Estimation of Evapotranspiration and its relationship to Land use and Water resources in Luapula Catchment, Zambia

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***Abstract*— This study delves into the estimation of evapotranspiration (ET) and its intricate relationship with land use and water resources in Zambia's Luapula catchment. Utilizing data from DIVA-GIS and AppEEARS, based on MOD16-A2GF data, the analysis reveals a consistent increase in average evapotranspiration from 2000 to 2021, albeit persistently lower than potential evapotranspiration, indicative of water stress. This observation aligns with global findings, underscoring the prevalence of water limitations and stress in various ecosystems. Employing a vector autoregression (VAR) model incorporating MOD16-A2GF and Global Forest Watch data, the study scrutinizes the impacts of tree cover loss due to deforestation and gross emissions on water availability (precipitation) in Luapula catchment. The analysis demonstrates statistically significant results at a 5% level of significance, revealing that tree cover loss initially exhibits a positive impact on average precipitation at lag 1 (Coef= .026, P-value = 0.000), followed by a significant negative effect at lag 2 (Coef= -.012). Similarly, non-CO2 gross emissions display negative impacts on average precipitation (Coef= -.005, P=0.000), while CO2 equivalent emissions, particularly CO2 and Mg, show positive effects (Coef= .0002, P=0.000). Furthermore, the study assessed the impact of land use on evapotranspiration and results showed that tree cover loss due to deforestation initially stimulates average evapotranspiration at lag 1 (Coef= .009, P-value = 0.000), but later leads to negative impacts at lag 2 (Coef= -0.004, P=0.000). Similarly, non-CO2 gross emissions negatively influence average evapotranspiration at both lags, while CO2 equivalent emissions exhibit mixed effects, initially positive at lag 1 and turning negative at lag 2 (P-value = 0.000). These findings underscore the urgent need for policy interventions to mitigate the adverse effects of deforestation and emissions on water resources. Strengthening forest protection laws, promoting sustainable agriculture, and fostering afforestation and reforestation efforts are essential to ensure water availability and ecosystem services. Transitioning to renewable energy sources and reducing greenhouse gas emissions across sectors are vital steps in addressing climate change impacts and promoting sustainable land use practices.**

***Index Terms*— Evapotranspiration, precipitation, water, tree cover, emissions, land use**

I. INTRODUCTION

Evapotranspiration is the movement of water from the land to the atmosphere by evaporation from soil and other surfaces, as well as transpiration from plants (USGS, 2018). This process includes water evaporation from soil, groundwater, and land-based water bodies, along with water transport from soil to atmosphere through plants. Land use refers to how land is utilized for various human activities such as housing, industry, and recreation (OECD, 2022). It varies by region, with rural areas focusing on forestry and farming, while urban areas concentrate on housing and industrial uses (Internet Geography, 2022).

Water resources include all water bodies available for agricultural, industrial, commercial, recreational, public, and domestic use (Law Insider, 2022). These resources are crucial as only 3% of the Earth's water is fresh, with most of it frozen in glaciers and polar ice caps (Definitions, 2022). The remaining fresh water is primarily groundwater, with minimal amounts above ground or in the air. The interplay between evapotranspiration, land use, and water resources is significant. Land use affects evapotranspiration by altering soil properties and plant states, influencing water movement from soil and plants to the atmosphere (Chen et al., 2011).

Zambia's water resources are vital, particularly for rain-fed agriculture and electricity production. The country's reliance on variable rainfall makes it sensitive to water supply changes (Musonda, 2013). Hydropower, which provides over 75% of Zambia's electricity, depends on water availability in the Kariba dam (Aljazeera, 2022). Reduced water levels in 2022 led to plans for power cuts, highlighting the impact of limited water resources on economic activities. Despite this, Zambia is generally considered to have minimal water availability issues due to its diverse climatic zones (Mwenya, 2011).

Statistics based on data from Land and Carbon Lab (2022) shows that from 2002 to 2021, Luapula lost 328ha of humid primary forest, making up 0.11% of its total free cover loss in the same time period. Besides that, a total area of humid primary forest in Luapula decreased by 44% in this time period (as shown in **Figure 1**).

Figure 1 Primary Forest loss in Luapula, Zambia
Source: (Land and Carbon Lab, 2022)

In this regard, land use in the context of deforestation in Luapula has highly contributed to the decrease in humidity by 44% according to Land and Carbon Lab (2022). Although there has been an increase in the magnitude of deforestation in Luapula, computations of data form CHRS (2021) show evidence that Luapula is still among the provinces with the highest magnitude of rainfall estimated to be about 2453.500mm (as shown in **Figure 2**).

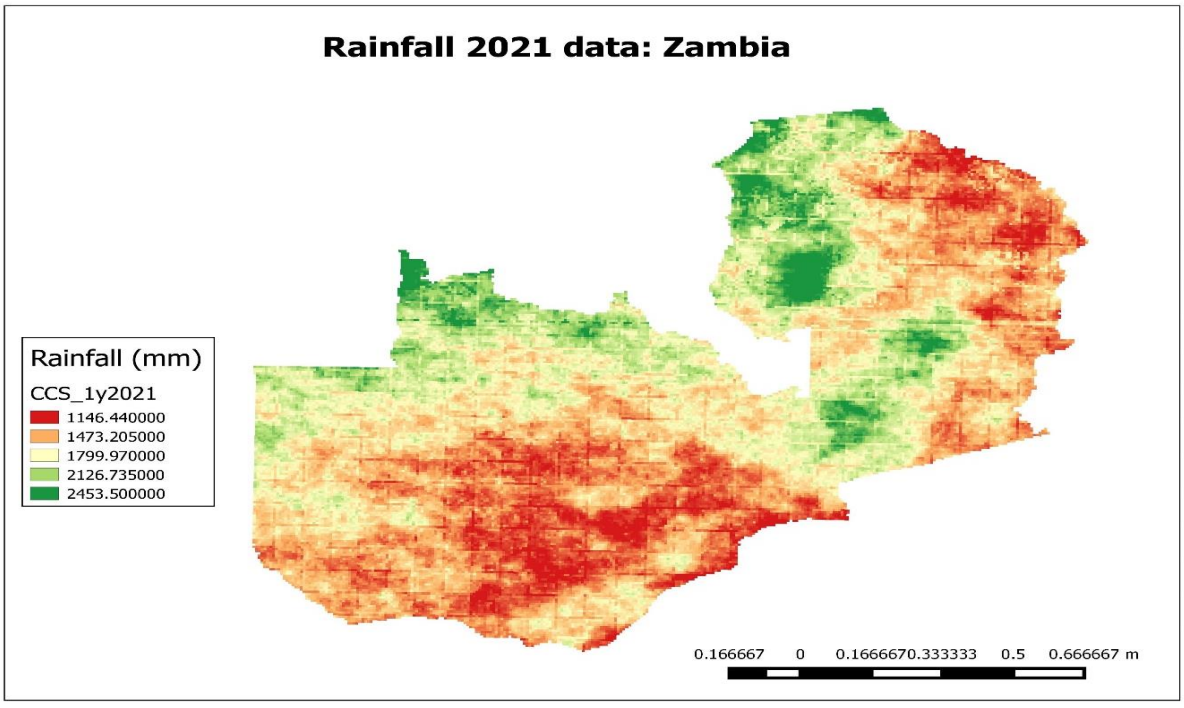

Figure 2 Rainfall 2021 data in Zambia
Source: (Land and Carbon Lab, 2022)

Nevertheless, despite Luapula being among the provinces with the highest record of rainfall, the magnitude of average daily rainfall in 2020 has decreased in comparison to the average daily rainfall in 2019 (as shown in **Figure 3**). As such, possible explanations for the decline can be proposed to be due to the increase in deforestation with regards to land use and other land use activities which may have had negative impacts on evapotranspiration. The decline in the magnitude of rainfall in the province can have detrimental effects on the potential for growth in the agricultural sector, hydropower production and other forms of economic activities dependent on water resources.

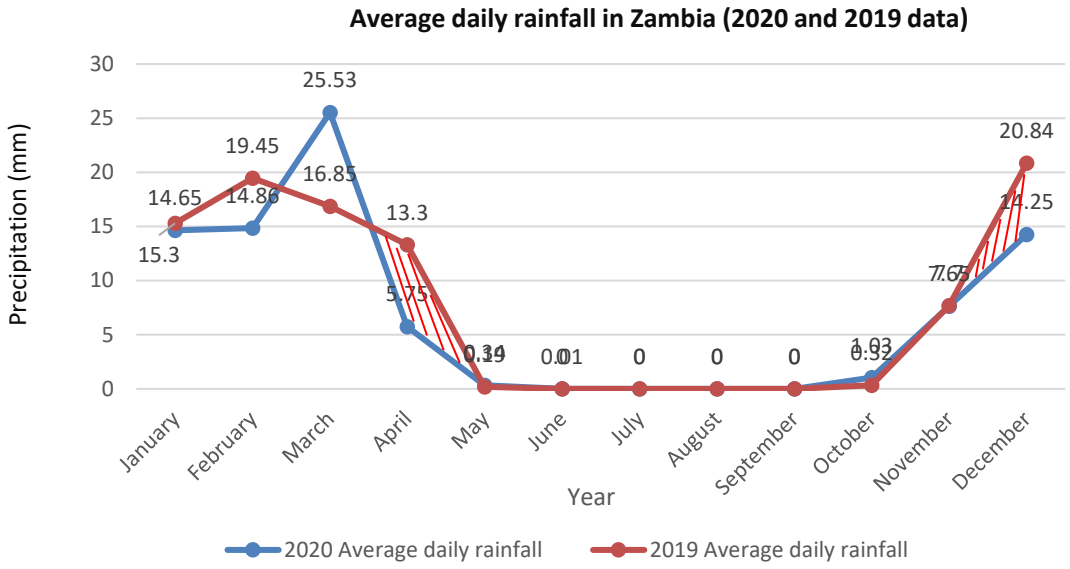

Figure 3 Average daily rainfall in Luapula province
Source: (Land and Carbon Lab, 2022)

II. RESEARCH PROBLEM

Among all resources, water is considered the most important resource in the world. With regards to this, (Kılıç, 2021) postulates that water is one of life's most basic need. However, only around 0.3% of the world's water resources are exploitable. In addition, water scarcity already exists in many areas, with over one billion people lacking access to safe drinking water (Kılıç, 2021). This issue is one of the most prominent signs of why it is imperative to be extremely concerned about water resources (Kılıç, 2021). As the world's population grows, so does the need for water. However, as a result of several effects, particularly human activities, water supplies are depleting, polluted, and being utilized unintentionally (Kılıç, 2021).

Zambia is sensitive to variations in water supply because its precipitation is very variable on a wide variety of scales. Therefore, the country's huge rural population, which relies mostly on rain-fed agriculture, is heavily impacted by regional climatic fluctuation. Rainfall is the most significant climatic variable in Zambia, because various industries rely heavily on water resources. Its variability and predictability are thus key aspects to explore in regional climate studies (Musonda, 2013).

Water as an important resource is also widely used for the production of electricity. Pertaining to this, Zambia highly depends on the availability of water in the Kariba dam to supply electricity to various parts of the country. Moreover, (Aljazeera, 2022) postulated that hydropower contributes more than 75% of Zambia's power generation. However, in 2022, due to lower water levels in lake Kariba, it was announced that the Zambian government was planning to implement policies for power cuts (Aljazeera, 2022). With regards to this, the minister announced that following a significant reduction in water levels in Lake Kariba, which threatens hydropower output, Zambia will begin restricting energy supplies to domestic users on December 15, 2022 (Aljazeera, 2022).

Luapula is located in the Agro-ecological Region (AER) III, which has the most yearly rainfall in the country. As a result, the province has the longest rain-fed agricultural season in the country, lasting about 140 200 days. There are also several natural water bodies, such as streams, rivers, and lakes (Prodevelopment, 2020). Zambia is recognized as a nation with minimal problems related to water availability (Mwenya., 2011), based on the geographical heterogeneity of water distribution throughout the country's climatic zones. However, there is a significant disparity between the amount of water accessible at the national level and access to this resource for socioeconomic development (Kunda, 2019).

Statistics based on data from Land and Carbon Lab (2022) shows that from 2002 to 2021, Luapula lost 328ha of humid primary forest, making up 0.11% of its total tree cover loss in the same time period. Besides that, a total area of humid primary forest in Luapula decreased by 44% in this time period (as shown in figure 2; above). In this regard, Land use in the context of deforestation in Luapula has highly contributed to the decrease in humidity by 44% according to Land and Carbon Lab (2022).

