supply, especially in areas with good potential, is constantly on the increasing (Adewoye et al., 2017) hence the need to understand and analyse the degree of recharge in the dam environment to allow easy agricultural activities and water availability. Dams are predicted to elevate groundwater, especially those near lakes, but it is important to investigate how they can affect groundwater through lower basins. (Çelik, 2018). Consequently, there is a pressing need to bridge this research gap by conducting in-depth investigations to unravel the intricate connections and quantify the effects of hydrological trends on the stability of dams, surface water, and rainfall on groundwater recharge in the dam.

Research Questions

It is crucial to provide sufficient empirical evidence or a clear understanding of the mechanisms through which hydrological trends influence dam stability, groundwater level fluctuation, and the effect of reservoir storage and rainfall on groundwater recharge.

So, the main research question behind this study is, what are the factors influencing groundwater recharge and stability of the Bagre dam under climate change?

Specific research questions are as follows:

- How will the trend, variability and seasonality of hydrological variables affect the dam stability?
- What is the fluctuation and impact of water storage on groundwater in relation to the Bagre Dam?

- What is the relationship between water storage and rainfall on groundwater recharge?

Research Hypothesis

The regular increasing trend of the hydrological variables under climate change would affect the dam stability and efficiency, while the reservoir water level will result in a rise and recharge of the groundwater level.

Specifics hypothesis are as follows:

- Increasing the trend, variability and seasonality of the hydrological variables would affect dam stability.
- Increasing impact in groundwater level is due to the consistent availability of the reservoir water level.
- Increasing the quantity of water storage would result in stable and constant groundwater recharge, while the effect of rainfall would be minimal and seasonal to groundwater recharge.

Research Aim and Objectives

This research objective is to evaluate the impact of hydrological variables on dam stability and the interaction between surface water level and rainfall on groundwater recharge and fluctuations at the Bagre embarkment dam.

Therefore, to understand and analyse the influence of hydrological variables on the stability of the dam, the relationship between surface water and groundwater in the dam, the following objectives would be achieved.

- Identify the trend, variability, and seasonal behaviour of hydrological variables on dam stability.
- Examine the fluctuations and impact of water level on groundwater level around the Bagre dam.
- Evaluate the effect of water storage and rainfall on groundwater recharge.

CHAPTER ONE: LITERATURE REVIEW

The stability of dams is a critical concern in the management of water resource, and understanding the hydroclimatic parameters that influence them is crucial for the effective design, operation, and maintenance of these structures. It is crucial to determine the most influencing factor on groundwater recharge around any dam.

1.1. Dam Safety, Monitoring, and Hydrological Variables

Environmental factors (such as water temperature and level) and effect factors (such as deformation, cracking, and seepage) are typically included during dam monitoring. For managers to understand the operating state of a dam, the associated monitoring data are crucial, as they can indicate trends in these variables over time. The safety of dams must therefore be monitored, and research into monitoring data analysis techniques is crucial. The trends effect of variables can be learned for tracking and forecasting by looking at how variables interact with each other. There is a constant need to provide fundamental ideas, areas for improvement, and current developments to further investigate dam safety monitoring and monitoring data analysis techniques (Bin et al., 2019). Since dams are exposed to harsh and frequently unpredictable settings, it is important to adequately maintain and inspect their conditions (In-Soo et al., 2015).

(Obahoundje et al., 2022) investigated how Kossou and Taabo in the Bandama dams in Côte d'Ivoire, as well as the input, outflow, reservoir water level, and storage and hydraulicity indices, are affected by climate change and hydroelectric generation. Furthermore, statistical analysis was used to determine how sensitive to climate change was the hydropower generation of these dams. The findings show that the inflow is primarily dependent on rainfall, while the outflow, which is a function of the input to the reservoirs and the water management policy, heavily influences the water level. The Mann Kendall test showed that while precipitation shows a significant rising trend only within the Taabo dam catchment region, temperature and potential evapotranspiration have increased significantly in all three subbasins. The change in land use and cover is likely what caused the substantial and significant increase in reservoir inflow relative to precipitation. The Kossou dam is more affected by water level and electricity generation at the Buyo and Taabo dams is more responsive to reservoir inflow.

1.2. Climate Change Impacts on Dams

The implications of climate change on dam safety are often examined independently and with a focus on the components. Most studies (Bahls et al., 2014; Chernet et al., 2014; Novembre et al., 2015) tend to ignore other factors or focus solely on how climate change affects hydrological burdens. The quality and quantity of water resources (streamflow and runoff) will be directly impacted by climate change (Nonki et al., 2021). It is obvious that the hydrological cycle is intensified by climate change, causing an increased number of meteorological extremes. Climate change has been shown to be a key factor that changes the hydrological cycle on a global scale (dey et al., 2020). The current assessment focuses on the effects of climate change on dam stability in a hydrological scenario, which means that the main load component that the dam-reservoir system is subject to is flooding (IPCC, 2014).

The global effect of climate change on dam risk must be assessed through the integration of the various projected effects acting on each aspect, considering them interdependencies, rather than by a simple accumulation of separate impacts. Adopting a comprehensive strategy to address the impact of climate change on dam safety management is therefore beneficial. Dam risk models serve as an effective foundation for structuring such analyses in this context. Many authors seek a multidisciplinary and structured review of the most relevant impacts of climate change on the different safety components of the dam, from input hydrology to the calculation of the downstream consequences of the flood on the population and assets at risk. However, the anticipated changes caused by climate change are likely to have an impact on various factors that influence dam risk. Although some reference institutions create guidelines for incorporating climate change into their decision support strategies, the application of this information to analyses like dam safety assessments is still difficult due to the vast amount of disparate information that is still available.

As climate changes, longer and more frequent droughts will result in less water being captured by dams, reducing electricity production. As temperatures continue to rise, nations dependent on hydropower will be particularly vulnerable. (DW - 06/25/2020) The effects of mega-dams on the ecosystem. Dams are designed to deal with surface water issues. These issues include an abundance of water during the rainy seasons and a lack of water during the dry ones. Engineers and scientists are expected to consider the effect of climate change on dam safety as it has been acknowledged by people all over the world (Heri et al., 2022).

1.3. Singular Spectrum Analysis (SSA)

Over the past 20 years, singular spectrum analysis (SSA) has become popular and is now regarded as one of the most effective methods for analysing a wide range of time series. Although its origins lie in the natural sciences, and the series arisen from such processes, it can be applied in several different fields (Hassani et al., 2010). SSA, a time series analysis method that is relatively new but effective, has been studied and used to solve a variety of real-world issues in recent years.

Decomposing time series into several time series can be useful in retaining the most important information. Singular Spectrum Analysis is one decomposition algorithm; it shows how to break down a time series into various subseries and visualizes the various subseries that are extracted. The goal of SSA is to reduce the original series to a handful of easily interpreted elements, such as trend, oscillatory components, and noise. According to Golyandina et al. (2013), it is based on the singular value decomposition of a certain matrix built using the time series.

The Singular Spectrum Analysis (SSA) technique is a novel and powerful time series analysis technique that incorporates elements of classical time series analysis, multivariate statistics, multivariate geometry, dynamical systems, and signal processing. SSA is nonparametric time series method which decomposes, reconstructs, and forecasts time series (Golyandina et al., 2013).

1.3.1. The Purpose and Application of SSA

The possible application areas of SSA are diverse: from mathematics and physics to economics and financial mathematics, from meteorology and oceanology to social science and market research. Another illustration of a good use of SSA is any seemingly complex series with a potential structure (Golyandina et al., 2001). The goal of SSA is to break down the original series into a handful of distinct, comprehensible elements, such as a slowly changing trend, oscillatory elements, and random noise. SSA is a very helpful tool that can be used to address the issues listed below: identifying trends at various resolutions; smoothing; identifying seasonality components; 4) simultaneous extraction of cycles with small and large periods; 5) extraction of periodicities with varying amplitudes; 6) simultaneous extraction of complex trends and periodicities; 7) finding structure in short time series; and 8) change-point detection. Some of the usefulness was achieved in hydrological variables (Hassani, 2007).

1.3.2. Singular Spectrum Analyses on a Hydrological variable Data Set

The singular spectrum analysis (SSA) method is applied to several hydrological univariate time series to evaluate both its forecasting and its ability to extract significant information from those series. In the SSA, the time series of annual precipitation, monthly runoff, and hourly water temperature are used. The SSA method is already well-known as a potent time series analysis tool. The findings have demonstrated that the SSA technique, in addition to time series analysis, may be successfully applied as a time series forecasting algorithm, or at least for certain of its extracted components, such as the hydrological time series employed in this work. Important elements of hydrological time series with characteristically erratic behaviour, including precipitation and runoff series, could be extracted by the SSA (Marques et al., 2006).

1.4. Piezometric Data Analysis and Water Level on an Embankment Dam

The groundwater pressure and level of a location can be measured using submerged piezometers in the subsurface in the given area or location which would give information about the water level in the subsurface.

It is difficult to evaluate the readings obtained from the equipment used to monitor dam behaviour accurately; it is necessary to solidify engineering judgment and analysis, as well as robust statistical analysis approaches, to prevent misinterpretation. Various anomaly detection techniques are investigated to, i) propose which data analytics are appropriate for different anomalous scenarios as well as piezometer locations, and ii) test whether the commonly work of anomaly detection necessitates the use of basic assumptions on piezometer data, such as linearity between piezometer data and pool levels and normally distributed piezometer data. This evaluation focuses on anomaly identification methods that can be used to analyse piezometer data (gathered from embankment dams) and unusual situations that could result in internal erosion. Numerous anomalous scenarios and piezometer data from a case study dam are recreated using a numerical model to verify how effectively the anomaly identification approaches work. Piezometers (and other sensors) in an embankment dam may not always be placed in the best locations in the actual world, and their behaviours may not always be consistent over time. Therefore, rather than analysing only one major piezometer at a time, it is crucial to understand how the data from a set of piezometers have evolved over time. It is challenging to pinpoint precisely when and where anomalies that occur inside dams would start and be identified because they may start with very minor deformations and no visible symptoms.

However, it may be possible to get better interpretations by tracking variations over time between several (or grouped) piezometer readings or between the piezometers around a certain place. As a result, it also includes research on combining the analyses of various piezometers. The study compares the effects of evaluating numerous piezometers with studying individual piezometers to determine whether the combination of multiple piezometers analyses can improve the interpretation and detection of piezometric anomalies (In-Soo et al., 2015).

1.4.1. Groundwater Recharge and Estimation

Groundwater is the water found in the earth subsurface within a porous geological formation of fracture. The water table is the level and depth at which the aquifer is saturated with water. The aquifer is the subsurface layer of permeable and fractured rocks which holds water. According to De Vries and Simmers (2002), groundwater recharge is the downward movement of water from the unsaturated zone to the water table, which increases the amount of water stored in the aquifer formation.

Both natural hydrologic cycle recharge and human-induced recharge can occur in ground water, either directly through spreading basins or injection wells, or because of human activities such as waste disposal and irrigation. In many places, artificial recharge using surplus surface water or recycled wastewater is growing and becoming a more significant part of the hydrological cycle. Artificial recharge is the process of enhancing the natural infiltration of precipitation or surface water into subsurface permeable formations using certain construction techniques, the application of water, or the manipulation of the environment (Prasad, 2011). It is observed from the Pandan Duri Dam that the water levels inside the dam had a significant impact on the surrounding groundwater levels (H Sulistiyono et al., 2021).

Diffuse or localized natural recharge of the water table is also possible. The extensive transfer of water from the land's surface to its water table due to precipitation over substantial areas seeping into and percolating through the unsaturated zone is known as diffuse recharge. Diffuse recharge is more uniform in space than localized recharge, which involves the transfer of water from surface water bodies to the groundwater system. Most groundwater systems receive localized and diffuse recharge. Diffuse recharge becomes less significant when a place becomes more arid in general

(Alley, 2009). Groundwater recharge depicts the addition of water, indicated as a rate (mm / year) or volume (mm^3 / year), to the saturation zone. The groundwater recharge zone includes a region where the water has absorbed enough surface water to reach the saturation zone. This is a location where an aquifer's hydraulic head (a water-bearing and yielding deposit) has downward components. Infiltration in a recharge area moves downhill to deeper regions of a water-bearing deposit (Prasad, 2011).

Groundwater recharge can be categorized as (i) direct or indirect depending on where the recharging water comes from, (ii) piston or preferential flow depending on how the water moves through the unsaturated zone, (iii) point, line, or areal depending on where it acts, and (iv) current, short-term, or long-term recharge on the basis of the time scale during which it occurs (Beekman et al., 1999; Lerner et al., 1999; Lerner et al., 1990). Again, recharge can be classified as actual, which refers to water that has infiltrated and reaches the water table, or potential, which refers to infiltrated water that may or may not reach the water table because of the unsaturated zone processes or the ability of the saturated zone to accept recharge (Rushton, 1997). Zone of saturation is an area of the subsurface environment where, ideally, water is pressurized to a pressure greater than atmospheric pressure and fills all gaps. Percolation is the downward movement of water at hydraulic gradients of 1.0 or less across the unsaturated zone. The process by which water permeates or filters through soil without following a clear path (Prasad, 2011).

For the resource to be developed and managed effectively, an accurate estimation of groundwater recharge is crucial. There are various ways to estimate groundwater recharge, from direct methods that deduce values from simpler physical and chemical data to simulation models of different complexity. Each approaches have advantages, disadvantages, and restrictions. It is crucial to have a thorough understanding of the methods, as well as their applicability and limitations, and the governing elements that impact the recharge, to choose the right method for a given geohydrologic and climatic situation (Ali et al., 2017). In the Bagre dam recharge is good in relation with rainfall and water storage.

1.4.2. Water Table Fluctuation (WTF) Approach for Groundwater Recharge

Atta-Darkwa et al. (2013) carried out research on quantification of groundwater recharge in the Oda River catchment using the water table fluctuation method. This investigation showed the role of water level fluctuations in groundwater using piezometric and rainfall data. Every time a groundwater system is assessed, the quantification of groundwater recharge is quantified using different estimating methodologies, resulting in varying recharge estimations. A crucial component of any sustainable planning strategy for the management of groundwater resources is quantifying the portion or percentage of infiltrating water that reaches the water table. Groundwater recharge was calculated using the fluctuation method of the water table, which was also used to assess seasonal and annual fluctuations in the rise of the water level. The findings revealed that the annual increase in water level varied between 397 and 3070 mm in 2010 and between 1105 and 3115 mm in 2009. The 14 piezometers installed for the study produced recharge estimates for the study region that ranged from 133 to 467 mm, or 9 to 31% of the annual rainfall in 2009, and 47.6-427.9 mm in 2010, or 4 to 34% of the annual rainfall. Additionally, data on groundwater recharge rates for three consecutive months show that in 2009 and 2010, the highest recharge rates were in March through May and April through June, respectively. The two periods with the lowest recharge rates were November–January (26.4 mm) and December–February (26.9 mm).

Anna et al. (2021) worked on the estimation of groundwater recharge in a shallow sandy aquifer using unsaturated zone modelling and the water table fluctuation method. One of the most crucial hydrogeological concerns is quantifying groundwater recharge, particularly considering continuous climatic and land use changes. In this investigation, analyses on local-scale recharging of a shallow sandy aquifer in the Brda outwash plain in northern Poland are performed using computational models of 1D vertical flow in the assessments of the vadose zone and water table fluctuation (WTF). Since the master recession curve technique was followed, the WTF model recharge rates (410 mm to 606 mm every three years) were in good agreement with numerical simulations to account for the effect of the groundwater table natural recession caused by lateral outflow. The Colorado River in Austin, Texas, USA, contains a 300 m long by 80 m broad sand and gravel island with established flora that is prone to >1 m daily river stage changes due of upstream dam activities. Through multiple cycles of dam-induced stage fluctuations, piezometer nests with probes tracked the development of the water table and groundwater flow pathways. The results indicate a close correlation between the hydraulic head and the island's water table and the river level associated with dam release. The groundwater-surface water connectivity of the Colorado River and the fluvial island aquifer has been substantially changed by dam operations because they pump a significant amount of water into and out of the aquifer throughout the dam release and storage cycles (Francis et al., 2010).

In the Bagre Dam, the WTF model can be used due to the direct connection of the groundwater from the piezometers to the groundwater under the reservoir of the dam.

1.4.3. Statistical Approach to Groundwater Fluctuation and Water Level

Juanizar et al. (2022) carried out an investigation to evaluate the hydraulic behaviour of embankment dams in the Sindang Heula Dam in Serang Regency, Banten Province, Indonesia, as reflected by seepage circumstances. Data from the piezometer and V-notch monitoring are evaluated using various techniques. A trend analysis of the instrumentation data, a regression analysis of the instrumentation monitoring data, and the water level were conducted. Charting based on time, in which piezometer data are linked to reservoir water levels to time and obtaining correlation by doing a correlation analysis on piezometer data vs. reservoir water level, were the methods used to analyse the trends. The outcome of the regression analysis (the R^2 value), which shows that the piezometers in the upstream portion of the core material respond well to fluctuation in water level, confirms this. The findings also reveal a slight correlation between several piezometers in the downstream region of the core material and water level. Because of the very low permeability of the core material, changes in water level have less of an impact on the pore water pressure present in the downstream region of the core downstream.

Christian (2018) worked on the analysis of piezometer measurements and stratigraphy at Sugar Lake Dam. Piezometric measurements at the right abutment of Sugar Lake Dam was higher than the reservoir level and vary seasonally with reservoir operation. This investigates how the geometry of the abutment, the stratigraphy, the operation of the reservoir, and the local groundwater affect the piezometric readings within the abutment. Statistical evaluations of previous piezometer readings were carried out using the free R software. Fourier coupled ARIMA modelling, cross-correlation analysis, spectral decomposition, and time-series decompositions were completed. The higher piezometer readings are caused by regional groundwater levels, while the reservoir dominates the variations, according to the results of statistical and finite element modelling. This is made possible by the geometry of the dam and its ancillary components, as well as the stratigraphy of the abutment.

CHAPTER TWO: DATA AND METHODOLOGY

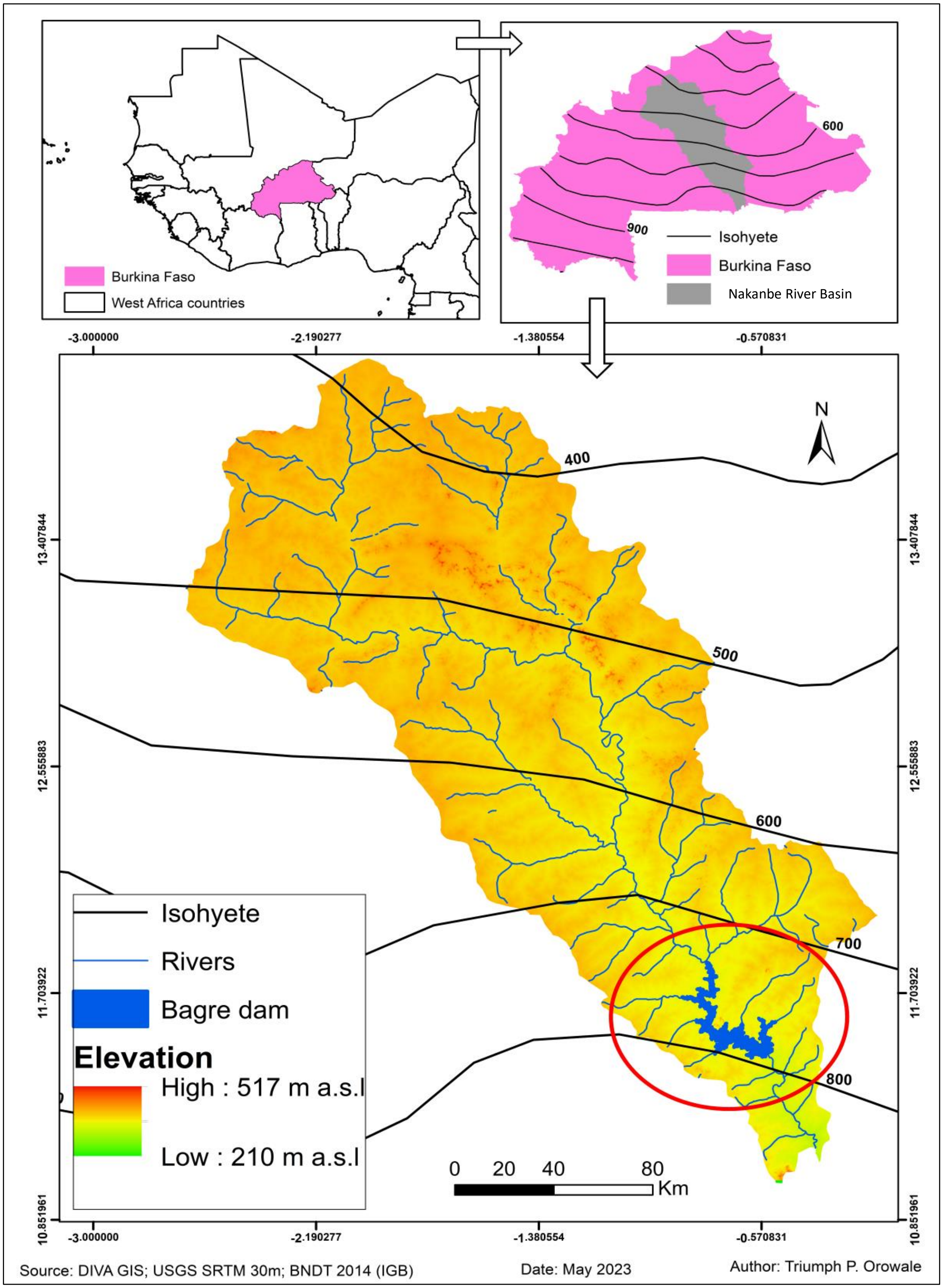
2.1. STUDY AREA: BAGRE DAM

This chapter explains the physiology and geology of the study area; data and method used to carry out the objectives of the study in Bagre dam.

2.1.1. Location and Physiography

The Bagré dam is a multifunctional dam located in the province of Boulgou, Tenkodogo, the village of Bagre in Burkina Faso. It is at the downstream of the Nakanbe River Basin (NRB) which is in White Volta Basin. The dam lies approximately 150km southeast of Burkina Faso's capital, Ouagadougou. It lies mainly within the department of Bagré in Boulgou province, although it also overlaps into the Zoundwéogo, Kouritenga, and Ganzourgou provinces.

It is situated between latitudes 11° 110$^{`}$ and 14° 10$^{`}$ north and longitudes 2° 10$^{`}$ and 0° 30$^{`}$ west. At the Niaogho station, it covers an area of approximately 32,623 km^2, and a portion of it is in the Sahelian and North Sudanese climate zones (DGRE, 2010).



Source: DIVA GIS; USGS SRTM 30m; BNDT 2014 (IGB)

Date: May 2023

Author: Triumph P. Orowale

Figure 2.1. Map of the Study Area: Bagre Dam

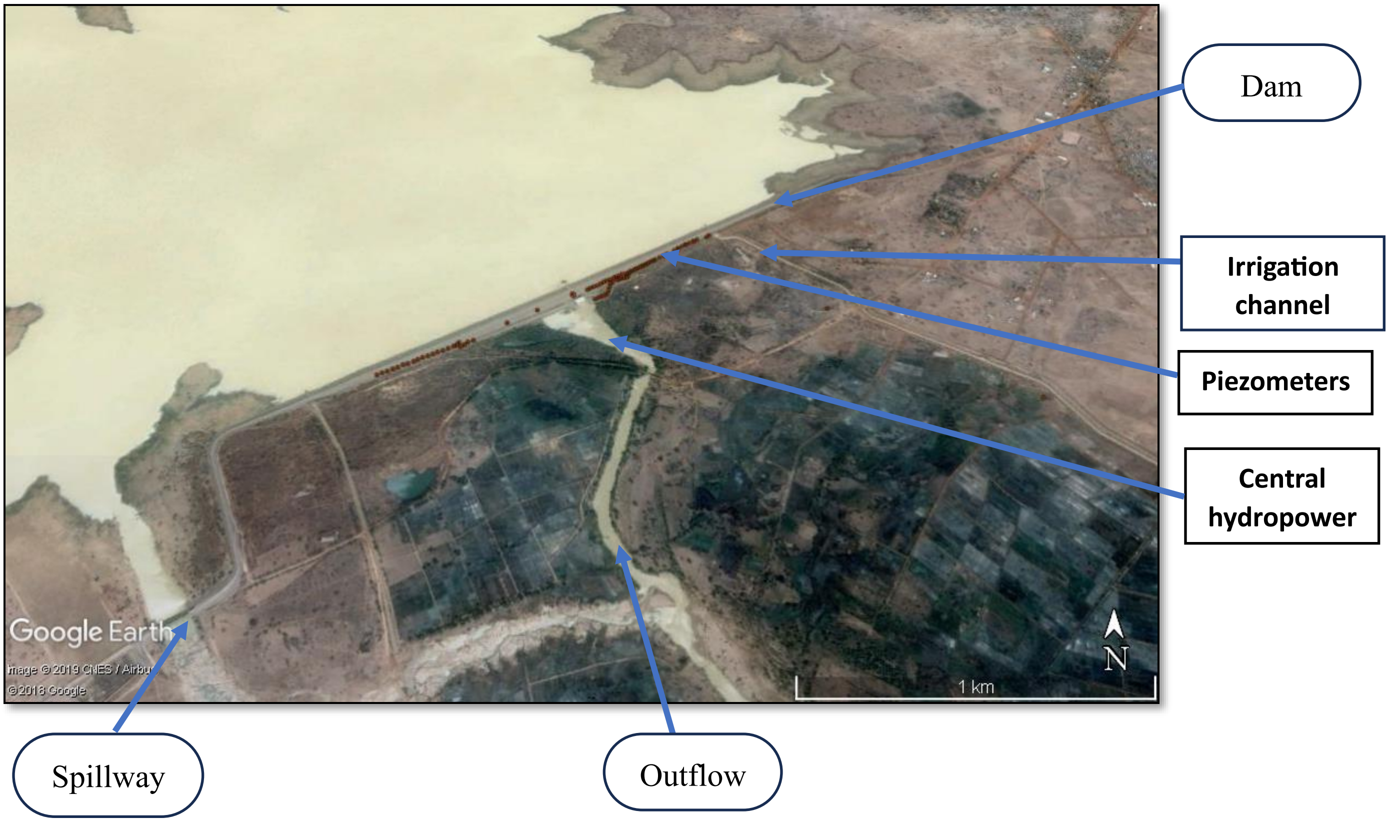


Figure 2.2. Aerial photograph of the Embarkment Dam and Piezometers

2.1.2. History and Function of the Bagre Dam

The Bagre dam is located in the downstream section of Nakanbe River Basin (NRB's), which is the largest dam in the basin. It was constructed in 1992 and inaugurated in 1994. It has a water storage capacity of 1.7 billion m^3, with water surface of 255 km^2, 80 km length, and a width of 3-4 km width (Zoungrana, 2007). It is a multipurpose dam with the primary objective of producing 44 million kWh of hydroelectric power annually, which represents 20% of the country's demand for power (Kabore & Bazin, 2014). The installed hydropower plant (HPP) can generate 16 MW of power when both units are operating at full capacity, which is 8 MW per unit during peak hours. Additionally, the dam provides water for fishery and irrigation of about 6,000 ha of rice fields (Zoungrana, 2007).

The creation of hydropower and extensive irrigated agriculture were the Bagre dam's two principal goals during construction. The area under control of the Bagre Pole extends to 493,000 hectares with an estimated potential of 29,900 hectares to be developed for irrigated agriculture. In 2012, a public-private partnership, Bagre Pole took over management of the dam and its irrigation scheme. The objective of irrigation of the dam is to address food security for the local and national population. Traditional cereal farming on rain-fed land is the main source of income in the region, along with the raising of livestock, including pastoralism. Improving and increasing rice production is a key component of government national development policies. The rainfed land in the area covers approximately 25,500 acres of potential irrigated land which brings the total potential cultivable land to 54, 900 acres. Only 3,300 hectares of the 29,000 acres of potential irrigated agricultural land have been developed and given to smallholders as of the end of 2013. In total, 1,673 families, grouped in 16 villages, work on this irrigated land. Each family's head of the household is a representative member of the village collective and responsible for the family's allocated plot. Currently, the Bagre dam is being managed by SONABEL (https://www.iied.org/global-water-initiative-burkina-faso).

2.2. GEOLOGY

2.2.1. Geology of Burkina Faso

The Precambrian strata of the Guinea Rise, a dome of Archaean rocks made primarily of migmatites, gneisses and amphibolite, dominate the geology of Burkina Faso. Over these rocks there are greenstone belts from the early Proterozoic era. The latter consist of metasediments and metavolcanics that are mostly attributable to the Birimian Supergroup, a group of rocks where considerable mineralization occurs on an economic scale. The oldest rocks in the nation are pre-Birimian migmatites, gneisses, and amphibolite, which are found underneath the Birimian strata. Clastic and volcanoclastic formations typically make up the Birimian deposits in the southwest of the nation (Schlüter and Thomas, 2008).

In figure 2.3, Burkina Faso's geology is divided into three major litho-tectonic regions according to accounts from (Castaing et al., 2003). The Neoproterozoic to Paleozoic sedimentary cover, the Pan-African chains of the Buem Attacora in the east, in its northern and western boundaries field of the Taoudeni and Voltaian basins, and the Paleoproterozoic region generally known as "Birimian" in the central portion. A broad mass of Eburnean granitoids and small ultrabasic to basic plutons are intruded into the belts of volcanic and volcano-sedimentary rocks that make up the Birimian basement.

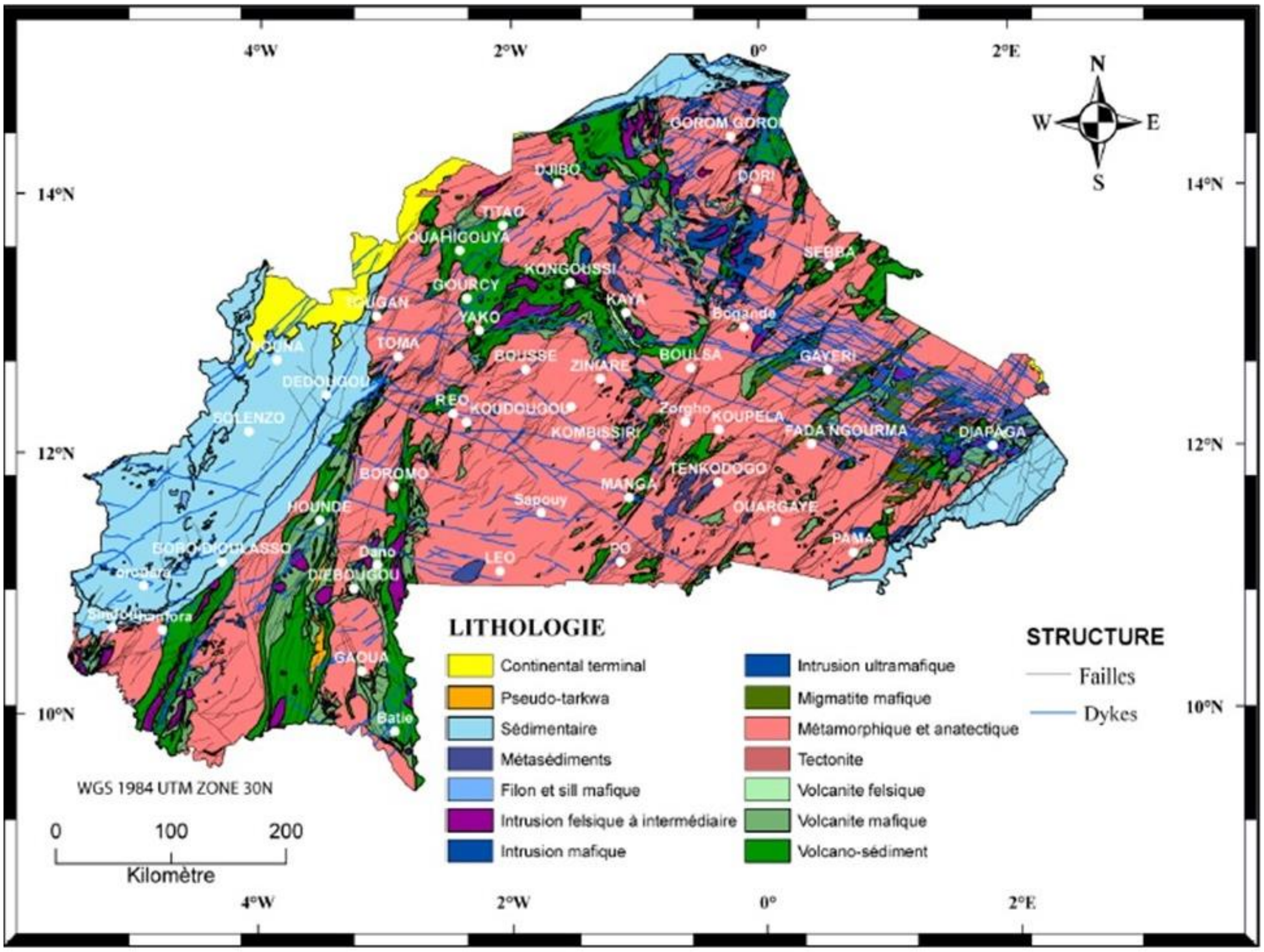


Figure 2.3. The Geologic map of Burkina Faso (Giovenazzo et al., 2018).

