

Research Paper



Assessing ecosystem water-use efficiency and its implications for sustainable water resource management in Ghana using satellite remote sensing

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ABSTRACT

Water scarcity and efficient water resource management are growing concerns in the face of climate change and increasing demands for freshwater. This study focuses on assessing ecosystem water-use efficiency by investigating the ratio of Gross Primary Productivity (GPP) to evapotranspiration within Ghana. The study sought to explain the interactions of vegetation productivity and water use, shedding new light on the efficient use of this precious resource. The current research provides an extensive analysis of the Ecosystem Water-Use Efficiency (WUE) in Ghana, using satellite remote sensing images to map water-stressed regions throughout the country. A spatial analysis by us found that a large area of Ghana, spanning 4090750Ha, had low WUE levels in evidence, typical of water-stressed ecosystems. Of notable interest, the Upper West and Savannah regions had the greatest cover of water-stressed vegetation of 605650Ha and 1263150Ha, respectively, in the grasslands, and the Bono region had a dominance of water stress in the Savana land use category. The OTI region had a special case, wherein both Savannas and riverine vegetation were prone to water stress. These observations highlighted the importance of region-specific, target-led interventions to boost water-use efficiency, conserve ecosystems, and adopt water resource management practices in Ghana.

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1. INTRODUCTION

Water is a valuable resource that is essential to ecosystems, life, and the socioeconomic advancement of countries [1]. Due to environmental deterioration, shifting climatic patterns, and expanding populations, managing water supplies has become a more pressing issue globally. This problem is particularly relevant in Ghana, a country in West Africa, where competition for water resources and water scarcity are growing issues [2]. In light of this, evaluating Ecosystem Water-Use Efficiency (WUE) becomes essential to managing water resources sustainably [3]. WUE provides important insights into the delicate balance between ecological health, agricultural productivity, and water resource sustainability. It assesses how well vegetation uses water for photosynthesis and biomass production [4].

Ghana, which is located on the Gulf of Guinea, is home to a wide variety of ecosystems, including savannah grasslands and dense rainforests, all of which have unique water usage dynamics [5]. Knowing and maximizing WUE is more important than ever as the country struggles with issues brought on by growing agricultural practices and a changing climate. Underpinned by the integration of state-of-the-art satellite remote sensing technology, a strong dedication to sustainable resource management, and a keen understanding of Ghana's distinct socio-environmental landscape, this study sets out on a thorough investigation of Ecosystem Water-Use Efficiency in Ghana.

Ghana's agricultural sector, which mostly depends on rainfed and irrigated agriculture, is closely related to the country's socioeconomic development [5]. However, there are significant obstacles to the sustainability of this crucial industry, including water scarcity, fluctuations in rainfall patterns, and heightened rivalry for water among other sectors [6]. Therefore, evaluating WUE is essential for improving farming methods, guaranteeing food security, and protecting the rural population's means of subsistence in the country. Additionally, Ghana is home to a variety of ecosystems that are essential to the country's environmental health, such as river basins, wetlands, and vital forest reserves [7]. Understanding the WUE of these ecosystems is vital for preserving biodiversity, mitigating the effects of deforestation, and maintaining the resilience of the ecosystems of Ghana in the face of climate change [8].

2. RELATED WORK

There have been related studies within this domain. A study on evaluating the spatiotemporal dynamics of ecosystem water usage efficiency throughout China and the reaction to both natural and human activities was conducted by [9]. This study conducted a comprehensive examination of China's vegetation Water Use Efficiency (WUE) from 2001 to 2017. This analysis encompassed the examination of spatiotemporal distributions, trends in change, associations with meteorological factors, alterations in diverse vegetation coverage types, and the assessment of the predominant driving factors.