Nevertheless, despite luapula being among the provinces with the highest record of rainfall, the magnitude of average daily rainfall in 2020 has decreased in comparison to the average daily rainfall in 2019. As such, possible explanations for the decline can be proposed to be due to the increase in deforestation with regards to land use and other land use activities which may have had negative impacts on evapotranspiration. The decline in the magnitude of rainfall in the province can have detrimental effects on the potential for growth in the agricultural sector, hydropower production and other forms of economic activities dependent on water resources. Consequently, these activities are sources of pressure on the water availability and their cumulative impacts could result in change of hydrological patterns.

Most studies have analysed the effect of Land use on evapotranspiration but have overlooked possible effects of evapotranspiration on water availability at catchment level while others focus much on the impact of evapotranspiration on water availability without considering effects of land use on evapotranspiration. As such, this study aims to fill this gap in literature by

investigating the relationships between land use change, evapotranspiration distribution, and water availability at the catchment level with a focus on Luapula catchment. This study is therefore important for improving our water management practices.

III. OBJECTIVES OF THE STUDY

The aim of this study is to establish the relationships between land use change, evapotranspiration distribution, and water availability at the catchment level, with a focus on Luapula catchment in Zambia. One objective of this study is to establish the correlation between land use and water availability (precipitation) in Luapula catchment. This involves analyzing how different land uses influence the amount of precipitation in the region. Another objective is to examine the impact of tree cover loss due to deforestation on water availability (precipitation) in Luapula Province. This entails studying how deforestation affects the region's precipitation patterns and overall water availability. Additionally, the study aims to determine the impact of gross emissions that are carbon dioxide equivalent on water availability (precipitation) in Luapula catchment. This involves investigating how carbon dioxide emissions influence precipitation levels in the catchment area. The study also seeks to determine the impact of gross emissions that are not carbon dioxide equivalent on water availability (precipitation) in Luapula catchment. This involves examining how other types of emissions affect precipitation in the region. Furthermore, the study aims to estimate fluctuations of evapotranspiration in Luapula Province. This includes analyzing how evapotranspiration levels vary over time in the province. Finally, the study seeks to determine the impact of land use on evapotranspiration in Luapula Province. This involves investigating how different land uses influence evapotranspiration rates in the region.

IV. LITERATURE REVIEW

Biotic Pump Theory (BPT)

A new meteorological theory posits that forests are crucial for rainmaking (Hence, 2012). Radical scientific theories often take time to gain acceptance, especially when they challenge long-held beliefs. The biotic pump theory, proposed in 2007 by Russian scientists Gorshkov and Makarieva, argues that forests drive precipitation over land. Despite resistance from some meteorologists, this theory could significantly impact global forest policies if proven true. It suggests focusing on conditions for condensation rather than temperature gradients to understand atmospheric circulation (Hence, 2012).

The biotic pump theory asserts that forests create low-pressure systems over land, attracting moist ocean winds. This process relies on forest evaporation supplying water vapor more efficiently than open water surfaces. Natural forests, not monoculture plantations, can sustain this biotic pump due to their complex, evolved characteristics. These include root systems that manage soil moisture, biogenic aerosols that control vapor condensation, and tall trees that maintain vertical temperature gradients and prevent extreme weather. Such forests ensure stable moist air flows from the ocean, preventing severe droughts and floods (Gorshkov and Makarieva, 2007).

If the biotic pump theory is accurate, it highlights the economic and environmental importance of preserving natural forests. Economic development should not come at the cost of destroying forests, as this threatens water and food security. The theory implies that only wild forests can maintain the biotic pump due to their intricate biological processes. These forests support essential atmospheric moisture transfer, preventing soil moisture depletion and ensuring consistent evaporation. Monocultures or plantations cannot replicate these functions, as they lack the necessary interconnected features and can either evaporate too little or deplete soil moisture rapidly (Hence, 2012).

In essence, the biotic pump theory emphasizes the critical role of natural forests in the water cycle and climate regulation. It suggests that understanding and preserving these forests is vital for sustaining atmospheric moisture and preventing extreme weather events. The theory's implications extend to global environmental policies, underscoring the need for forest conservation to ensure ecological and economic stability.

Finally, in panel (c), there is a deforested Australia. Many people believe that Australia is unusually dry because it is located in the Hadley cell's descending branch (Hence, 2012). However, this graph demonstrates that such an interpretation is incorrect. Precipitation over Australia is four to six times lower than over the ocean in both wet and dry seasons. There is no biological pump in that location. Because the Australian continent is unforested, marine rainfall cannot penetrate regardless of how much moisture is above the ocean; during the rainy season, it precipitates in the coastal zones, generating floods. Restoring natural forests in Australia from coast to interior would gradually restore the continent's hydrological cycle (see **Figure 5**).

Therefore, in respect to the Biotic Pump Theory, the relationship between land use and evapotranspiration would be negative given that land use is in form of deforestation activities. Consequently, this suggests that, deforestation practices have potential to reduce rainfall in particular regions. In this regard, following postulates with regards to the Biotic Pump Theory, water availability is dependent on evapotranspiration which is influenced by land use. Henceforth, the Biotic Pump Theory is fundamental for analysing relationships between land use, evapotranspiration and water availability in this study.

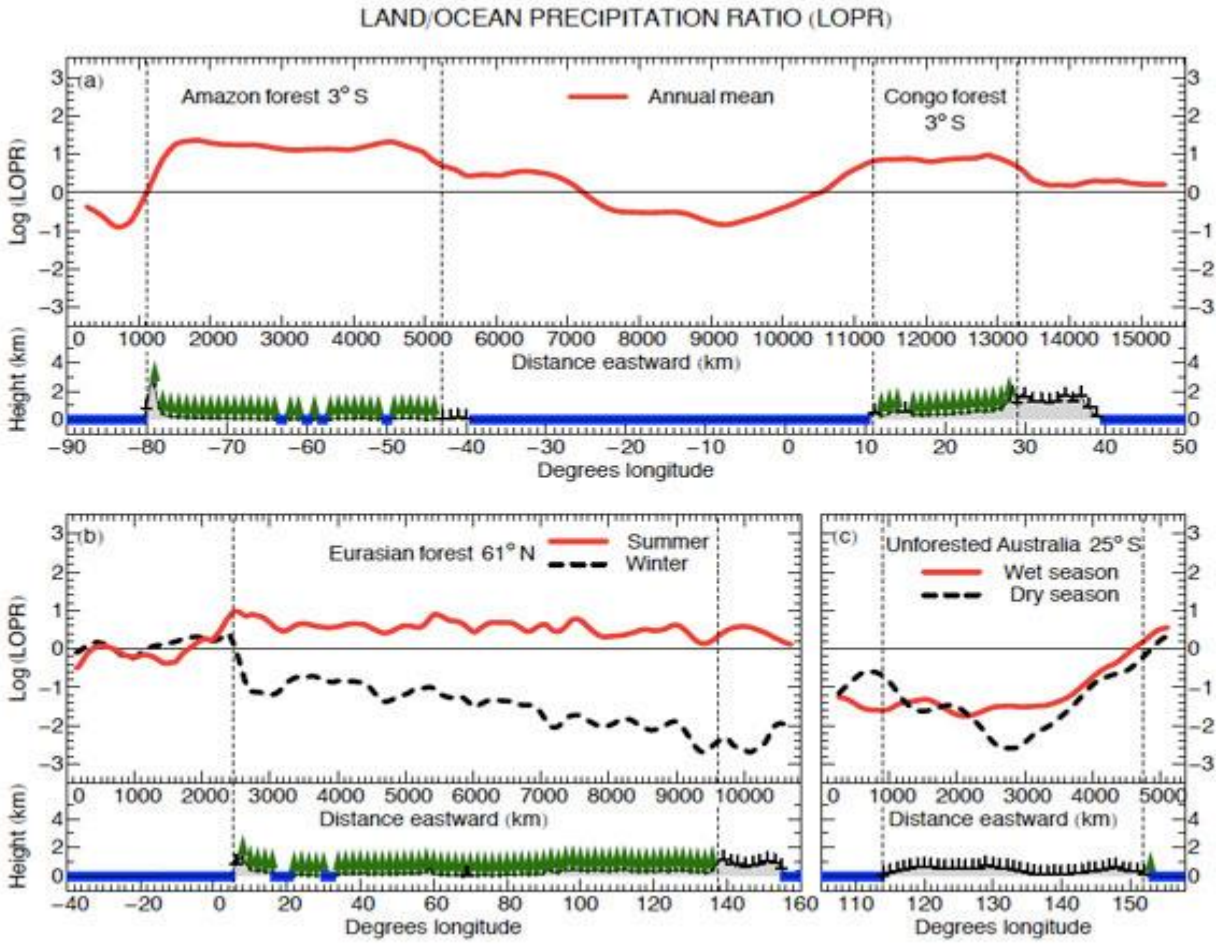

Figure 4 Biotic Pump Theory
Source: (Hence, 2012)

Empirical literature

The empirical review of similar studies in this research highlights several critical findings and gaps in the context of land use/land cover (LULC) changes, evapotranspiration (ET), and water availability. Kourouma et al. (2021) used remote sensing and GIS tools to analyze land use changes and environmental indicators in Chingola, Zambia, discovering significant increases in built-up areas, farmlands, and mining regions at the expense of natural resources, along with a decrease in rainfall and an increase in temperature. However, their study did not address the interplay between land use changes, evapotranspiration, and water availability at the catchment level.

Similarly, Tena et al. (2019) studied the influence of LULC changes on hydrological components in the Chongwe River Catchment, Zambia, finding significant increases in built-up areas and irrigated agriculture, coupled with a decrease in forest land. Their results indicated a negative impact on the catchment's hydrology, but they did not focus on the specific impacts of LULC changes on evapotranspiration and water availability.

Turk et al. (2021) established daily, monthly, and yearly evapotranspiration values for various land-use systems using satellite data in the Eastern Region of Saudi Arabia, demonstrating significant variability in ET based on land use type. However, they did not address how land use patterns influence ET and water availability under different climatic conditions.

Tshikeba (2016) quantified ET and its link to land use and water resources in the Lufimi watershed, DRC, noting that ET was more related to hydro-meteorological factors than land use patterns. This study did not explore the complex interactions between land use changes, ET, and water availability comprehensively.

Other studies, such as those by Mutayoba et al. (2018) and Aghsaei et al. (2020), examined the effects of LULC changes on hydrological water balance components and dynamic LULC changes on hydrological effects, respectively. Both studies identified significant impacts on ET and water yield but did not provide comprehensive analyses of the relationship between land use changes, ET distribution, and water availability.

The gaps identified in these studies are addressed by this research, which focuses on the specific impacts of land use changes on evapotranspiration and subsequent water availability in similar catchment areas. This study aims to provide a more comprehensive understanding of these interactions and their implications for water resource management (see Table 1).

Table 1 Summary of reviewed empirical studies

Author(s)	Focus of the Study	Region of Study	Results Obtained	Gap in the Study Addressed by This Study
Kourouma et al., 2021	Analyzing land use/cover change and environmental indicators using remote sensing and GIS tools	Chingola district, Zambia	Significant increase in built-up areas, farmlands, and mining regions at the expense of natural resources. Decrease in rainfall and increase in temperature.	Did not focus on the interplay between land use changes, evapotranspiration, and water availability at the catchment level.
Tena et al., 2019	Influence of LULC changes on hydrological components using WEAP Model	Chongwe River Catchment, Zambia	Built-up area increased by 382.77%, irrigated agriculture increased by 745.62%, forest land decreased by 41.11%. Streamflow grew at a rate of 0.13 Mm3/year. Negative impact on the hydrology of the catchment.	Lack of focus on the specific impacts of LULC changes on evapotranspiration and subsequent water availability in a similar catchment area.
Turk et al., 2021	Establishing daily, monthly, and yearly evapotranspiration for various land-use systems using satellite data	Eastern Region of Saudi Arabia	Yearly evapotranspiration values varied by land-use type. The SEBAL model showed high agreement with FAO P-M technique.	Did not address how land use patterns influence evapotranspiration and water availability in different climatic conditions.
Tshikeba, 2016	Quantifying evapotranspiration and its link to land use and water resources	Lufimi watershed, DRC	Remote sensing rainfall products closely matched ground measurements. ET was more related to hydro-meteorological factors than land use patterns.	Did not explore the complex interactions between land use changes, evapotranspiration, and water availability comprehensively.
Mutayoba et al., 2018	Effects of LULC changes on stream flows and hydrological water balance components using SWAT	Mbarali River Sub Catchment, Tanzania	Increase in cultivated land led to higher surface runoff but minor changes in water yield.	Did not investigate the detailed effects of evapotranspiration on water availability considering dynamic land use changes.
Aghsaei et al., 2020	Hydrological effects of dynamic LULC changes using SWAT model	Anzali wetland catchment, Iran	Increase in agricultural area and decrease in forest coverage led to changes in ET, water yield, and sediment yield.	Did not provide a comprehensive analysis of the relationship between land use changes, evapotranspiration distribution, and water availability.
Afzal & Ragab, 2020	Effects of climate and land use changes on hydrology using DiCaSM model	Don Catchment, UK	Significant decreases in streamflow and groundwater recharge predicted under high emission scenarios. Forest increase reduced streamflow and groundwater recharge.	Limited focus on the impact of land use changes on evapotranspiration and water availability in varied climatic scenarios.