2.2.2. Hydrogeology of Burkina Faso

The primary factor influencing aquifer productivity and groundwater potential is geology. An overview of the hydrogeology of Burkina Faso's main aquifers is given in this section. There are four (4) aquifer types in Burkina Faso, see Figure. 2.4.

Unconsolidated rocks that have an Alluvium aquifer show a general description of location when coarse-grained sand and gravel predominate, and alluvial deposits in river valleys and floodplains can have great permeability and storage capacity. Groundwater in alluvial deposits is often in hydraulic continuity with groundwater in the underlying bedrock aquifer where it is underlain by permeable bedrock, such as sandstones or a worn basement. The water table in the alluvium is frequently shallow, less than 10 m below the ground surface (Obuobie and Barry, 2012). There are no water quality issues with this layer, but water quantity issues with this layer such that local aquifers are formed because alluvial deposits are not continuous. Recharge shows that both deeper wells and shallow wells can be used to extract them. Recharge occurs by river leakage and direct rainwater infiltration and is largely seasonal.

Sedimentary intergranular flow has a Continental Terminal aquifer. This aquifer has an uneven structure and varying lithology. Sandstones and mudstones make up the upper layers. sandstone aquifer layers typically have hydraulic continuity with the older dolomitic limestone below them. Most of the aquifer is unconfined. The depth of the water table might be anywhere between 10 and more than 90 meters. There are no observed water quantity and quality issues while the recharge shows that recharge occurs through direct infiltration of rainfall and is largely seasonal (Obuobie and Barry, 2012). The aquifer of Proterozoic to Palaeozoic (meta)sedimentary rocks is in the **sedimentary fracture flow** layer. Sandstones, dolomites, and limestones make up the 50 to 1000 m thick aquifer layers, which often have low productivity. The best aquifers are formed by dolomitic limestones (BGS, 2002). Weathering has occasionally increased the permeability of the top aquifer levels (Obuobie and Barry, 2012). Groundwater is frequently in hydraulic continuity with the unconfined upper bedrock aquifer layers, with the water table ranging from 10 to 60 m below the ground surface. Most recharge to the aquifer is thought to occur from infiltration of seasonal rainfall by preferential flow through fractures (Obuobie and Barry, 2012).

The crystalline basement has an aquifer characterized by granites, gneisses, schists, quartzites, and greenstones. Discontinuous aquifers are formed by basement rocks. Between 5 and 30 meters below the surface of the ground, the water table can be found in the weathered zone. The groundwater of the weathered zone aquifer is often unconfined. The fractured bedrock from the basement rocks also creates an aquifer, sometimes underneath and connected to weathered zones. The water table might be 20 to 60 meters below the surface and aquifer fracture zones can be 10 to 80 meters thick. The water quantity issues implies that mineral water and other commercial and industrial applications account for 25% of groundwater usage from crystalline basement aquifers, with 2% of groundwater being withdrawn for agricultural use. Rural water supply accounts for 70% of groundwater consumption.

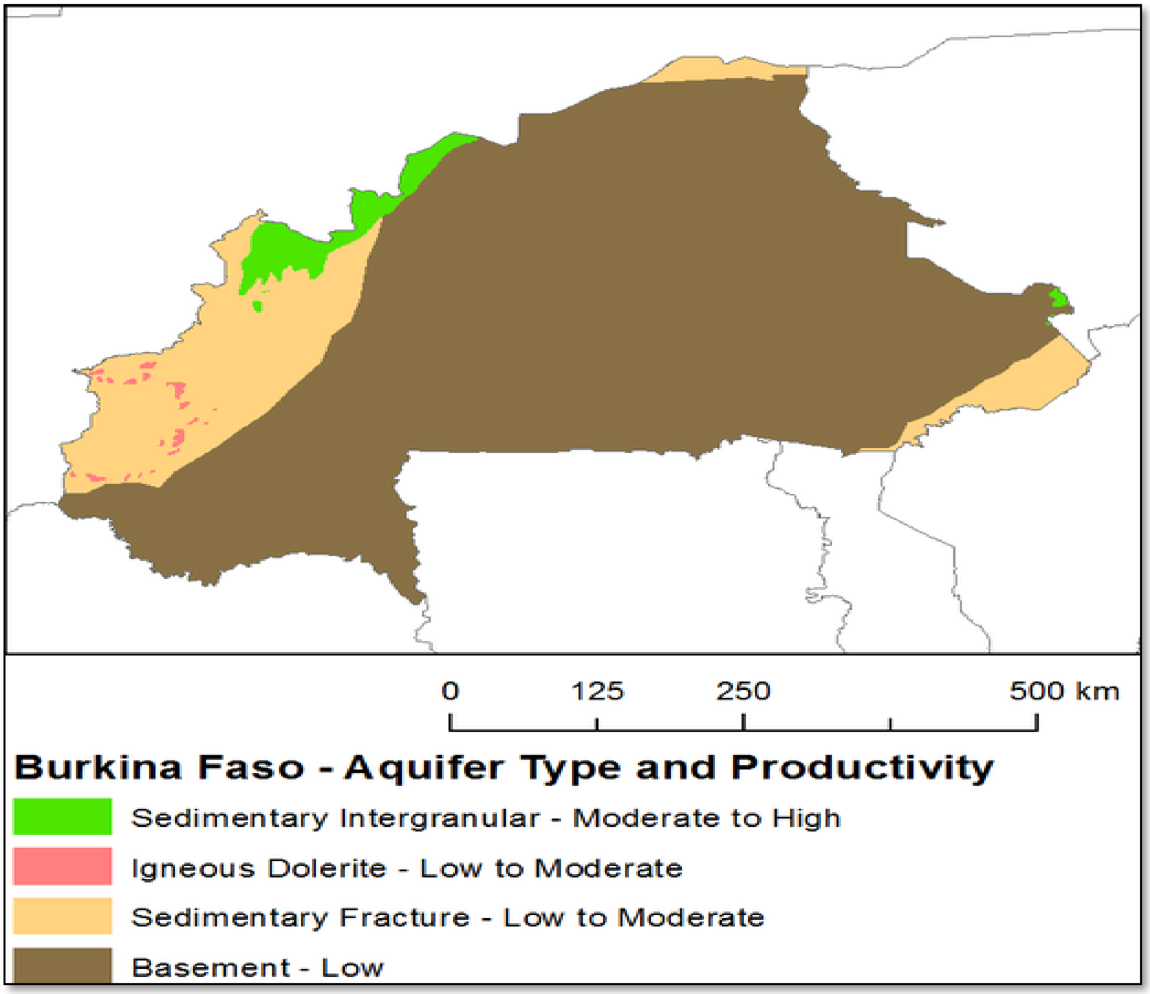


Figure 2.4 Aquifer Type and Productivity Map of Burkina Faso (Koussoube et al., 2019).

2.2.3. Geology of the Bagre Dam

The geology of the Bagre dam is underlined by migmatite gneiss in Figure 2.5. The minerals were observed to be well oriented with mineralization lineaments. Most of the rocks along the downstream were out of place and they were not in situ. There is a granite distribution and intrusion of pegmatite.

There is a similar orientation of geological features in general at the downstream. There is an orientation of N 165^0. Two locations at the downstream were visited to analyse the geology of the place. Metamorphic granite, which is gneiss and pegmatite, is the common rock found at the Bagre dam downstream. Quartzite intrusion is common. The grain size ranges from fine to coarse rocks. The pegmatitic rocks are distributed in the south of the downstream.

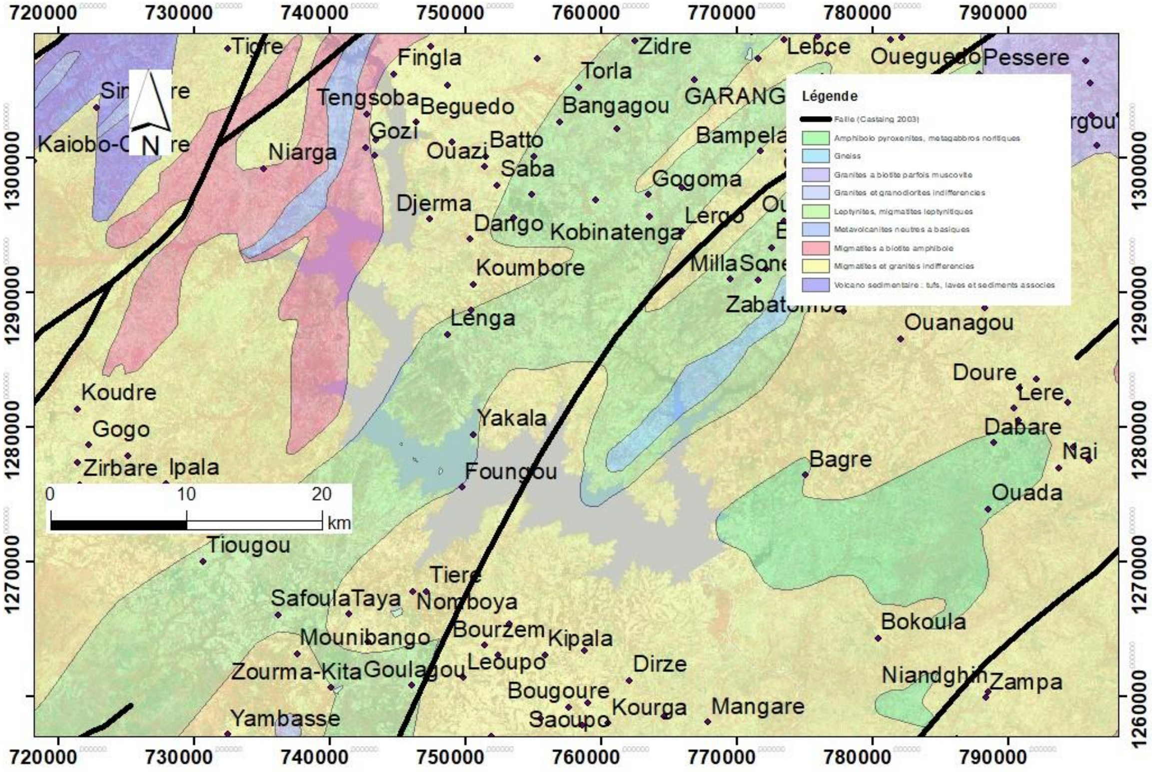


Figure 2.5 The Geology of Bagre Dam

2.2.4. Climate and Relief around the Dam

The climate of Burkina Faso can be divided into three climatic zones, with rain decreasing from south to north. There is a distinct dry season during the winter months and a wet season during the summer months. (Koussoube, 2022). Rainfall in the basin is unimodal, and the rainy season lasts from June through October. From north to south, the average annual rainfall ranges between 500 and 800 mm south. In addition, 400 reservoirs are present in the NRB, according to the Water Resources General Directorate (DGRE 2010). The rainfall trend is decreasing in Burkina Faso, and the results from the Po, Bogande, and Fada Gourma rainfall weather station near the Bagre dam reflect this assertion.

The climatic distribution of the dam is in the Sahel savanna, which can be due to the availability of water distribution from the dam. There is more vegetation cover in Bagre compared to surrounding areas.

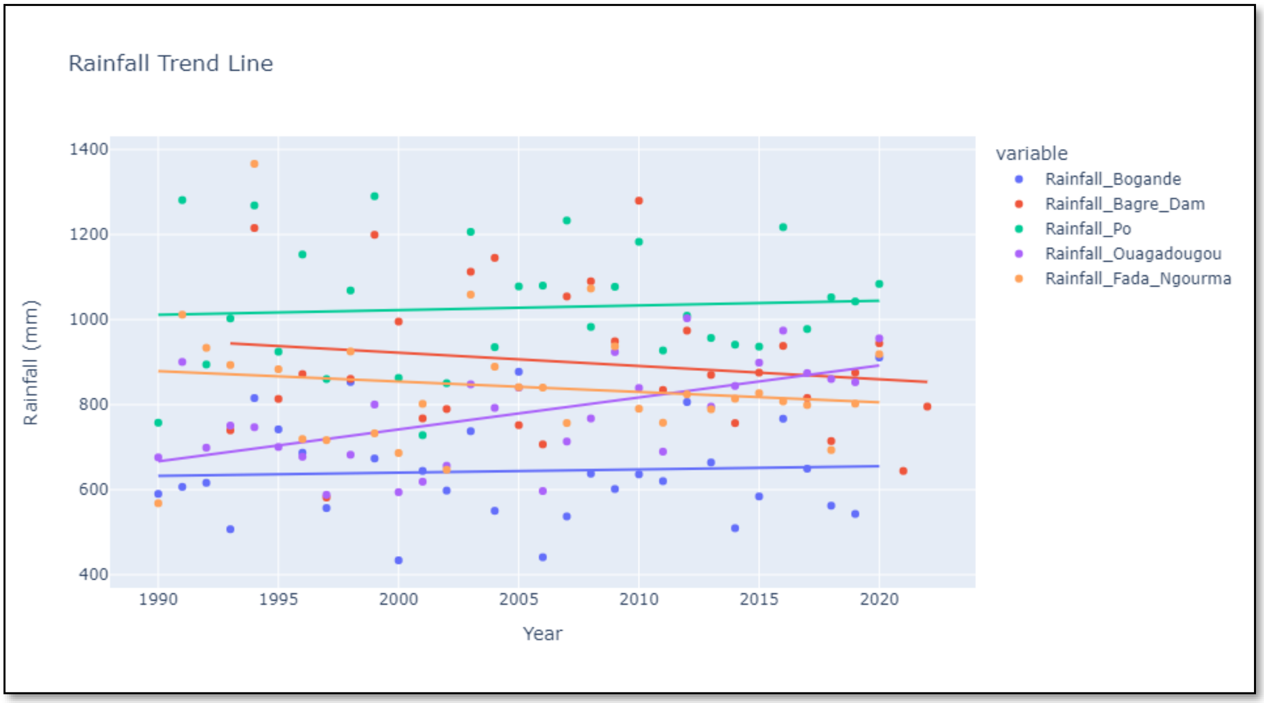


Figure 2.6 Trend of Rainfall Distribution Around the Bagre Dam

2.3. DAM VISITATION AND DATA ACQUISITION

2.3.1. Dam Visitation

The purpose of the visit was to have up to date information on site about the Bagre dam. The objectives of the visit were to view the various structures and components of the dam, investigate geologic and geotechnical structures in the downstream and for data collection (hydrological and geological data). On 13 February 2023, Triumph Orowale and Dr. Youssouf Koussoube visited the Bagre dam located in Bagre area of Tenkodogo Burkina Faso. In furtherance of the research on the analysis of the hydrological variables' trends and the impact of surface water and rainfall impact on groundwater recharge, it was necessary to visit the study site.

An interactive session was held with the dam hydrologist chief, in the dam, Mr. Sanou Ernest. The purpose of the visit was related to how I could tour dam site. I went through the embarkment dam, the spillways (artificial and natural), the water level metric, the hydroelectric session with different heavy machines and instruments for power generation. I also saw the irrigation outlets, which has two channels and different piezometric points. After the embarkment visitation was completed, I then moved to the dam downstream to carry out geologic investigation at the dam downstream.

2.3.2. Downstream Geological Investigation

The geologic mapping of the outcrops was used to describe the primary lithology and morphology of the rock bodies, as well as the age relationships between the rock units in the dam downstream. Mapping of the downstream gave structural information, such as veins, faults, and lineaments, that can be used to predict the geology in the subsurface. In addition to the visit geological investigations was conducted along the downstream to assess the influence of geological features and rock distribution on the dam and its foundation. The minerals were observed to be well oriented with mineralization lineaments. Most of the rocks along the downstream were out of place and were not in situ. There is a distribution of granitic gneiss and intrusion of pegmatite.

There is a similar orientation of geological features in general at the downstream. There is an orientation of N 165^0. Two locations downstream were visited to analyse the geology of the place. Granite gneiss and pegmatite are the common rock found at the Bagre dam downstream. Quartzite intrusion is common. The grain size ranges from fine to coarse rocks. The pegmatitic rocks are distributed in the south of the downstream.

Figure 2.7 Gneiss with pegmatitic veins

Figure 2.8 Cross section of Pegmatite in the dam downstream

2.3.3. Data Acquisition

All requested data on the dam was made available that included hydrological variables and piezometers. Climatic data for regions near the dam were also made available.

The hydrological variables were acquired from the dam; these are datasets among others depicting the activities that take place on the dam, operational information was acquired to be able to analyse the series and sequence of activities on the embarkment. The following hydrological variables were useful for this study, such as spillage, rainfall, inflow, water level, irrigation, and evaporation; other parameters were available, but this were of more interest to the study. The dataset is a monthly time series from January 1993 to December 2022 which is a thirty (30) year span.

Seven (7) hydrological variable information were considered to analyse the behaviour of the dam.

1. The volume of spillage is the volume of water that is released from the spill way either naturally or artificially. It is measured in cubic hectometre (hm^3) which is the unit for measurement of volume.
2. Rainfall is the quantity of rainfall recorded at the dam entry measured in millimetres (mm).
3. The water level or depth is the level of water across the dam. This is which is measured in meters (m).
4. The volume of irrigation is the volume of water released from the dam which serves as a source of water for farmers for livestock and farming. This is measured on a cubic hectometre (hm^3).
5. The volume of inflow is the quantity of water that is allowed to flow into the dam from the upstream and other surrounding river. This is measured on a cubic hectometre (hm^3).
6. The volume of evaporation is the volume of water that escapes and evaporates from the dam. This is measured in a cubic hectometre (hm^3).
7. The volume of turbine is the volume of water that is used for hydropower generation from the dam. This is measured in a cubic hectometre (hm^3).

2.3.4. Piezometric Dataset

A piezometer is a device that measures groundwater pressure (more precisely, the piezometric head) or the height to which a liquid column rises in a system that defies gravity (Dunnicliff, 1993, 1988). It measures the level of the water table manually or through an automatic level logger The piezometer measures the groundwater level in the dam. At the installation site, the piezometers determine indirectly the groundwater pressure.

Piezometric data from January 2000 to December 2022 that spanned twenty (20) years were acquired from the Bagre dam. Fifteen (15) piezometric data points were acquired and were abbreviated and labelled “PZ1”, PZ105, PZ106, PZ107, PZ108, PZ109, PZ110, PZ111, PZ2, PZ3, PZ4, PZ5, PZ6, PZ7 and PZ8. The record of piezometric information started in 1993, but not all installed piezometers had regularity in data acquisition. Normality began around year 2000, therefore selected period was based on observed data stability also to avoid data complexity.

Dry season: Some level piezometers were observed to have seepage on the southeastern flank of the embarkment. The inspection on the embarkment was completed to view the dam at high water levels and to examine evidence of seepage occurring in the right abutment.

2.3.5. Climatic Data

Climatic data for weather stations across the Bagre dam was collected as acquired from the Agence Nationale de la Météorologie (ANAM) Ouagadougou Burkina Faso. Temperature and precipitation were collected for Ouagadougou, Fada Ngourma, Po, and Bogande.

Table. 1: Description of the data set

Data Class	Data Type/Unit	Resolution	Temporal	Spatial	Source
Hydrological Variables	Evaporation(hm^3) Irrigation (hm^3) Inflow (hm^3) Outflow (hm^3) Water level (m) Turbin (hm^3)	Monthly	1993 -2022	Bagre Dam	SONABEL
Piezometric Data	PZ1 – PZ5, PZ105 – PZ111 (m)	Weekly	2002-2022	Bagre Dam	SONABEL
Climate Variables	Rainfall (mm)	Daily	2002 - 2022	Ouagadougou, Fada Ngourma, Po, Bogande	ANAM
		Monthly	1993 - 2022	Bagre Dam	SONABEL

2.4. Data Processing

2.4.1. The Application of SSA On Hydrological Variables

It is necessary and important to carry out data control and check before analysing any given data set, it ensures data accuracy and confidence. There are various factors that are targeted in data quality control, which included missing data, erroneous data, exaggerated data etc.

The data set was visualized using the Pandas' package in Python to check for missing values and erroneous data. The hydrological variables were observed to lack missing data, whereas erroneous data were recalculated to get the correct figures. Hydrological variables were analysed using the Singular Spectrum Analysis (SSA) and statistical analysis such as Pearson and partial correlation, normal correlation, and multiple linear regression modelling. The SSA is the main tool used to get information from the dam trend output. This method was adapted to examine the time series for each hydrological variable dam into different trend patterns throughout the dam. The correlation matrices were used to infer the relationship between the various hydrological variable events. Multiple regression modelling was performed to depict the control and determining factor on the stability of the dam reservoir.

SSA is a decomposition algorithm for analysing a data set from its original series as trend, period, and noise. It classifies a data set into this category, which helps to give more information about the nature of the data set. SSA enables the ability to solve problems of decomposition of time series into the sum of interpretable components extraction of periodic component and noise removal.

Steps or levels involved in SSA: The basic SSA method primarily involves two stages: decomposition and reconstruction, and both stages contain two separate steps. These two stages make up the basic SSA algorithm (Golyandina et al., 2001). Two phases make up the decomposition stage: embedding and singular value decomposition (SVD), whereas two steps make up the reconstruction stage: eigentriple grouping and diagonal average.

SSA parameters

There are basic parameters that the algorithm works with window length (L), components r for reconstruction, and grouping. The choice of parameters depends on the data we have and the analysis we must perform (Golyandina et al., 2001). The window length L and the number of components r for reconstruction are the two factors that make up Basic SSA (Briceoa et al., 2013). The values for L and r could be defined using information provided by the time series under study or through additional indices.

Window length (L)

The sole parameter in the decomposition stage is the window length L. The challenge at hand and preliminary data regarding the time series must be taken into consideration while choosing the appropriate window length (Hassani et al., 2007). Knowing that the time series may have a periodic component with an integer period, to get a better separability of these components, it is recommended to choose the window length proportional to that period. Theoretical results show that L should be large enough, but not greater than $N/2$ (Hassani et al., 2010). The window length enables the decompositions to get the desired range of trend and periodicity.

Selection of the window length (L) of the dam hydrological variables

The SSA method was used to determine and analyse hydrological variables. It was used to determine the trend of the dam across period, it shows the yearly trend by using different window lengths without grouping. From the decomposition of the timeseries the most interested decomposition output is the trend, the noise has a negligible impact on the series, and the periodicity was not considered. To obtain the required trend, a window length was selected to process the trend of various periods of years. The window length is parameterized to give the trend. The window length should not exceed the timestamps of any data set otherwise the trend result will not be feasible.

When window length (L) is set at 12 this is equal to the trend for one year (1) year; The choice of window length is based on the number of months. The table below shows the trend output when the window length is set to any of the given months. The hydrological variables data set is a monthly time series that consisting of 360 timestamps, which is equivalent to 30 years. The 360 timestamps divided by 12 months equals 30 years.

Table. 2: Window length and the trend equivalent

Window Length (WL)	Trend
12	1 year
24	2 years
60	5 years
120	10 years

Rainy and Dry Season Trends

The window length that was used for the seasonal trend shows that when the window length (WL) = 6, a one (1) year trend is generated while WL = 12, a two (2) years trend is generated during the raining and dry season. Further analysis was performed to view the behaviour of the dam during the raining and dry season, six (6) months for the dry season, the dry season consists of months in January, February, March, April, November, and December. While the remaining six (6) months were the raining season, which is the month of May, June, July, August, September, and October. The original timestamps were divided into two parts; therefore, 180 timestamps were generated for the two different seasons which were then analysed.

Implementation: The main library that was used to successfully carry out this process is a python package class of the SSA known as "pyts.decomposition.SingularSpectrumAnalysis".

2.4.2. Partial correlation matrix

Correlation heatmaps are a type of plot that visualizes the strength of relationships between numerical variables. Typically, a correlation plot has multiple numerical variables, each of which is represented by a column. The relationships between each pair of variables are shown by the rows. Heat maps of correlation can be used to identify potential links between variables and to gauge how strong these relationships are. It is simple to quickly discover correlations between variables when cells are color-coded. Finding both linear and nonlinear associations between variables is possible with the aid of correlation heatmaps. Partial correlation is meant to find the relationship between variables used to find the refined relationship between two variables with the effect of the other influencing variables being excluded and controlled.

2.4.3. Multiple Regression Analysis

Regression analysis is a method to determine the relationship between a dependent variable and one or more independent variables by analysing historical data. It enables prediction of potential outcomes and makes better judgments in the future by understanding which variables are related and how they evolved in the past. From the hydrological variable, the water level and rainfall were used as dependent variables to determine the most influence factor among five (5) on the dam.

The data set is divided into two subsets, namely, training (70%) and testing (30%). The training data set is used to train the machine learning model, whereas the testing data set is used to evaluate the model's performance and resilience. The degree of uncertainty in calculating the absolute error rates is gauged by the residual mean square errors (RMSE).

2.4.3a. The Water Balance Models.

$$\boldsymbol{Water\ Level} = C + A_1X_1 + A_2X_2 + A_3X_3 + A_4X_4 + A_5X_5 \ \ldots.\ A_NX_N$$

Where C is the intercept, A_N is the coefficient generated from the trained dataset and X_N is the dataset. X_1 = Evaporation; X_2 = Inflow; X_3 = Rainfall; X_4 = Irrigation; X_5 = Spillage

The coefficient of determination is generated from the trained output to generate the model prediction. The likelihood of the anticipated and actual values is compared using R^2 (Ishfaque et al., 2022).

2.4.4. Piezometric Data Visualization and Processing

Statistical analyses of historical piezometer measurements were performed with the open-source Python via the Jupyter Anaconda notebook. Time series decompositions, linear model, monthly mean, yearly mean, and cross-correlation analysis were completed. This was done to characterize and check the quality of the data and mostly for quality control. This process was done, and it was discovered that there are missing data and gaps, a summary of the dataset is shown in Table 2.

The piezometers, when analysed, were seen to have missing data which is shown in the table below. A benchmark of thirty percent (30%) was chosen to eliminate any column with missing data above this range. Eliminating null values was done to reduce background noise of the causal stage.

2.4.4a. Linear Interpolation

This is a gap filling method used to generate new data points within the range of the dataset available in the columns and rows where missing data points are noticed. The interpolation limit direction was done using the forward and backward for each column. Subsequently, three (3) piezometers (PZ105, PZ5 and PZ106) were dropped, out the fifteen (15) PZ and twelve (12) were linearly interpolated. The interpolation output was satisfactory for further data analysis.

Table. 3: Weekly data summary (January 2002, to December 2022).

S/N	**Piezometers**	**Missing points**	**Total points**	**Percentage of missing (%)**
1	PZ1	8	692	1.14
2	PZ105[1]	383	317	54.7
3	PZ106	2	698	0.28
4	PZ107	1	699	0.14
5	PZ108	1	699	0.14
6	PZ109	1	699	0.14
7	PZ110	1	699	0.14
8	PZ111	1	699	0.14
9	PZ2	1	699	0.14
10	PZ3	1	699	0.14
11	PZ4	5	695	0.71
12	PZ5[1]	288	412	41.14
13	PZ6[1]	700	0	100
14	PZ7	33	667	4.71
15	PZ8	44	656	6.28

2.4.4b: Data Processing

These data were summarized from weekly time-scale information into monthly scale to smooth out the noise and provide clear information about the trend. When the data set was converted into a monthly time frame, about nine percent 9% gaps were observed, linear interpolation was carried out to fill these gaps. The monthly mean was also deduced to allow suitable analysis with the corresponding dam operation data (water level and rainfall).

---

[1] PZ 105 percentage of missing data is above 30%

[1] PZ 5 percentage of missing data is above 30%

[1] PZ 6 percentage of missing data is above 30%

After data cleaning, a profiling was performed to see the head of the groundwater level of each piezometer. Statistical analysis was carried out, such as yearly mean, the Pettitt test, Mann-Kendal test, linear and polynomial regression model and correlation between rainfall and each piezometer. A table below shows the details of the monthly data set.

Table. 4: Monthly data summary (January 2002, to December 2022).

All data set	Missing points	Total points before interpolation	Percentage missing	Total points after interpolation
PZ1…. PZ8	25	227	9.9	252

2.4.4c. Linear and polynomial regression

The train using machine learning tool employs the supervised machine learning technique of linear regression to identify the linear equation that most accurately captures the relationship between the explanatory variables and the dependent variable. This is accomplished by utilizing least squares to fit a line to the data. Piezometric data were used as the dependent variable to be able to forecast the groundwater level, while the water level was the independent variable used to enable the prediction about the groundwater flow. The general linear equation model is given in equation (1).

$$y = mx + c \quad \text{-----------} (1)$$

Where y is the dependent variable; m is the slope; x is the independent variable and c is the intercept. while the linear equation used to generate the R^2 and the correlation between piezometers and the water level of the Bagre dam is given in equation (2).

$$PZ = m * water\ level + c \quad \text{-----------} (2)$$

Polynomial terms are added to linear regression to make it into a polynomial regression when the relationship between the dependent and independent variables is nonlinear. The link between dependent and independent variables is treated as an n-degree polynomial function in polynomial regression. A quadratic model is used when the degree of the polynomial is 2. The degree of the polynomial used is two (2), which makes it a quadratic model in equation (3).

$$y = a_0 + a_1x_1 + a_2{x_2}^2 + \cdots + a_n{x_n}^n \text{ ----- (3)}$$

Where y = PZ; a_0 = intercept; a_1, a_2, a_n = water level

Linear and polynomial correlation between water level and individual piezometers was executed to determine the extent of influence between these events.

2.4.4d. Evaluation of the Coefficient of Determination (R^2)

The correlation strength is analysed using the Spearman rho results which are interpreted as follows: 0 - 0.20 is negligible, 0.21- 0.40 is weak, 0.41 - 0.60 is moderate, 0.61 - 0.80 is strong and 0.81 - 1.00 is considered a very strong correlation (Prion and Haerling, 2014).

2.4.5a. Pettitt Test

The method developed by Pettitt (1979) is frequently used to identify a single change point in continuous hydrological series or climate series. The benchmark was established to determine the breaking point for each PZ; when the p-value < 0.05.

2.4.5b. Mann-Kendall Test

The nonparametric Mann-Kendall test (Mann, 1945; Kendall, 1975) is widely used to evaluate statistically significant trends in hydrological time series (Ribeiro et al., 2015). In groundwater hydrology, the test has been widely utilized to identify trends in piezometric data (Rivard et al., 2009; Panda et al., 2012; Tabari et al., 2012). This is used to calculate each PZ's trend, significance, and slope. The Mann Kendall (MK) trend test was used to analyse the trend of the chosen indices. The MK test is a popular statistical tool for spotting trends in hydroclimate studies and extreme climate indices (Larbi et al., 2018).

2.4.6: Programming Language and Libraries

The programming language that was used to perform the data analysis and statistical analysis was Python. Various Python libraries and packages were used to enable the processing of the data. The list of the libraries and package used are: datetime, pandas, matplotlib.pyplot, numPy, plotly_express, seaborn, matplotlib.gridspec, pymannkendall, pyhomogeneity, pingouin, partial_corr, sklearn.metrics, r2_score, metrics, sklearn.datasets, load_boston, sklearn.model_selection, train_test_split, sklearn.linear_model, LinearRegression, pyts.decomposition and SingularSpectrumAnalysis. The enabling coding environment used was the Jupyter notebook from Anaconda, Excel as the raw data file in csv format, and Qgis.

2.4.7. Groundwater Recharge Estimation Method

Ground water recharge in the Bagre dam was analysed using two (2) models which includes.