In a related study conducted by [10] on Assessing the response of ecosystem water use efficiency to drought during and after drought events across central Asia, various environmental parameters including Gross Primary Productivity (GPP), Evapotranspiration (ET), Land Surface Temperature (LST), and the Normalized Difference Vegetation Index (NDVI) were utilized to compute WUE and the Temperature Vegetation Dryness Index (TVDI). The Moderate Resolution Imaging Spectroradiometer (MODIS) dataset served as the source of this data. The results of this study revealed a noteworthy trend: ecosystems with high productivity showed lower WUE, whereas habitats with poor productivity showed higher WUE. Additionally, there were significant differences in the mean WUE of ecosystems in Central Asia across different countries, vegetation types, and drought levels. [11] Looked at the Resource Use Efficiency (RUE) and Water Use Efficiency (WUE) of a shrub ecosystem in Central Asia from 2000 to 2014 in their study on

the resilience of this ecosystem to drought and its rain and water-use efficiencies. The resilience of the ecosystem based on these metrics using statistical methods like the contextual Mann-Kendall test and a resilience index was assessed. Their analysis utilized data from MODIS and CRU covering the years 2000 to 2014.

Meanwhile, a study by [12] showed that with an R-squared value of 0.76 and a p-value below 0.001, Increased Interception Induced by Vegetation Restoration Counters Ecosystem Carbon and Water Exchange Efficiency in China demonstrated a strong correlation between the WUE calculated using an analytical WUE model and the WUE values found in the body of existing literature. The study found that the leaf area index, which might explain anywhere from 10% to 55% of the variability in E_i/ET (evaporative fraction) across different locations, was a key factor. These results, therefore, highlight how important it is to take into account the evaporative percentage, or E_i , when assessing how plant changes affect the interchange of water and carbon in ecosystems.

These insights have important implications for the sustainable management of vegetation changes in China. In the research conducted by [13] on the Impact of diffuse radiation on evapotranspiration and its coupling to carbon fluxes at global FLUXNET sites, the study delved into the effects of diffuse radiation on the process of ecosystem evapotranspiration (ET) and its interrelation with net ecosystem exchange (NEE). According to their study, they used data from 201 monitoring stations in the FLUXNET network to determine the derived proportion of diffuse radiation, or K_d , and based their analysis on long-term, extensive eddy-covariance measurements. This study stands apart from earlier investigations because of its distinct emphasis on Ghana.

This research uses satellite remote sensing technologies to provide a thorough and spatially wide investigation of water-use efficiency, in contrast to previous studies that are mostly focused on China or Central Asia. The study intends to cover a specific temporal span by utilizing sophisticated methodology and particular satellite sensors, providing crucial insights into the long-term dynamics of water-use efficiency in Ghana from a wider viewpoint. The study will also examine local environmental metrics and characteristics that have not been thoroughly investigated, illuminating the complex interrelationships among vegetation, climate, and water-use efficiency in the area. The practical importance and potential influence of this study on guiding policies and strategies for efficient water resource management are highlighted by the incorporation of findings into sustainable water resource management practices that are adapted to Ghana's socioeconomic and environmental circumstances.

This study uses satellite remote sensing, a technique that has transformed our ability to track and analyze the dynamics of the Earth's surface, to carry out this ambitious assessment. This study gathered vital data on Gross Primary Productivity (GPP) and Evapotranspiration (ET) of a wide range of satellite data sources, such as Landsat and MODIS (Moderate Resolution Imaging Spectroradiometer) [14]. These data sources allowed this study to make precise and thorough inferences about WUE dynamics through a thorough understanding of Ghanaian ecosystems over a range of regional and temporal scales. This research project is motivated by several distinct but related goals: to evaluate and chart the water-use efficiency of ecosystems in Ghana's various landscapes. To identify regions with low WUE, pinpointing areas vulnerable to water stress and ecological degradation.

To evaluate the implications of WUE on agricultural productivity, ecosystem health, and water resource management, and to offer policy and management recommendations that promote sustainable water resource management practices in Ghana. This study is designed to include several essential elements to achieve these goals. The theoretical underpinnings of WUE are examined first, and then the body of research on WUE evaluation, satellite remote sensing, and Ghanaian water resource management is thoroughly reviewed. The techniques used, the data sources used, and the complexities of WUE assessment are covered in detail in later chapters. After that, we present our research, go over its ramifications, and make suggestions for Ghana's sustainable management of its water resources. This research endeavor represents a sincere commitment to comprehending and tackling the challenges posed by water resource management in Ghana. It aims to promote a holistic approach that balances the needs of agriculture, ecosystems, and human populations, all under the watchful eye of satellite remote sensing technology. Our ultimate goal is to help protect Ghana's water resources, preserve its distinctive

ecosystems, and advance a sustainable and prosperous future for all of its citizens.