Fan et al., 2022	Local Land Use Planning framework for Evapotranspiration Ratio regulation (ETR-LLUP)	Dongjiang River Basin, China	Identified spatially-varying connections between land-cover proportions and evaporative index. Addressed water stress and hydrological management strategies.	Did not focus on the specific impacts of land use changes on evapotranspiration and water availability at the catchment level.
Aguilos et al., 2021	Impacts of land-use change and drought on evapotranspiration and water balance	Lower coastal plain, USA	ET varied with stand age and drought conditions. Managed plantations showed different ET dynamics compared to natural forests.	Did not investigate the complex interactions between land use, evapotranspiration, and water availability in a diverse climatic context.
Pluntke et al., 2022	Long-term changes in water budget components due to climate change, plant change, and methodological aspects	Thuarandt Forest, Germany	Increase in ET and storage variability over time. Notable discrepancy between ET measurements and actual ET.	Limited exploration of how different land use changes affect evapotranspiration and water availability comprehensively.
Odongo et al., 2019	Impact of land use conversions between grassland and cropland on ET using SEBS	Lake Naivasha Basin, Kenya	Conversion from grassland to cropland increased ET by up to 12%. Annual ET decreased due to climatic factors.	Did not thoroughly explore the interplay between land use changes, evapotranspiration, and water availability in a similar catchment area.
Zitouna-Cebbi et al., 2022	Measuring evapotranspiration and surface energy fluxes in a Mediterranean agrosystem	Mediterranean region	Provided insights into energy flux dynamics and evapotranspiration ratios.	Did not focus on the specific impacts of land use changes on evapotranspiration and water availability at the catchment level.
Zhang et al., 2020	Simulating the influence of land use change on water balance using SWAT model	North Johnstone River watershed, Australia	Land use change influenced all hydrological variables. Urbanization increased surface runoff.	Did not provide a comprehensive analysis of the relationship between land use changes, evapotranspiration distribution, and water availability.

V. RESEARCH METHODOLOGY

Research approach

This study employs a quantitative approach to analyze the relationships between evapotranspiration, land use, and water availability in the Luapula catchment. For the first objective, the study uses Pearson correlation tests on time series data of land use patterns and precipitation levels to establish the correlation between land use and water availability. Regression modeling will quantify this relationship. To examine the impact of deforestation on water availability (objective 2), the Vector Autoregression (VAR) model will be used to assess changes in precipitation patterns. For objectives 3 and 4, focusing on CO2 emissions' impact on water availability, regression models will analyze emissions data and their correlation with precipitation, using the VAR model. Objective 5 involves estimating evapotranspiration fluctuations using remote sensing and meteorological data. Lastly, for objective 6, the VAR model will quantify the influence of land use changes on evapotranspiration dynamics. The quantitative approach ensures precise measurement, statistical inference, and informed decision-making for water resource management.

Data collection

Since there is lack of an adequate hydrometeorological network for the luapula catchment under investigation, the study will make use of other several remote sensing products which offer an opportunity for availability of hydrometeorological and land use information for the area of study. As such, different sources of data will be used to obtain relevant information pertaining to the research questions. With regards to this, information on rainfall or precipitation will be obtained from Weather and Climate (WC), Earth Explorer and GLDAS and CHIRPS from Climate Engine whereas information on evapotranspiration will be obtained from NASA at AppEEARS based on MOD16-A2GF data. Besides that, data on water sheds, lakes and other land features will be collected from the Hydrosheds website. Subsequently, data on land types and catchment area shapefiles will be collected from DIVA-GIS.

Data validation

To ensure the reliability of remote sensing data and the accuracy of model predictions, this study employed several validation methods. Given the inadequate hydrometeorological network in the Luapula catchment, the study used remote sensing products from various sources. Firstly, cross-validation techniques were implemented, splitting the data into subsets to train and test the model, identifying inconsistencies, and refining the analysis. Secondly, ground-based observations, though limited, were used to validate remote sensing data by comparing estimates of precipitation, evapotranspiration, and land use with available measurements. Sensitivity analysis was also performed to assess the model's robustness to variations in input parameters and data sources. This involved systematically varying key parameters and evaluating changes in model outputs. Additionally, spatial and temporal consistency checks identified anomalies or discrepancies by examining the spatial distribution of variables and analyzing temporal trends. These validation methods ensured the reliability and accuracy of the remote sensing data, enhancing confidence in the study's findings.

Time period of focus

The study will incorporate data covering the period from 2010 to 2021 with regards to precipitation (rainfall data), data on deforestation and gross emissions. However, data on Evapotranspiration and Potential Evapotranspiration will cover the period from 2000 to 2021.

Model for estimating potential and average evapotranspiration levels

The study will use two empirical models, in particular, Turc equation and the soil conservation service curve number approach. In respect to this, the Turc equation will be used to derive the catchment evapotranspiration based on the observed maximum and minimum temperature, and net ration. This is imperative in ensuring that there is simplicity for using less parameters that are usually available at our observed meteorological monitoring stations. Hence, following postulates by Fisher and Pringle (2013), the Turc relationship can be specified as:

$$ET_0 = 0.40 * \left(\frac{T_{mean}}{T_{mean+15}}\right) * (R_n + 50) \quad (1)$$

Note that ET_0 is potential evapotranspiration (mm/month), R_n is the net radiation (W/m^2), and T mean is the average air temperature (C^0) calculated as $(T_{max} + T_{min})/2$. Furthermore, the SCS-CN technique will be used to compute catchment runoff based on soil type and land use input. The usage of a digital elevation model can be utilized as an additional input (Kabiri, 2014). The following connection (Equation 2) expresses the primary input parameters required by the SCS CN method:

$$Q = \begin{cases} \frac{(P-0.25)^2}{P+0.85}, & P \geq 0.25 \\ 0, & P < 0.25 \end{cases} \quad (2)$$

Where Q is the catchment's runoff depth in millimetres, P is the storm rainfall in millimetres, and S is the possible maximum retention capacity of the catchment soil or infiltration in millimetres. For the sake of appropriateness and standardization, S is stated as a non-dimensional runoff Curve Number (CN):

$$S = \frac{25400}{CN} - 254 \quad (3)$$

Where CN represents the potential of runoff of the land cover-soil complex characteristics ruled by soil type, soil Antecedent Moisture Condition (AMC), and land use, management practices and treatment.

Model for estimating the impact of tree cover loss, gross emissions and non-carbon dioxide gross emissions on water availability(precipitation)

In order to estimate the impact of tree cover loss, gross emissions and non-carbon dioxide gross emissions on precipitation (water availability), this study used the Vector Autoregressive (VAR) model as:

$$Av\_precipitation_t = \sigma + \sum_{i=1}^{k} \omega_i Av\_precipitation_{t-i} + \sum_{i=1}^{k} \beta_s Tree\_cover\_loss_{t-s} + \sum_{j=1}^{k} v_j Gross\_emissions_{t-j} + \sum_{m=1}^{k} \emptyset_m Non\_carbon\_emissions_{t-m} + e_{1t}$$

Where $\omega_i, \beta_s, \nu_j \; and \; \emptyset_m$, are short run dynamic coefficients of the model and e_{1t} is the error term. $Tree\_cover\_loss$ denotes (1) Tree cover loss, $Gross\_emissions$ denotes (2) Gross emissions and $Non\_carbon\_emissions$ denotes (3) non-carbon dioxide gross emissions as independent variables. On the other hand, $Av\_precipitation$ denotes (4) average precipitation as the dependent variable.

Model for estimating the impact of gross emissions that are not carbon dioxide equivalent on water availability (precipitation)

Furthermore, in order to estimate the impact of tree cover loss, gross emissions and non-carbon dioxide gross emissions on average Evapotranspiration, this study used the Vector Autoregressive (VAR) model as:

$$Mean\_Evapotranspiration_t = \sigma + \sum_{i=1}^{k} \omega_i Mean\_Evapotranspiration_{t-i} + \sum_{i=1}^{k} \beta_s Tree\_cover\_loss_{t-s} + \sum_{j=1}^{k} \nu_j Gross\_emissions_{t-j} + \sum_{m=1}^{k} \emptyset_m Non\_carbon\_emissions_{t-m} + e_{1t}$$

Where $\omega_i, \beta_s, \nu_j \; and \; \emptyset_m$, are short run dynamic coefficients of the model and e_{1t} is the error term. $Tree\_cover\_loss$ denotes (1) Tree cover loss, $Gross\_emissions$ denotes (2) Gross emissions and $Non\_carbon\_emissions$ denotes (3) non-carbon dioxide gross emissions as independent variables. On the other hand, $Mean\_Evapotranspiration$ denotes (4) average Evapotranspiration as the dependent variable.

Rationale for choosing the VAR model

In this study, the impact of tree cover loss, gross emissions, and non-carbon dioxide gross emissions on precipitation (water availability) and average evapotranspiration in the Luapula catchment area was investigated using the Vector Autoregressive (VAR) model. This model was chosen due to its suitability for analyzing time series data and capturing the dynamic interactions between multiple variables over time.

The VAR model utilized in this study includes short-run dynamic coefficients, denoted as $\omega_i, \beta_s, \nu_j \; and \; \emptyset_m$, which represent the effects of the independent variables (tree cover loss, gross emissions, and non-carbon dioxide emissions) on the dependent variables (average precipitation and average evapotranspiration). These coefficients allow for the estimation of the immediate impact of changes in the independent variables on the dependent variables.

The rationale behind using the VAR model lies in its ability to account for the interdependence between variables in a system and capture how changes in one variable may affect others in the system over time. This is particularly relevant in studying complex environmental systems like the Luapula catchment, where various factors such as land use changes and emissions can influence both precipitation and evapotranspiration patterns.

Furthermore, by incorporating tree cover loss, gross emissions, and non-carbon dioxide emissions as independent variables, the study aims to assess their individual contributions to changes in precipitation and evapotranspiration in the Luapula catchment. This approach allows for a comprehensive analysis of the drivers of water availability and evapotranspiration dynamics in the study area.

The choice of using average precipitation and average evapotranspiration as dependent variables is justified by their importance in understanding water availability and hydrological processes in the Luapula catchment. These variables provide valuable insights into the overall water balance of the region and how it may be influenced by changes in land use and emissions.

Therefore, the utilization of the VAR model in this study enables a rigorous and systematic examination of the relationships between land use, emissions, and hydrological variables in the Luapula catchment. By providing detailed explanations of the statistical methods and the rationale behind their selection, this study ensures transparency and clarity in its approach, allowing readers to gain a deeper understanding of how the conclusions were reached.

Data analysis techniques

The defined watershed will be used to clip the global raster map of the two monthly remotely sensed rainfall products, GLDAS and CHIRPS, for which the extracted monthly values will be then calculated using a correlation technique with the observed monthly rainfall data. The procedure will be carried out using the Q-GIS program. To handle evapotranspiration data, the study will use two techniques. In particular, the first technique will be based on the previously described Turc empirical relationship, and the output potential evapotranspiration will be used to validate the derived remotely sensed evapotranspiration. The catchment polygon will be employed in the second strategy to cut the global raster map of remote sensing evapotranspiration. Statistical analysis, such as the Pearson correlation coefficient test, analysis of variance ANOVA test and Vector autoregression (VAR)will be used to determine the impact of land use on precipitation (rainfall) and the impact of land use on evapotranspiration (ET).