1. The water table fluctuation model (WTF) model
2. The water balance coupled with infiltration model.

2.4.7a. The Water Table Fluctuation Model (WTF)

Several methods can be used to estimate groundwater recharge, which can be obtained using the water table fluctuation (WTF) model, it is one of the best and most suitable for groundwater estimation. This method is the most widely used method for recharge estimating the recharge. Only unconfined aquifers can use the WTF approach, which works best with shallow-water tables that exhibit abrupt peaks and falls in water level (Healy & Cook, 2002). In contrast to other approaches where assumptions are made for most of the components, this method considers the response of groundwater level variations and specific yields, which is more scientific, realistic, and directly quantifiable. When there is unknown groundwater storage, the approach is employed (Maréchal et al., 2006). According to the WTF technique, water reaching the water table via recharge is what raises groundwater levels in unconfined aquifers. The following formula is used to compute recharge at each time step (Healy & Cook, 2002).

Based on average readings of the water level from the piezometers for each day of the observation period, the WTF analysis was performed. Calculating the yearly recharge amount R is as follows:

$$R = \frac{S_y dh}{dt} = \frac{S_y \Delta h}{dt} \text{ ---------- } (4)$$

$$R = S_y \Delta h \text{ -------------- } (5)$$

Equation (4) is simplified into equation (5), where S_y is the specific yield or drainable porosity of the unconfined aquifer, h is the height of the water table, and dt is the time. The difference between the rise's peak and the extrapolated antecedent recession curve's low point at the time of the peak is equal to Δh. The calculation assumes that all other components are zero and that the water entering the water table is stored instantly during the recharge period. The procedure should be applied within this time because this assumption is most reliable over brief periods of time, such as a few hours or days. The WTF technique is an intriguing option due to its simplicity, usability, and insensitivity to the water moving mechanism in the unsaturated zone.

During the recharge period, the equation assumes that the water arriving at the water table is stored instantaneously and that all other components are zero. This assumption is most valid for short periods of time, such as a few hours or days, and this is the time frame in which the method should be used. Because of its simplicity, ease of use, and insensitivity to the water flowing mechanism in the unsaturated zone, the choice of the WTF technique is appealing. The ratio of the volume of water drained by gravity to field capacity determines the specific yield. To determine an accurate estimate of a certain yield, a relationship between outflow and groundwater levels could be applied (Olmsted & Hely, 1962). The Thornthwaite Mather (TM) technique was used in the study (Addisie et al., 2020) to estimate discharge and water table in the same watershed. S_y values were derived from this study.

The specific yield for Burkina Faso is 8 - 12 % (Cuthbert et al., 2019). The maximum specific yield of (0.12) was used to calculate groundwater recharge in the Bagre dam. The yearly mean of each piezometer was obtained and the sum of rainfall for the year. The yearly mean of each PZ was multiplied by the specific yield (0.12) to generate an estimate of groundwater recharge. The percentage of rainfall that results in recharge was obtained by the $recharge\ x\ 100\% \ /\ maximum\ rainfall$. Where the maximum rainfall is 465.7(mm). Rainfall plots were performed to determine the impact of rainfall on the groundwater recharge.

2.4.7b. Quantification of Surface Infiltration from The Hydrological Variables Resulting To Groundwater Recharge.

The water balance consists of balancing the inflows and outflows, considering the variations in stock in the reservoir surface. In equation (6) and (7), this model was carried out to determine the rate of seepage and infiltration of surface water into the groundwater in the dam which also quantifies the percentage of recharge in equation (8) and (9) from the infiltration rate of the surface water and to analyse the percentage of rainfall in equation (10) from the surface. Two (2) scenarios of porosity were considered 5% of porosity for clayey layer and 10% of porosity for sandy. The yearly mean was generated for each hydrological variables, the unit of all the hydrological variable were maintained at hm^3, water storage equivalent to water volume was given while rainfall (mm) was converted to hm^3 by rainfall (mm) $\times 10000 \times 25500\ area\ of\ the\ dam.$

The water balance and infiltration model for the Bagre dam is given by the following relationship.

$$\boldsymbol{Water\ storage} = Rainfall + Inflow - Spillage\ (outflow) - Irrigation - Turbine - Evaporation - Infiltration$$ -------------------------- equation (6)

$$\boldsymbol{Infiltration}\ (hm^3/\text{ year}) = Rainfall + Inflow - Spillage\ (outflow) - Irrigation - Turbine - Evaporation - water\ storage$$ -------------------- equation (7)

Recharge at 5% porosity which the soil type is considered as clayey.

$$\boldsymbol{Recharge} = infiltration - infiltration \times 0.05$$ ------------ equation (8)

Recharge at 10% porosity which the soil type is considered as sandy.

$$\boldsymbol{Recharge} = infiltration - infiltration \times 0.1$$ ------------- equation (9)

The unit of recharge is given as hm^3/ year.

The percentage of recharge in rainfall was generated by,

$$\boldsymbol{Percentage}\ (5, 10)\% = Recharge \times 100\ /\ Rainfall$$ -- equation (10)

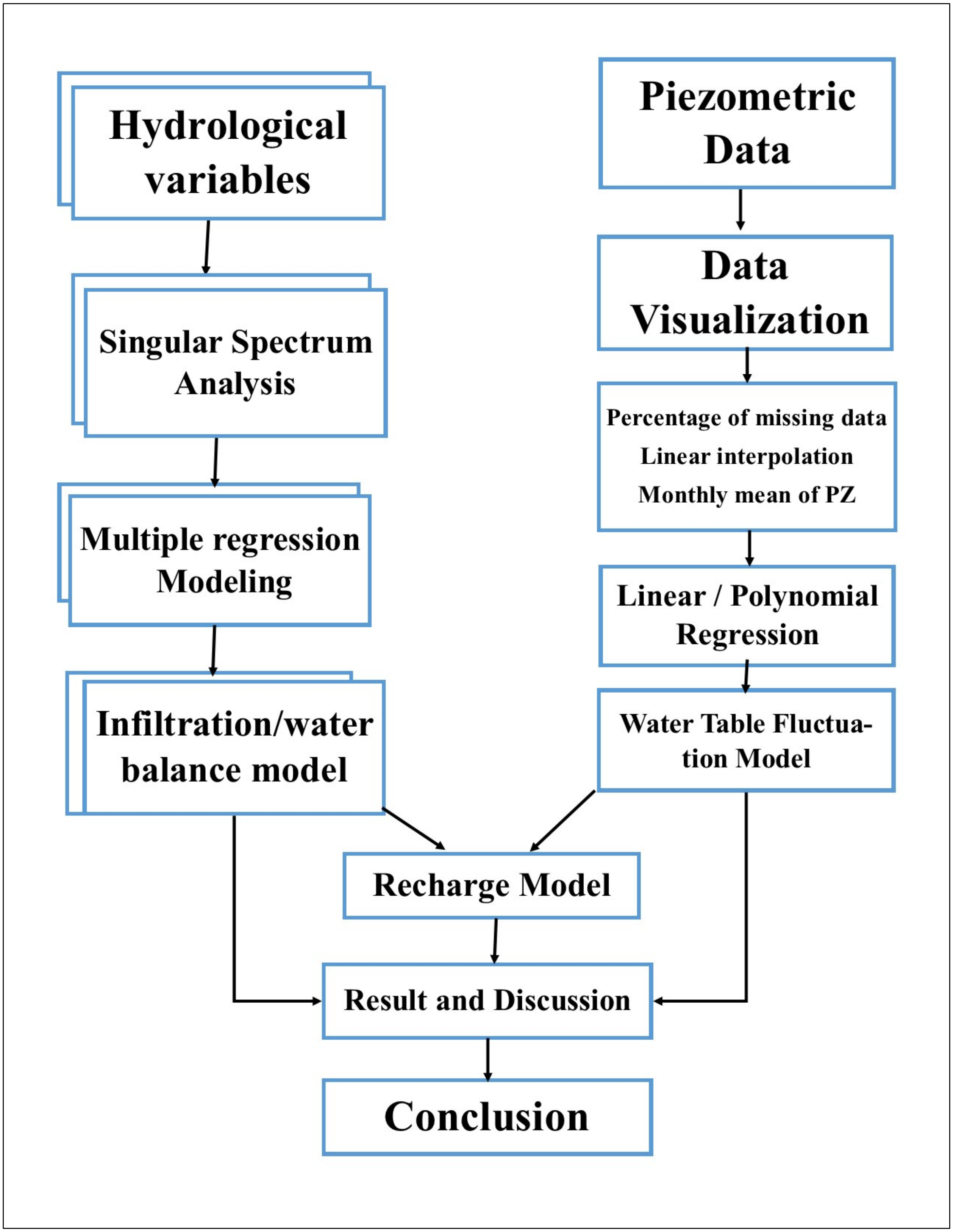


Figure 2.9. Workflow of the study

2.5. Data Interpretation

This is a method that uses different analytical approaches to review data output, thereby giving relevant information to the results. The significant information in a developed result would describe the importance of the analysis.

2.5.1. Qualitative Interpretation

This approach is the opposite of quantitative interpretation; it uses descriptive context. This interpretation method is analysed by how the output is observed, what information is the observed output inferring. The interpretation technique employed mostly in this, is the quantitative interpretation method, numerical analysis would be the expected output of all the result which would be analysed quantitatively. The importance of quantitative analysis is to determine the significance and reliability of research findings, explore, and interpret data sets. It helps identify patterns, relationships, and trends within the data, providing valuable insights into the underlying phenomena and drawing reliable conclusions.

2.5.2. Quantitative Interpretation

This method of interpretation consists of numerical analysis which also involves a correlation test between two or more variables. It involves the use of statistical modelling such as mean, median, standard deviation, etc. This research interpretation is basically based on quantitative analysis.

CHAPTER THREE: RESULTS AND DISCUSSION

3.1. Introduction

In this study, the trend behaviour of the hydrological variables in the dam are analysed to understand the historical nature of the dam operations. The information gives the state of the dam over the thirty-years period. The result also infers how groundwater fluctuates and recharges with the influx of surface water. The impact of surface water and rainfall around the dam on groundwater fluctuations and recharge has been analysed.

3.2. The Trend and Seasonality of the Hydrological Variables on the Bagre Dam

The trend of the hydrological variable in the entire time series and the seasonality which includes the raining and dry season were considered in the dam operations. The SSA carried out analysis of the hydrological variables on the dam; this method was used to analyse how the trend fluctuates over the period different window length and time lag. SSA decompose the time series, therefore the trend is the decomposed output of the time series.

The seasonal trend shows the state of the dam during the raining season and the dry season. The window length at 12, 24, 60 and 120 depicts one, two, five-, and ten-year trend over the time series while for the seasonal trend, the window length of 6 and 12 shows the trend of one and two years over the period. These varying window lengths were chosen to give different year trends. The leap-frog moving average for the raining and dry season is between one and two years. The higher the moving average of the year, the more smoothen the trend. The one- and two-year trend indicates a short time while the five- and ten-year trend portrays a decadal trend. More fluctuations are observed on the short-time trend compared to long-time trend. The 5 and 10-years window length gives low variability, the change is low compared to examining trend between 1 or 2 - years. One, two, three, five, and ten-year time lag is a repeated sequence throughout the hydrological variables to extract the trend. The higher-year period shows either a sharp increasing or decreasing trend without any variability and fluctuations, but the lower years show the variability and fluctuations of the trend. The trend over one- and two-years trend shows a vivid fluctuation of the trend during the raining and dry season. It is observed that increasing the window size which is the leapfrog decreases the variability and fluctuations in the trend. The decreasing window length shows more variability and fluctuations.

3.2.1. Rainfall Trend and Seasonality at the Dam

In 2009, it is observed in Figure 3.1 that rainfall is having a consistent decreasing trend compared to the previous years, this can be confirmed and inferred from the rainfall distribution around the province where the dam is located. At different leapfrog years, rainfall illustrates a peak and declining trend across the dam; this is due to the impact and influence of climate change. Sylla et al. (2016) found an increasing trend of rainfall in Burkina Faso over 1983–2010. The Black Volta's yearly rainfall increased noticeably between 1980 and 2010 according to the results of the MK trend test (Aziz and Obuobie, 2017).

Most activity and productivity from the dam are more evident during the raining season. This season has most of the rainfall activity more than the dry season as expected, and this has a direct effect on the water accumulation, storage, and production from the dam. The decreasing trend of rainfall infers that the reservoir level resource from rainfall would also decrease due climate change impact. The natural factors affecting the intra-seasonal variability of the rainfall regime in the Sahel were summarized in (Salack et al., 2016).

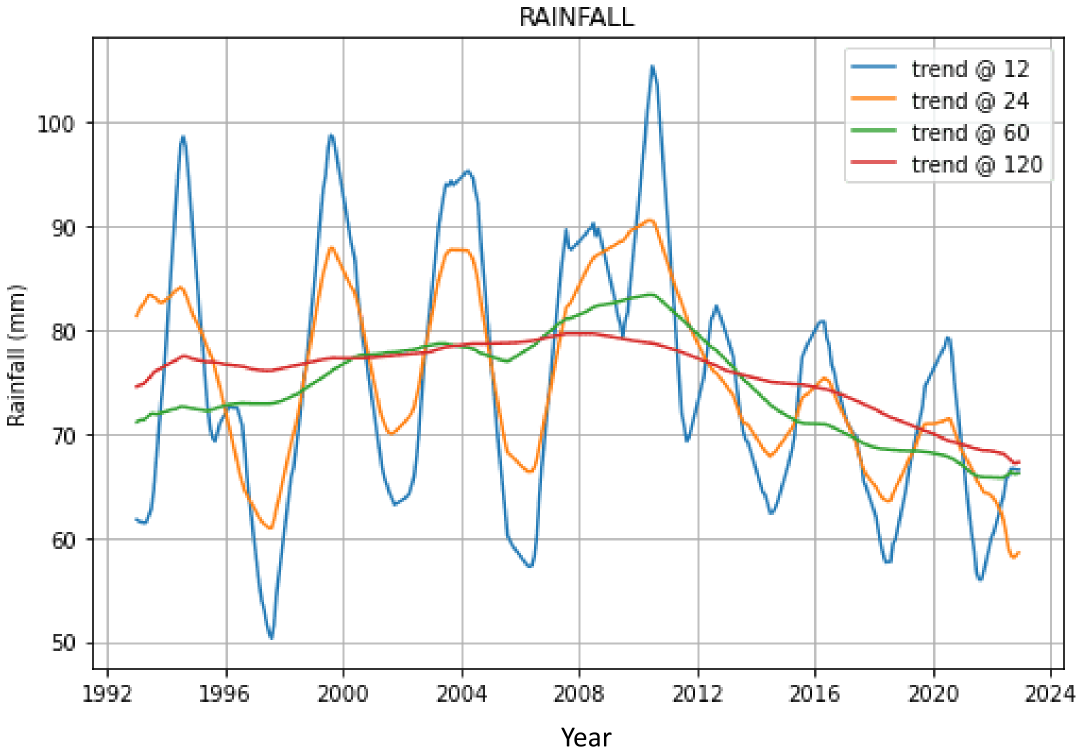


Figure 3.1. Rainfall Trend on the Bagre Dam

Figure 3.1a shows that during the raining season there is an increasing amount of water in the embarkment dam due to rainfall. The level of water storage increases during the raining season from the trend over the period. While during the dry season in Figure 3.1b the rainfall is less than 25mm, this can be the result of little rainfall events in April and June. The trend of rainfall in the dry season has a negligible annual slope and is therefore not relevant in terms of water balance (Yangouliba et al., 2022). During the raining season we have up to 200 mm of rainfall at the peak of the raining season in the raining months. The decreasing trend of rainfall began around 2010 – 2012. The long-term and short-term trend of rainfall is showing a huge decrease in rainfall from 2012 to 2022. The one- and two-years trend over the time series shows a clear scenario of the nature of rainfall in the dam.

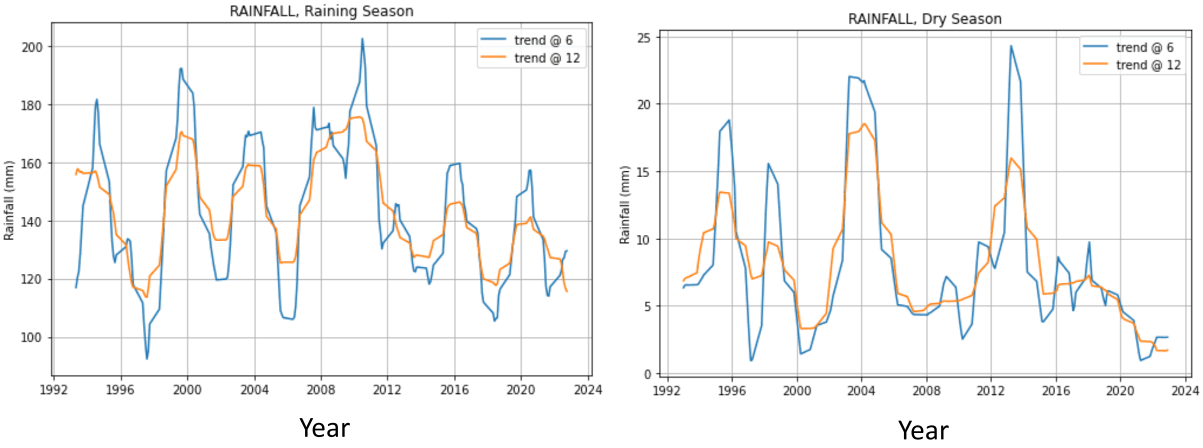


Figure 3.1. Rainfall trends (a) Raining season; (b) Dry season

3.2.1a. Impact of Climate Change on the Trend of Rainfall in the Bagre Dam

Between 1985 to 2015 there was an increasing trend for all climatic variables (Yangouliba et al., 2022). From all indications at different meteorological stations near the dam, it shows that rainfall trend is decreasing from 2012 to 2022 in Figure 3.1c. Climate change results to the decreasing trend of rainfall and increasing temperature trend in Burkina Faso. The locations of Ouagadougou, PO, Bagre Dam, Bogande and Fada Ngourma all indicate a decreasing rainfall index. These trends could be temporary but could in the future also be exacerbated by the impacts of climate change, in particular because of the projected increases in magnitude and frequency of extreme flood events.

The projected increase in climate variability as a result of climate change is expected to increase the risk of these hydroclimatic hazards in the region (Salack et al., 2015; Asare-Kyei et al., 2017). A high variability of daily events observed in the form of mixed dry/wet patterns (or hybrid rainfall regime) attributed to global and regional warming rates (Salack et al., 2016). During the last decade, global warming and climate changes have impacted the Pakistan Tarbela Dam (Ishfaque, 2022).

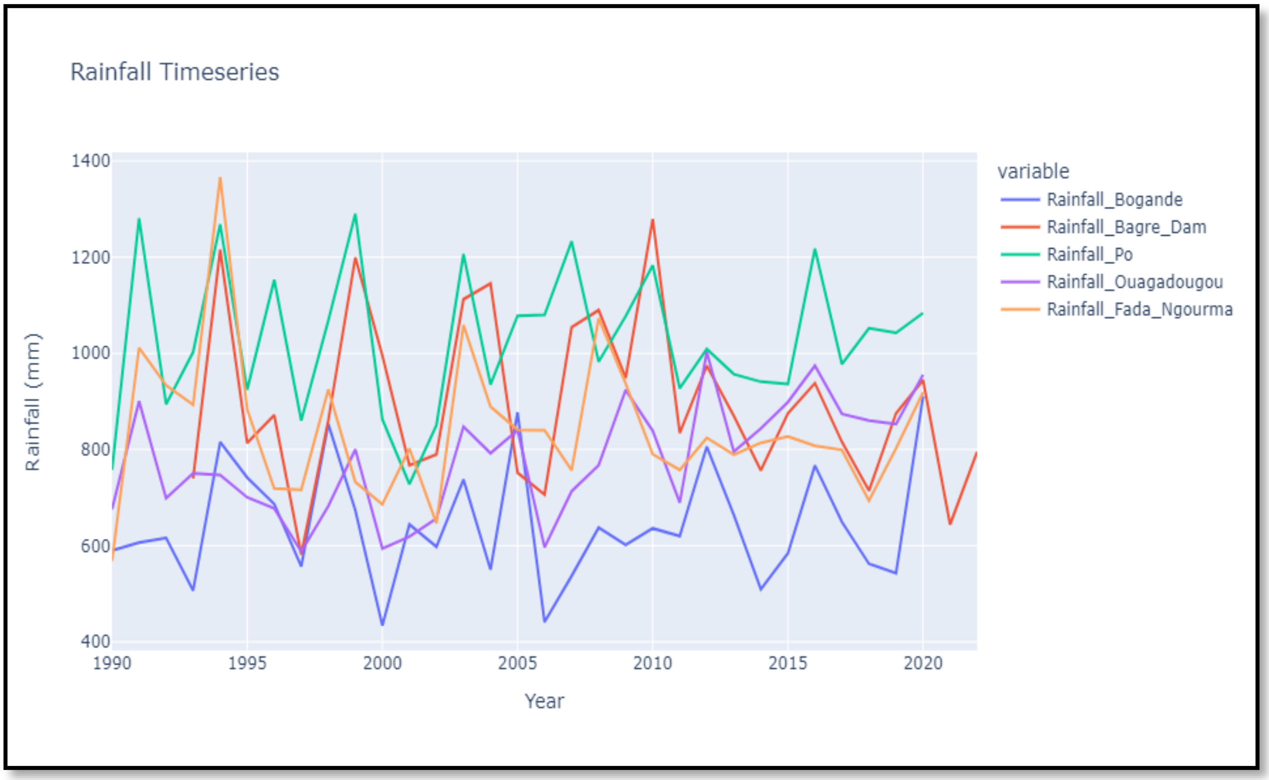


Figure 3.1c Rainfall distribution of areas surrounding the Bagre Dam.

3.2.2. Inflow Trend and Seasonality on the Dam

The volume inflow depicts the influx of water into the dam from the upstream, from the Figure 3.2 the analysis shows over the years an increasing trend of inflow. This is the main source of water in the embarkment dam for various activities to occur, such as hydropower generation, irrigation, water supply, and groundwater recharge. The raining season depicts an increasing trend of water entering the dam; this is due to the release of water from various neighbouring lakes. Figure 3.2(a) shows the highest volume of inflow recorded during the raining season which is 700 hm^3. During the dry season in Figure 3.2(b) the volume of inflow is drastically low (17hm^3) in compared to the raining season from the one- and two-year trend, the little inflow might be due to the topography of the upstream to the downstream. Compared to the time the dam operation began, inflow has been low compared to the future events, with time the quantity of water that would flow into the dam has increased. There is a strong correlation between rainfall and the inflow during the raining season, and this infers that inflow is dependent on rainfall. The correlation matrix shows a strong relationship between rainfall and the inflow of 0.75.

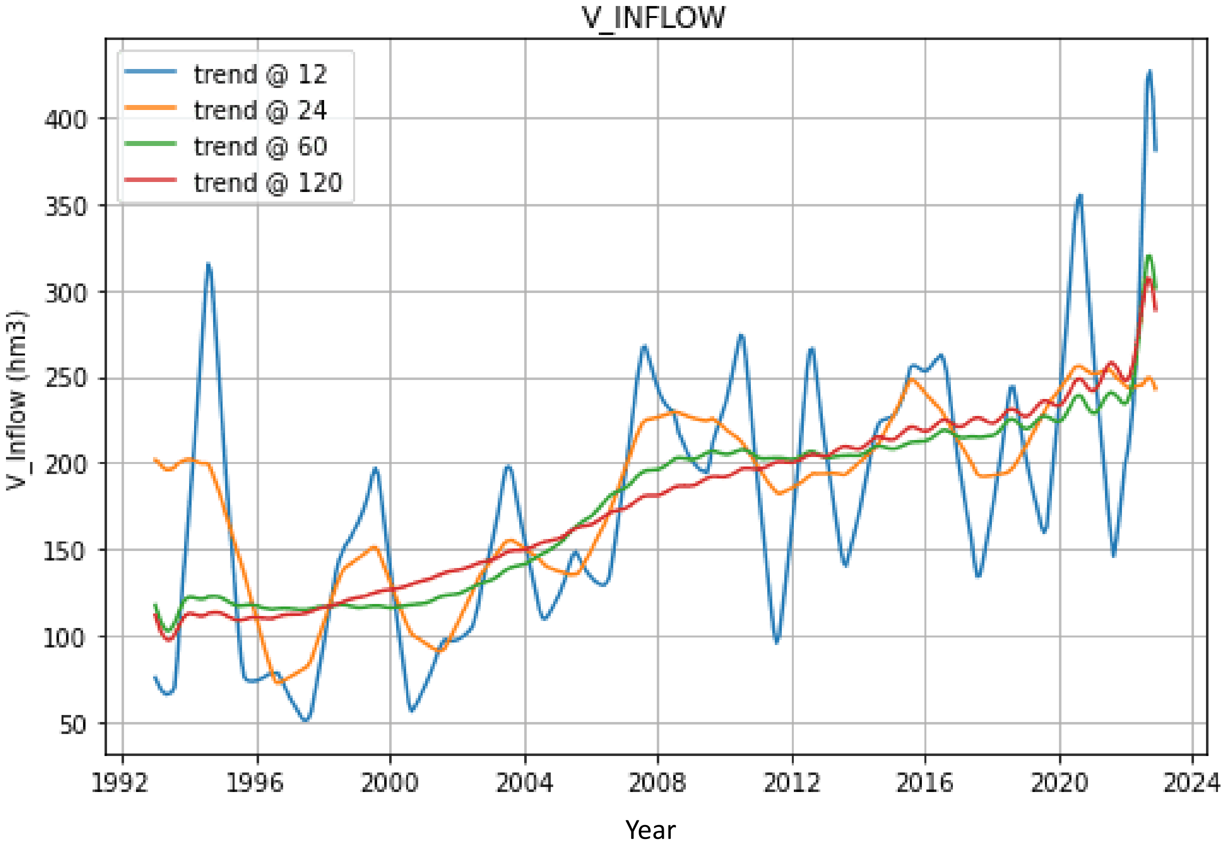


Figure 3.2. Inflow Trend on the Bagre Dam

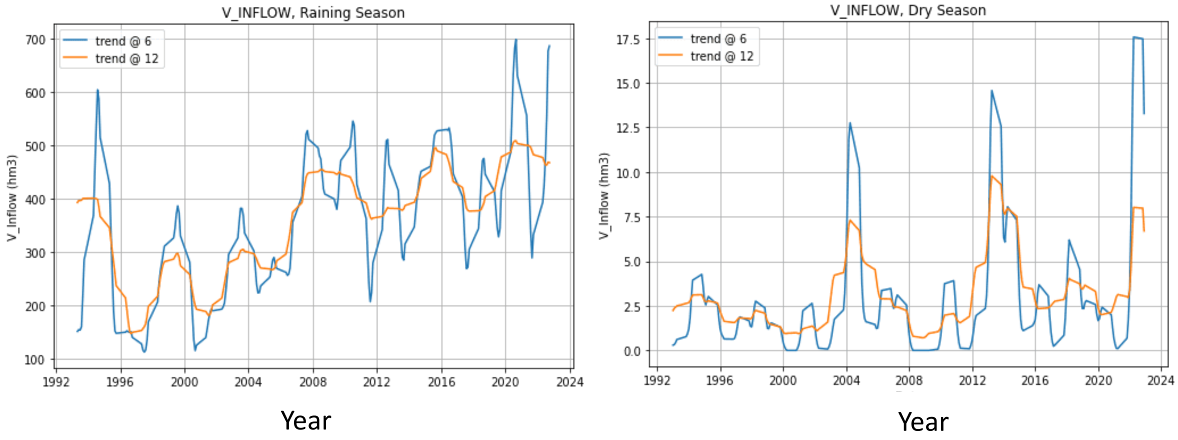


Figure 3.2. Inflow trend (a) Raining season; (b) Dry season

3.3.3. Trend And Seasonality of The Spillage in The Dam

High and consistent inflow would lead to consistent discharge of water from the dam spillway, and this is necessary to curtail the volume of water in the dam also to enhance dam stability. The volume of spillage is having an increasing trend in Figure 3.3, this is based on the influx of inflow. The threshold of the reservoir is around 235m, and when this is attained water must be released from the dam to avoid dam collapse and for dam efficiency, because consistent inflow without commensurate outflow discharge poses serious threat to dam stability over time. As the inflow increases in Figure 3.3(a) there would be a corresponding release. The seasonal impact on the outflow is felt such that during the dry season the volume of water released from the spillway is zero (Figure 3.3(b)) and this is due to the drastically decreasing amount of rainfall and inflow. The increase in outflow if not controlled may result in flooding of some villages downstream around the Bagre village**.** The increasing spillage trend is also due to the lost of the dam capacity caused by the accumulation of mud in the reservoir.

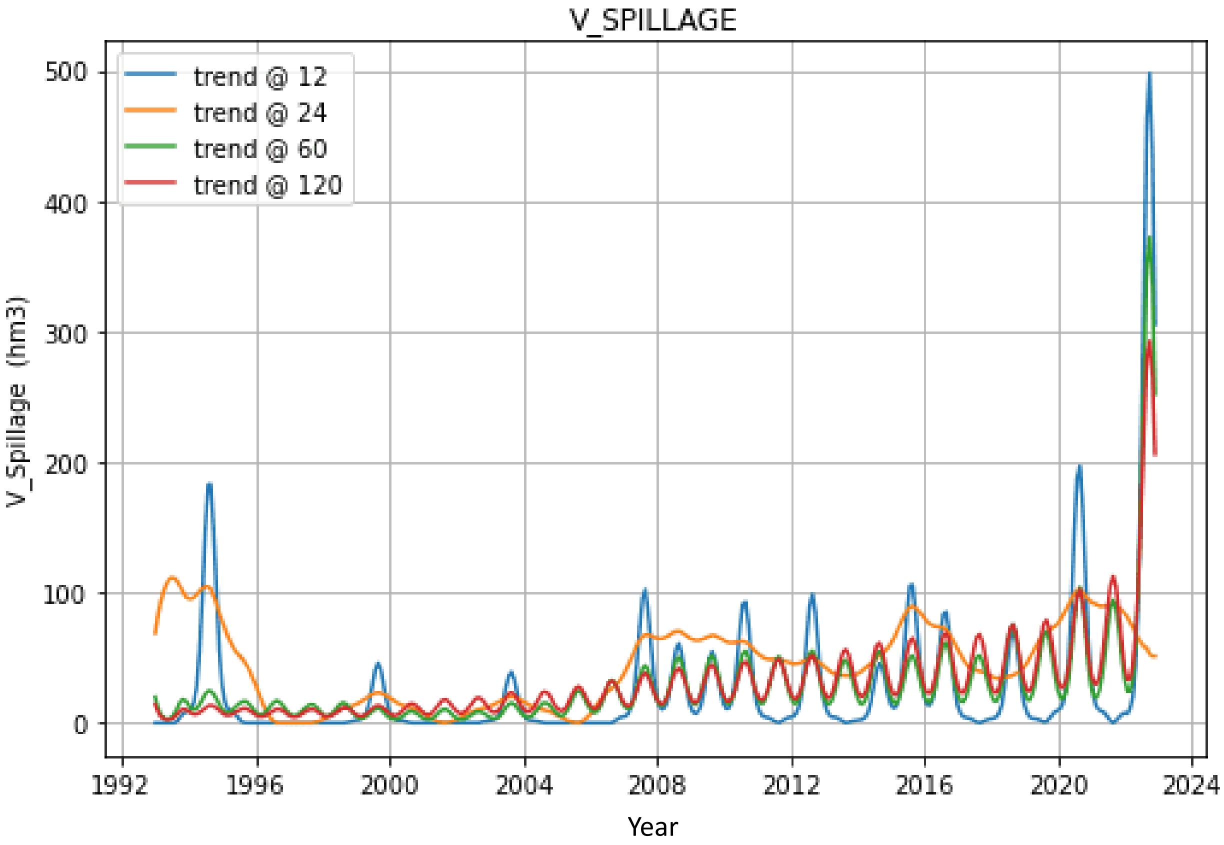


Figure 3.3. Spillage Trend on the Bagre Dam

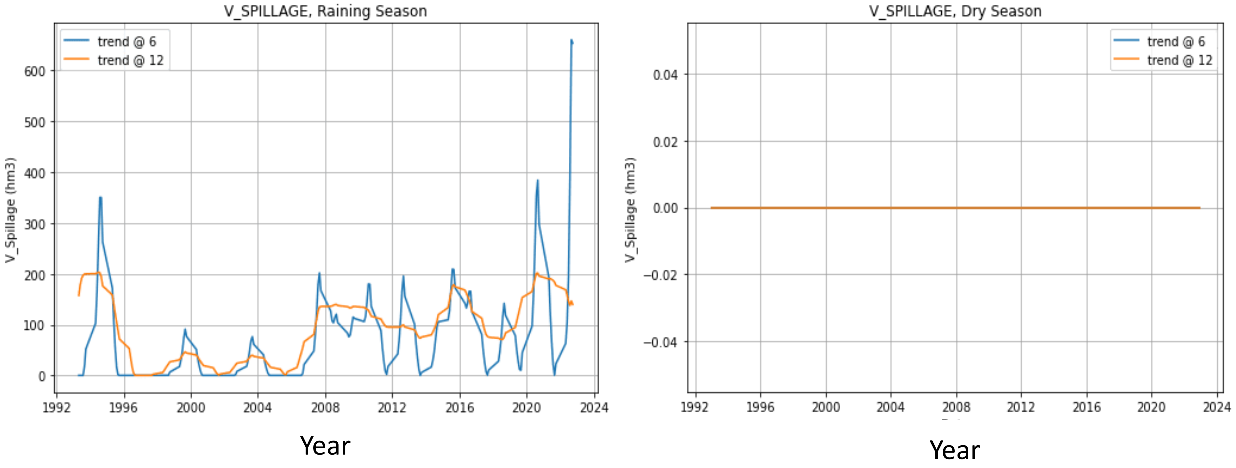


Figure 3.3. Spillage trend (a) Raining season; (b) Dry season trend

3.3.4. Irrigation Trend and Seasonality on the Dam

From the trend in Figure 3.4 at the beginning of the dam the irrigation information was seen to be low and slow with a gradual increasing trend. In Figure 3.4(a) and (b) reveals the increasing trend of irrigation which tends to be consistent and constant throughout the period. The volume of irrigation increased significantly for all months (Yangouliba et al., 2022).