3. METHODOLOGY

Study Area

Ghana, which is located on the picturesque coasts of West Africa, is a fascinating and varied research destination that attracts scholars with its varied landscapes, lively communities, and exciting research opportunities. Ghana, which stretches across the Gulf of Guinea, has a diverse topography that includes the majestic Akwapim-Togo mountain range, lush rainforests, expansive savannas, and stunning beaches [15]. Scholars are encouraged to investigate a wide range of environmental and socioeconomic aspects, each with unique opportunities and problems, due to its geography. The variability of Ghana's climate adds to its appeal as a research destination. There is a wide variety of climates in the country, ranging from the tropical rainforests in the south to the semi-arid regions in the north. These differences offer a rich environment for studying the effects of climate change, seasonal variations, and how resilient ecosystems, agriculture, and water supplies are to harsh weather. Ghana's extensive water resources are of special interest.

One of the biggest artificial reservoirs in the world, Lake Volta, is the result of the Volta River, a well-known African stream that flows through the country. Research on the production of hydroelectric power, irrigation techniques, fishery management, and water quality evaluation all depend on an understanding of the dynamics of these aquatic ecosystems. In Ghana, agriculture dominates the economy and employs a sizable section of the populace.

As a result, the country provides an intriguing backdrop for researching crop diversification, sustainable farming methods, and the complex interrelationship between agriculture and food security in a developing country. Researchers interested in wildlife conservation, deforestation, and the delicate balance between ecological preservation and human activity are drawn to Ghana's amazing biodiversity, which is housed within national parks and protected regions. Socioeconomically speaking, Ghana's expanding population and vibrant economy provide opportunities for studies on population dynamics, urbanization, poverty reduction, and educational advancement.

Research opportunities are abundant in the fields of cultural preservation, heritage tourism, and community-driven initiatives aimed at preserving Ghana's rich traditions. Beyond the academic realm, Ghana boasts an enriching cultural heritage with diverse ethnic groups, traditions, and historical landmarks. This country's dedication to democratic governance and political stability further enhances its appeal as a conducive environment for research endeavors.

Furthermore, Ghana is a melting pot of knowledge and creativity because it actively engages in international relationships and collaborations. Scholars have the exceptional chance to collaborate closely with regional organizations and specialists, promoting intercultural discussions and enhancing their research projects. In summary, Ghana is a fascinating and diversified research destination where scholars from various fields can set out on a voyage of exploration, tackling intricate problems and assisting in the sustainable growth of the country while being enmeshed in its rich cultural tapestry [16], Figure 1.

Materials and Data Used

In this study, a comprehensive assessment of ecosystem water-use efficiency (WUE) in Ghana was conducted using a combination of remote sensing datasets and geospatial tools. The primary remote sensing datasets employed were MODIS/006/MOD16A2.061, which provides Terra Net Evapotranspiration data at an 8-day global scale with a spatial resolution of 500 meters, and MODIS/006/MYD17A2H.006, offering Aqua Gross Primary Productivity data at the same temporal and spatial resolution. These databases played a crucial role in measuring important ecological parameters associated with gross primary productivity and evapotranspiration, which made it possible to analyze WUE across Ghana's varied landscapes. The Ghana Boundary Asset, which provides an accurate depiction of Ghana's national borders, was used to determine the study's geographic scope on the Google Earth Engine (GEE) platform.