Study location

Luapula Province is located in northern Zambia and is bounded to the west, north, and south by the Democratic Republic of the Congo, and to the east by the Northern Province. Luapula is located in the Agro-ecological Region (AER) III, which has the most

yearly rainfall in the country (1,000mm 1,500mm). As a result, the province has the longest rain-fed agricultural season in the country, lasting 140 200 days. There are also several natural water bodies, such as streams, rivers, and lakes (Prodevelopment, 2020). Kawambwa is a district in Luapula where rainfall totals roughly 1406mm (as shown in figure 1). This enables a farming season of up to 190 days which is the longest in Zambia. Kawambwa also has a plethora of marshes, lakes, and rivers, including the province's biggest, the Luapula. These factors would appear to make Kawambwa of significant agricultural importance to the rest of the province and the country. Unfortunately, this has not resulted in changes in the socioeconomic position (Prodevelopment, 2020).

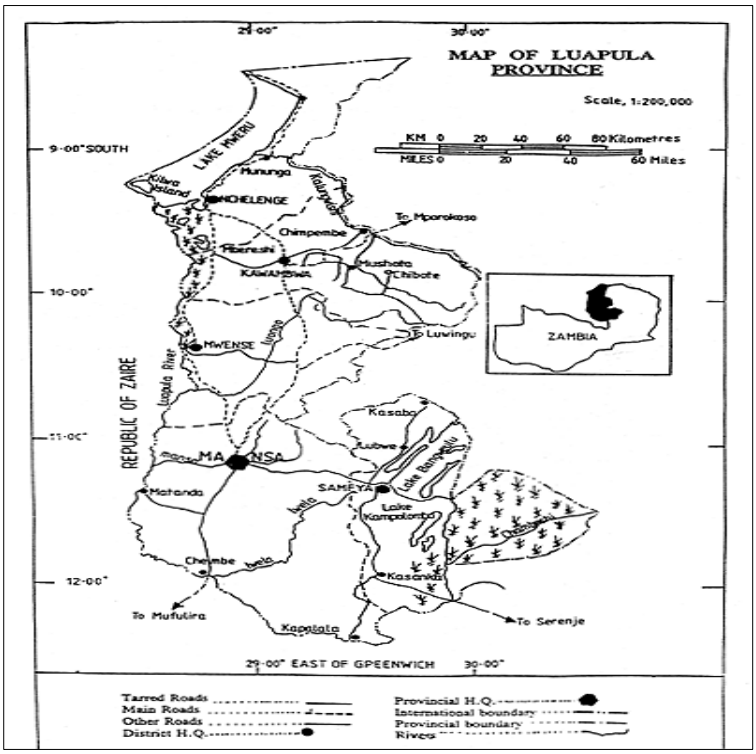

Figure 5 Study location

VI. RESULTS

Geographic analysis of features of Luapula catchment area

Luapula Province is divided into twelve districts namely, Chembe District, Chiengi District, Chifunabuli District, Chipili District, Kawambwa District, Lunga District, Mansa District, Milenge District, Mwansabombwe District, Mwense District, Nchelenge District and Samfya District (as shown in figure 6).

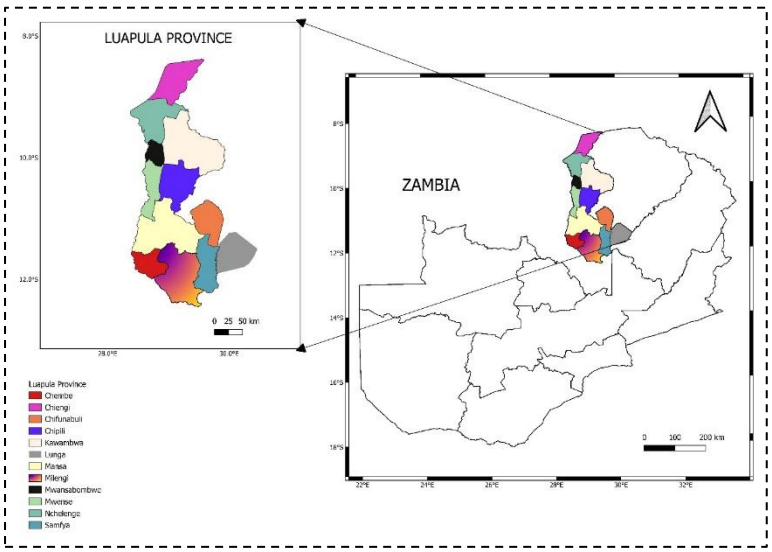

Figure 6 Study area analysis

Furthermore, with regards to the waterbodies in Luapula province, there are two lakes found in Luapula. In particular, the area is also covered by Lake Mweru and Lake Bangweulu (near Samfya) as shown in figure 7.

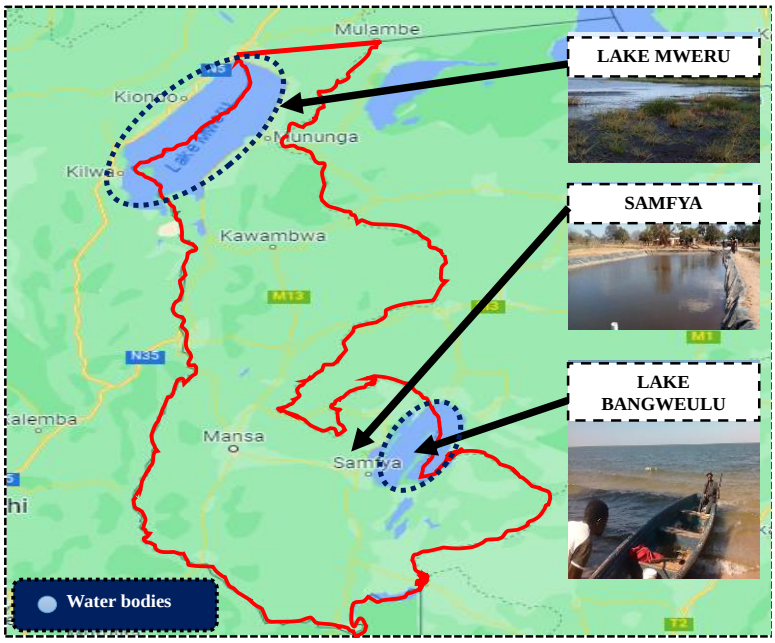

Figure 7 Water bodies in Luapula province

Furthermore, land use and land cover 2011 data from DIVA-GIS shows that most of the land in luapula catchment area is covered by forests (50-70%) and mostly used for planting crops. However, in comparison to the north-western province and Western province, North-Western province is also mostly covered by 75% forests but with relatively a few 50-70% crops. However, Western province is mostly covered by 50-70% crops but with a few grass/shrubs. Nonetheless, Luapula catchment area is covered by more water bodies compared to North-Western province, Western province, Southern province, Lusaka Province, Central Province, Copperbelt Province, Muchinga and Eastern province (as shown in figure 8; below).

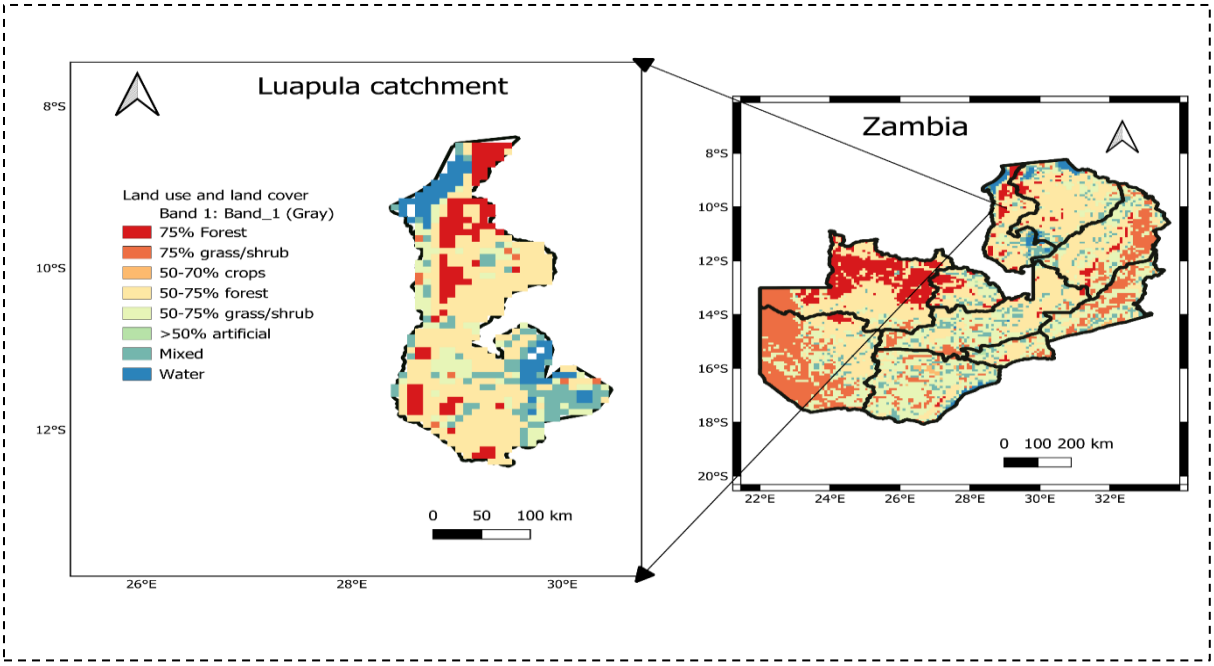

Figure 8 Land use and land cover in Luapula catchment

Furthermore, data from the Food and Agriculture Organization (FAO) on soil types shows that the soil type mostly found in Luapula province is Fo28-3ab. In addition, the data also shows that Luapula province has a few Kf88-1/3ha soil type. However, North-Western province has different soil types such as Fr13-2ab, Fx26-1a, Ge33-2/3a and Fo28-3ab. On the other hand, Central province mostly has Fo28-3ab soil type and Western province as Qc26-1a and Ge33-2/3a soil types (as shown in **Figure 9**).

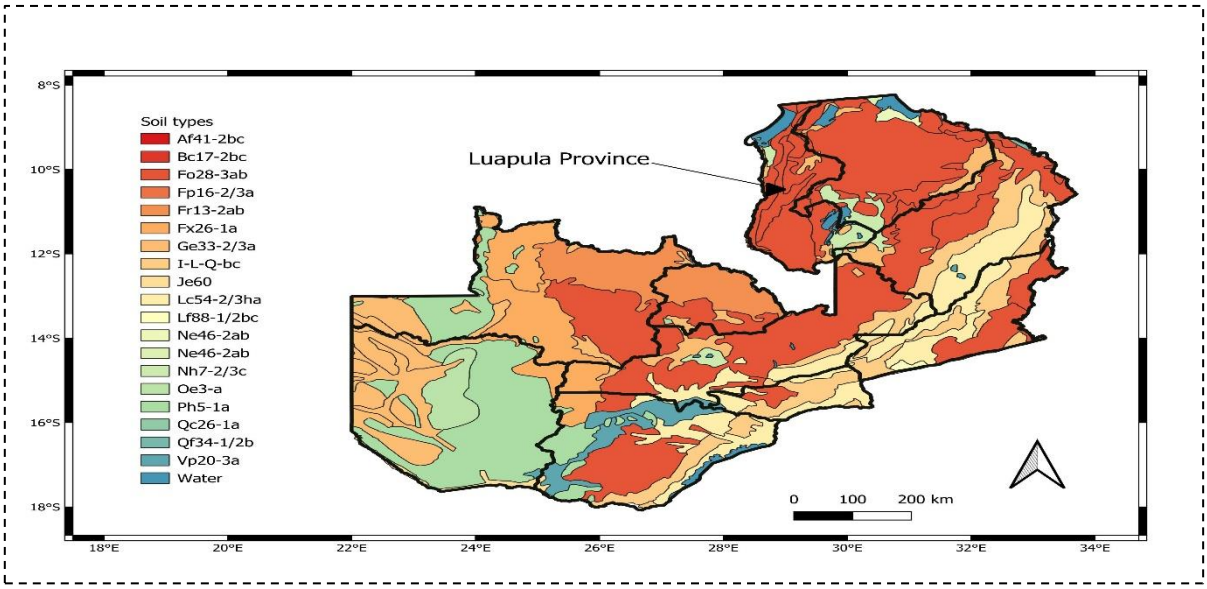

Figure 9 Soil types in Luapula province

Furthermore, statistics based on data from Weather and Climate running from 2010 to 2022 show that average precipitation in the Luapula catchment area measured in millimetres in 2010 was about 5.00mm and increased in 2011 to 5.72mm but later decreased to 4.24mm in 2012. Subsequently, in 2013, average precipitation in the Luapula catchment area increased to 13.56mm but later decreased by 78.02% to 2.98mm in the year 2014. More than that, in 2015, there was a slight increase in the magnitude of average precipitation in the Luapula catchment area to 4.04mm but it still later decreased to 2.25mm in the year 2016. However, average precipitation improved in the year 2017 following the increased from 2.25mm to 5.7mm (as shown in figure 10).