A relatively consistent amount of water is released for irrigation during the dry season and raining season, this will enable farmers at the downstream to have regular supply of water for irrigation purposes from the dam throughout the period of the year. The dam downstream encourages agricultural activities during and after the raining season, resulting in an increase in agricultural production. The dam serves as water supply for agricultural purposes hence it is expected to constantly increase the amount of water for agricultural purposes when the raining season ends. The withdrawals from the downstream irrigation systems are made directly from the Bagre reservoir and cannot be used to produce hydropower. Due to increased irrigation needs in Pakistan during the summer, the Tarbela dam's water outflow rises, which immediately and dramatically lowers the reservoir's level (Ishfaque, 2022). The increasing trend of irrigation enables dam stability.

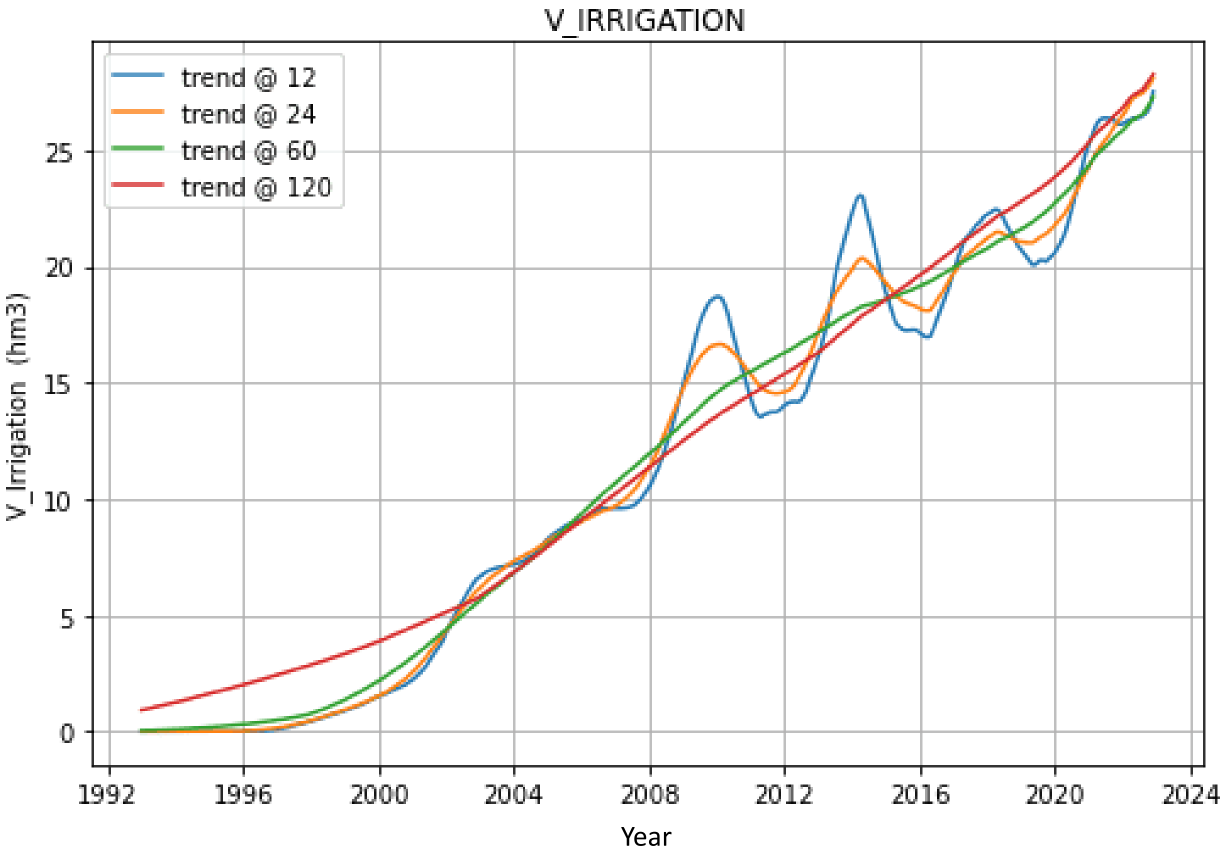


Figure 3.4. Irrigation Trend on the Bagre Dam

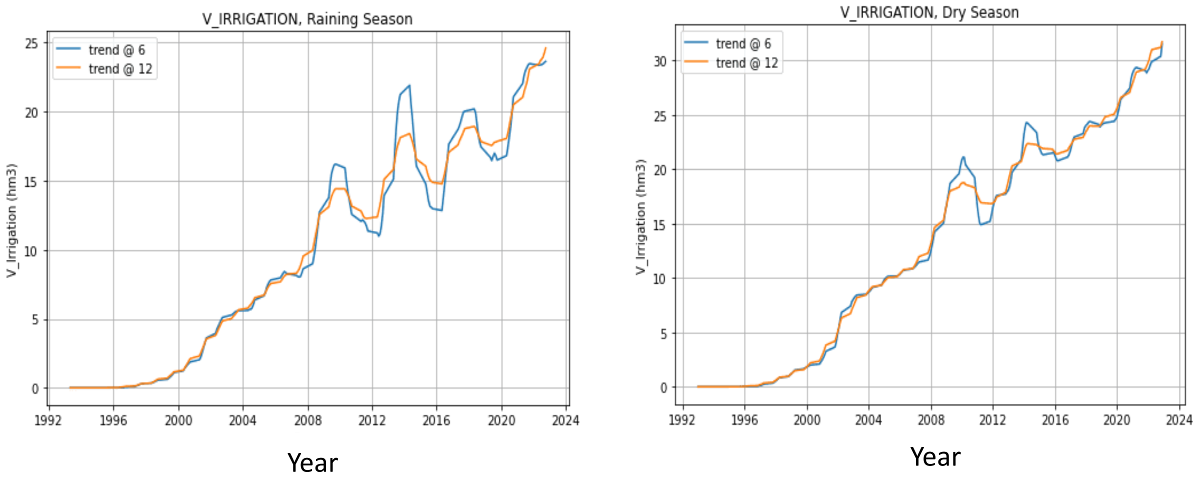


Figure 3.4. Irrigation trend (a) Raining season; (b) Dry season

3.3.5. Evaporation Trend and Seasonality in the Dam

One of the most significant hydrological cycle mechanisms is evaporation. According to Gibson et al. (2002), it is one of the main causes of climate change in the terrestrial environment, particularly in arid areas.

Figure 3.5 indicates an increasing (1992 - 2008) to decreasing (2012 -2022) trend of evaporation in the dam, this is due to climate change where the decreasing trend is temporal. In Figure 3.5(a) and (b), the volume of evaporation is higher in the dry season compared to the rainy season. The increasing trend of temperature in Burkina Faso would result to an increase in temperature, this would also depict an increasing and high rate of evaporation during the dry season, resulting to water loss which is not good for the dam and agricultural practice. (Yangouliba et al., 2022). Similarly, the increasing temperature results in an increase of evaporation of water from the dam, which also decreases the reservoir level (Ishfaque, 2022). The evaporation was also enabled by the magnitude of the area of the surface water reservoir in the catchment. The loss of water from the dam, in addition to irrigation and the spillage is evaporation.

Climate change trend of increasing temperature would lead to water level reduction in the dam hence an increasing trend of evaporation during the dry season, the increase of evaporation during the dry season is slightly high compared to the raining season, the rise in temperature would result in high evaporation. The water lost because of evaporation each year could be used to irrigate more land and serve as a source of water supply to residents; this is a result of climate change. It also affects the economic generation for agricultural activities. Evaporation losses from reservoirs are significant and should be included in all basin water balance analysis and cost-benefit analysis of reservoirs.

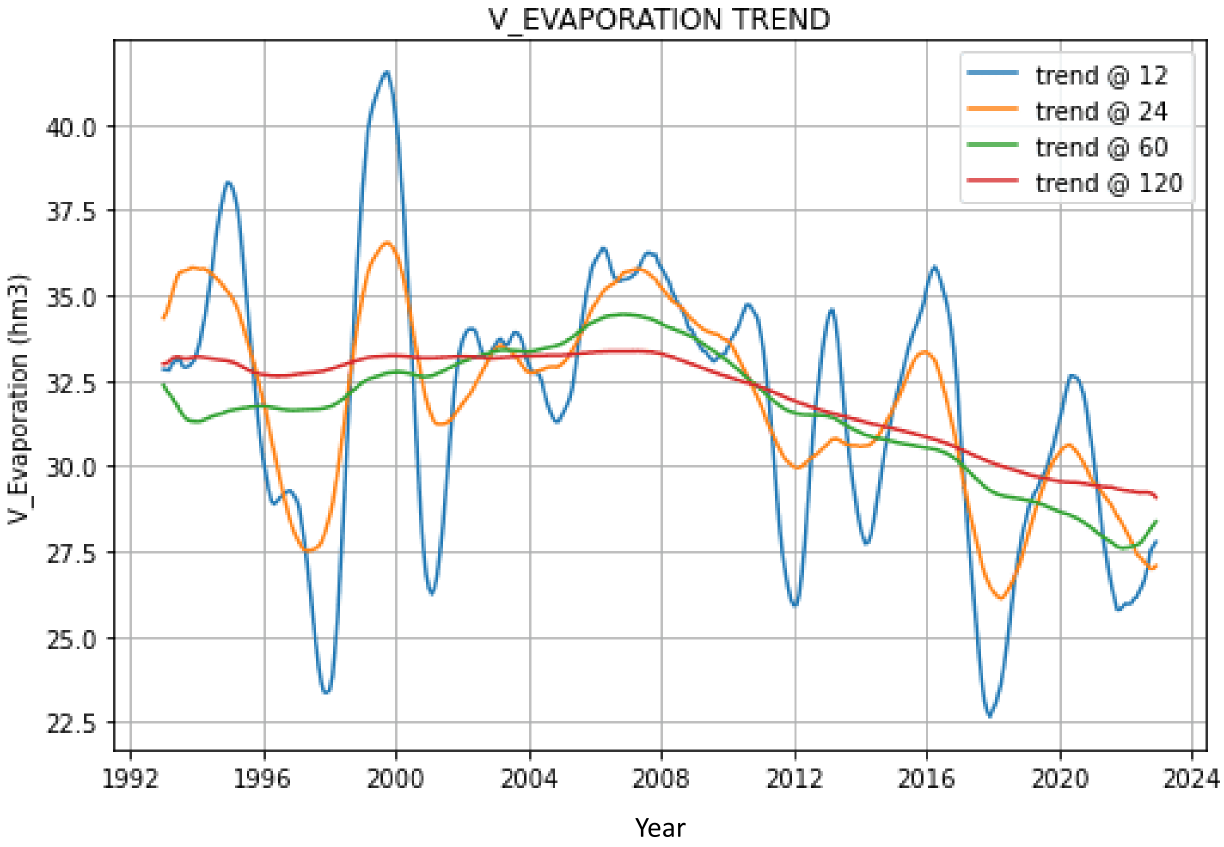


Figure 3.5. Evaporation Trend in the Bagre Dam

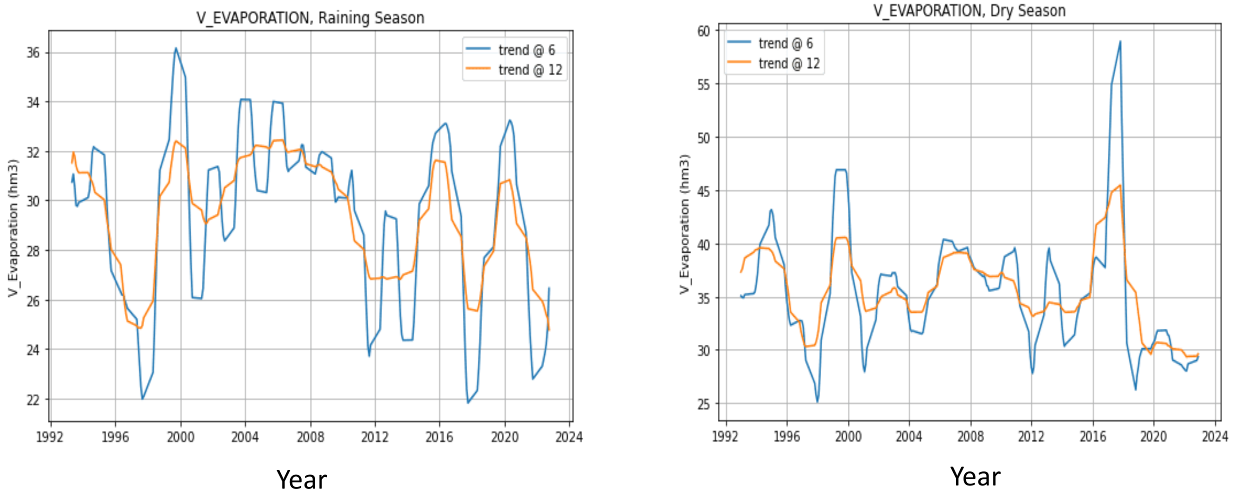


Figure 3.5. Evaporation trend (a) Raining season; (b) Dry season

3.2.6. Trend And Seasonality of Water Levels in the Dam

The reservoir water level shows an increasing trend from 2012 in Figure 3.6, inflow and rainfall contribute to the accumulation of water into the dam embarkment. Therefore, the water level tends to be stable during the raining and dry season in Figure 3.6 (a) and (b), this will be due to the zero-spillage rate and a very slight inflow into the dam during the dry season. Increasing the water level is a positive indication of the performance and its ability to generate hydropower and provide water for irrigation purposes. The water level is seen to be fluctuate even though it is relatively stable at 232m, when the water level exceeds this point spillage will take place. Fluctuations in the reservoir water levels in water storage are due to variability in precipitation, evaporation, inflow, and decreased outflow.

Seasonal variation tends not to have much effect on the water level, there is a regulated water level balance for the dam, this shows that the dam has relatively similar level at all seasons, zero spillage in the dry season which accounts for more than 70% of water released from the dam could be the controlling factor for this. From the inflow trend in Figure 3.4, the water inflow into the dam increases over the period. This causes an increase in the level of the dam reservoir, which in turn increases the stresses on the water outflow of the dam body (Ishfaque, 2022) water outflow along with the inflow. As the water inflow increases, the outflow is also increased to reduce the excess water coming into the dam and enable dam stability (Ishfaque, 2022) this shows why these two have strong correlation.

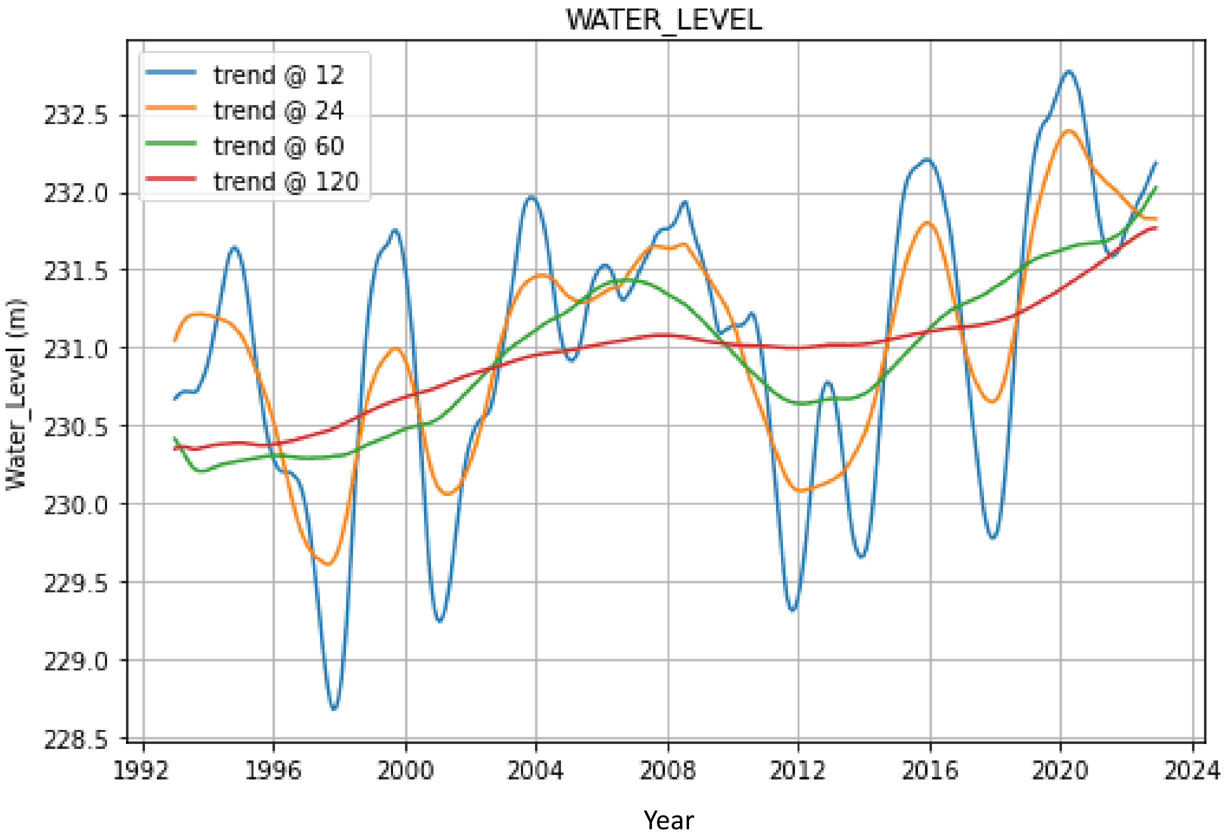


Figure 3.6. Water level Trend at the Bagre Dam

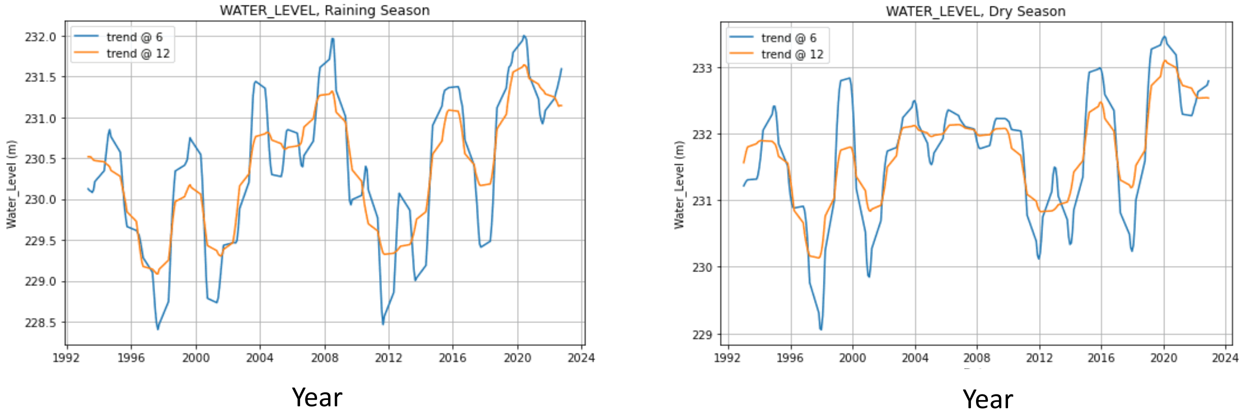


Figure 3.6. Water level trend (a) Raining season; (b) Dry season trend

The trend results portray the nature and fluctuations of the various hydrological parameters on the dam; this enables the understanding of how this contributes to the dam stability, source, and loss of water to the dam. The hydrological variables functionality of the dam is analysed through the output results. The water level is the base and funnel of all the other functionalities; hence the correlation and model between this to discover the degree of influence this variable has on it. The SSA trend shows the behaviour of these functionalities and how it moves, the past and the possible future of each parameter, their importance and function over the years. SSA gives the true trend analysis of the time series over a long period of time, as it has decomposed the time series and enabled the subtraction of the noise and periodicity in the dam time analysis. The two main sources of water into the dam, which include the inflow and rainfall, while several release and discharge from the dam are enhanced through spillage, irrigation, evaporation, and turbine. All of these are having an impact on the reservoir water level and dam stability.

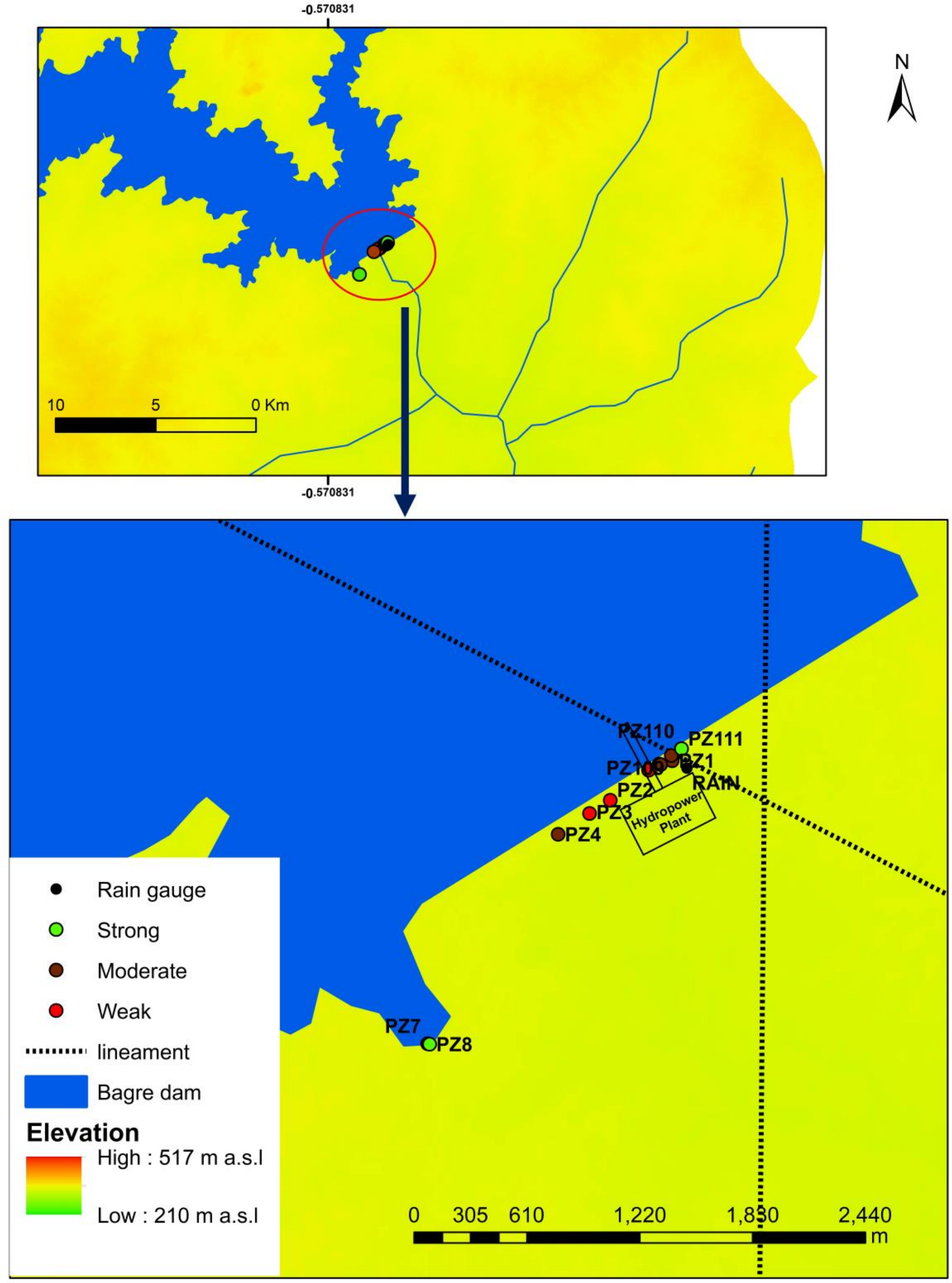
3.3.4. The Effect of Geologic Structure on the Bagre Dam Stability

The Figure 3.7 showing the piezometers and their amplitude of variation in relation to the water stock in the dam shows a green point where the variation is great. This is precisely where there would be a strong infiltration through the dike on the left bank. There is normally a symmetrical distribution of variation amplitudes low edge amplitude, medium to high mileage. The fluctuation anomaly is at point PZ106 on the left bank.

A lineament is an identifiable structure on a satellite image which is a fault and can result to a fracture. The lineament can be linear or curvilinear. In some cases, it may correspond to a geological contact between two different rocks. In Figure 3.7 it is observed that the long lineament of orientation at the southeast is passing through the zone of strong piezometric fluctuation on the left embarkment. There are no lineaments on the right embarkment.

This will have to be linked to SONABEL's preoccupation with the dam leaks, which led to the installation of the piezometers, to reduce the dam's internal pressure. Leaks are observed on the left bank only, but not on the right bank, where there are no major fractures crossing the dike.

There are lineaments on the left embarkment which results to leaks and affect dam stability, most of the fractures are observed at the left embarkment due to strong infiltration.



Source: DIVA GIS; USGS SRTM 30m; BNDT 2014 (IGB) Date: May 2023 Author: Triumph P. Orowale

Figure 3.7. Spatial distribution piezometer points and the lineaments.

3.2.7. Correlating the Hydrological Variables

Correlation graphs were used to understand which variables are related to each other and the strength of this relationship. Positive values indicate a strong relationship, while negative values indicate a weak relationship. The values in the cells represent the strength of the relationship.

Rainfall and inflow have a strong correlation of 0.79, the rest correlation is drastically low. Rainfall and inflow contribute to the volume of water we have in the reservoir. Inflow and spillage have a strong correlation of 0.78. This may imply that a corresponding high volume of inflow would result into a corresponding amount of spillage to keep the reservoir level balance. As stated above, spillage is dependent on input. R^2 is the coefficient of determination to ascertain the performance of the model.

3.2.7a. Partial Correlation

Correlation between hydroclimatic variables, the results of the partial correlation test showed that all correlation coefficients variables vary from -0.01 to 0.76 in Figure 3.8(a) and (b). The effect of each input parameter on the output is visualized in the model in Figure.3.9. The absolute magnitude of the effect of each feature is displayed in all the models used to predict the impact of hydrological variables on the reservoir storage performance. Rainfall is strongly correlated with inflow and inflow is strongly correlated to outflow generated at the Bagre dam, while other hydrological variables are low in correlation to each other. The results show that with increasing precipitation and stream flow, the risk of dam failure will significantly increase. The correlation between inflows, precipitation, water level, irrigation, evaporation, and outflows emphasize the need for robust hydrological monitoring to ensure the stability of the dam. Despite a considerable upward trend in yearly rainfall and inflow, an increase in annual mean lake water level was found to be insignificant (Yangouliba et al., 2022). This is a result of the operator's choices and the requirements for the dam's design (Jia et al., 2017).

This low correlation could be due to the datasets used and the method of hydroclimatic variables' anomalies calculation (Yangouliba et al., 2022). Depending on the dataset utilized, the method of anomalies calculation, and the ENSO phase, the amount of hydroclimatic anomalies could differ dramatically (Salas Parra 2020). The force that the water body exerts on the dam's structure rises with the reservoir's level (Ishfaque, 2022). Additionally, the reservoir level is also directly influenced by global warming and climate change (Ishfaque, 2022). Rainfall and inflow are the most important parameter that affects the dam, increasing the inflow of water in the river and influences the reservoir water level.

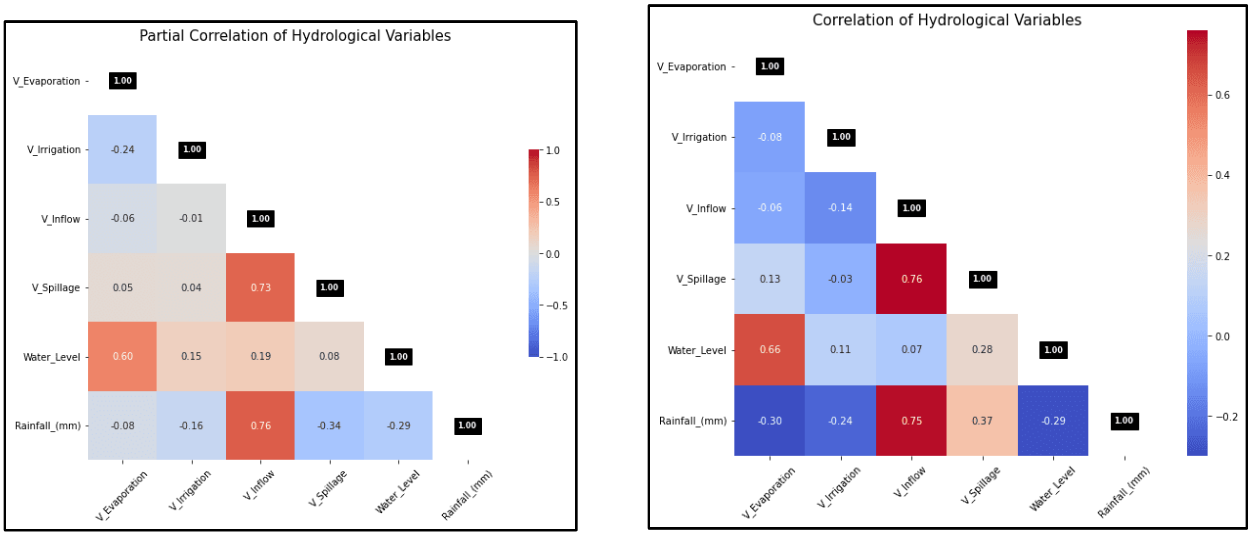


Figure 3.8(a) Partial correlation

(b) Correlation of variables

3.2.8. Water Balance Model

The water balance can be controlled by the inflow and outflow and groundwater if permeable rocks are in contact with the reservoir, the evaporation rate in an open dam is approximately 80% of the potential evapotranspiration rate. There is one decade that has a decrease in rainfall in the dam.

Summary of the Model

The generated coefficients from the trained dataset are given below.

$$\mathit{Water\ level} = 227.05 - 0.01\,X_1 + 0.13\,X_2 + 0.01\,X_3 + 0\,X_4 + 0\,X_5$$

The coefficient of determination (R^2) from the model is given as 53.75%

Mean Absolute Error = 1.41; Mean Square Error = 2.85; Root Mean Square Error = 1.68.

The prediction of the reservoir water level using the regression analysis is to see the factors and the influence of the hydrological variables on the reservoir surface water. The model was able to produce 53% model performance, which is low-moderate; this shows that the hydrological variables have weak correlation to the reservoir water level. From Figure 3.9 the performance of the model from the predicted and observed water level is well represented. This model could be used to predict the water level fluctuation of any reservoir. Rainfall model gave a R^2 of 72% (Appendix 1) this shows that rainfall is have a much more controlling influence on the activities that take place on the dam operation.