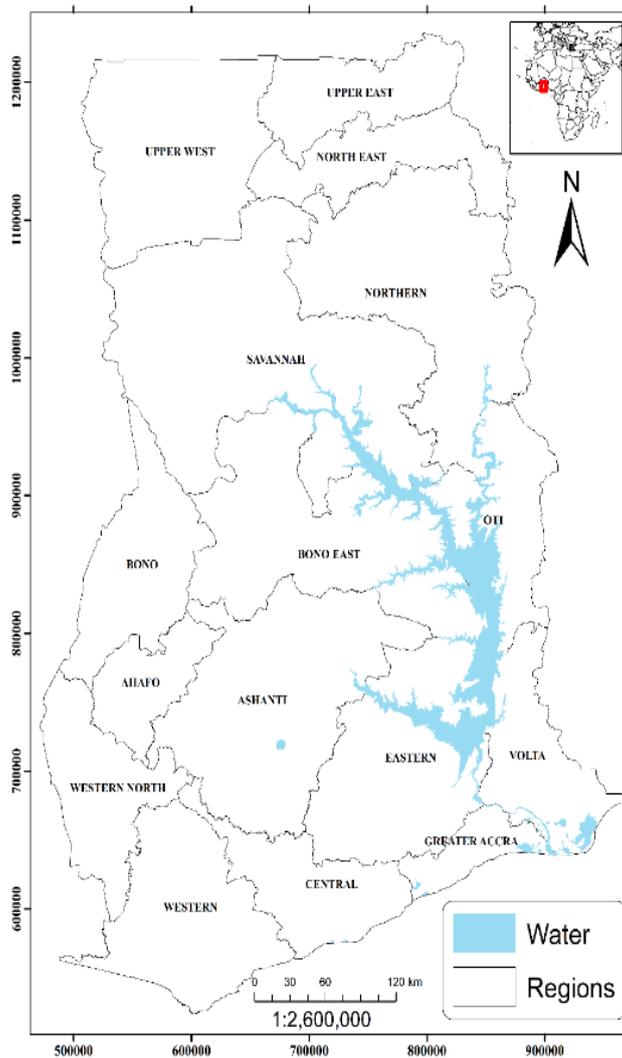


Figure 1. A Map of Ghana (Study Area)

The Google Earth Engine Code Editor API was used for data processing and spatial analysis, which made calculation and result presentation more efficient. ArcGIS 10.4.1 was also used as an additional tool for particular geographic procedures. A thorough evaluation of WUE and its implications for sustainable water resource management in Ghana was made possible by the extensive range of resources and instruments listed in Table 1, which guaranteed the validity and precision of the study findings.

Table 1. Materials and Data Used

Sr. No.	Material	ID	Source	Spatial Resolution
1	Terra Net Evapotranspiration 8-Day Global	MODIS/006/MOD16A2	https://developers.google.com/earth-engine/datasets/catalog/MODIS_061_MOD16A2#description	500m
2	Aqua Gross Primary Productivity 8-Day	MODIS/006/MYD17A2H	https://developers.google.com/earth-engine/datasets/catalog/MODIS_006_MYD17A2H	500m

	Global			
3	Land Cover Type Yearly Global	MODIS/006/MCD12Q1	https://developers.google.com/earth-engine/datasets/catalog/MODIS_061_MCD12Q1	500m
4	Ghana Boundary Asset in GEE	users/oseijeffreydacosta/Ghana	https://code.earthengine.google.com/?asset=users/oseijeffreydacosta/Ghana	
5	Google Earth Engine Code Editor API	GEE	https://code.earthengine.google.com/	
6	ArcGIS Desktop 10.4.1	ArcGIS	https://www.esri.com/en-us/arcgis/products/arcgis-for-student-use/overview	

Methods

The ratio of Gross Primary Productivity (GPP) to evapotranspiration (ET), often referred to as Water-Use Efficiency (WUE), can be a valuable indicator for classifying water scarcity. The regions with differing levels of water shortage can be detected by analyzing this ratio and comparing it across different locations.