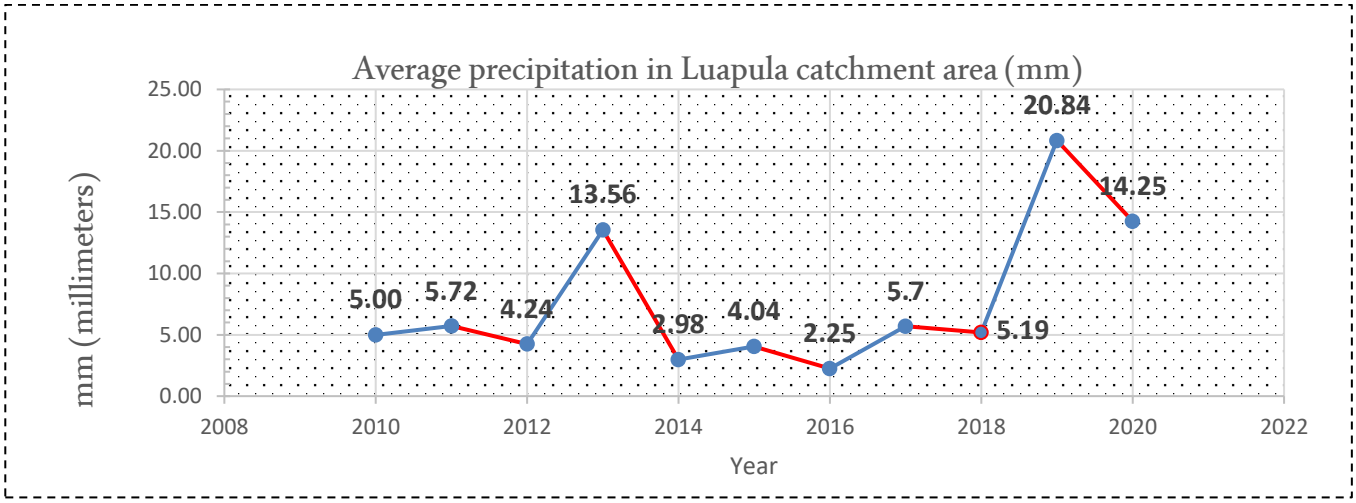

Figure 10 Average Precipitation in Luapula Province (2010 to 2020)

Nonetheless, average precipitation began to decrease slowly towards the year end in 2018 to 5.19mm. Notwithstanding, there was a huge improvement with regards to average precipitation in the Luapula catchment area by 75.1% in 2019, specifically, there was an increase from 5.19mm to 20.84mm. However, towards the end of 2020, average precipitation in the Luapula catchment area decreased by 31.6%, specifically to 14.25mm (in 2020) from 20.84mm (in 2019) (as shown in figure 10; above).

In addition, the study also investigated the extent to which Tree cover has been lost over the years from 2010 to 2020 in Luapula province. With a view to this, statistics based on data from Global Forest Watch shows that in 2010, there was a loss of tree cover by 45836.65 ha due to deforestation activities in Luapula catchment area. However, in 2011, the amount of tree cover lost due to deforestation activities in the Luapula catchment area reduced to 928.27 ha. More than that, in 2012, the magnitude of tree cover lost due to deforestations increased in Luapula catchment area to about 24459.22 ha (as shown in **Figure 11**).

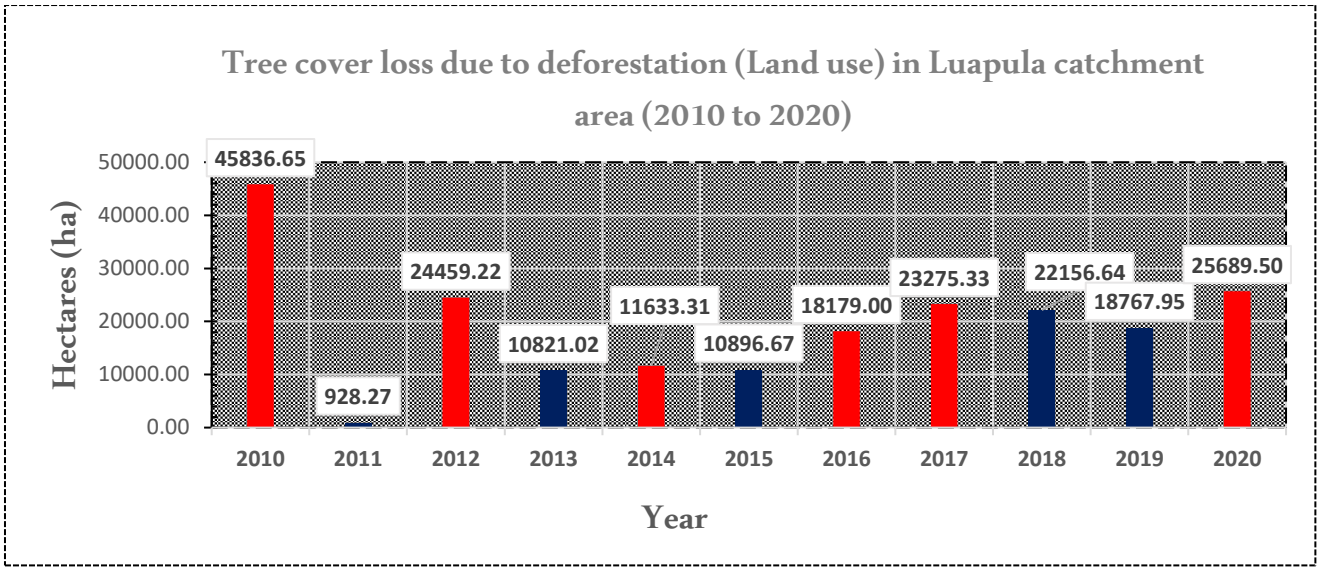

Figure 11 Deforestation (land use) in Luapula catchment area (2010 to 2020)

Furthermore, tree cover loss reduced in 2013 to 1082.02 ha but slightly increased in the year 2014 to 11633.31 and later reduced to 10896.67 ha in 2015. Subsequently, the magnitude of tree cover loss in Luapula catchment area increased to 18179.00 ha in 2016 and further increased to 23275.33 ha in 2017. Nonetheless, tree cover loss due to deforestation activities in Luapula catchment area reduced in 2018 to 2215.64 ha and further reduced to 18767.95 ha in 2019 but increased in 2020 to 25689.50 ha (as shown in **Figure 11**).

Besides that, statistics based on data from Global Forest Watch shows that the magnitude of gross carbon dioxide equivalent/Co2e (or non-Co2_Mg) emissions in Luapula was 831353.84 which later reduced to 15336.17. However, in 2012 gross carbon dioxide equivalent/Co2e (or non-Co2_Mg) emissions increased to 522097.29 but consequently reduced to 199040.02 in 2013. Moreover, in 2014, gross carbon dioxide equivalent/Co2e (or non-Co2_Mg) emissions increased to 209138.44 and further increased to 45788.90 in 2017 (as shown in figure 12; below).

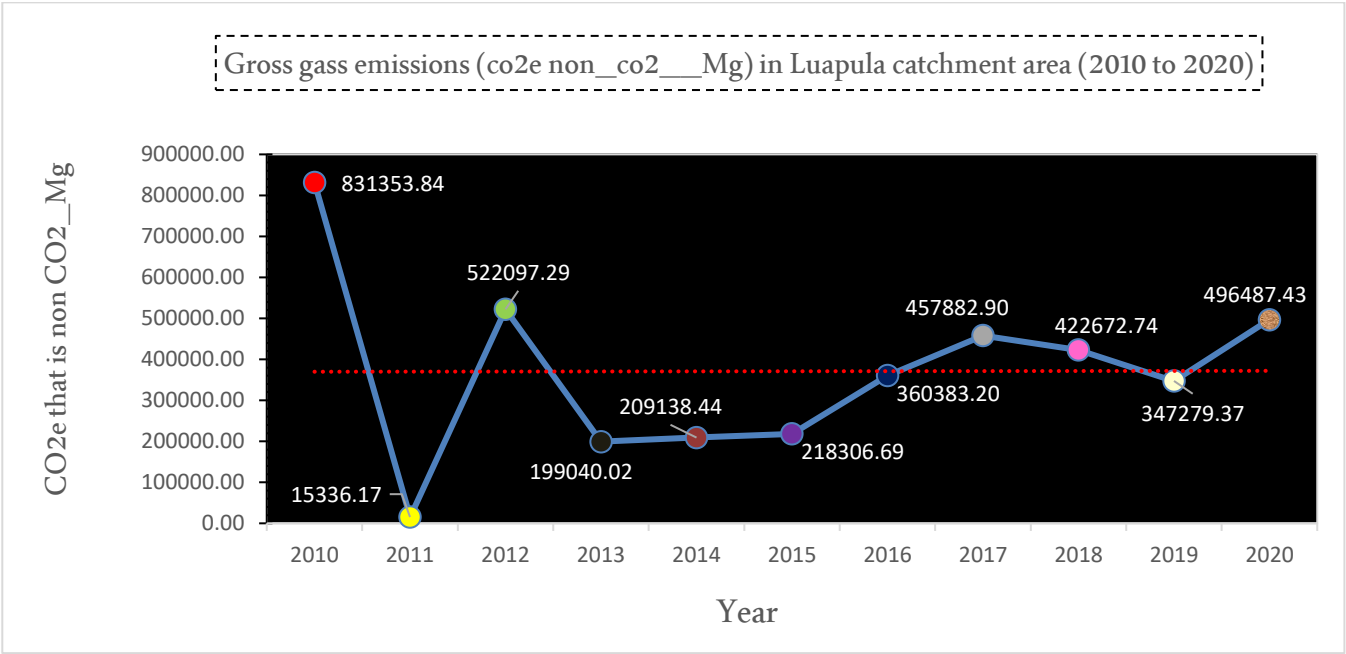

Figure 12 Gross emissions (Co2e /non_Co2_Mg) in Luapula catchment

In addition, despite reducing to 347279.37 in 2019, gross carbon dioxide equivalent/Co2e (or non-Co2_Mg) emissions in Luapula catchment area increased to 496487.43 in 2020 (as shown in figure 12; above). In this regard, overall, there has been a reduction in the magnitude of gross carbon dioxide equivalent/Co2e (or non-Co2_Mg) emissions in Luapula catchment area (see **Figure 12**). Similarly, statistics based on Global Forest Watch data also shows that the magnitude of Carbon dioxide equivalent emissions in Luapula which contain carbon dioxide with Mg only (Co2e_Co2_Mg) in 2010 was about 16333617.29 but later decreased to

338722.81 in 2011 but later increased to 8795923.528 in 2012. Since, the has further decreased to 8512631.05 in 2020 (as shown in **Figure 13**).

Deforestation and gas emissions can have a significant impact on the local and global environment, including water availability and precipitation patterns. Understanding the trends in deforestation and gas emissions can help to identify the potential impacts of land use on these factors. Deforestation can reduce the amount of moisture that is retained in the soil, which can lead to a decrease in water availability in the area. Trees and other vegetation act as natural water catchments, and when they are removed, water can no longer be stored in the same way. This can also result in reduced transpiration, which is the process by which plants release water into the atmosphere.