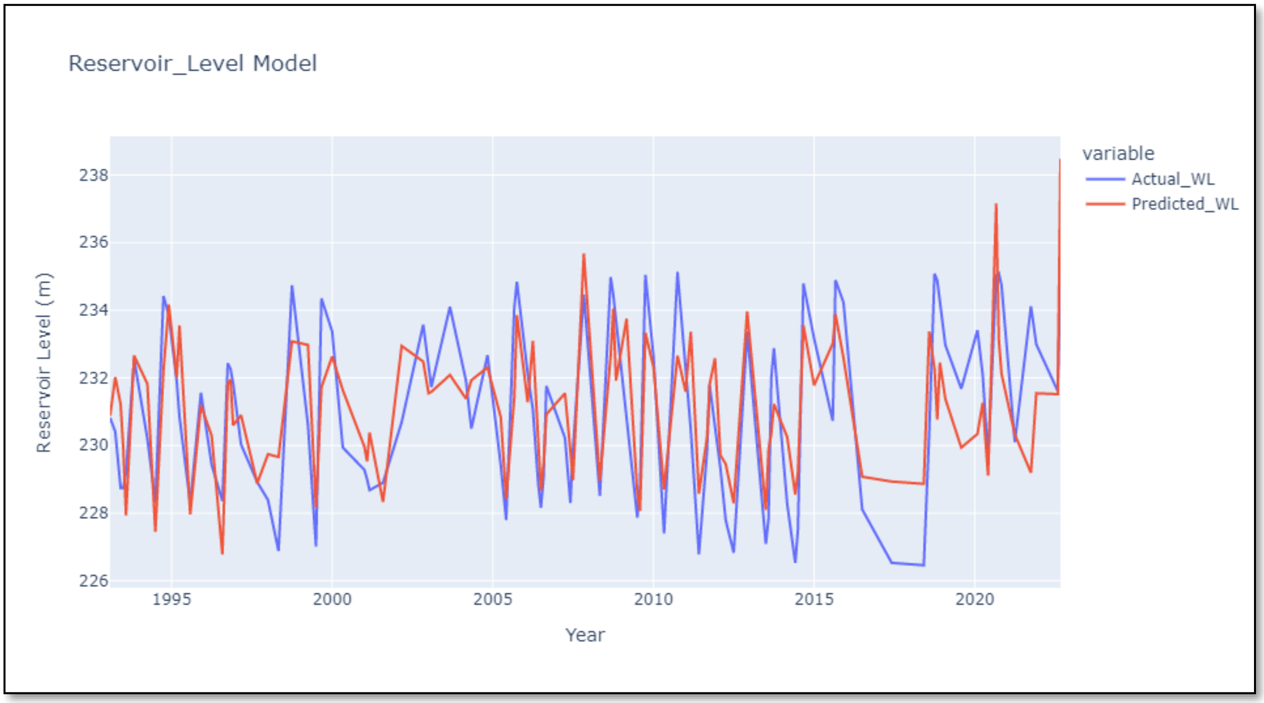


Figure 3.9. The reservoir water-level prediction model

3.3. Groundwater Recharge and Estimation in the Bagre Dam

3.3.1 Profile of the Piezometers and Water Level

The piezometer data was plotted over time to show the profile, trend, and fluctuations of groundwater at the embarkment dam. The Piezometers data are used to determine groundwater level, flow patterns, and recharge. In Figure 3.10, three (3) different profiles depth are categorized and classified from the groundwater level at the Bagre dam; the low groundwater level elevation are PZ2, PZ3, PZ106 which ranges from (208 – 215 m); the moderate groundwater level which are PZ4, PZ1, PZ107, PZ108, PZ110, PZ111, PZ109 (216 –224 m) and the high groundwater level is around PZ7 and PZ8(227 – 233m). Generally, the piezometric elevation ranges from 208 – 233 m (Appendix 2.). Between 2007 to 2010, the high elevation profiles shows that the recharge of groundwater is fast in PZ7 and PZ8. The moderate elevation of PZ4, PZ1, PZ107, PZ108, PZ110, PZ111, PZ109 shows slow and low recharge rate and the low elevation PZ2, PZ3, PZ106 profile has a very low recharge rate due to its closeness to the turbine flow channel. The groundwater level of PZ7 and PZ8 is not affected by the turbine flow channel and outflows hence the high-water level of 233m while the influence of water outflow (hydropower) affects PZ4, PZ1, PZ107, PZ108, PZ110, PZ111, PZ109 PZ2, PZ3, and PZ106 (220 - 210 m) this is the reason for low groundwater level. This is generally the rate of recharge of groundwater across the dam in all the period.

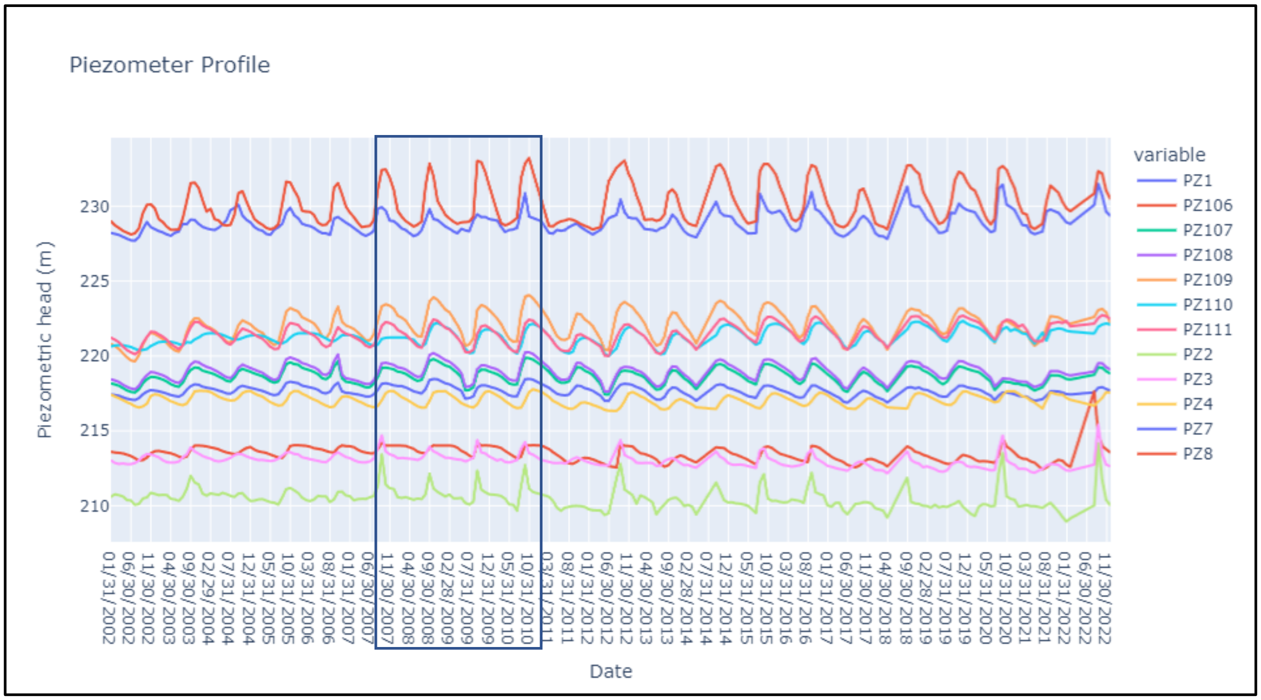


Figure 3.10. Piezometer profile at the Bagre dam.

3.3.2. Piezometer Profile and Reservoir Water Level.

In the Time-history plot, piezometer data are plotted with reservoir water level fluctuation data against time. From the observation of the profiles in Figure 3.11, no piezometric readings show measurements higher than that of the reservoir water level, rather as expected, the reservoir water level is above all the piezometric head. These elevated levels appeared to fluctuate seasonally with the reservoir level and respond almost immediately to reservoir fluctuations according to their location on the dam. The reservoir level tends to be operated most frequently in the 230 – 235 m range. The piezometer levels follow a normal distribution, and there is a similar and stable fluctuation rate of the water level. Piezometric measurements around the embarkment of the Bagre dam are lower than the reservoir level and fluctuate seasonally with the operation of the reservoir. The fact that the water level is above all the PZ infers to the surge of infiltration which result to groundwater recharge. The reservoir level and the groundwater level fluctuate together.

Fluctuations in the dam reservoir levels exert a direct influence on groundwater dynamics, demonstrating a clear correlation between water level and groundwater level. Compared to the piezometers, the reservoir has high range of water level that is close to PZ7 and PZ8 in comparison to others. While the median is significantly bigger than the mean of the reservoir elevation data, the mean and median of the piezometers are similar. This is because the reservoir is typically operated with the goal of maintaining storage (Appendix 2.).

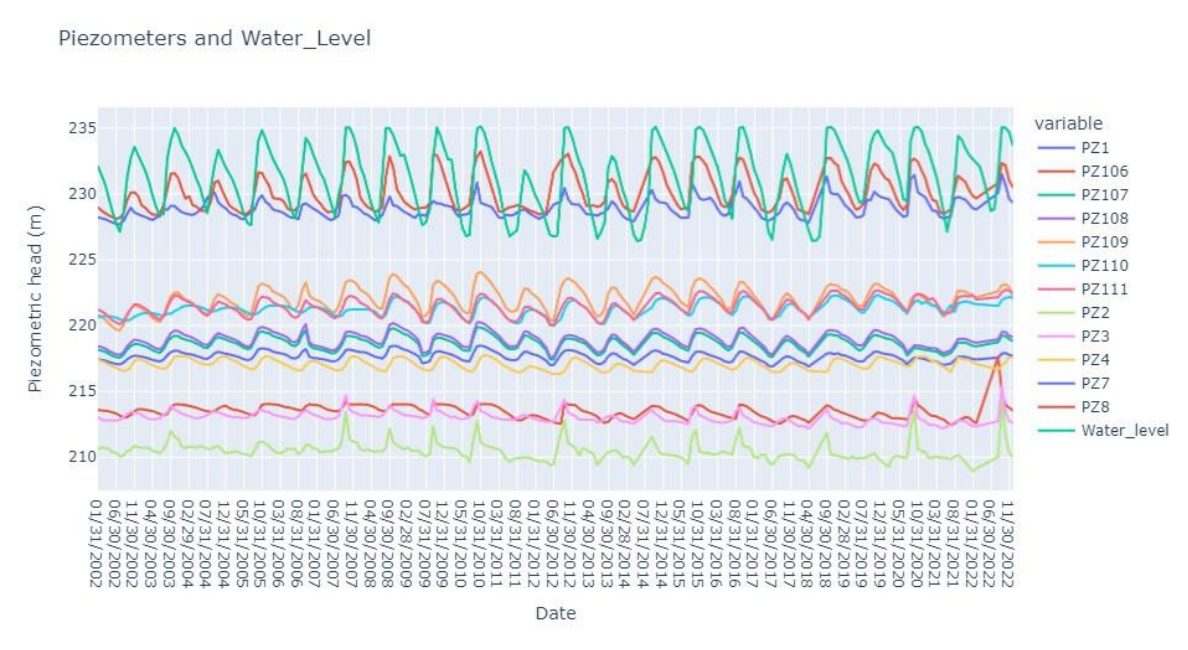


Figure 3.11. Piezometer against the water level of the reservoir with time.

3.3.3. Trend Analysis of Piezometers

The result of the Pettitt and Mann Kendall test shows an increasing and decreasing trend at most of the PZ and the breaking points in Table. 5. The breaking point signifies a change in the trend in a particular year. PZ108 and PZ107 show no breaking points, which infers constant functionality of the piezometer throughout the year. The Mann-Kendall test was used to assess if the piezometer and reservoir levels across the observation period had a monotonic (consistently growing or falling) pattern. The low groundwater level profiles portray a decreasing trend, while the moderate intermediate between increasing and no trend, the high groundwater level shows an increasing trend. Most of the piezometric trends are not statistically significant.

The yearly mean on each piezometer shows that in 2021 there is a peak and increasing trend of groundwater level at the dam in Appendix 3. Undoubtedly there is an expected rise in groundwater on the dam's reservoir slope (ÇELİK, 2018).

Table. 5: Summary of the Pettitt and Mann Kendall test for each piezometer

Pettitt Test			Mann Kendall Test		
	Breakpoint	Year	Trend	Significant	Trend slope
PZ1	Yes	2013	Decreasing	Yes	Negative
PZ106	Yes	2011	Decreasing	No	Negative
PZ107	-	-	No trend	No	Negative
PZ108	-	-	No trend	No	Negative
PZ109	Yes	2005	Increasing	Yes	Positive
PZ110	Yes	2014	Increasing	No	Positive
PZ111	Yes	2014	Increasing	No	Positive
PZ2	Yes	2011	Decreasing	No	Negative
PZ3	Yes	2011	Decreasing	Yes	Negative
PZ4	Yes	2011	No trend	No	Negative
PZ7	Yes	2014	Increasing	No	Positive
PZ8	Yes	2012	Increasing	No	Positive

3.3.4. Groundwater and Reservoir Water level Prediction

Buldan et al. (2021) and U. Cita Sari et al. (2017) stated that there is a strong correlation between the pressure of the pore water (groundwater) and the elevation of the reservoir water level. The rise in the reservoir water level will cause an increase in pore water pressure in Figure 3.12- 3.14.

Variations in the rate of increase in the reservoir water level affect the time required for the pore water pressure to stabilize. The higher the rate of increase in the water level in the reservoir, the faster the pore water pressure becomes stable (Su et al., 2021).

To find the correlation between pore water pressure and reservoir water level, linear and polynomial regression analyses were performed on each piezometer data series, which are shown in Figure 3.12 – 3.14. The R^2 values and correlation obtained from the regression analysis are shown in Table 6. The individual piezometer was correlated with the intention of predicting the influence of the reservoir water level on the groundwater level. The predicted groundwater level is classified into three categories: first, the strong reaction to reservoir water level in Figure 3.12. Secondly, the moderate reaction to reservoir water level in Figure 3.13 and finally the weak reaction to reservoir water level in Figure 3.13. Strong correlation to the water level is observed at; PZ111, PZ8 and 109 while moderate to low are PZ1, PZ107, PZ108, PZ110, PZ4, and PZ7; the weak is PZ3, PZ2, and PZ106.

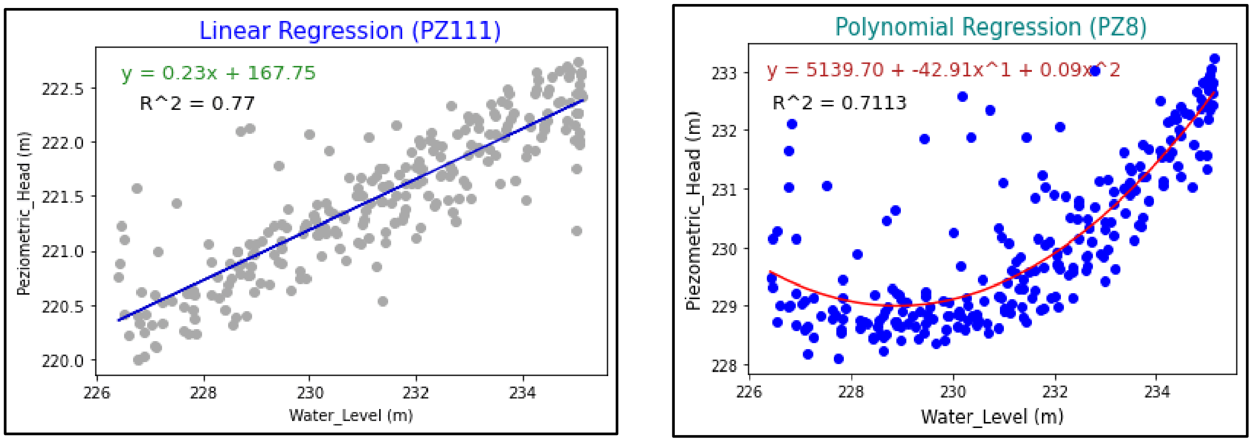
The corelation shows the effect and influence of the reservoir water level on the piezometers, this infers the position and profile of piezometers to the water level. The strong to moderate correlation confirms the groundwater elevation profiles in Figure 3.10. The high piezometric levels are located where reservoir levels are high, they are located where the topography of the dam supports high level of surface water while the low groundwater level are located where the reservoir level is always low.

Figure 3.15 shows the position of each piezometer at the embarkment of the dam. The pressure from the reservoir has an impact on the groundwater and, where there is a high-water level, the piezometric head would also be high. The result shows that predicted groundwater level increases with increasing water level. Figure 3.14 shows the spatial distribution of each piezometric location and the correlation, this is to corroborate the results of the predicted analysis.

When pathogenic organisms can go from the surface to groundwater due to its proximity to surface water and the nature of the aquifer, this condition is known as groundwater under direct influence (GWUDI) of surface water. Surface water - groundwater interactions characterized by poor connectivity will result to low aquifer productivity while good connectivity results in moderate - high productivity aquifers. The interactions between surface water and groundwater, as well as storage releases, can be affected by reservoirs, as is well documented (Francis et al., 2010; Murgulet et al., 2016).

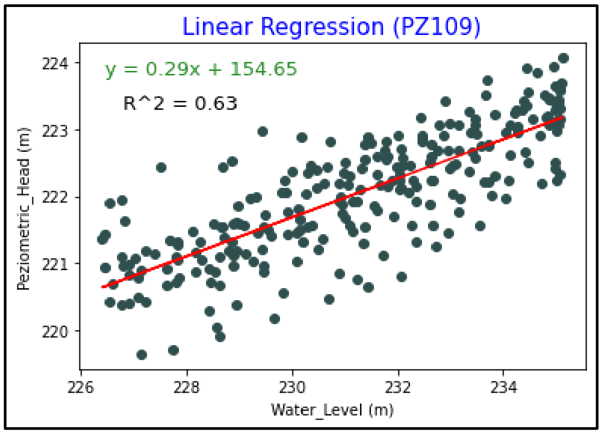
The distance of each PZ from the turbine flow channel on the embarkment dam is a contributing factor to the reaction of the groundwater to the dam water level. In Figure 3.15, PZ4, PZ2, PZ3, PZ7, PZ8 are located at the right embarkment to the dam and PZ106, PZ107, PZ108, PZ109, PZ111, PZ1 PZ110 are located at the left embarkment. The proximity of PZ106, PZ2 and PZ3 to the turbine flow channel has led to the low reaction with the reservoir water level. While piezometers at the extreme end of the dam far from the turbine flow channel shows strong to moderate interaction with the reservoir water level. The volume of water at the turbine channel often supplied to the hydropower plant hence the low recharge to the groundwater. The irrigation release from the dam is has a negligible contribution to the recharge of groundwater around the embarkment dam due to the concrete formation of the channel without a leakage point. Man made constructions and structures will affect the rate of shallow groundwater level recharge.

Also, the low influence of the water level on this PZ (3, 2, 106), is due to time response caused by low permeability of the subsurface layer. The strong to weak correlation between the reservoir water level and piezometer fluctuation is dependent on factors like topography, soil type etc.

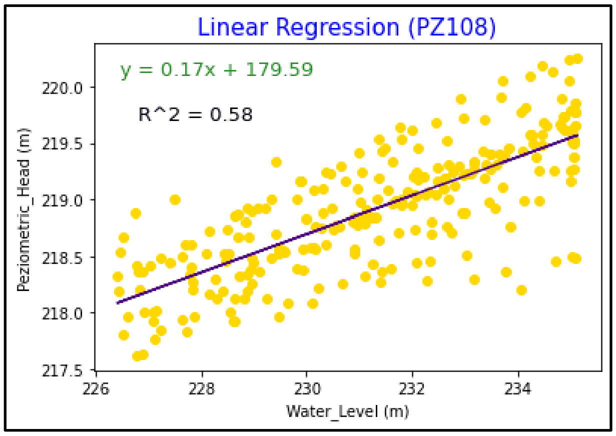


(a) (b)

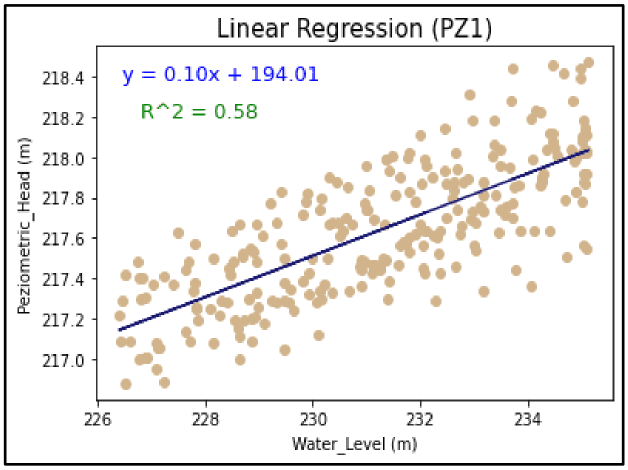
Figure 3.12(a-b) Strong reaction to reservoir water level.


Linear Regression (PZ109)
y = 0.29x + 154.65
R^2 = 0.63
Peziometric_Head (m)
224
223
222
221
220
226
228
230
232
234
Water_Level (m)

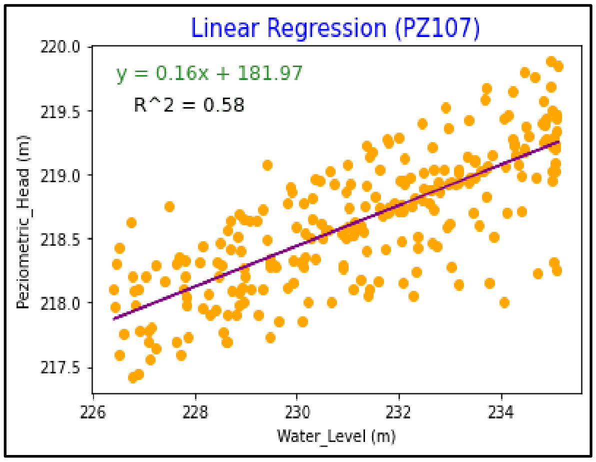
(c)


Linear Regression (PZ108)
y = 0.17x + 179.59
R^2 = 0.58
Peziometric_Head (m)
220.0
219.5
219.0
218.5
218.0
217.5
226
228
230
232
234
Water_Level (m)

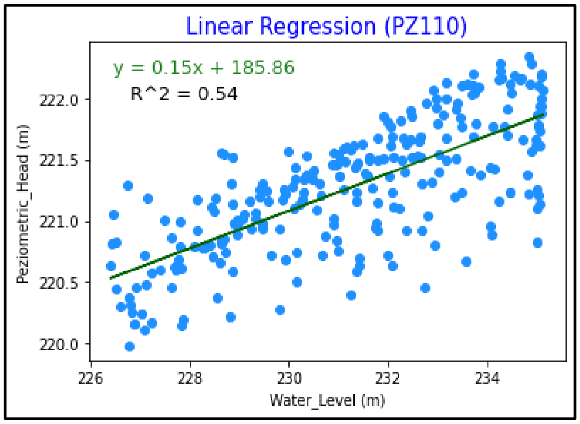
(d)


Linear Regression (PZ1)
y = 0.10x + 194.01
R^2 = 0.58
Peziometric_Head (m)
218.4
218.2
218.0
217.8
217.6
217.4
217.2
217.0
226
228
230
232
234
Water_Level (m)

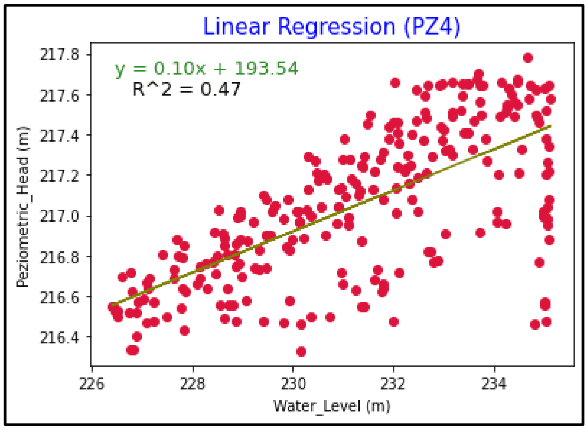
(e)


Linear Regression (PZ107)
y = 0.16x + 181.97
R^2 = 0.58
Peziometric_Head (m)
220.0
219.5
219.0
218.5
218.0
217.5
226
228
230
232
234
Water_Level (m)

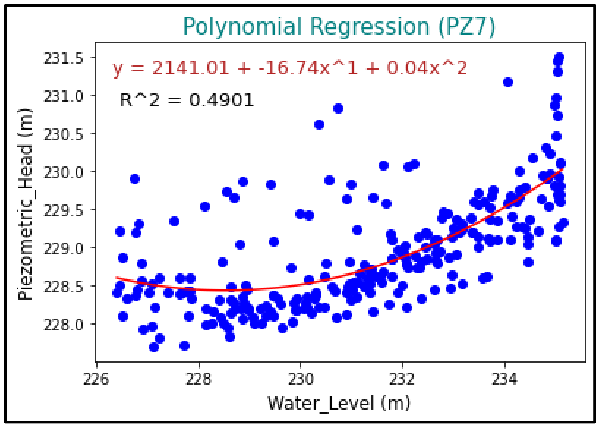
(f)


Linear Regression (PZ110)
y = 0.15x + 185.86
R^2 = 0.54
Peziometric_Head (m)
222.0
221.5
221.0
220.5
220.0
226
228
230
232
234
Water_Level (m)

(g)

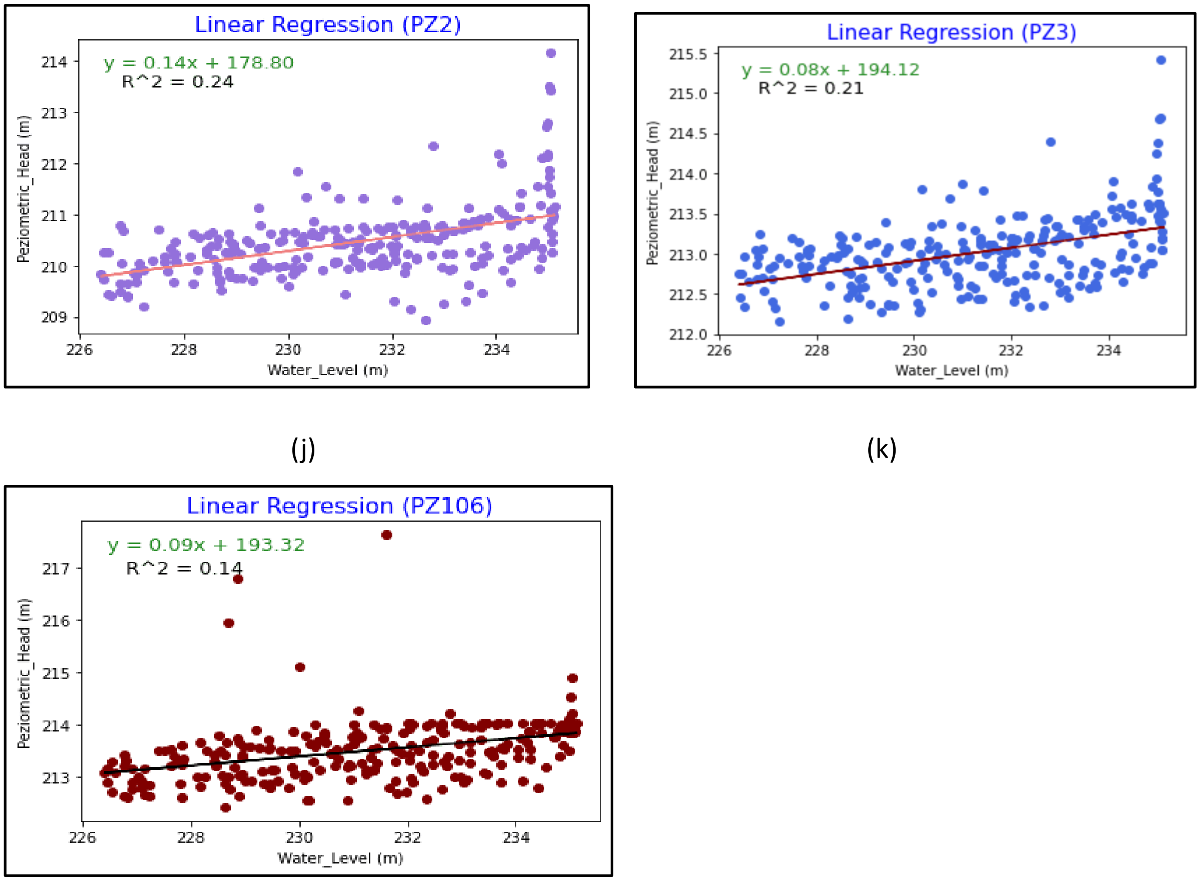

Linear Regression (PZ4)
y = 0.10x + 193.54
R^2 = 0.47
Peziometric_Head (m)
217.8
217.6
217.4
217.2
217.0
216.8
216.6
216.4
226
228
230
232
234
Water_Level (m)

(h)



(i)

Figure 3.13(c-i) Moderate reaction to reservoir water level.

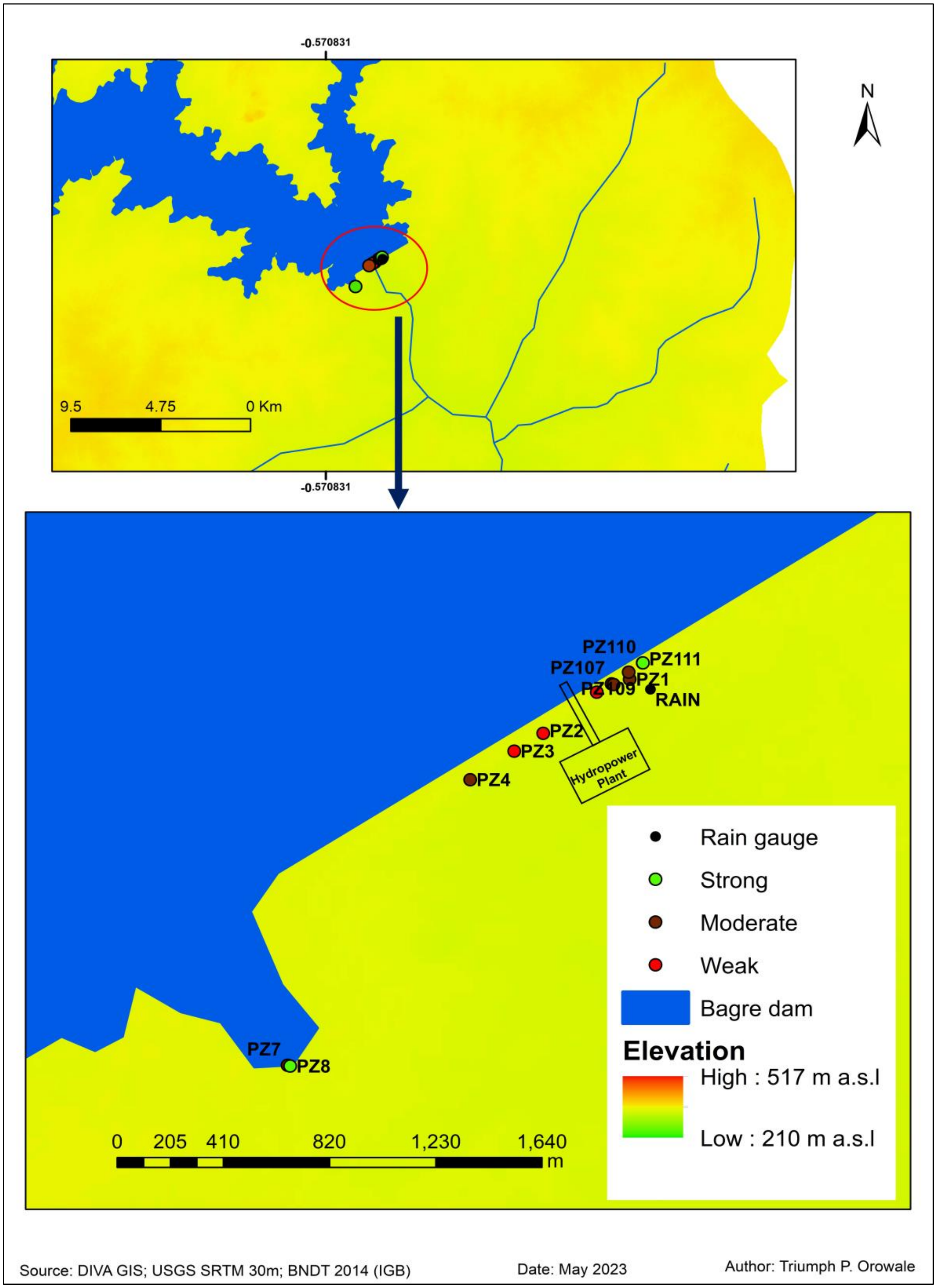


(j)

(k)

(l)

Figure 3.14(j-l) Low reaction to reservoir water level.