The MODIS GPP Estimation Algorithm

In evaluating water-use efficiency (WUE) and classifying water shortage, the MODIS Gross Primary Productivity (GPP) method is essential, especially when using MODIS data for environmental monitoring and decision-making. The GPP of terrestrial vegetation is computed globally using the MODIS GPP algorithm. GPP is an important measure of vegetation productivity since it shows how much carbon dioxide (CO₂) is fixed by plants during photosynthesis. Vegetation indices used in the MODIS GPP method include the Enhanced Vegetation Index (EVI) and the Normalized Difference Vegetation Index (NDVI), which are obtained from MODIS data. These indices capture the vegetation's greenness and health. The algorithm utilizes empirical relationships between these vegetation indices, meteorological variables, and GPP to estimate GPP values regularly, typically at an eight-day interval. The equation used by the MODIS (Moderate Resolution Imaging Spectroradiometer) algorithm to compute Gross Primary Productivity (GPP) is based on the concept of light use efficiency (LUE).

Equation (1) is used by the MODIS GPP algorithm to estimate GPP.

$$\text{GPP is equal to } f\text{PAR} \times \epsilon \times \text{PAR} \quad (1).$$

Where: Grams of carbon per square meter per day (g C/m²/day) is the standard unit of measurement for Gross Primary Productivity, or GPP.

The Fraction of Photosynthetically Active Radiation, or fPAR, is the percentage of radiation from the sun that is absorbed by plants. It is a dimensionless value between 0 and 1.

ϵ (epsilon) is the Light Use Efficiency, which quantifies the efficiency of converting absorbed photosynthetically active radiation (APAR) into GPP. It is expressed in units of GPP per unit of APAR (g C/MJ).

The amount of solar radiation that plants absorb and use for photosynthesis is known as PAR, or photosynthetically active radiation. Usually, megajoules per square meter per day (MJ/m²/day) are used to express it.

Photosynthetically Active Radiation Fraction (fPAR)

The Normalized Difference Vegetation Index (NDVI) and additional vegetation indicators are used by MODIS to compute fPAR. The percentage of available PAR that is taken up by the vegetation canopy and utilized for photosynthesis is known as fPAR.

Light Use Efficiency (ϵ):

One of the equation's crucial parameters is light use efficiency. It shows the efficiency with which vegetation transforms absorbed PAR into GPP. Several variables, including land cover, vegetation type, and environmental conditions, might affect ϵ . [16] [17] [18].

The quantity of solar energy in the 400–700 nanometer wavelength range that is available for photosynthesis is known as photosynthetically active radiation, or PAR. It provides photosynthesis with its energy. The MODIS GPP algorithm estimates fPAR and ϵ by combining land cover information, meteorological data, and remote sensing data (such as NDVI). After determining these values, the program multiplies them by PAR to determine GPP. Estimates of GPP are provided by the MODIS GPP algorithm at a somewhat coarse spatial resolution, usually around 250, 500, or 1 km. These estimations are useful for evaluating carbon cycling and vegetation production on a wide scale.

MODIS GPP Estimation Data Inputs

The algorithm makes use of data from MODIS instruments, which are satellite-based remote sensing devices that have several spectral bands, including the Red and Near-Infrared (NIR) bands. These bands are necessary to estimate GPP. Weather information, including temperature, precipitation, sun radiation, and vapor pressure deficit, is also included in the algorithm. The environmental factors influencing photosynthesis are shown by this data. After pre-processing, the MODIS GPP data was masked to the Ghanaian border. Using the GEE code editor, as Figure 2 illustrates.

The MODIS Total Evapotranspiration (ET) Estimation Algorithm

The Penman-Monteith equation serves as the foundation for the evapotranspiration (ET) calculation algorithm used by the Moderate Resolution Imaging Spectroradiometer (MODIS). A popular technique for calculating possible ET in remote sensing applications is the Penman-Monteith equation. Here is the general form of the Penman-Monteith equation (Equation (2)) used by MODIS [19], [20], [21].

$$ET = \frac{0.408 \cdot \Delta (R_n - G) + \gamma \left(\frac{900}{T + 273} \right) U (e_s - e_a)}{\Delta + \gamma (1 + 0.34U)} \quad (2)$$

Where:

ET = the potential evapotranspiration (ET) in millimetres per day.