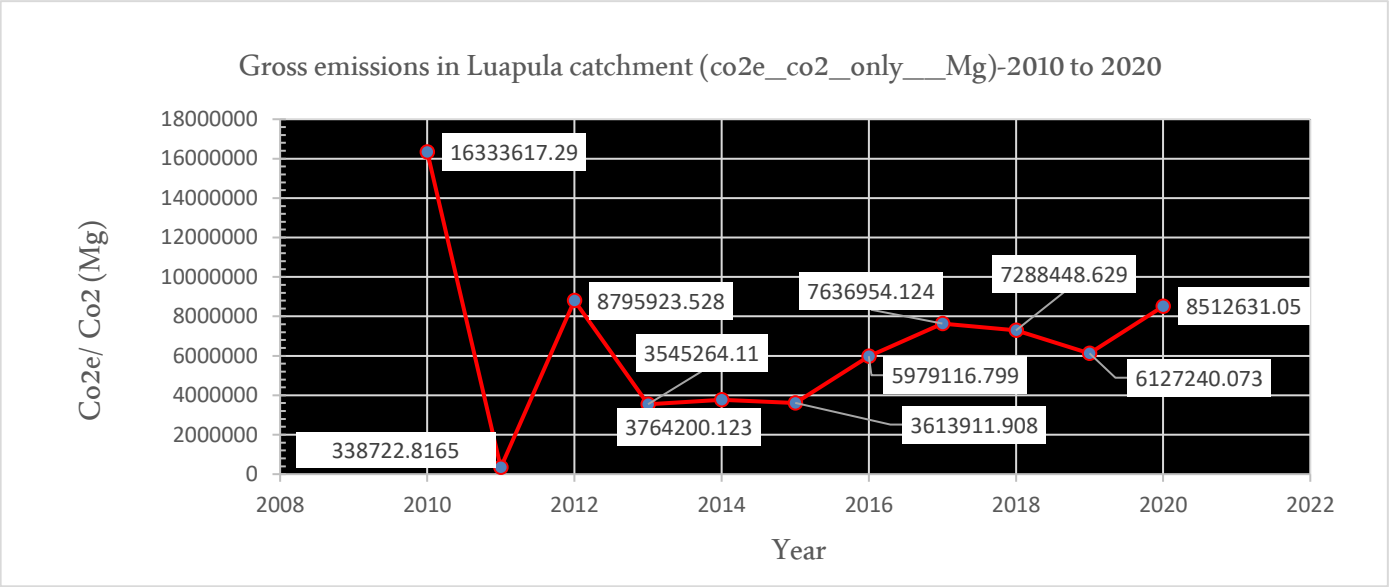

Figure 13 Gross emissions Carbon dioxide equivalent emissions in Luapula

The correlation between land use and water availability (precipitation) in Luapula catchment

The Luapula catchment is an important region in Zambia that provides a significant amount of water resources to the country, including the Luapula River, which is a major tributary of the Congo River. Understanding the correlation between land use and water availability in this region is critical for several reasons: Land use practices can affect water availability in a given area. For example, deforestation can reduce the amount of water that infiltrates into the ground, leading to decreased groundwater recharge and surface water flows.

Conversely, reforestation can increase water availability by improving infiltration rates and promoting greater soil moisture retention. On the other hand, Agriculture is a major land use activity in the Luapula catchment, and the amount of water available for irrigation can have a significant impact on crop yields. Understanding the correlation between land use and water availability can help farmers make informed decisions about crop selection and irrigation practices.

The Luapula catchment is home to a rich diversity of flora and fauna, and changes in land use can have a significant impact on ecosystem health. For example, excessive use of fertilizers and pesticides can lead to pollution of water bodies, while deforestation can lead to soil erosion and loss of habitat. Access to clean water is critical for human health, and understanding the correlation between land use and water availability can help identify areas where water quality may be compromised.

For example, areas with high levels of agricultural runoff or industrial pollution may pose a risk to human health. In summary, understanding the correlation between land use and water availability in the Luapula catchment is critical for ensuring the sustainable use of water resources, promoting agriculture and ecosystem health, and protecting human health. Therefore, this study also further investigated the correlation between land use in terms of deforestation which leads to tree cover loss on water availability in terms of average precipitation (as shown in **Table 2**).

Results based on computations of data show that the correlation between average precipitation in Luapula catchment and tree cover loss due to deforestation activities is negative. However, this correlation test was found to be statistically insignificant at 5% level of significance considering the P-value of 0.966 associated with the Pearson correlation coefficient of -0.015. On the other hand, the correlation between average precipitation in Luapula catchment and gross emissions of Co2e that is non Co2 with is also negative but statistically insignificant at 5% level of significance following the Pearson correlation coefficient of -0.038 associated with a P-value of 0.912. Similarly, the Pearson correlation coefficient yield a coefficient of -0.038 associated with a P-value of 0.912 which showed statistical insignificance at 5% level of significance (as shown in Table 2).

Table 2 Pearson correlation test

Correlations

		Average Precipitation in Luapula catchment	Tree cover loss due to deforestation activities in Luapula	Gross emissions (Co2e that is non Co2 with Mg)	Gross emissions (Co2e that is Co2 with Mg only)
Average Precipitation in Luapula catchment	Pearson Correlation	1	-.015	-.038	-.038
	Sig. (2-tailed)		.966	.912	.912
	N	11	11	11	11
Tree cover loss due to deforestation activities in Luapula	Pearson Correlation	-.015	1	.994**	.998**
	Sig. (2-tailed)	.966		.000	.000
	N	11	11	11	11
Gross emissions (Co2e that is non Co2 with Mg)	Pearson Correlation	-.038	.994**	1	.992**
	Sig. (2-tailed)	.912	.000		.000
	N	11	11	11	11
Gross emissions (Co2e that is Co2 with Mg only)	Pearson Correlation	-.038	.998**	.992**	1
	Sig. (2-tailed)	.912	.000	.000	
	N	11	11	11	11

**. Correlation is significant at the 0.01 level (2-tailed).

Conversely, the Pearson correlation test showed that the correlation between tree cover loss due to deforestation activities in Luapula and gross emissions (Co2e that is non Co2 with Mg) is positive and statistically significant at 5% level of significance. With regards to this, the Pearson correlation test yield a correlation coefficient of 0.994** with a P-value of 0.000 (see, table 0.1; above). Subsequently, the correlation between tree cover loss due to deforestation activities in Luapula and gross emissions of Co2e that is Co2 with Mg only is also positive and statistically significant following the Pearson correlation coefficient of 0.998** with a P-value of 0.000 (as shown in **Table 2**).

Furthermore, measuring the effect of deforestation or land use change on precipitation is important, but it is not enough to fully understand the impact of these activities. It is also necessary to measure the impact on average precipitation because it provides a more comprehensive picture of the long-term effects. Deforestation and land use change can affect the local and regional climate by altering the balance of energy and water in the ecosystem. Trees play a crucial role in regulating the water cycle by absorbing and releasing water through their leaves. When trees are removed, the land surface becomes more reflective, which can lead to increased solar radiation absorption and higher temperatures. This can lead to changes in the atmospheric circulation and precipitation patterns.

Examining the impact of tree cover loss due to deforestation and gross emissions on water availability (precipitation) in Luapula catchment area

Measuring the effect of deforestation on precipitation only tells us how much the precipitation has changed due to the activity. However, measuring the impact on average precipitation takes into account the long-term effects of deforestation. It provides a more accurate understanding of how deforestation can alter the water cycle and ultimately impact the local and regional climate. Furthermore, measuring the impact on average precipitation can help policymakers and stakeholders make informed decisions about land use management. If the impact on average precipitation is significant, it may be necessary to implement measures to mitigate the effects of deforestation or to develop alternative land use strategies that have a smaller impact on the water cycle. As such, this study also went a step further by investigating the impact of deforestation activities or land use on precipitation in Luapula catchment area (as shown in **Figure 12**).

Vector autoregression

Sample: 2012 - 2020			Number of obs	= 9
Log likelihood =	667.254		AIC	= -140.2787
FPE =	.		HQIC	= -141.9811
Det(Sigma_ml) =	4.72e-70		SBIC	= -139.4898

Equation	Parms	RMSE	R-sq	chi2	P>chi2
average_precip~m	9	0	1.0000	.	.
umd_tree_cover~a	9	0	1.0000	2.40e+22	0.0000
Gross_emission~2	9	0	1.0000	5.93e+22	0.0000
Gross_emission~g	9	0	1.0000	7.03e+22	0.0000

	Coef.	Std. Err.	z	P>|z|	[95% Conf.	Interval]
average_precipitationmm						
average_precipitationmm						
L1.	-3.121468	4.88e-11	-6.4e+10	0.000	-3.121468	-3.121468
L2.	-8.902094	1.50e-10	-5.9e+10	0.000	-8.902094	-8.902094
umd_tree_cover_loss__ha						
L1.	.0262389	6.05e-13	4.3e+10	0.000	.0262389	.0262389
L2.	-.0123313	3.35e-13	-3.7e+10	0.000	-.0123313	-.0123313
Gross_emissions_non_Co2						
L1.	-.004541	7.08e-14	-6.4e+10	0.000	-.004541	-.004541
L2.	-.000738	1.40e-14	-5.3e+10	0.000	-.000738	-.000738
Gross_emissions_Co2e_Mg						
L1.	.0001986	2.60e-15	7.6e+10	0.000	.0001986	.0001986
L2.	.0000713	1.62e-15	4.4e+10	0.000	.0000713	.0000713
_cons	58.2804	1.13e-09	5.2e+10	0.000	58.2804	58.2804

Figure 12 Impact of deforestation activities (Land use) on precipitation in Luapula catchment using Vector autoregression

The vector autoregression was performed to investigate the impact of tree cover loss due to deforestation activities in Luapula catchment, gross emissions of Co2e but non-Co2 and gross emissions of Co2e with Co2 (only Mg) on average precipitation. Pertaining to this, the regression was done based on the period from 2012 to 2020 which amounted to 9 observations. Consequently, results showed that the impact of tree cover loss due to deforestation on average precipitation is positive at lag 1 but becomes negative on deforestation at lag 2 (see table 0.2; above). These results were found to be statistically significant at 5% level of significant considering the P-values of 0.000*** yield for the variable. This implies that the immediate impact of deforestation or loss of tree cover in Luapula on average precipitation maybe positive (at lag 1) but would take some time after lag 1 (at lag 2) to reveal negative and statistically significant impacts on average precipitation overtime (as shown in **Figure 12**).

On the other hand, results also showed that gross emissions that are carbon dioxide equivalent but not carbon dioxide (Co2) have negative and statistically significant impacts on average precipitation in Luapula catchment. However, results showed that carbon dioxide based gross emissions with Mg only which are Co2e tend to have positive and statistically significant impacts on average precipitation (as shown in **Figure 12**).

Estimating fluctuations of Evapotranspiration in Luapula province

Accurate estimation of ET can help farmers to determine the water requirements of crops and irrigate accordingly. By knowing the amount of water that is evaporated and transpired by crops, farmers can optimize the amount of water they use to irrigate their crops, thereby reducing water wastage and improving yields. ET plays a crucial role in the hydrological cycle and is a major component of the water balance. In Luapula province, where water resources are limited, understanding the fluctuations of ET can help water managers to make informed decisions on water allocation, storage, and distribution. It can also help in the management of watersheds, river systems, and reservoirs.

Climate change is expected to affect the water balance in Luapula province, and accurate estimation of ET can help to assess the impact of climate change on the hydrological cycle. By monitoring fluctuations of ET over time, it is possible to identify long-term trends and changes in the water cycle, which can help in planning and adaptation to climate change. In Luapula province, where irrigation is essential for crop production, accurate estimation of ET can help farmers to determine the optimal timing and frequency of irrigation. By knowing the daily fluctuations of ET, farmers can schedule irrigation to coincide with periods of high-water demand

by crops, thereby improving water use efficiency and reducing water stress. Overall, estimating fluctuations of Evapotranspiration in Luapula province is crucial for sustainable agriculture, water management, and adaptation to climate change. It can help farmers, water managers, and policy-makers to make informed decisions on water allocation, irrigation scheduling, and climate change adaptation. Therefore, this study also went further by estimating evapotranspiration in Luapula province using data from Earth data or AppEEARS running from 2000 to 2023 based on estimated of MOD16ATGF dataset (shown in **Figure 13**).