Source: DIVA GIS; USGS SRTM 30m; BNDT 2014 (IGB)

Date: May 2023

Author: Triumph P. Orowale

Figure 3.15. Spatial distribution correlation of each piezometer points

Table. 6: Summarized table showing the correlation of R^2 and Recharge% due to rainfall

Piezometers	Elevation	R^2	Correlation	Location on the embarkment	% of recharge due to rainfall (WTF)
PZ111	227.68	0.77	Strong	LE	70
PZ109	227.65	0.63	Moderate	LE	114
PZ108	227.72	0.58	Moderate	LE	68
PZ107	227.85	0.58	Moderate	LE	63
PZ1	218.47	0.58	Moderate	LE	41
PZ110	227.69	0.54	Moderate	LE	61
PZ106	227.91	0.14	Weak	LE	134
PZ8	237.16	0.71	Strong	RE	132
PZ7	237.18	0.49	Moderate	RE	98
PZ4	217.98	0.47	Moderate	RE	37
PZ2	217.75	0.24	Weak	RE	135
PZ3	217.91	0.21	Weak	RE	84

---

[1] RE = Right Embarkment

[2] LE = Left Embarkment

3.3.5. Groundwater Recharge Quantification from the Water Table Fluctuation (WTF)

The groundwater recharge level across the dam subsurface is stable in Figure 3.16, this is due to the constant availability of the reservoir water level, most of the groundwater level around the Bagre dam is determined and influenced by the reservoir water level. The WTF model groundwater recharge ranges between 25 to 27% within the subsurface. In Table 6, the percentage of recharge due to rainfall is between 41 – 135% of rainfall. PZ8, PZ109, PZ106, PZ7, PZ3, PZ2 shows high percentage of infiltration from rainfall, this shows that the pore space in this groundwater points responds quickly to rainfall infiltration, thus resulting to recharge. While low infiltration from rainfall is seen on PZ1, PZ111, PZ110, PZ4, PZ108 which has a slow response of recharge due to rainfall infiltration.

The hydrologic action in which surface water moves downward to the subsurface which results in accumulation of water and increase in the aquifer is considered as groundwater recharge. Generally, it can be said that the dams contribute to raising the level of groundwater resources; there is an undeniable expected groundwater rise in the dam reservoir slope. Although the main effect of dams is to increase the groundwater substantially especially in the vicinity of the dams. The changes in groundwater level also depend on other factors, as well as climatic changes, the period of precipitation and its changes, the topographical structure of the region, and especially the human factor, namely the extraction of the agricultural irrigation from the groundwater resources (Celik, 2018).

When it comes to water table (unconfined) aquifers, areas located at higher altitudes and have deeper water tables often make up the areas of recharge, while those located at topographic lows and have shallower water tables make up the areas of outflow in Figure 3.16. Water table fluctuation characterizes groundwater recharge through seepage infiltration, and this model gives the infiltration rate from the unsaturated zone to the zone of saturation. It is a complicated procedure for the groundwater table of an unconfined aquifer to change because of rainfall. It involves aquifer flow across unsaturated areas. It involves flow through unsaturated regions of the aquifer. The rate of infiltration depends upon soil moisture level present in the soil, type and density of cover and type of land use. The rate of seepage results in the varying low and high groundwater level in the Bagre dam.

The increasing infiltration rate tends to affect the dam safety, at different case it can be natural infiltration or infiltration through the dam. The increasing seepage results to increasing pressure in the subsurface and base of the dam which lead to instability. It can result to subsurface erosion which can affect the dam and result to flooding. Dam rehabilitation such as grouting the foundation, using impermeable materials, monitoring seepage rates and regular inspection would enable dam stability and reduce seepage and infiltration rate.

3.3.5a. Examining the Role of Rainfall in Groundwater Recharge

From the estimation of groundwater recharge across the dam, the recharge is stable and shows little influence on the recharge of the water table by rainfall since the level of reservoir water level is the main source of groundwater at the Bagre dam in Figure 12 and 13. Groundwater points from far from the dam might be said to have rainfall contribution to recharge. The effect of rainfall on the dam is minimal compared to the reservoir water level, it slightly has effect on groundwater recharge. In the downstream areas, flow is typically characterized by smaller, shallower nested groundwater circulations cells more connected with the surface drainage network (Goderniaux et al., 2013), whereby connecting to streams have strong control over groundwater recharge and discharge.

Geris, (2022) discovered that Gaborone Reservoir maintained a high-water table in urban areas located immediately downstream, which likely increased groundwater contamination. This helped extend conditions for groundwater recharging. Groundwater resources replenishment at the Bagre dam is not affected by dry seasons and drought because of the consistent availability of water from the reservoir. Groundwater also appeared to be recharged majorly by reservoir surface water level. The aquifer is grouped into high and moderate and low productivity aquifer type responses, the water quantity dynamics in the high are more pronounced. Recharge due to reservoir would follow the reservoir trend while groundwater points far from the reservoir would be affected by the increasing or decreasing trend of infiltration due to rainfall.

The availability of water resources around the world could vary due to climate change, which would have a significant impact on human society and daily living. Intensifying or altering the frequency of extreme hydrological events, such as floods and droughts, due to climate change, would place more strain on available water supplies in the future. Several studies have recently focused on the potential for reservoir operation as a climate adaptation strategy by expanding the storage capacity and quantity of reservoirs (Saritha, et al., 2020).

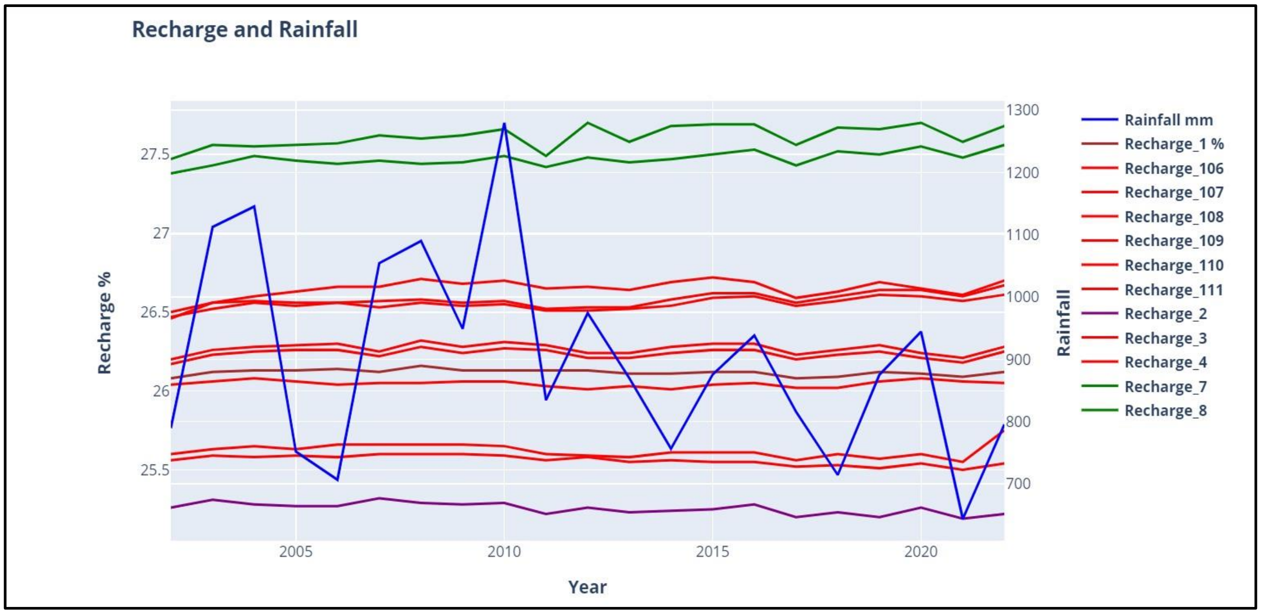


Figure 3.16. Groundwater Recharge Profile in the Subsurface

3.3.6. Surface Water Impact on Groundwater Recharge below Bagre Dam reservoir

The results of surface water infiltration and recharge are observed in Table 7, this output shows the analysis of the surface water consisting of the hydrological variables contribution to groundwater recharge over thirty (30) years. The mean, maximum, and minimum of each output from the model is shown in Table 7.

3.3.6a. The Infiltration Rate

The rate of infiltration resulting to recharge ranges from 629.3 to 2481.7 hm^3/year which is equivalent to 1483.08 to 3262.73 hm^3/year of rainfall mean (2291.48 hm^3/year) across the embarkment subsurface.

Generally, the infiltration across the dam is affected by the volume of rainfall experienced in a year. Low rainfall volume in 2021 influences a low rate of infiltration over the year. The highest value of rainfall is experienced in 2010 by the yearly sum analysis, this quantity has effect recharge due to rainfall on the infiltration rate and groundwater across the dam.

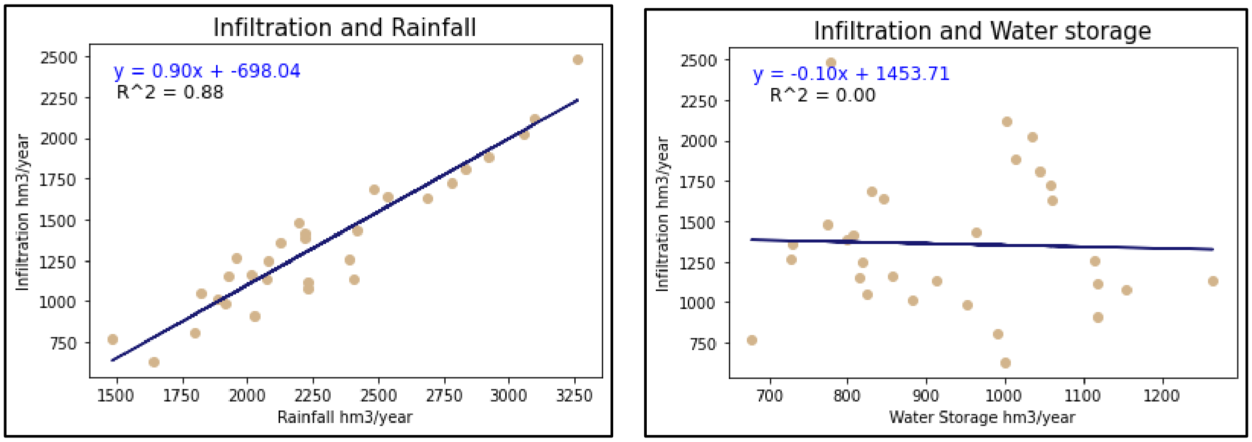


Figure 3.17. Correlation of (a) Rainfall and Infiltration (b) Infiltration and water storage

In Figure 3.17(a) rainfall and infiltration are well related and correlated, the infiltration model is seen to be controlled by rainfall, there is an indirect relationship between rainfall and infiltration, rainfall raises soil moisture. Increasing rainfall and infiltration intensity are increasing in the same direction. There is no significant relationship between infiltration and water storage, the infiltration model is not influenced by water storage in Figure 3.17(b). The initial and constant infiltration rates were higher with greater rainfall intensity. Infiltration is primarily influenced by soil variables, such as the kind of soil and its moisture content. The findings demonstrated that infiltration was significantly influenced by rainfall intensity.

3.3.6b. The Recharge Rate

In Table 7, the mean value of rainfall is 2291.48 hm^3/year which ranges from 1483.08 to 3262.73 hm^3/year throughout the period of evaluation 1993 – 2022, the percentage of recharge due rainfall is referenced to this volume of rainfall. The contribution of the surface water to groundwater recharge at 5% of porosity shows rate of recharge ranging 733.1 – 2357.6 hm^3/year while the 10% of porosity shows rate of recharge ranging 597.8 – 2357.6 hm^3/year, the minimum is experienced in 2021 and the maximum in 2010. The 5% porosity signifies a clayey layer while the sandy layer has 10% porosity. The recharge due to 5% porosity result to 36.4 – 72.3 % recharge due to rainfall while the recharge due to 10% porosity results to 34.5 – 68.5 % recharge due to rainfall.

The coexistence of different recharge types which may include focused recharge, direct recharge, and diffused recharge. The groundwater recharge rate is one of the most crucial factors in determining how vulnerable an aquifer or source of groundwater supply is. Despite this, because the recharge rates are so unpredictable and difficult to properly monitor, it is the component that is least understood and constrained. The recharge rate affects how long a groundwater supply can last. The main way that water enters the aquifer is through groundwater recharge. Water travels from the surface to the groundwater through both natural and artificial processes.

Rainfall and recharge have good relation from the infiltration model, this shows that rainfall would result to infiltration which would result to groundwater recharge in Figure 3.18.

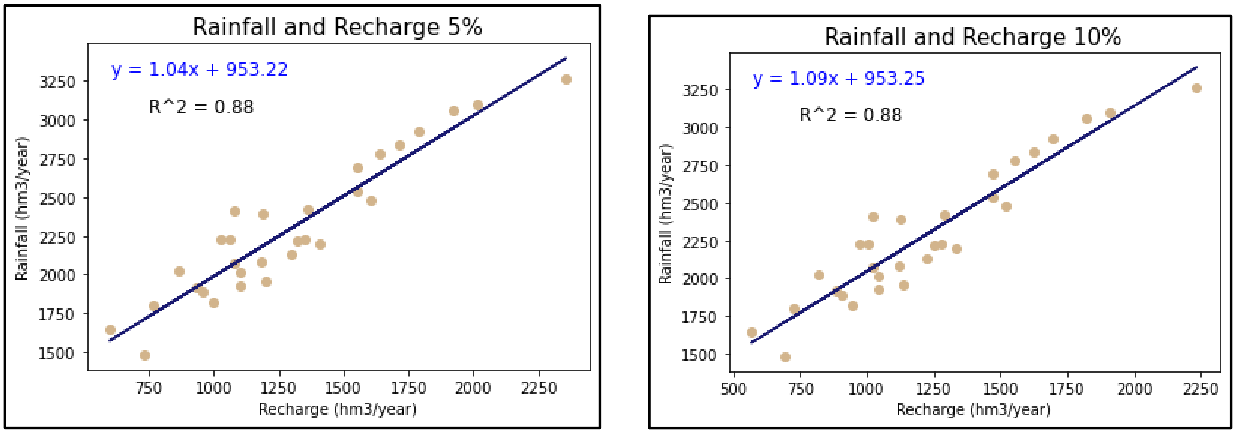


Figure 3.18. Correlation of Rainfall (a) Recharge 5%; (b) Recharge10%

From the infiltration model the water storage is having a negligible influence on groundwater recharge in Figure 3.19.

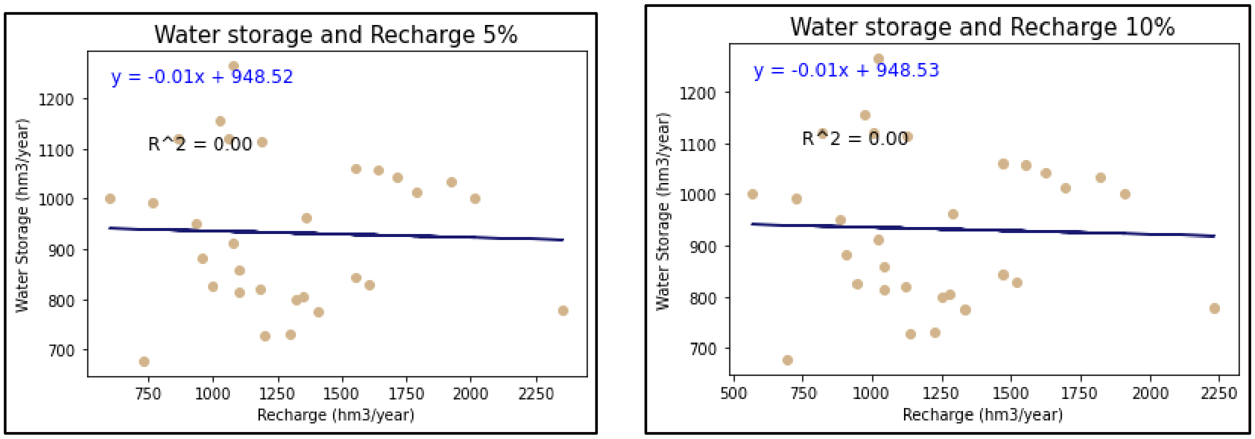


Figure 3.19. Correlation of Water storage (a) Recharge 5% (b) Recharge10%

3.3.6c. Relation Between Infiltration and Recharge from The Infiltration Model

Figure 3.20 shows that the relationship between infiltration and recharge is very strong, this is shows that the infiltration results to groundwater recharge across the dam from the infiltration model. The rate at which groundwater is replenished depends on infiltration rate but it is distinct from it. Groundwater recharge varies greatly in time and space at all sizes due to a variety of causes. The capacity of soil to absorb and transfer surface water under a specific circumstance is measured by the infiltration rate. After various processes have had their impact on the infiltrating water, recharge is the net infiltration rate.

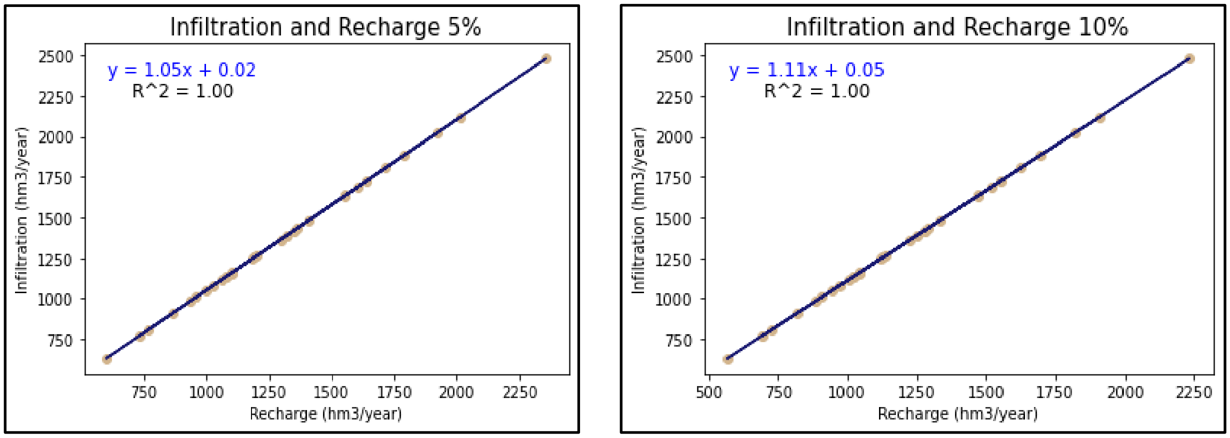


Figure 3.20. Correlation of (a) Infiltration and Recharge 5%; (b) Infiltration and Recharge10%

These results of infiltration and recharge rates are mean values across thirty (30) years of measurements. According to the position of the observation point, this result can change from a higher or smaller value. Rainfall is the influencing variable in the infiltration model, it will result to groundwater recharge as infiltration with time.

Table. 7: Summarized result from the infiltration model and recharge from the surface

Date	Rainfall (hm^3/year)	Infiltration (hm^3)	Recharge at 5% (hm^3/year)	Recharge at 10% (hm^3/year)	5% of recharge on rainfall	10% of recharge on rainfall
1993	1885.73	1009.8	959.3	908.8	50.9	48.2
1994	3099.02	2121.9	2015.8	1909.7	65	61.6
1995	2074.09	1132	1075.4	1018.8	51.8	49.1
1996	2222.84	1419.5	1348.5	1277.6	60.7	57.5
1997	1483.08	771.7	733.1	694.5	49.4	46.8
1998	2194.28	1483	1408.8	1334.7	64.2	60.8
1999	3058.34	2025.2	1924	1822.7	62.9	59.6
2000	2537.89	1636.3	1554.5	1472.7	61.3	58
2001	1957.13	1263.2	1200.1	1136.9	61.3	58.1
2002	2013.48	1160.9	1102.9	1044.8	54.8	51.9
2003	2836.62	1806.3	1716	1625.7	60.5	57.3
2004	2920.01	1881.8	1787.7	1693.6	61.2	58
2005	1916.84	982.3	933.1	884	48.7	46.1
2006	1801.58	806	765.7	725.4	42.5	40.3
2007	2688.47	1632.5	1550.9	1469.2	57.7	54.6
2008	2779.25	1726.3	1640	1553.7	59	55.9
2009	2419.70	1435.2	1363.4	1291.6	56.3	53.4
2010	3262.73	2481.7	2357.6	2233.5	72.3	68.5
2011	2127.72	1363.2	1295	1226.8	60.9	57.7
2012	2483.70	1689.3	1604.9	1520.4	64.6	61.2
2013	2217.99	1388.1	1318.7	1249.3	59.5	56.3
2014	1929.08	1156.7	1098.9	1041	57	54
2015	2231.76	1119	1063.1	1007.1	47.6	45.1
2016	2391.90	1253.4	1190.7	1128	49.8	47.2
2017	2079.78	1242.7	1180.6	1118.5	56.8	53.8
2018	1821.47	1048.3	995.8	943.4	54.7	51.8
2019	2231.76	1077.3	1023.5	969.6	45.9	43.4
2020	2407.71	1134	1077.3	1020.6	44.7	42.4
2021	1642.20	629.3	597.8	566.3	36.4	34.5
2022	2028.27	911.8	866.2	820.6	42.7	40.5
Minimum	1483.1	629.3	597.8	566.3	36.4	34.5
Maximum	3262.7	2481.7	2357.6	2233.5	72.3	68.5
Mean	2291.5	1359.6	1291.6	1223.7	55.4	52.5
Standard deviation	446.6	426.6	405.3	384.0	8.1	7.7

3.3.7. Evaluating The Possible Impact of Rainfall and Climate Change on Groundwater Recharge on The Dam

Relationship between groundwater and rainfall is long known phenomenon (Celik, 2018). It is crucial to determine and analyse the role of rainfall in groundwater recharge at the Bagre dam. Although, it is established that groundwater recharge at the dam is majorly from the dam, it is necessary to consider the impact of rainfall and climate change on the groundwater recharge.

The protracted drought that has plagued West Africa since the 1970s is evidence of the region's significant climatic variability. The effects of the drought on surface water resources are widely known, but groundwater resources have received less attention. It is not well understood how climate variability and changes in groundwater levels are related. There is a lot of climate variation in the West African region. The relationship between climate variability and groundwater level fluctuation has been the subject of some recent studies, but this area of research is still in its infancy, particularly in Africa (Tirogo et al., 2016).

Climatic change effect on water storage and groundwater in the case of Bagre Dam and over areas in Soudano Sahelian zones shows that water supplies are unstable and insufficient to satisfy the rising population's water needs, global climate change threatens to exacerbate the already severe scarcity of water resources. The climate change decreasing trend of rainfall in the Sahelien zones will affect groundwater recharge dependent on infiltration due to rainfall in the Bagre dam.

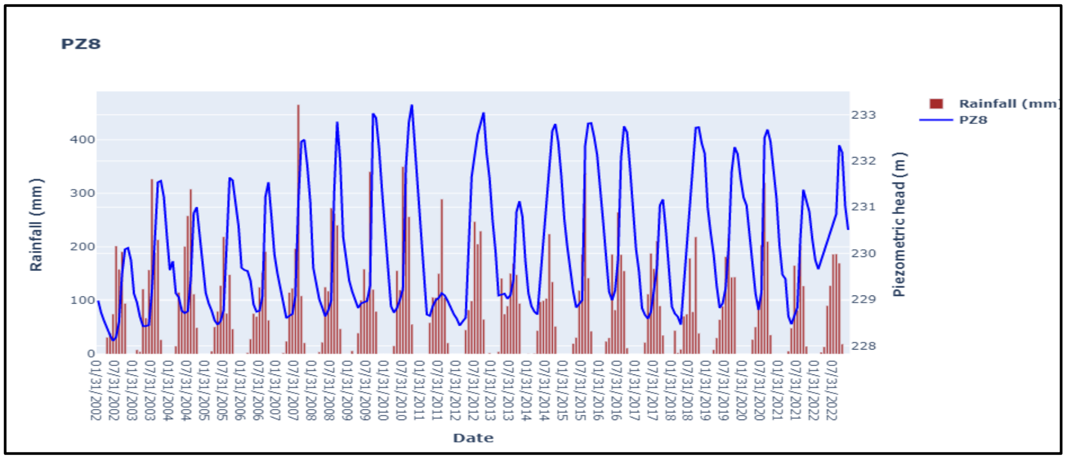
A possible proxy for the groundwater resources in West African basement rock aquifers that are vulnerable to climate change is surface water level (Ali et al., 2017). There are different reaction and response of each PZ to rainfall the delay varies, in Figure 3.22 (i-l) rainfall effect on this groundwater points are intense, and all the peaks are mostly observed during the raining season, this is attributed to the low ground water level elevation. In Figure. 3.21 (a-h) the peaks of groundwater are during the dry season and the effect of rainfall is low. Generally, groundwater recharge occurs by river leakage and direct rainwater infiltration, and it is largely seasonal. The recharge of the water table is mostly owned to rainfall amidst other factors like topography and soil layers, but this varies at any dam or a water body location. The effect of the dams is not the main parameter on groundwater level changes as moving away from dams (Celik, 2018). Groundwater level away from dams and surface water are dependent on rainfall for recharge.

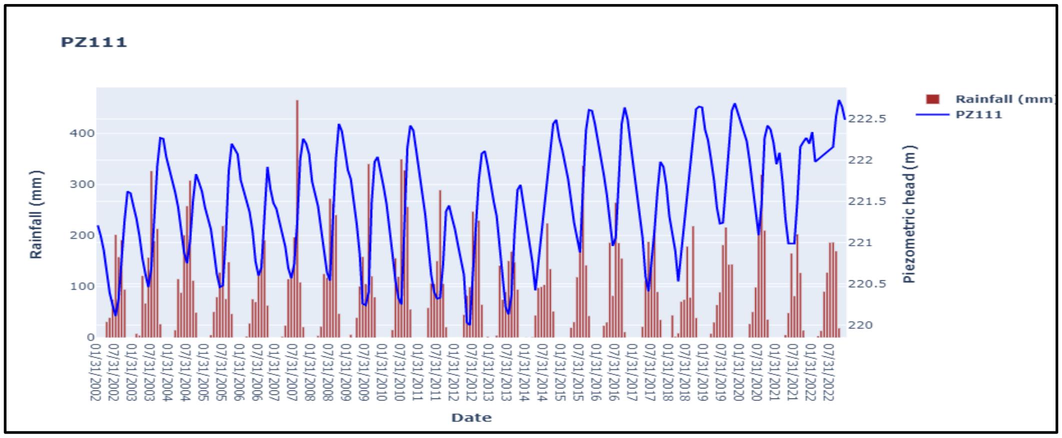
In Figure 18, PZ110, from 2002 to 2008 there is a strong influence of reservoir water level on the groundwater. The correlation of rainfall and groundwater in Figure 21 confirms the prediction of groundwater to the reservoir level, in Figure 12 and 13, the strong to moderate correlation of groundwater levels are influenced by the water level except for PZ7 which benefits from both the reservoir and rainfall infiltration. These groundwater points rates of recharge are fast and happens mostly during the dry season. The peak is fast until august during the dry season but decrease slowly in July as the raining season begins, this scenario is general in Figure 21. In Figure 22 the weak correlation also affirms the weak reaction to the water level in Figure 14, they are mostly influenced by rainfall. Figure 22 shows slow recharge rate and infiltration due to rainfall, this groundwater points are recharged during the raining season. In table 6, PZ7, 2, 3, 106 shows high percentage of recharge rate due to rainfall, PZ106 and PZ2 are ranking the highest infiltration with 135% and 134% of rainfall this is due to low elevation in the embarkment.

In Figure 21 and 22 considering and comparing the relationship between groundwater and rainfall at the dam is necessary to ascertain the interaction of rainfall to groundwater. It is observed that delay time is a defining factor for rainfall to reach the water table for recharge. The comparison shows that it will take about three to four (3-4) months for rainfall to influence the quantity of recharge in the subsurface at the dam. In Figure 21, the peak of recharge is observed at the dry season period, which shows that time is taken for rainfall to percolate to the water table therefore causing recharge. The overall information from the correlation infers the nature of groundwater response to rainfall away from the dam vicinity in Boulgou province. Rainfall decreasing trend in the dam is so evident that the recharge profile of some groundwater points follows the decreasing trend. The groundwater table has steadily declined because of a decrease in recharge from rainfall. The decreasing trend of rainfall across the dam is not a direct threat to groundwater recharge since groundwater recharge across the dam is not completely dependent on rainfall but on reservoir water level.

In appendix 6, PZ1, PZ2, PZ3 and PZ106 groundwater recharge follow the decreasing trend of rainfall. This corroborates the reason for low impact of reservoir water level on this groundwater points, these points have low reaction to the reservoir, thereby making rainfall to have a significant impact on these points. PZ (107, 4, 109, 8, 110, 108,111, 7) do not follow the increasing trend of rainfall rather they are all have an increasing trend. This shows that reservoir water is having the major percentage on the influence of groundwater recharge compared to rainfall that is having a low influence of less than 35%. PZ (2, 3, 106) tend to have more influence by rainfall than reservoir water level, this is a result of the far distance from the high-pressure water level. The response of the aquifer to rainfall is low and slow at the Bagre dam. The dams are the reason for the rising groundwater level. Especially, Upstream and Downstream sides and the side near the reservoir groundwater level rises. Dams also cause groundwater levels to rise in cultivated areas via its irrigation (ÇELİK, 2018). Factors such as time taken for percolation to occur, topography, degree of porosity and the nature of the saturated and unsaturated zone and the subsurface geologic structure of the layers are influencing the rate of recharge.

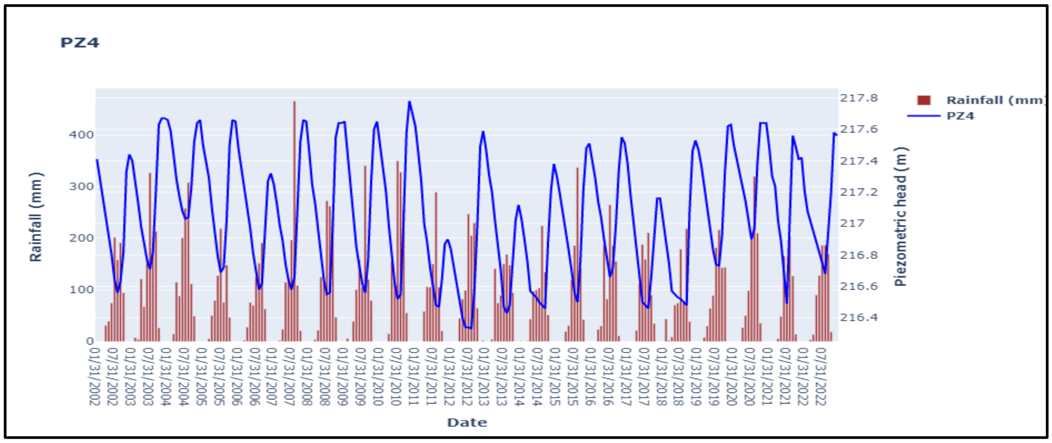
Based on the correlation of rainfall on groundwater recharge, climate change is resulting to a decreasing trend of rainfall. The recharge of groundwater will also decrease when rainfall is considered as a recharge factor. Compared to the past high quantity of rainfall in 2002 to 2012, climate change will also affect groundwater recharge trend in the regions around Bagre dam and Burkina Faso.