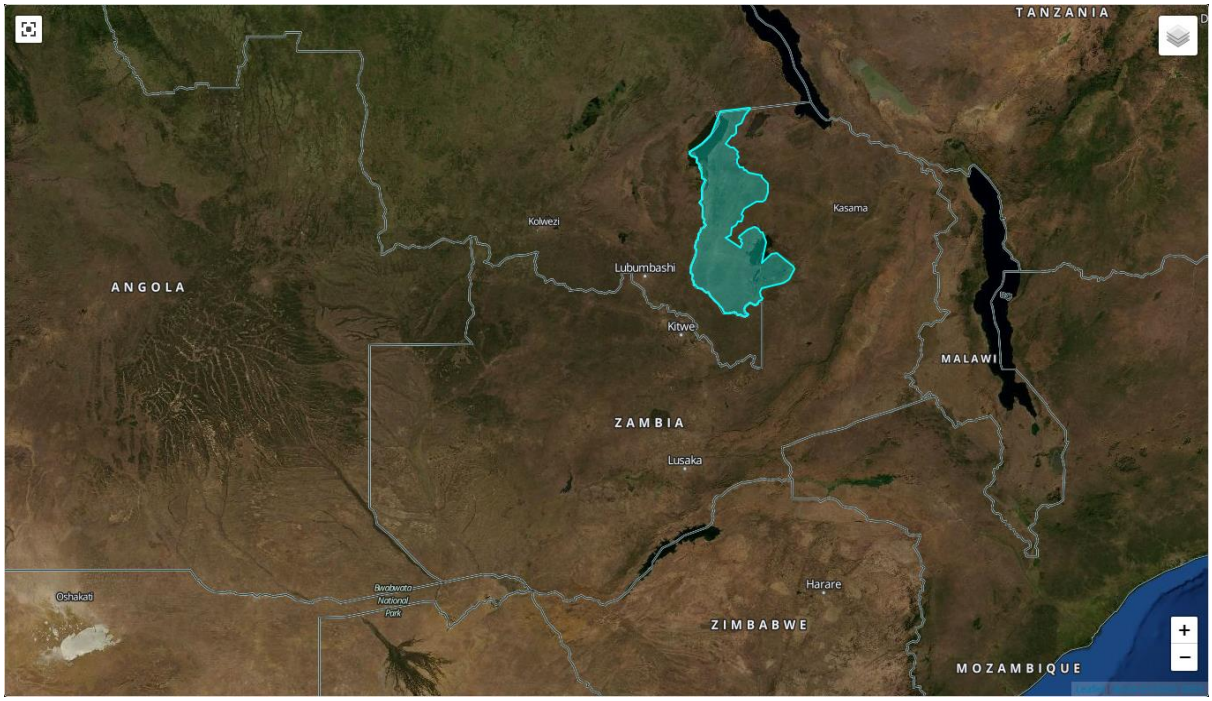

Figure 13 Estimation of ET on Luapula catchment
Author's submission of Luapula catchment shapefile data to AppEEARS

In respect to the results obtained based on estimations of Average Evapotranspiration in Luapula catchment, the maximum average evapotranspiration exhibited over the years from 2000 to 2021 is 39mm whereas the minimum is 4mm (as shown in **Figure 14**).

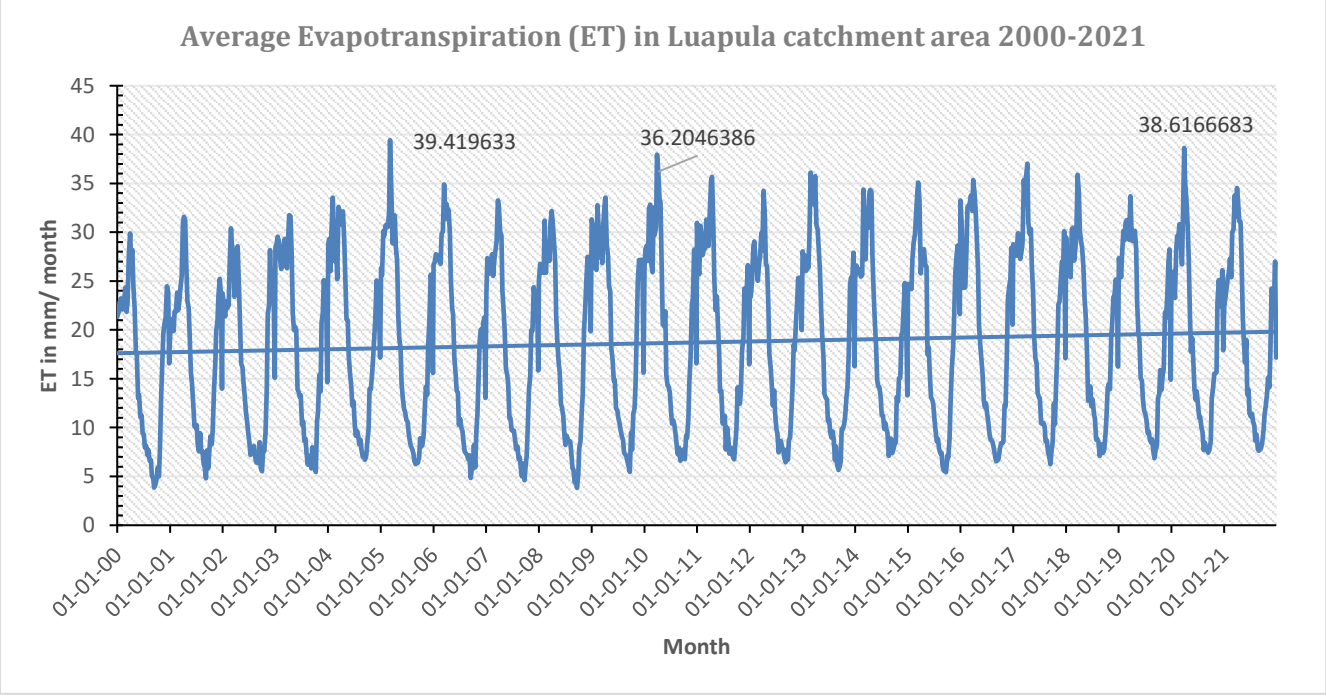

Figure 14 Average Evapotranspiration (ET) in Luapula catchment area 2000-2021
Author's computation (2024) using data from AppEEARS

Overall, the average evapotranspiration in Luapula catchment seems to have been increasing as can be observed from the trendline fitted in the data running from 2000 to 2021 (in **Figure 14**).

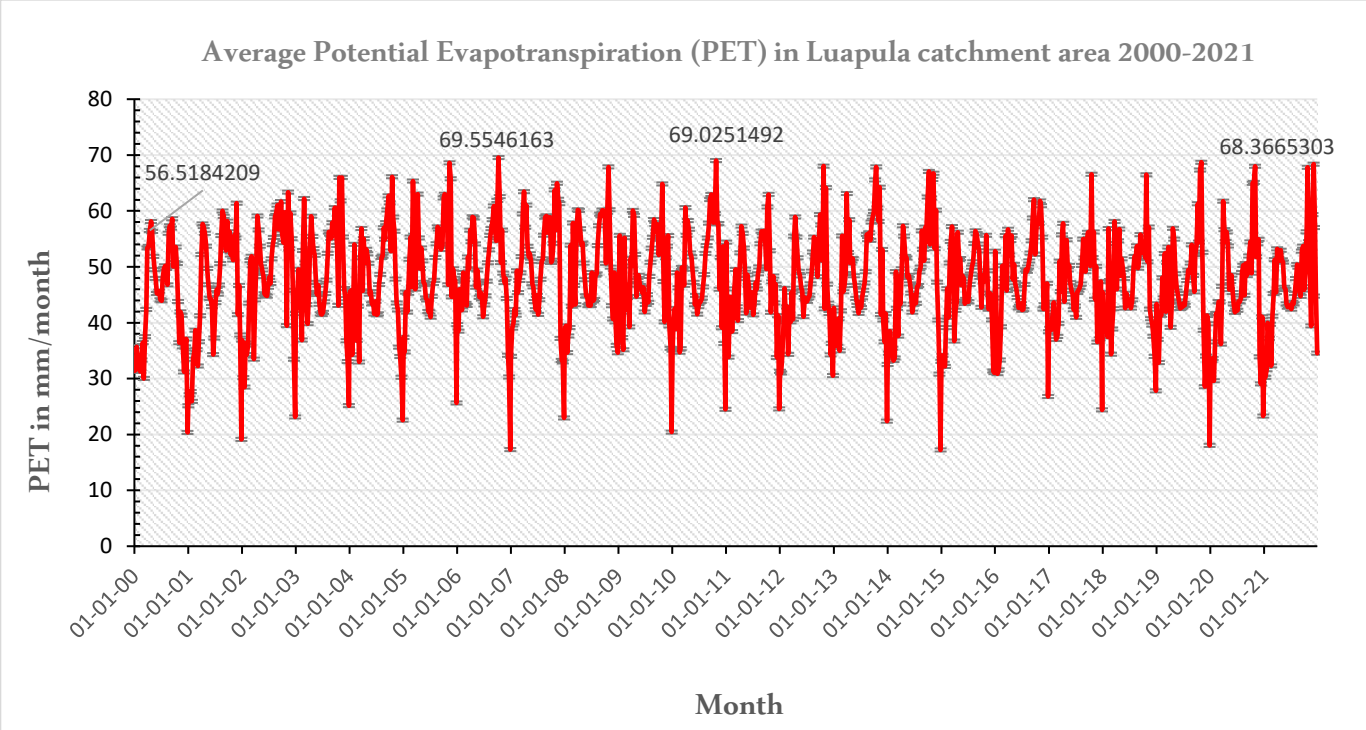

Figure 15 Average Potential Evapotranspiration (PET) in Luapula catchment area 2000-2021
Author's computation (2024) using data from AppEEARS

Similarly, results obtained based on estimations of the average potential evapotranspiration (PET) show that the maximum average potential evapotranspiration exhibited in Luapula catchment area is 17mm while the minimum is 70mm (as shown in **Figure 15**). Subsequently, fluctuations over the years from 2000 to 2020 of potential evapotranspiration show that the magnitude of potential evapotranspiration has been increasing along with magnitudes of evapotranspiration (compare **Figure 14** to **Figure 15**).

Notwithstanding, overall, it can be observed (in **Figure 16**) that from 2000 to 2021, the magnitude of average evapotranspiration (ET) has been lower than the potential evapotranspiration (PET) in Luapula catchment area (see **Figure 16**). When the average actual evapotranspiration (ETa) is lower than the average potential evapotranspiration (ETp) in a catchment area, it indicates that the water demand of the crops and vegetation in the catchment is not being met, which could be due to several factors, such as Water deficit, Soil limitations, Vegetation type or crop management.

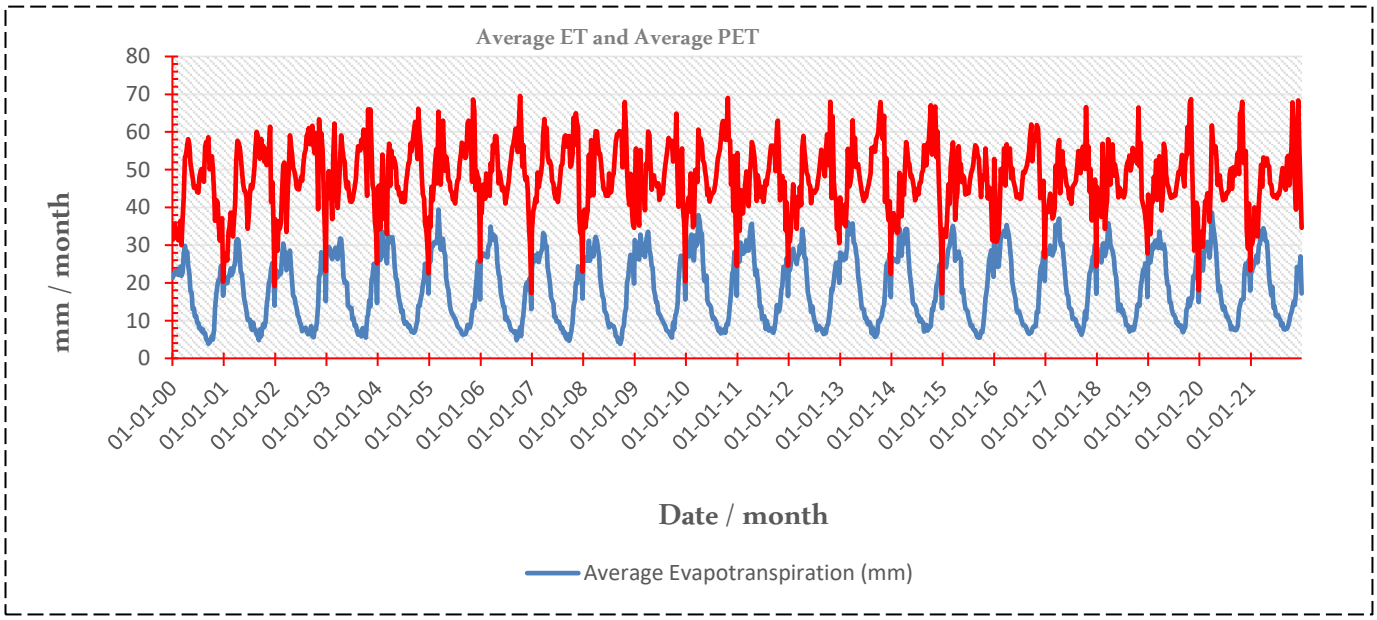

Figure 16 Graphical analysis of Average ET and Average PET in Luapula catchment area
Author's computation (2024) using data from AppEEARS

Actual amount of water available in the catchment may be insufficient to meet the water demand of crops and vegetation, leading to a water deficit. This can be caused by factors such as low rainfall, high temperatures, low soil moisture, or water abstraction for human use. On the other hand, when evapotranspiration is lower than potential evapotranspiration in a catchment, the soil in the catchment may have physical or chemical limitations that restrict water availability to crops and vegetation, resulting in a lower ETa. This can be caused by factors such as low soil water holding capacity, soil salinity, or soil compaction.