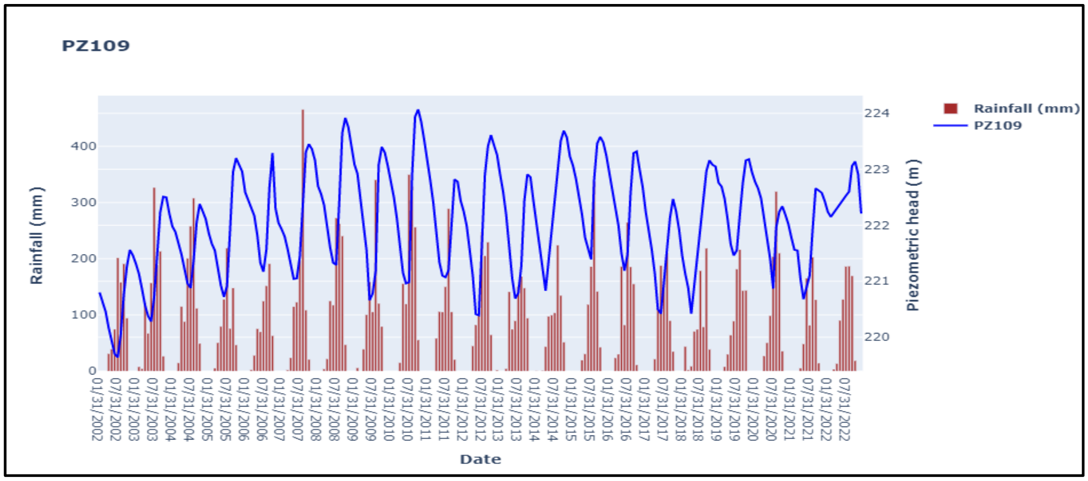

PZ111
Rainfall (mm)
PZ111
Rainfall (mm)
0
100
200
300
400
Piezometric head (m)
220
220.5
221
221.5
222
222.5
Date
01/31/2002
07/31/2002
01/31/2003
07/31/2003
01/31/2004
07/31/2004
01/31/2005
07/31/2005
01/31/2006
07/31/2006
01/31/2007
07/31/2007
01/31/2008
07/31/2008
01/31/2009
07/31/2009
01/31/2010
07/31/2010
01/31/2011
07/31/2011
01/31/2012
07/31/2012
01/31/2013
07/31/2013
01/31/2014
07/31/2014
01/31/2015
07/31/2015
01/31/2016
07/31/2016
01/31/2017
07/31/2017
01/31/2018
07/31/2018
01/31/2019
07/31/2019
01/31/2020
07/31/2020
01/31/2021
07/31/2021
01/31/2022
07/31/2022

(a)

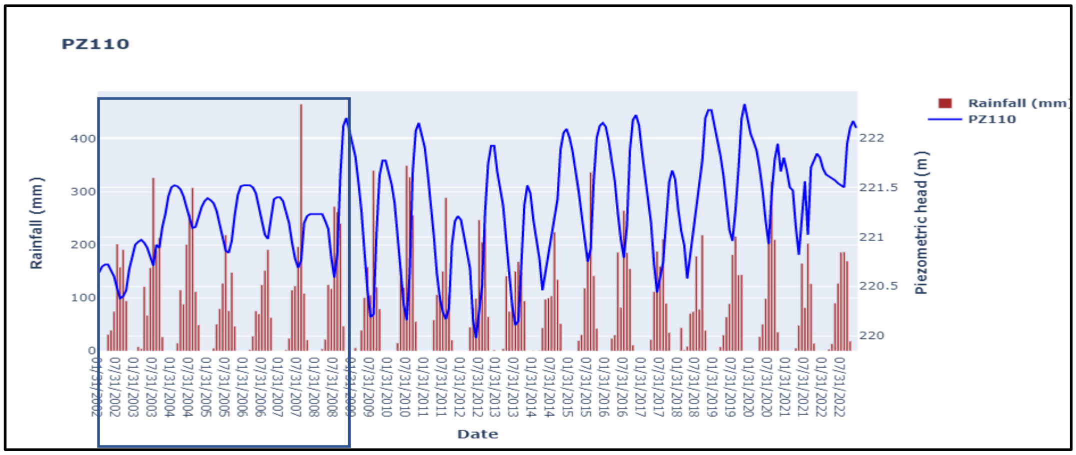
(b)


PZ4
Rainfall (mm)
PZ4
Rainfall (mm)
0
100
200
300
400
Piezometric head (m)
216.4
216.6
216.8
217
217.2
217.4
217.6
217.8
Date
01/31/2002
07/31/2002
01/31/2003
07/31/2003
01/31/2004
07/31/2004
01/31/2005
07/31/2005
01/31/2006
07/31/2006
01/31/2007
07/31/2007
01/31/2008
07/31/2008
01/31/2009
07/31/2009
01/31/2010
07/31/2010
01/31/2011
07/31/2011
01/31/2012
07/31/2012
01/31/2013
07/31/2013
01/31/2014
07/31/2014
01/31/2015
07/31/2015
01/31/2016
07/31/2016
01/31/2017
07/31/2017
01/31/2018
07/31/2018
01/31/2019
07/31/2019
01/31/2020
07/31/2020
01/31/2021
07/31/2021
01/31/2022
07/31/2022

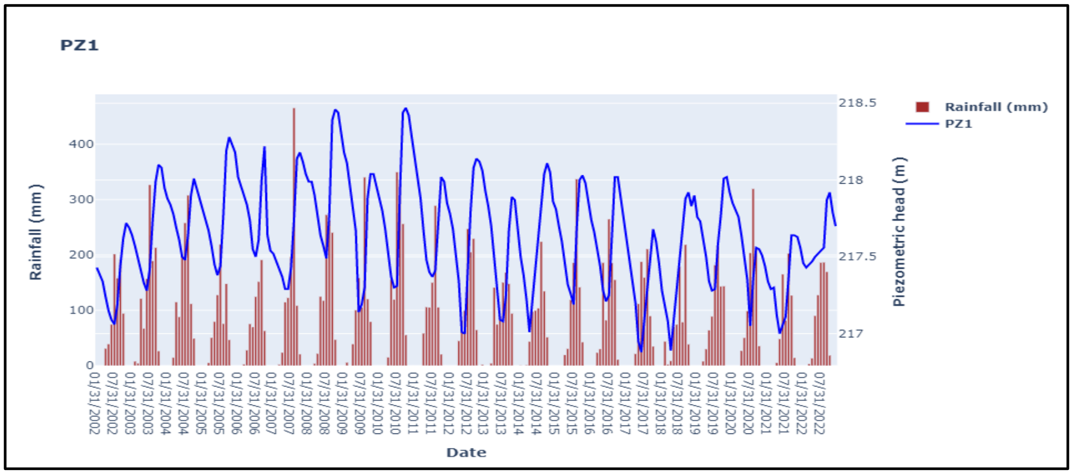
(c)


PZ109
Rainfall (mm)
PZ109
Rainfall (mm)
0
100
200
300
400
Piezometric head (m)
220
221
222
223
224
Date
01/31/2002
07/31/2002
01/31/2003
07/31/2003
01/31/2004
07/31/2004
01/31/2005
07/31/2005
01/31/2006
07/31/2006
01/31/2007
07/31/2007
01/31/2008
07/31/2008
01/31/2009
07/31/2009
01/31/2010
07/31/2010
01/31/2011
07/31/2011
01/31/2012
07/31/2012
01/31/2013
07/31/2013
01/31/2014
07/31/2014
01/31/2015
07/31/2015
01/31/2016
07/31/2016
01/31/2017
07/31/2017
01/31/2018
07/31/2018
01/31/2019
07/31/2019
01/31/2020
07/31/2020
01/31/2021
07/31/2021
01/31/2022
07/31/2022

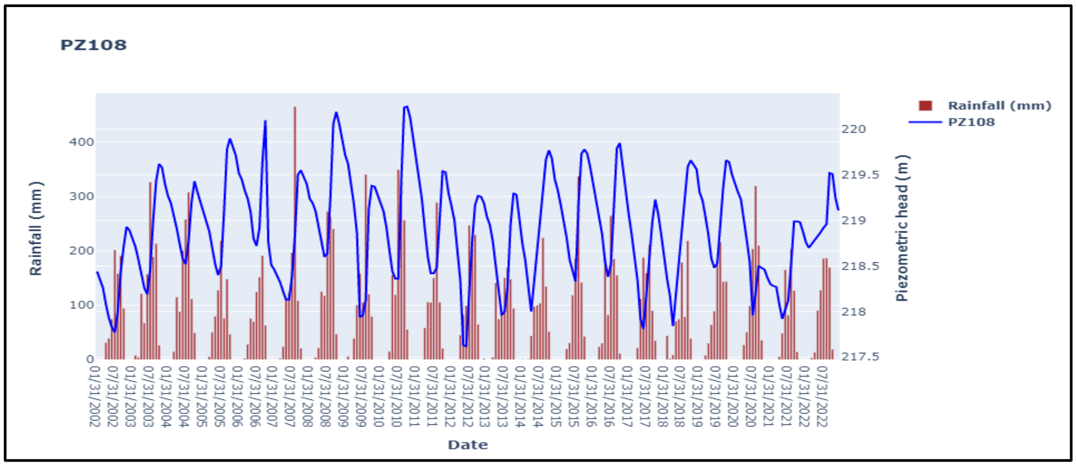
(d)


PZ110
Rainfall (mm)
Piezometric head (m)
Date
Rainfall (mm
PZ110
0
100
200
300
400
220
220.5
221
221.5
222
01/31/2002
07/31/2002
01/31/2003
07/31/2003
01/31/2004
07/31/2004
01/31/2005
07/31/2005
01/31/2006
07/31/2006
01/31/2007
07/31/2007
01/31/2008
07/31/2008
01/31/2009
07/31/2009
01/31/2010
07/31/2010
01/31/2011
07/31/2011
01/31/2012
07/31/2012
01/31/2013
07/31/2013
01/31/2014
07/31/2014
01/31/2015
07/31/2015
01/31/2016
07/31/2016
01/31/2017
07/31/2017
01/31/2018
07/31/2018
01/31/2019
07/31/2019
01/31/2020
07/31/2020
01/31/2021
07/31/2021
01/31/2022
07/31/2022

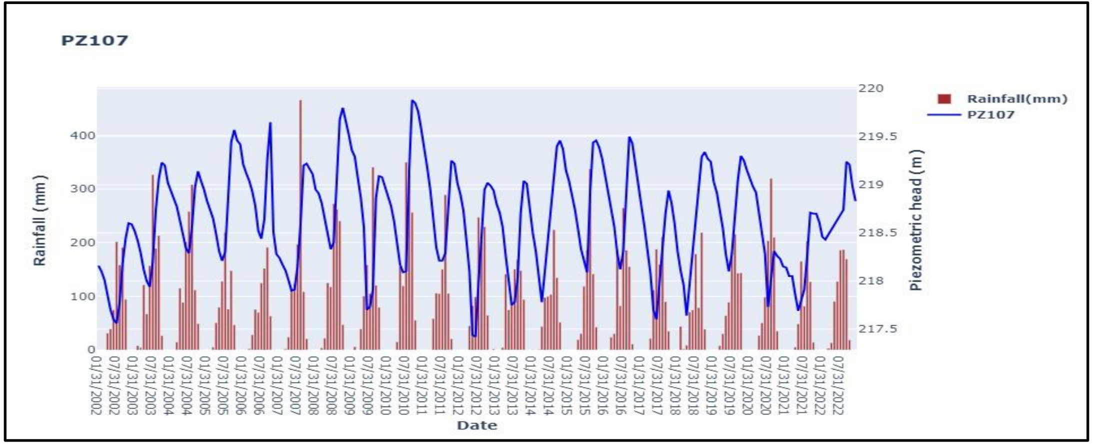
(e)


PZ1
Rainfall (mm)
Piezometric head (m)
Date
Rainfall (mm)
PZ1
0
100
200
300
400
217
217.5
218
218.5
01/31/2002
07/31/2002
01/31/2003
07/31/2003
01/31/2004
07/31/2004
01/31/2005
07/31/2005
01/31/2006
07/31/2006
01/31/2007
07/31/2007
01/31/2008
07/31/2008
01/31/2009
07/31/2009
01/31/2010
07/31/2010
01/31/2011
07/31/2011
01/31/2012
07/31/2012
01/31/2013
07/31/2013
01/31/2014
07/31/2014
01/31/2015
07/31/2015
01/31/2016
07/31/2016
01/31/2017
07/31/2017
01/31/2018
07/31/2018
01/31/2019
07/31/2019
01/31/2020
07/31/2020
01/31/2021
07/31/2021
01/31/2022
07/31/2022

(f)

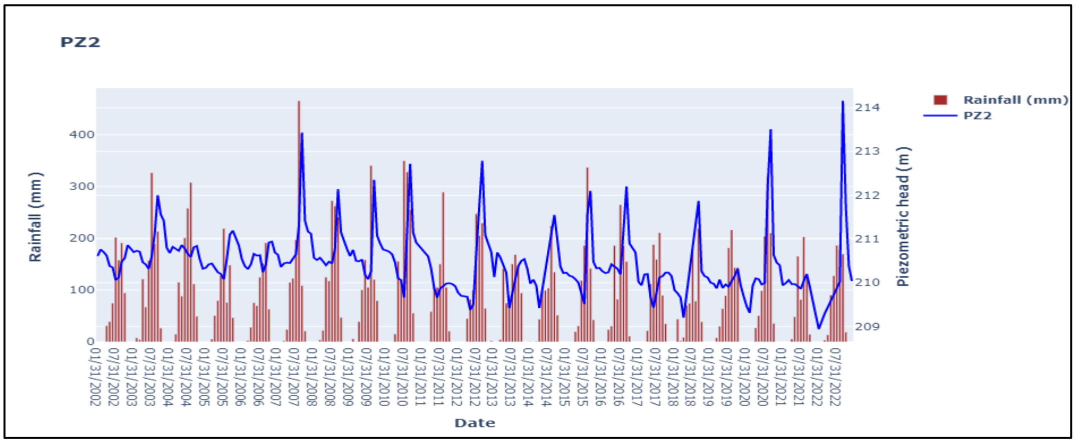

PZ108
Rainfall (mm)
Piezometric head (m)
Date
Rainfall (mm)
PZ108
0
100
200
300
400
217.5
218
218.5
219
219.5
220
01/31/2002
07/31/2002
01/31/2003
07/31/2003
01/31/2004
07/31/2004
01/31/2005
07/31/2005
01/31/2006
07/31/2006
01/31/2007
07/31/2007
01/31/2008
07/31/2008
01/31/2009
07/31/2009
01/31/2010
07/31/2010
01/31/2011
07/31/2011
01/31/2012
07/31/2012
01/31/2013
07/31/2013
01/31/2014
07/31/2014
01/31/2015
07/31/2015
01/31/2016
07/31/2016
01/31/2017
07/31/2017
01/31/2018
07/31/2018
01/31/2019
07/31/2019
01/31/2020
07/31/2020
01/31/2021
07/31/2021
01/31/2022
07/31/2022

(g)

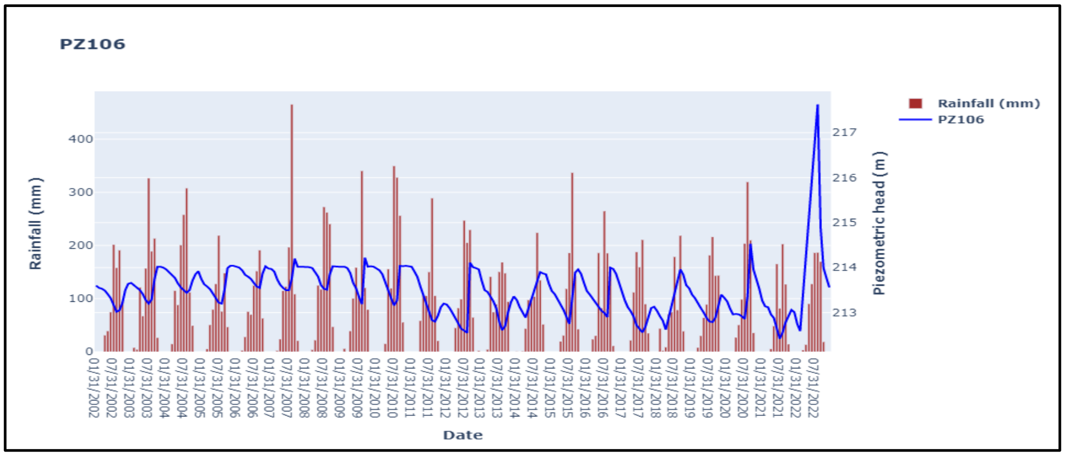


(h)

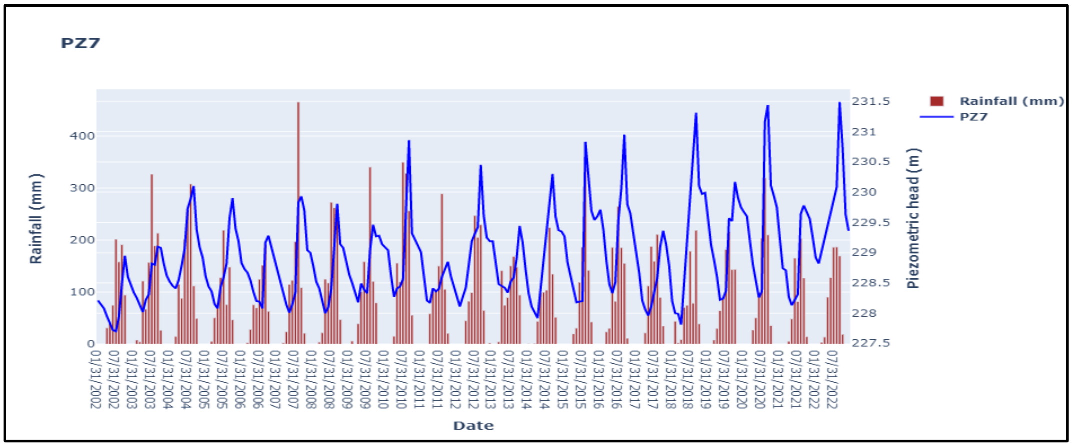
Figure 3.21(a-h) Correlation of Rainfall and Groundwater



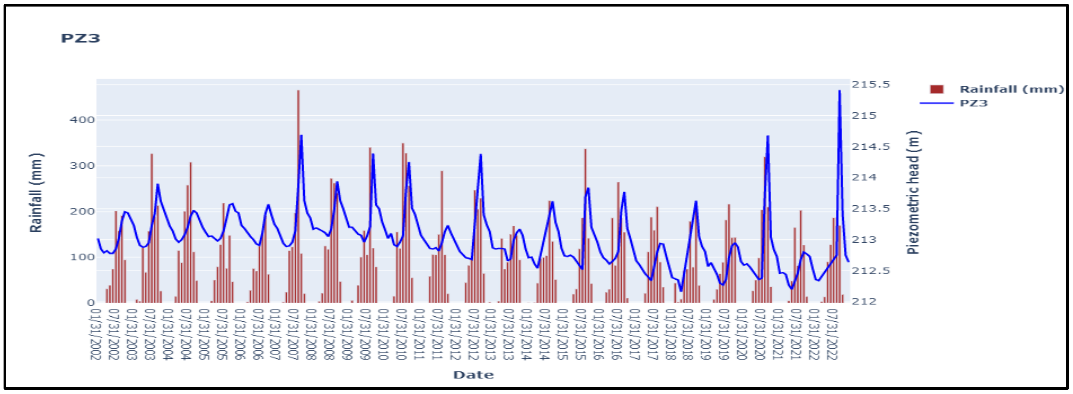
(i)



(j)



(k)



(l)

Figure 3.22(i-l) Correlation of Rainfall and Groundwater

Conclusion and Recommendations

This study explored the historical dynamics of hydro-climatic trend and prediction of water level over the dam, it also juxtaposes the role of reservoir water level and rainfall impact on groundwater recharge. The long time series data enables a better analysis and output of the results. In the context of hydroclimatic variability over the years, different variable trends depicted their role in the dam stability and efficiency. Overall, the results showed that increasing trend of inflow, rainfall and spillage in the dam possess threat to the dam stability and flooding over the downstream. Nevertheless, the spillage, irrigation and evaporation will enable the dam water balance consistency and control the reservoir water level. Rainfall with decreasing trend will affect the water level of the dam which would affect the dam efficiency, the increasing trend of inflow from the upstream if not controlled and managed would serve as a huge threat to the dam stability. Climate change will affect the dam stability and reservoir water storage thus affect hydropower generation and irrigation supply. Hydrological variables directly influenced groundwater fluctuations, highlighting the need for integrated water management strategies. This demonstrates the importance of considering hydrological variables such as surface water level and rainfall influence on groundwater recharge.

According to these findings, the linear and polynomial regression should be used to predict dam groundwater level with water level at any dam to understand the correlation and degree of influence and impact the reservoir has on groundwater. Results revealed that water level has remained virtually unchanged over the period of record. We can conclude that reservoir water level is the main source of groundwater recharge across this dam while rainfall contribution is low, this can be applicable to any groundwater table near any water body(dam). Stable and increasing reservoir storage quantity would result to stable and constant groundwater recharge, while the effect of rainfall would be minimal and seasonal to groundwater recharge. The percentage of groundwater points recharged by the reservoir water level is 67% while those recharged by rainfall is rainfall is 33%.

The consistent recharge of groundwater from the dam infers that there is regular availability of water for residents around the dam downstream and the Bagre village. The farmer does not need to care about the seasonality of rainfall because throughout the year farming activities can occur both in dry season and wet season. The infiltration rate shows the impact of the surface water on groundwater recharge, this seepage is evident that the volume of infiltration from the surface is resulting to groundwater recharge. The increasing seepage rate could pose a threat to the dam stability which will result to instability and reduction in hydropower generation.

The water balance model explanation is highly important for the industry in critical decision making, as it can help in taking control measures to prevent probable accidents by controlling certain parameters, how they can be applied to other dams and locations, these findings could be useful in making choices. Separate from the hydropower generation the dam serves as groundwater recharge and source of water for cultivation of crops. Groundwater is a game changer during adverse climate change across the Bagre dam.

Recommendations

1. More agricultural practice should be encouraged and practiced throughout the year, due to the influence of the reservoir storage. Farmers can move to the Bagre region for continuous cultivation. Agricultural irrigation should be provided by water wells and groundwater springs in Bagre dam downstream where these dams are built in.
2. Due to the increasing groundwater level across the dam, government can construct more wells and drill boreholes to provide portable water for the dwellers around the dam.
3. The stability of recharge infers that there is constant water available from the groundwater resource hence industries related to water production can be sighted at the Bagre region. This will enable groundwater abstraction due to good groundwater potential.
4. The SSA approach could be used further to forecast the future behaviour of the hydro-climatic variables to enable proper management the dam.
5. Geophysical and geotechnical survey can be carried out across the dam embarkment to delineate the geologic structures that might poses threat to the dam in future.
6. The rate of infiltration should be regularly monitored to enable maintenance and stability of the dam.

References

Addisie, M. B., Ayele, G. K., Hailu, N., Langendoen, E. J., Tilahun, S. A., Schmitter, P. & Steenhuis, T. S., 2020: Connecting hillslope and runoff generation processes in the Ethiopian Highlands: the Ene-Chilala watershed. *Journal of Hydrology and Hydromechanics 68* (4), 313–327.

Adewumi, I., and Olorunfemi, M.O., 2005: "Using Geoinformation in Construction Management. *Journal of Applied Sciences. 5*(4): 761 – 767.

Ali Houmadi Mouhouyouddine, Suzanne Yameogo, Pierre Genthon, Jean Emmanuel Paturel, Maurice Guilliod, 2017: Groundwater Level Changes since 1978 in an African City on Basement Rocks: The Case of the CIEH Borehole in Ouagadougou (Burkina Faso). Journal of Water Resource and Protection Vol.9, No.10.

Al-Riffai, M., Nistor, I., 2010: Impact and analysis of geotechnical processes on earth fill dam breaching. Nat Hazards (2010) 55:15–27. DOI 10.1007/s11069-010-9586-6

Anna Gumuła-Kawęcka, Beata Jaworska-Szulc, Adam Szymkiewicz, Wioletta Gorczewska-Langner, Małgorzata Pruszkowska-Caceres, Rafael Angulo-Jaramillo, Jirka Sim, 2021: Estimation of groundwater recharge in a shallow sandy aquifer using unsaturated zone modeling and water table fluctuation method. Journal of hydrogeology, 2021. https://doi.org/10.1016/j.jhydrol.2021.127283

Asare-Kyei. D.K, F.G. Renaud, J. Kloos, Y. Walz, J. Rhyner, 2017: Development and validation of risk profiles of West African rural communities facing multiple natural hazards PLoS One, 12 (3) , 10.1371/journal pone.0171921e0171921

ASCE, 2009: Report card for America's infrastructure, American society of civil engineers. http://www. asce.org/report card.

Atta-Darkwa, T., Kyei-Baffour, N., Ofori, E., Mensah, E. & Agyare, W. A., 2013: Quantification of groundwater recharge in the river Oda catchment using the water table fluctuation method. *G.J. E.D.T.*, Vol. *2*(1) 2013:96-103 ISSN 2319 – 7293.

Aziz, F. & Obuobie, E. 2017: Trend analysis in observed and projected precipitation and mean temperature over the Black Volta Basin, West Africa. *International Journal of Current Engineering andTechnology7*(4),2. https://www.researchgate.net/deref/http%3A%2F%2Finpressco.com%2Fcategory%2Fijcet

B.A. Francis, L.K. Francis, M.B. Cardenas, 2010: Water table dynamics and groundwater-surface water interaction during filling and draining of a large fluvial island due to dam-induced river stage fluctuations Water Resources Research, 46 (7) (2010), 10.1029/2009WR008694.

Bahls, V. and Holman, K., 2014.: Climate Change in Hydrologic Hazard Analysis: Friant Dam Pilot Study - Part I: Hydrometeorological Model Inputs, Tech. rep., U.S. Department of the Interior, Bureau of Reclamation.

Behanzin I. D., Thiel M., Szarzynski J., & Boko M., 2016: GIS-based mapping of flood vulnerability and risk in the Bénin Niger River Valley. *International journal of Geomatics and Geosciences, 6*(3), 1653-1669.

Beekman, HE, Gieske A, Selaolo ET, 1996: GRES: Groundwater recharge studies in Botswana 1987-1996. Botswana. *J. of Earth Sci*., Vol. III: 1-17.

Beekman HE, and Xu Y, 2003: Review of Groundwater Recharge Estimation in Arid and Semi-Arid Southern Africa. UNESCO IHP Series No. 64, UNESCO Paris. ISBN 92-9220-000-3

BGS. 2002: Groundwater Quality: Burkina Faso. British Geological Survey. http://www.wateraid.org/~/media/Publications/groundwater-quality-information-burkina-faso.pdf

Bin Li, Jie Yang, Dexiu Hu, 2019: Dam monitoring data analysis methods: A literature review, https://doi.org/10.1002/stc.2501Citations: 36.

Biswas, A.K., and Charttergee, S., 1971: Dam Disasters - An Assessment. *Eng. J.* (Canada), *54*(3): 3- 8.

Byakatonda, B.P. Parida, D.B. Moalafhi, P.K. Kenabatho, 2018: Analysis of long-term drought severity characteristics and trends across semiarid Botswana using two drought indices, *Atmospheric Research, 213* (2018), pp. 492-508, 10.1016/j.atmosres.2018.07.002

C.A.F. Marques, J.A. Ferreira, A. Rocha, J.M. Castanheira, P. Melo-Gonçalves, N. Vaz, J.M. Dias, 2006: Singular spectrum analysis and forecasting of hydrological time series.

Castaing, C., Bila, M., Milési, J.-P., Thiéblemont, D., Le Metour, J., Egal, E., Donzeau, M., Guerrot, C., Cocherie, A., Chevremont, P., Teygey, I., Itard, Y., Zida, B., Ouédraogo, I., Koté, S., Kabore, B.-E., Ouédraogo, C., Ki, J.-C. and Zunino, C., 2003 : Notice explicative de la carte géologique et minière du Burkina Faso à 1/1000 000. 3 ème édition, BRGM, Orléans, France, 148p.

Chernet, H. H., Alfredsen, K., and Midttømme, G. H., 2014: Safety of Hydropower Dams in a Changing Climate, J. Hydrol.Eng., 19, 569–582, https://doi.org/10.1061/(ASCE)HE.1943-5584.0000836.

Clague JJ, Evans SG, 2000: A Review of catastrophic drainage of moraine-dammed lakes in British Columbia. *Quat Sci Rev* 19 :1763–1783

Cuthbert, M.O., Taylor, R.G., Favreau, G., 2019: Observed controls on resilience of groundwater to climate variability in sub-Saharan Africa. *Nature 572*, 230\u2013234 (2019) doi:10.1038/s41586-019-1441-7.

D. Murgulet, V. Murgulet, N. Spalt, A. Douglas, R.G. Hay, 2016: Impact of hydrological alterations on river-groundwater exchange and water quality in a semi-arid area, 2016: *Nueces River, Texas Science of the Total Environment, 572*, pp. 595-607, 10.1016/j.scitotenv.2016.07.198

De Vries, J. J. and I. Simmers, 2002: Groundwater recharge: an overview of processes and challenges, Hydrogeol.J., 10(1), 5-17

DGH (Direction Génerale dès l'Hydraulique) 2001 : "Etat des Lieux des Ressources en Eau du Burkina Faso et de leur Cadre de Gestion." Ouagadougou : ministère de l'Environnement et de l'Eau

DGRE, 2010 : Etat des Lieux de la Gestion des Ressources en eau du Bassin du Nakanbé : Rapport Final. Available from : https://eaunakanbe. bf/wp-content/uploads/2019/06/Rapport-etat-des-lieux-des-RE-du-Nakanbé-de-2010-Final.pdf

Eccles R., Zhang H., & Hamilton D.**,** 2019: A review of the effects of climate change on riverine flooding in subtropical and tropical regions. Journal of Water and Climate Change, 10(4), 687-707.

FEMA, 2004: Federal guidelines for dam safety: hazard potential classification system for dams, FEMA333, U.S. Department of Homeland Security, FEMA, Oct 1998 (reprinted January 2004)

Felix O. Ojo, Olademeji L. Ademilua, Isaac B. Osazuwa, 2013: Two-Dimensional Electrical Imaging of the Subsurface Structure of Bomo Dam, Zaria, Kaduna State North Central Nigeria. *Transnational Journal of Science and Technology*, February 2013 Edition Vol.3, No 2. ISSN 1857-8047

Foster M, Fell R, Spannagle M., 2000: The statistics of embankment dam failures and accidents. *Can Geotech J 37*:1000–1024

Francis, B. A., L. K. Francis, and M. B. Cardenas, 2010: Water table dynamics and groundwater–surface water interaction during filling and draining of a large fluvial island due to dam-induced river stage fluctuations. *Water Resour. Res., 46*, W07513, doi:10.1029/2009WR008694.

Giovenazzo D. et al., 2018: "Notice Explanatory of the Geological, Structural, and Mineral Substance Synthesis of the Burkina Faso at Scale 1/1,000,000", Effigis Geo-Solutions Team.

H. Hassani and D. Thomakos, 2010: A review on singular spectrum analysis for economic and financial time series, Statistics, and its Interface, 3, pp. 377-397.

HAPS 2006: Hydrological assessment of the Northern Regions of Ghana: A bibliographical review of selected papers. CIDA, WRC, SNC-LAVALIN International.

Hassani, H. 2007: Singular Spectrum Analysis: Methodology-and Comparison. *Journal of Data Science 5* 239–257.

Healy, R. W. & Cook, P. G. 2002: Using groundwater levels to estimate recharge. *Hydrogeology Journal 10* (1), 91–109

Héctor Briceñoa, Claudio M. Roccoa, Enrico Zio, Singular Spectrum Analysis for Forecasting of Electric Load Demand. 2013: Aidic.it. Retrieved from http://www.aidic.it/cet/13/33/154.pdf

Heri Sulistiyono, Ery Setiawan and Humairo Saidah, 2022: Impact of Climate Change on Dam Safety. *Accesses Part of the Lecture Notes in Civil Engineering book series* (LNCE, volume 225)

Hiscock, P.-F. Yeh, I. Holman, H. Treidel, 2013: Ground water and climate change Nature Climate Change, 3 (4), pp. 322-329 Honoré Houéménou, Sarah Tweed, Gauthier Dobigny, Daouda Mama, Abdoukarim Alassane, Roland Silmer, Milanka Babic, Stéphane Ruy, Alexis Chaigneau, Philippe Gauthier, Akilou Socohou, Henri-Joël Dossou, Sylvestre Badou, Marc Leblanc, 2020: Degradation of groundwater quality in expanding cities in West Africa. A case study of the unregulated shallow aquifer in Cotonou, Journal of Hydrology, Volume 582, 124438, ISSN 0022-1694, https://doi.org/10.1016/j.jhydrol.2019.124438.

Hiscock, P.-F. Yeh, I. Holman, H. Treidel, 2013: Ground water and climate change Nature Climate Change, 3 (4), pp. 322-329 Honoré Houéménou, Sarah Tweed, Gauthier Dobigny, Daouda Mama, Abdoukarim Alassane, Roland Silmer, Milanka Babic, Stéphane Ruy, Alexis Chaigneau, Philippe Gauthier, Akilou Socohou, Henri-Joël Dossou, Sylvestre Badou, Marc Leblanc, 2020: Degradation of groundwater quality in expanding cities in West Africa. A case study of the unregulated shallow aquifer in Cotonou, Journal of Hydrology, Volume 582, 124438, ISSN 0022-1694, https://doi.org/10.1016/j.jhydrol.2019.124438.

ICOLD: Risk assessment in dam safety management, A reconnaissance of benefits, methods and current applications, Bulletin 130, International Commission on Large Dams, 2005.