The type of vegetation in the catchment may have a lower water demand compared to other vegetation types, resulting in a lower ETa. For example, if the vegetation in the catchment is dominated by drought-tolerant species or non-vegetated areas, the ETa may be lower. In addition, Poor crop management practices, such as over-irrigation, under-irrigation, or improper timing of irrigation, can also lead to a lower ETa. When the ETa is lower than ETp, it suggests that the catchment may be experiencing water stress, which can have negative impacts on crop production, vegetation growth, and water availability for other uses. In such cases, it may be necessary to implement measures to increase water availability, improve soil quality, or adopt more water-efficient crop management practices to ensure sustainable water use in the catchment.

Estimation of the impact of land use on Evapotranspiration in Luapula catchment

Deforestation and gross emissions can reduce ET and affect the hydrological cycle, leading to reduced water availability in rivers and groundwater systems. Understanding the impact of land use changes on ET can help water resource managers to make informed decisions on water allocation and management. In addition, deforestation and gross emissions can also affect the local and regional climate, leading to changes in rainfall patterns, temperature, and humidity. This can have significant impacts on crop production, natural ecosystems, and human health. Estimating the impact of land use changes on ET can help in planning and adaptation to climate change, such as through the development of climate-resilient crops, water management strategies, and other adaptive measures.

Furthermore, Luapula catchment is home to several unique and diverse ecosystems, including wetlands, forests, and grasslands. Deforestation and gross emissions can lead to the loss of these ecosystems, which can have negative impacts on biodiversity and ecosystem services, such as water purification and carbon sequestration. Understanding the impact of land use changes on ET can help in the conservation and restoration of these ecosystems, which are essential for maintaining a healthy and functioning environment. More than that, Luapula catchment is an important agricultural area that supports the livelihoods of many local communities. However, deforestation and gross emissions can reduce crop yields and affect food security, leading to social and economic challenges. Estimating the impact of land use changes on ET can help in the development of sustainable land use practices that balance the needs of agriculture, water resources, and the environment. Overall, estimating the impact of land use changes on ET in Luapula catchment is crucial for sustainable water management, climate change adaptation, biodiversity conservation, and sustainable development. It can help in identifying the drivers of land use changes, evaluating the impacts of these changes on ET, and developing strategies to mitigate the negative impacts and promote sustainable land use practices. As such, this study also estimated the impact of land use in terms of deforestation and gross emissions on evapotranspiration (as shown in **Figure 17**).

```
Vector autoregression

Sample:  2012 - 2020                            Number of obs      =          9
Log likelihood =    684.2884                    AIC                =   -144.0641
FPE            =           .                    HQIC               =   -145.7665
Det(Sigma_ml)  =    1.07e-71                    SBIC               =   -143.2752

Equation              Parms      RMSE      R-sq       chi2      P>chi2
------------------------------------------------------------------------
meanevapotrans~n          9         0    1.0000          .          .
umd_tree_cover~a          9         0    1.0000   1.11e+24     0.0000
Gross_emission~2          9         0    1.0000   1.07e+24     0.0000
Gross_emission~g          9         0    1.0000   2.74e+24     0.0000
------------------------------------------------------------------------
```

	Coef.	Std. Err.	z	P>|z|	[95% Conf.	Interval]
meanevapotranspiration						
meanevapotranspiration						
L1.	-.0151118	7.29e-13	-2.1e+10	0.000	-.0151118	-.0151118
L2.	-.9200336	1.76e-12	-5.2e+11	0.000	-.9200336	-.9200336
umd_tree_cover_loss__ha						
L1.	.0085734	1.58e-14	5.4e+11	0.000	.0085734	.0085734
L2.	-.004211	1.19e-14	-3.5e+11	0.000	-.004211	-.004211
Gross_emissions_non_Co2						
L1.	-.0000207	2.02e-16	-1.0e+11	0.000	-.0000207	-.0000207
L2.	-.0001513	1.49e-16	-1.0e+12	0.000	-.0001513	-.0001513
Gross_emissions_Co2e_Mg						
L1.	-.0000228	3.55e-17	-6.4e+11	0.000	-.0000228	-.0000228
L2.	.0000196	4.16e-17	4.7e+11	0.000	.0000196	.0000196
_cons	33.42042	1.35e-11	2.5e+12	0.000	33.42042	33.42042

Figure 17 Graphical analysis of Average ET and Average PET in Luapula catchment area
Author's computation (2024) using data from AppEEARS

Consequently, results show that at 5% level of statistical significance, tree cover loss due to deforestation tends to have a positive and statistically significant impact on average evapotranspiration at lag 1 but overtime negatively impacts average evapotranspiration at lag 2 (since P-value = 0.000***). Furthermore, the gross emissions that are non Co2 have negative and statistically significant impacts on average evapotranspiration at both lag 1 and 2 following both P-values of 0.000***. In addition, gross emissions that are carbon dioxide equivalent (Co2e) and associated with Co2 and Mg also have a negative impact on average evapotranspiration at lag 1 despite having some positive impact on average evapotranspiration at lag 2. Hence, results show that land use in terms of deforestation which leads to tree cover loss and gross emissions tend to negatively impact average evapotranspiration in Luapula catchment (as shown in **Figure 17**; above).

VII. CONCLUSION

Correlation between land use and water availability (precipitation) in Luapula catchment.

The study's first research objective examined the relationship between average precipitation and deforestation in the Luapula catchment from 2010 to 2020. It found a negative but statistically insignificant correlation between precipitation and tree cover loss. Similarly, the negative correlations between precipitation and gross emissions were not statistically significant, indicating no strong evidence of a relationship between these variables. These findings align with previous studies. Mahdavi et al. (2019) in the Caspian Sea region, Li et al. (2018) in the Amazon rainforest, and Zhou et al. (2016) in the Three Gorges Reservoir Region, China, all reported no significant impact of deforestation on average precipitation. These studies suggest that while deforestation affects the environment, it may not significantly alter average precipitation levels, with effects potentially varying by ecosystem and climate. Additionally, research on gross emissions and precipitation showed similar results. Li et al. (2014) in northern China's grasslands, Chen et al. (2019) in constructed wetlands, and Aduna et al. (2019) in the Philippines' rice paddies found no significant correlation between gross emissions and precipitation. These studies indicate that other factors, such as soil moisture, temperature, and management practices, may play more substantial roles in determining emissions levels than precipitation alone.

The impact of tree cover loss due to deforestation on water availability (precipitation) in Luapula province.

The study's second, third, and fourth research objectives investigated the impacts of tree cover loss due to deforestation and different categories of gross emissions on average precipitation in the Luapula catchment. It found that deforestation negatively affects average precipitation, consistent with findings from Spracklen et al. (2012) and Oishi et al. (2017). These studies demonstrated that deforestation reduces cloud cover and rainfall, especially in heavily deforested areas like the Amazon Basin and Southern Appalachian Mountains. Chen et al. (2019) further underscored how tropical deforestation alters rainfall distribution and intensity, increasing flood risks and decreasing water availability.

Regarding gross emissions, non-carbon dioxide components were found to negatively impact precipitation, as indicated by studies on air pollution's effects on precipitation in Beijing and Guangzhou (Li et al., 2018; Chen et al., 2017). These studies linked higher levels of particulate matter and other pollutants to reduced precipitation intensity and increased drought frequency, highlighting indirect impacts of emissions on precipitation patterns.

Conversely, gross emissions that include carbon dioxide equivalents and specific carbon dioxide emissions were found to have a positive impact on precipitation, suggesting a complex relationship influenced by factors like aerosol composition and precipitation type. Studies examining aerosols' effects on precipitation have yielded mixed results, with some suggesting potential enhancements in certain contexts but overall emphasizing the negative effects of air pollution on precipitation dynamics. These findings collectively emphasize the critical role of maintaining tree cover and managing emissions to sustain precipitation patterns and water resources in the Luapula catchment and similar ecosystems globally.

Fluctuations of evapotranspiration in Luapula province

The fifth research objective of the study focused on estimating average evapotranspiration (ET) and potential evapotranspiration (PET) in the Luapula catchment area. Over the period from 2000 to 2021, the study found that average ET ranged from a minimum of 4mm to a maximum of 39mm, showing an increasing trend over the years. Conversely, PET ranged from a minimum of 17mm to a maximum of 70mm, also demonstrating increasing fluctuations from 2000 to 2020. Comparing ET to PET, it was observed that ET consistently remained lower than PET throughout the study period. This disparity is consistent with findings from several studies. For instance, Zhao et al. (2020) analyzed an oasis system in northwestern China and found that ET was consistently lower than PET, indicating water limitations affecting water use efficiency. Similarly, studies by Yan et al. (2017), Wang et al. (2016), Zhang et al. (2015), and Li et al. (2012) in different ecosystems across China also reported ET being lower than PET, highlighting widespread water stress conditions. These findings underscore the presence of water limitations in the Luapula catchment area and suggest that despite variations in ET and PET, actual evapotranspiration tends to lag behind potential evapotranspiration, indicating ongoing water stress in the region's ecosystems.

Impact of land use on evapotranspiration in Luapula province

With a view to the sixth research objective of the study, it was found that tree cover loss due to deforestation negatively impacts average evapotranspiration in Luapula catchment and that all gross emissions whether carbon dioxide equivalent or both carbon dioxide equivalent and carbon dioxide with Mag negatively impact average evapotranspiration. Similarly, in a study by Zhang et al. (2019), the authors analyzed the effects of deforestation on ET in the Brazilian Amazon and found that tree cover loss led to a significant decrease in ET, which in turn reduced the amount of water available for other ecosystem services.

Another study by Dantas et al. (2018) examined the impacts of land use change on ET in the Cerrado biome in Brazil and found that deforestation and conversion of native vegetation to pasture and cropland led to a significant reduction in ET. A study by Gao et al. (2015) investigated the effects of forest loss on water use efficiency in northern China and found that tree cover loss led to a significant decrease in ET, which in turn had negative impacts on local hydrology and water resources. In a study by Farley et al. (2005), the authors analyzed the impacts of forest conversion to pasture on ET in Costa Rica and found that tree cover loss led to a significant decrease in ET, which in turn had negative impacts on local hydrology and water availability. Overall, these studies suggest that tree cover loss due to deforestation and land use change can have negative impacts on average evapotranspiration, leading to reduced water availability for other ecosystem services and human use.

VIII. RECOMMENDATIONS

The study's policy recommendations are aimed at mitigating the negative impacts of deforestation and gross emissions on evapotranspiration in the Luapula catchment and beyond. Firstly, strengthening forest protection laws is advised, including stricter penalties for illegal logging and land conversion, and enhancing enforcement to safeguard Zambia's forests. Promoting sustainable agriculture is highlighted as crucial, advocating for practices like agroforestry and crop rotation to reduce deforestation for agricultural expansion. Additionally, supporting alternative livelihoods such as eco-tourism can alleviate pressure on forests, fostering sustainable forest management.

Furthermore, the study suggests increasing efforts in forest restoration through reforestation and afforestation, which can enhance evapotranspiration and mitigate deforestation impacts. Improving land use planning, including secure land tenure and community-based resource management, is also recommended to ensure sustainable land practices. Regarding gross emissions, promoting renewable energy sources like solar and hydro power is encouraged to reduce reliance on fossil fuels. Implementing sustainable land use policies that support afforestation and reforestation efforts can further enhance evapotranspiration by increasing regional tree cover. Additionally, policies aimed at reducing emissions from transportation and agriculture through low-carbon technologies and sustainable practices are advocated. Strengthening waste management regulations and promoting energy-efficient practices are also essential to curbing emissions and improving environmental sustainability in the region.

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