Ishfaque Muhammad, Saad Salman, Khan Zaib Jadoon, Abid Ali Khan Danish, Kifayat Ullah Bangash, and Dai Qianwei. 2022: "Understanding the Effect of Hydro-Climatological Parameters on Dam Seepage Using Shapley Additive Explanation (SHAP): A Case Study of Earth-Fill Tarbela Dam, Pakistan" *Water 14,* no. 17: 2598. https://doi.org/10.3390/w14172598

Josie Geris, Jean-Christophe Comte, Fulvio Franchi, Alfred K. Petros, Sithabile Tirivarombo, Ame T. Selepeng, Karen G. Villholth, 2022: Surface water-groundwater interactions and local land use control water quality impacts of extreme rainfall and flooding in a vulnerable semi-arid region of

Sub-Saharan Africa, *Journal of Hydrology,* Volume 609, 2022, 127834, ISSN 0022-1694, https://doi.org/10.1016/j.jhydrol.2022.127834.

Juanizar A.R, Suripin Fnu, Sriyana Fnu, Suprapto Fnu, Sadono K.W., 2022: Assessment of the hydraulic behavior of an embankment dam through the seepage instrumentation case study: HEULA DAM, INDONESIA. *Larhyss Journal*, ISSN 1112-3680, n°52, Dec 2022, pp. 7-28

Kalbus, E. Reinstorf, F.; Schirmer, M., 2006: Measuring methods for groundwater? surface water interactions: A review. Hydrol. Earth Syst. Sci. **2006**, 10, 873–887. [**Google Scholar**] [**CrossRef**][**Green Version**]

Kendall, M.G., 1975. Rank correlation methods. London: Griffin**No index entries found.**

Koussoube, 2022: Hydrogeology of Burkina Faso Book. https://www.researchgate.net/publication/359384706

Killian C D, Asquith W H, Barlow J R B, Bent G C, Kress W, Barlow P M, and Schmitz D W., 2019: Characterizing groundwater/surface-water interaction using hydrograph-separation techniques and groundwater-level data throughout the Mississippi Delta, USA. https://doi.org/10.1007/s10040-019-01981-6

L. Ribeiro, N. Kretschmer, J. Nascimento, A. Buxo, T. Rötting, G. Soto, M. Señoret, J. Oyarzún, H. Maturana & R. Oyarzún, 2015: Evaluating piezometric trends using the Mann-Kendall test on the alluvial aquifers of the Elqui River basin, Chile, *Hydrological Sciences Journal, 60:*10, 1840-1852, DOI: 10.1080/02626667.2014.945936

Lambs, L., 2004: Interactions between groundwater and surface water at riverbanks and the confluence of rivers. *J. Hydrol*., *288*, 312–326. [**Google Scholar**] [**CrossRef**][**Green Version**]

Larbi, I., Hountondji, F.C.C., Annor, T., Agyare, W.A., Gathenya, J.M., Amuzu, J., 2018: Spatio-temporal trend analysis of rainfall and temperature extremes in the Vea catchment, Ghana. Climate 6 (4), 1–17. doi:10.3390/cli6040087.

Lerner DN, Yang Y, Barrett MH, Tellam JH, 1999: Loadings of non-agricultural nitrogen in urban groundwater. Impacts of urban growth on surface and ground waters (Proc. IAHS symposium HS5, Birmingham, July 1999). *IAHS publ. 259,* 117-123

Liersch S., Fournet S., Koch H., Djibo A. G., Reinhardt J., Kortlandt J., Van Weert F., Seidou O., Klop E., & Baker C., 2019: Water resources planning in the Upper Niger River basin: Are there gaps between water demand and supply? *Journal of Hydrology: Regional Studies, 21*, 176-194.

M. H. Ali and S. Mubarak, 2017: Approaches and Methods of Quantifying Natural Groundwater Recharge. 5(1): 1-27, 2017; Article no. AJEE.36987 ISSN: 2456-690X Martin N, van de Giesen N (2005) Spatial distribution of groundwater use and groundwater potential in the Volta

Mann, H.B., 1945. Nonparametric tests against trend. Econometrica, 13, 245–259. doi:10.2307/1907187

Maréchal, J. C., Dewandel, B., Ahmed, S., Galeazzi, L. & Zaidi, F. K., 2006: Combined estimation of specific yield and natural recharge in a semi-arid groundwater basin with irrigated agriculture. *Journal of Hydrology 329* (1–2), 281–293.

Mark O. Cuthbert, 2019: Observed controls on resilience of groundwater to climate variability in sub-Saharan Africa. https://doi.org/10.1038/s41586-019-1441-7. *NA T U RE* | VOL 572 | 8 AUGUS T 2019. River basin of Ghana and Burkina Faso. *IWRA Water International* Vol. *30* (2):239-249

Martin N, van de Giesen N (2005) Spatial distribution of groundwater use and groundwater potential in the Volta River basin of Ghana and Burkina Faso. IWRA Water International Vol. 30 (2):239-249

N. Golyandina, V. Nekrutkin, and A. Zhigljavsky, Analysis of structure of time series: SSA and related techniques, 2001.

N.Golyandina and A. Zhigljavsky, Singular Spectrum Analysis for Time Series, Springer, New York 2013.

N. B. Narasimha Prasad., 2011: GROUND WATER RECHARGE Technical Report. https://www.researchgate.net/publication/317033555. January 2011 DOI: 10.13140/RG.2.2.21142.55367

Nonki, R. M., Lenouo, A., Tchawoua, C., Lennard, C. J., and Amoussou, E., 2021: Impact of climate change on hydropower potential of the Lagdo dam, Benue River Basin, Northern Cameroon, *Proc. IAHS, 384*, 337–342, https://doi.org/10.5194/piahs-384-337-2021.

Novembre, N., Holman, K., and Bahls, V., 2015: Climate Change in Hydrologic Hazard Analyses, Friant Dam Pilot Study – Part II: Using the SEFM with Climate-Adjusted Hydrometeorological In-puts, Technical Memorandum 8250-2015-010, U.S. Department of the Interior, Bureau of Reclamation.

Ntajal J., Lamptey B. L., Mahamadou I. B., & Nyarko B. K., 2017: Flood disaster risk mapping in the lower Mono river basin in Togo, West Africa. *International journal of disaster risk reduction, 23,* 93-103.

Obuobie E and Barry B. 2012. Burkina Faso, in Groundwater Availability and Use in Sub-Saharan Africa; a review of fifteen countries. Pavelic, P, et al. (Eds). *International Water Management Institute, Sri Lanka.*

Onsachi J., 2018: "The Effects of Flood in Relation to Geotechnical Properties of The Soil and Human Activities (Case Study of Lokoja Riverbank, North Central Nigeria) "*The International Journal of Engineering and Science (IJES),), 7.*11 (2018): 60-71

Oladunjoye, M.A., A.J. Salami, A.P. Aizebeokhai; O.A. Sanuaje and S.I. Kaka., 2017: *Journal of the Geological society of India 89:* 209. doi:1007/SI12594-017-0585-z

Olorunfemi, M.O., Ojo, J.S., Sonuga, F., Ajayi, O., and Oladapo., M.I., 2000: Geoelectrical and Electromagnetic Investigation of the Failed Koza and Nasarawa Earth Dams Around Katsina, NorthernNigeria. *J. Mining Geol., 36*(1): 51 - 65.

P. Goderniaux, P. Davy, E. Bresciani, J-R. de Dreuzy, T. Le Borgne, 2013: Partitioning a regional groundwater flow system into shallow local and deep regional flow compartments. *Water Resources Research, 49* (2013), pp. 2274-2286, 10.1002/wrcr.20186

Panda, D.K., Mishra, A., and Kumar, A., 2012. Quantification of trends in groundwater levels of Gujarat in western India. *Hydrological Sciences Journal, 57* (7), 1325–1336. doi:10.1080/02626667.2012.705845

Prion, S. & Haerling, K. A. 2014 Making sense of methods and measurement: spearman-rho ranked-order correlation coefficient. *Clinical Simulation in Nursing 10* (10), 535–536. https://doi.org/10.1016/j.ecns.2014.07.005.

Recep CELIK, 2018: Impact of Dams on Groundwater Static Water Level Changes: A Case Study Kralkızı and Dicle Dam Watershed. International Journal of Engineering Research and Development, Volume:10, Issue:2. https://doi.org/10.29137/umagd.442483.

Richard S. Olsen, Isaac J. Stephens, 2016: Relearning how to look at piezometric data for seepage evaluation. https://www.researchgate.net/publication/319206472. Conference Paper · April 2016

Rushton KR, 1997: Recharge from permanent water bodies. In: I. Simmers (Editor), Recharge of Phreatic Aquifers in (Semi) Arid Areas. A.A. Balkema, Rotterdam, p215-255

Rivard, C., et al., 2009. Groundwater recharge trends in Canada. *Canadian Journal. Earth Science, 46*, 841–854.

Seyni Salack, Inoussa A. Saley, Namo Z. Lawson, Ibrahim Zabré, Elidaa K. Daku, 2018: Scales for rating heavy rainfall events in the West African Sahel, *Weather and Climate Extremes*, Volume *21*, 2018, Pages 36-42, ISSN 2212-0947, https://doi.org/10.1016/j.wace.2018.05.004.

Salomon Obahoundje, Arona Diedhiou, Kouakou Lazare Kouassi, Marc Youan Ta, Eric Mensah Mortey, Philippe Roudier and Didier Guy Marcel Kouame, 2022: Analysis of hydroclimatic trends and variability and their impacts on hydropower generation in two river basins in Côte d'Ivoire (West Africa) during 1981–2017, *Environ. Res. Commun*. 4 065001

Sangita Dey, Diva Bhatt, Saidul Haq and Rajesh Kumar Mall, 2020: Potential impact of rainfall variability on groundwater resources: a case study in Uttar Pradesh, India. *Arabian Journal of Geosciences 13*:114 https://doi.org/10.1007/s12517-020-5083-8

Saritha Padiyedath Gopalan, Naota Hanasaki, Adisorn Champathong, Taichi Tebakari, 2012: Impact assessment of reservoir operation in the context of climate change adaptation in the Chao Phraya River basin. https://doi.org/10.1002/hyp.14005

Schlüter, Thomas, 2008: Geological Atlas of Africa: With Notes on Stratigraphy, Tectonics, Economic Geology, Geohazards, Geosites and Geoscientific Education of Each Country. *Springer Science & Business Media*. Retrieved October 18, 2016.

S. Salack, B. Sarr, S.K. Sangare, M. Ly, I.S. Sanda, H. Kunstmann, 2015: Crop-climate ensemble scenarios to improve risk assessment and resilience in the semi-arid regions of West Africa Clim. Res., 65, pp. 107-121

Sophocleous, M., 2002: Interactions between groundwater and surface water: The state of the science. *Hydrogeol. J.*, *10*, 52–67. [**Google Scholar**] [**CrossRef**]

Sangita Dey, Diva Bhatt, Saidul Haq and Rajesh Kumar Mall, 2020: Potential impact of rainfall variability on groundwater resources, 2020: a case study in Uttar Pradesh, India. *Arabian Journal of Geosciences* (2020) *13*:114 https://doi.org/10.1007/s12517-020-5083-8

Sirles, P.C., 2006: NCHRP Synthesis 357 use of Geophysics for transportation projects, Transportation Research Board of the National Academies, Washington D.C. Available at http:/onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_357.pdf

Sylla, M. B., Nikiema, P. M., Gibba, P., Kebe, I. & Klutse, N. A. B., 2016: Climate Change over West Africa: Recent Trends and Future Projections. In: Adaptation to Climate Change and Variability in Rural West Africa (Yaro, J. & Hesselberg, J., eds.). *Springer, Cham*. https://doi.org/10.1007/978-3-319-31499-0_3

T.R. Green, M. Taniguchi, H. Kooi, J.J. Gurdak, D.M. Allen, K.M. Hiscock, H. Treidel, A. Aureli., 2011: Beneath the surface of global change: Impacts of climate change on groundwater. *Journal of Hydrology, 405* (3–4), pp. 532-560, 10.1016/j.jhydrol.2011.05.002.

Tazen, F., Diarra, A., Kabore, R.F.W., Ibrahim, B., Bologo/Traoré, M., Traoré, K., Karambiri, H., 2019: Trends in flood events and their relationship to extreme rainfall in an urban area of Sahelian West

Africa: the case study of Ouagadougou, Burkina Faso. J. Flood Risk Manag. 12 (S1). doi:10.1111/jfr3.12507.

Tabari, H., Nikbakht, J., and Shifteh Some'e, B., 2012. Investigation of groundwater level fluctuations in the north of Iran. *Environmental Earth Sciences, 66* (1), 231–243. doi:10.1007/ s12665-011-1229z

Tirogo, J.; Jost, A.; Biaou, A.; Valdes-Lao, D.; Koussoubé, Y.; Ribstein, P., 2016: Climate Variability and Groundwater Response: A Case Study in Burkina Faso (West Africa). *Water*, *8*, 171. https://doi.org/10.3390/w8050171

Tripathi, S.S., & Isaac, R.K., 2016: Rainfall Pattern and Groundwater Fluctuation in Ramganga River Basin at Bareilly District, Uttar Pradesh, India. International Journal of Advanced Engineering, Management and Science, 2.

Valentina Krysanova, Fred Hattermann, Shaochun Huang, Cornelia Hesse, Tobias Vetter, Stefan Liersch, Hagen Koch & Zbigniew W. Kundzewicz, 2015: Modelling climate and land-use change impacts with SWIM: lessons learnt from multiple applications, *Hydrological Sciences Journal, 60*:4, 606-635, DOI: 10.1080/02626667.2014.925560

Wang, W., Wang, Z., Hou, R.; Guan, L., Dang, Y., Zhang, Z., Wang, H., Duan, L., Wang, Z. Modes, 2018: hydrodynamic processes and ecological impacts exerted by river–groundwater transformation in Junggar Basin, China. *Hydrogeol. J., 26,* 1547–1557. [**Google Scholar**] [**CrossRef**]

Y. Wada, L.P.H. van Beek, C.M. van Kempen, J.W.T.M. Reckman, S. Vasak, M.F.P. Bierkens., 2010: Global depletion of groundwater resources, Geophysical Research Letters, 37 (20), p. n/a-n/a, 10.1029/2010GL044571

Yangouliba, G.I., Kochb, H., Lierschb, S., Sintondjic, L.C., Sidibéd, M., Larbie, I., Manoba, A., Yiraf, L.Y., Dipamag, J-M., and Kwawuvia, D., 2022: Impacts of hydro-climatic trends and upstream water management on hydropower generation at the Bagré dam.

Young S, Balluz L, Malilay J., 2004: Natural and technologic material releases during and after natural disasters: a review. *Sci Total Environ* 322 :3–20

Zoungrana, T. P., 2007 : Problématique de l'accès à l'eau potable sur les rives du lac de Bagré, Burkina Faso. *Rev. Sc. Env. Univ. (*Togo), no 003 ISSN 1812-1413. https://www.academia.edu/30747796/Probl%C3 %A9matique_de_lacc%C3 %A8s_%C3 %A0_leau_ potable_sur_les_rives_du_lac_Bagr%C3 %A9_Burkina_FAso.

Articles

Fluixá-Sanmartín, J., Altarejos-García, L., Morales-Torres, A., and Escuder-Bueno, I., 2018 : Review article : Climate change impacts on dam safety, *Nat. Hazards Earth Syst. Sci., 18*, 2471–2488, https://doi.org/10.5194/nhess-18-2471-2018.

ICOLD: Bulletin on risk assessment in dam safety management, Tech. rep., International Commission on Large Dams, 2003.

IPCC: Glossary of terms, in: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, edited by: Field, C., Barros, V., Stocker, T., Qin, D., Dokken, D., Ebi, K., Mastrandrea, M., Mach, K., Plattner, G.-K., Allen, S., Tignor, M., and Midgley, P., A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, UK, New York, NY, USA, 555–564, 2012a.

Thesis

Casagrande, A., 1949: Soil Mechanics in the design and Construction of the Logan Airport. J. Boston Soc. *Civil Eng.,* Vol 36, No. 2. pp. 192–221.

Christian Desjarlais, 2018: Analysis of Piezometer Measurements and Stratigraphy at Sugar Lake Dam. B.A.Sc., University of British Columbia, 2018

Dunnicliff, John, 1993, 1988: Geotechnical Instrumentation for Monitoring Field Performance. *Wiley-Interscience.* p. 117. ISBN 0-471-00546-0.

In-Soo Jung, 2015: Anomaly Detection of Piezometer Data Collected from Embankment Dams Carnegie Mellon University CARNEGIE INSTITUTE OF TECHNOLOGY THESIS, ACCEPTED BY THE DEPARTMENTS OF Civil and Environmental Engineering Mario Berges February 18, 2015, AD. © Copyright by In-Soo Jung 2015 All Rights Reserved

Manual on Suburface Investigations, 1988: [[American Association of State Highway and Transportation Officials]] page 182

Links

"Barrage de Bagre". Ramsar Sites Information Service. Retrieved 25 April 2018.

"BOLGATANGA : More Spillage Expected From Bagre Dam". www.northernghana.com. Archived from the original on 2015-05-27. Retrieved 2015-05-27.

"Ghana News - Six more dead in Bagre Dam spillage". www.myjoyonline.com. Archived from the original on 2015-05-27. Retrieved 2015-05-27.

https://doi.org/10.1016/j.pce.2006.02.061

https://education.nationalgeographic.org/resource/dams https://www.pietrangeli.com/fr/bagre-barrage-en-terre-burkina-faso-afrique

https://docplayer.net/184406268-The-bagre-dam-spillage-conundrum-are-early-warning systems-leading-to-local-actions-in-flood-disaster-hotspot-communities-in-northern Ghana.

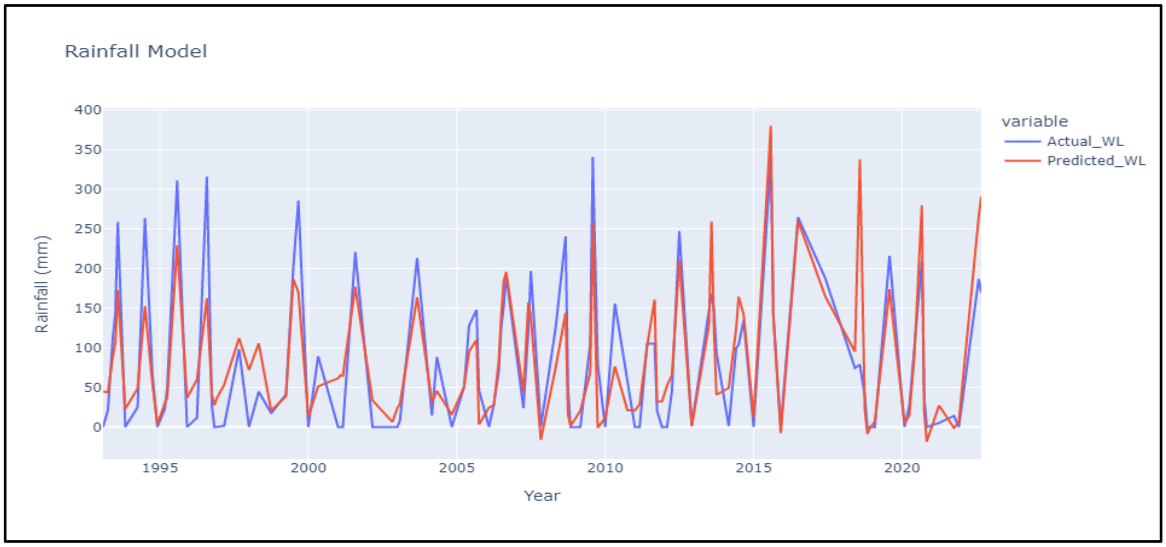
https://www.oregon.gov/oha/PH/HEALTHYENVIRONMENTS/DRINKINGWATER/SOURCEWATER/Documents/gwudi/gwudi-fact-sheet.pd

Appendix

Appendix 1. Rainfall model at the Bagre Dam

X1 = Water level; X2 = Evaporation; X3 = Irrigation; X4 = Spillage; X5 = Inflow

Rainfall = 2246.61 - 0.94 X1 - 0.50.13 X2 - 0.70X3 – 0.12 X4 + 0.26 X5



Model summary: R squared: 72.47%

Mean Absolute Error: 36.182507499938

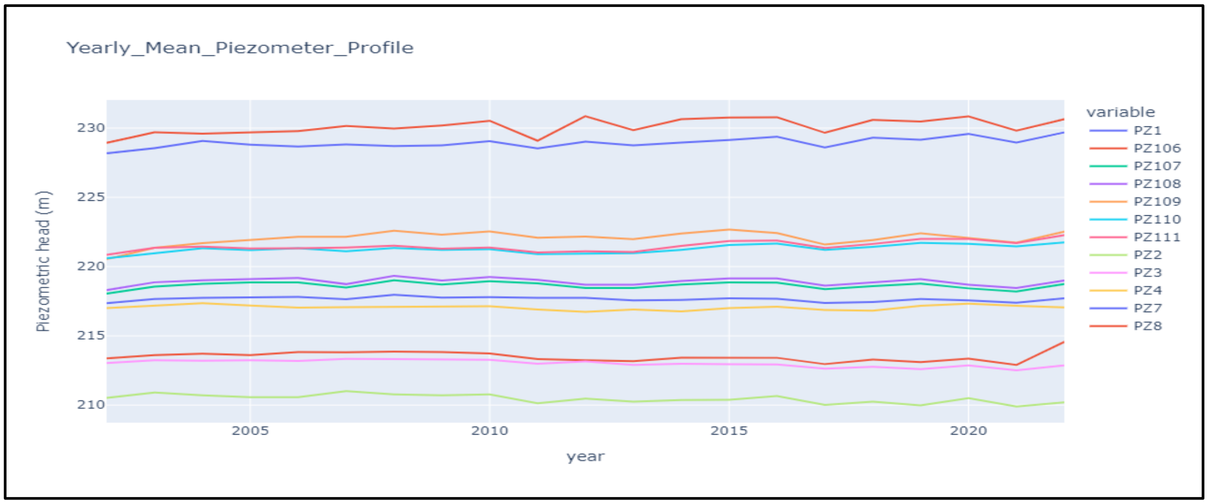
Mean Square Error: 2640.8972968541525

Root Mean Square Error: 51.389661381003016

Appendix 2. Data statistics for the period January 2002 to December 2022 (heads in meters)

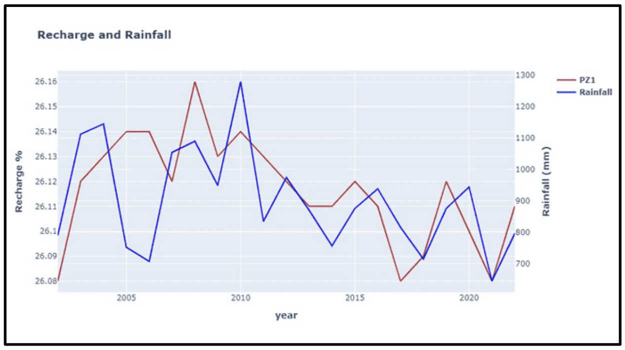
Dataset	Minimum	Maximum	Mean	1st quartile	Median	3rd quartile	Standard deviation
PZ1	216.88	218.47	217.6403	217.39	217.64	217.88	0.33805
PZ106	212.42	217.63	213.5001	213.115	213.5	213.87	0.588529
PZ107	217.42	219.88	218.6396	218.255	218.645	219.03	0.52551
PZ108	217.62	220.25	218.9113	218.48	218.92	219.31	0.563011
PZ109	219.64	224.07	222.0529	221.3375	222.12	222.78	0.926118
PZ110	219.98	222.34	221.2746	220.92	221.265	221.6525	0.528242
PZ111	220	222.73	221.484	220.9875	221.49	222.0475	0.669429
PZ2	208.94	214.16	210.4586	210.02	210.38	210.73	0.70683
PZ3	212.16	215.41	213.0134	212.72	212.965	213.2225	0.447212
PZ4	216.33	217.78	217.0482	216.73	217.02	217.3725	0.374106
PZ7	227.7	231.49	228.935	228.36	228.81	229.3725	0.732192
PZ8	228.11	233.22	230.1188	228.92	229.695	231.1475	1.377945
Water Level	226.41	235.13	231.2625	229.1025	231.41	233.3875	2.526244

Appendix 3. The yearly mean profiling of the groundwater

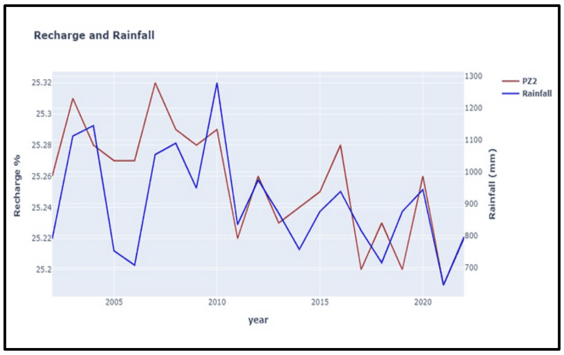


The position and closeness or farness of each PZ to the water level is the controlling factor to the groundwater recharge, those PZ which are having high influence by the reservoir are having an increasing trend while those which are far from the dam are having the slight decreasing this might be inferring that rainfall is playing a role in the recharge. In considering the factor of rainfall on the recharge it is safe to say that as climate change is affecting the release of rainfall so also it is observed that the recharge will decrease in most of the PZ showing a slight decreasing rate when rainfall is the factor of recharge.

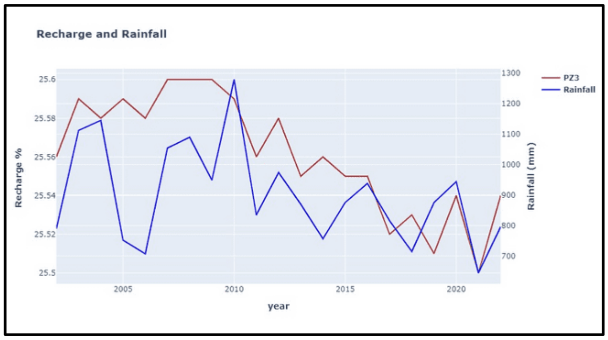
Appendix 4. Groundwater Recharge Trend and Rainfall



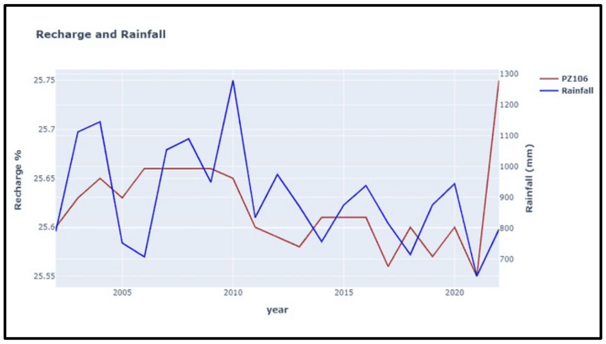
(a)



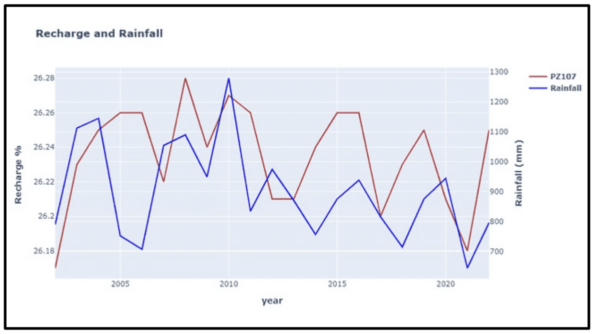
(b)



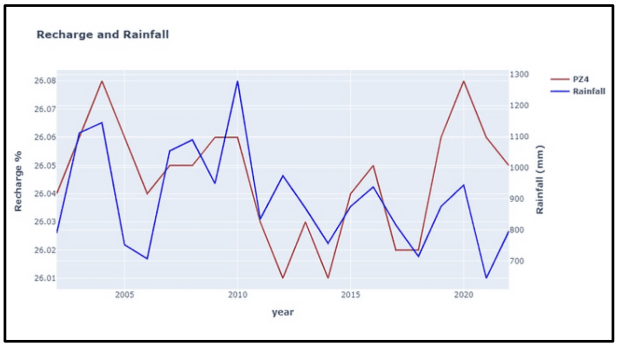
(c)



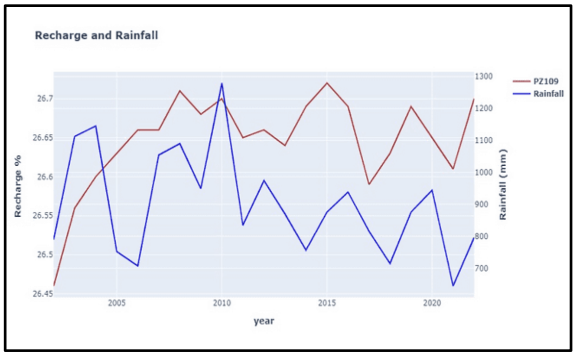
(d)



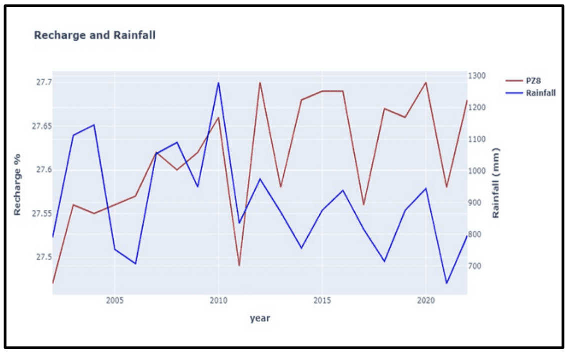
(e)



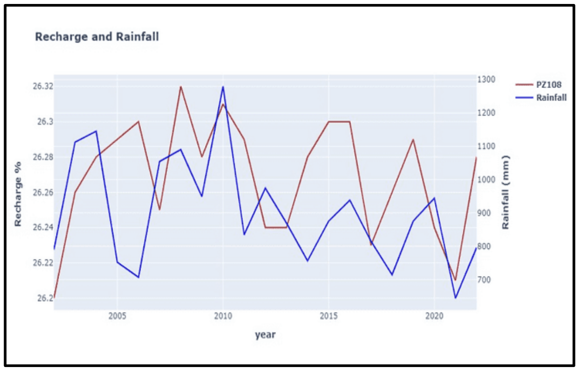
(f)



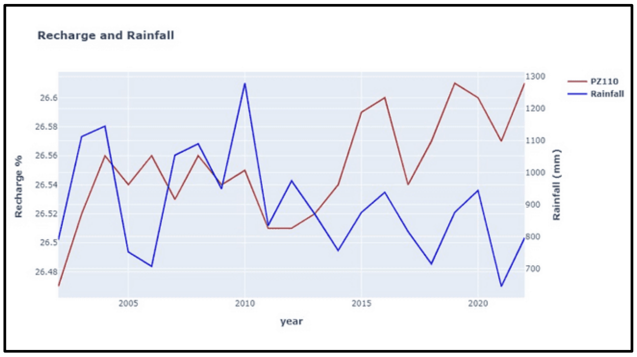
(g)



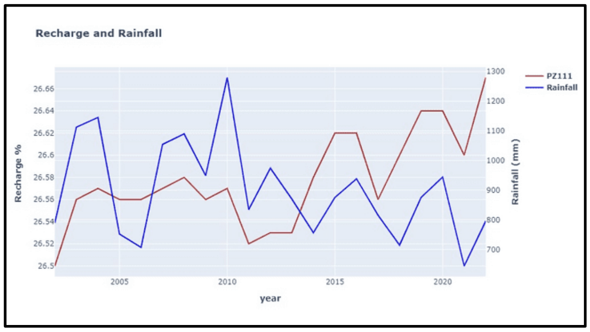
(h)



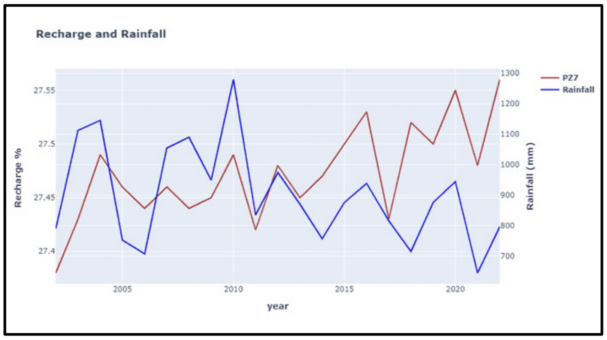
(i)



(J)



(k)



(l)

You can find the source codes and dataset used for this research in this repository: https://github.com/orowaletriumph/-Research-work-on-the-Bagre-Dam.git

Table of Contents