R_n = the net radiation at the crop surface in watts per square meter (W/m²).

G = the soil heat flux density in W/m².

Δ = the slope of the saturation vapor pressure-temperature curve in kilopascals per degree Celsius (kPa/°C).

γ = the psychrometric constant in kPa/°C.

T = the air temperature at 2 meters above the surface in degrees Celsius (°C).

U = the wind speed at 2 meters above the surface in meters per second (m/s).

e_s = the saturation vapor pressure in kPa.

e_a = the actual vapor pressure in kPa.

In this equation, R_n - G represents the net radiation minus the soil heat flux, which represents the available energy for ET. The equation calculates ET as the result of various factors, including net radiation, temperature, wind speed, and vapor pressure. The Penman-Monteith equation requires a variety of meteorological data inputs, including air temperature, wind speed, net radiation, and vapor pressure, which can be obtained from remote sensing or meteorological stations. After estimating these variables using meteorological inputs and remote sensing data, the MODIS algorithm calculates ET using the Penman-Monteith equation. For a variety of agricultural and environmental applications, the resulting ET values offer significant information about the possible water loss by evapotranspiration in a specific area. The ET

data was pre-processed and masked to the boundary of Ghana using the GEE code editor as shown in [Figure 2](#).

Water-Use-Efficiency (WUE) Calculation

The MODIS Annual ET data can be used in combination with Gross Primary Productivity (GPP) data, often derived from the same MODIS sensors, to calculate WUE. An important indicator of ecosystem water-use efficiency is the ratio of GPP to ET, which shows how well plants transform water into biomass [20], [21], [22], [23], [24]. Equation (3) was utilized in this work to calculate the WUE for Ghana as a whole, as seen in [Figure 4](#).

$$\text{WUE} = \text{GPP} / \text{Evapotranspiration (ET)} \quad (3)$$

Quintile Analysis for WUE Threshold

Quantile-based approach was used to define the threshold for WUE classification. The WUE data for Ghana was divided into quintiles (five parts). This was used to establish cut-off points for the efficiency of different water usage classes. As seen in [Figure 3](#) and [Table 3](#), the WUE threshold for Ghana was determined by utilizing Equation (4) to calculate the location of the first quintile (20th percentile) in ArcGIS 10.4.1.

$$\text{Position of 20th percentile} = 2 / 10 \times (n + 2) \quad (4)$$

Where n is the total number of data points (pixels or areas) in the dataset.

Classification of WUE in Ghana

A classification scheme was created where each pixel or area was assigned a label based on its WUE value to the first quintile threshold (20th percentile). The areas below the threshold were classified as "Low WUE" and areas above the threshold as "Moderate to High WUE". The classified WUE was used to create a WUE map to identify areas with low WUE. The areas with low WUE were extracted and quantified to identify the extent and location in Ghana to help in assessing water resource management and ecological implications. The WUE classification scheme used for Sustainable Water Resource Management in Ghana is shown in [Figure 4](#), [Table 2](#), and [Table 3](#).

Table 2. WUE Classification for Sustainable Water Resource Management in Ghana

WUE Class	Meaning
Very Low	Water-Stressed Areas
Low	Inefficient Water Use by vegetation
Moderate	Balanced use of water resources
High	Efficient Water Use by Vegetation
Very High	Very Efficient Water Use by Vegetation

Very High and High WUE (Efficient Water Use)

Areas with high WUE values indicate efficient water utilization by vegetation. These regions are producing biomass efficiently with the water resources that are available. These areas' ecosystems are probably more resistant to water stress. In terms of managing water resources, there is little need for quick action. Promoting sustainable land use and preserving current effective methods should be the key priorities.

Moderate WUE (Moderate Water Use)

Areas with moderate WUE values indicate a balanced use of water resources. These areas are using water reasonably well but may have room for improvement. Potential for optimizing water use for increased productivity. Water conservation measures and sustainable land management practices need to be implemented. Opportunities to improve water use efficiency should be tracked and evaluated.

Low WUE (Inefficient Water Use)

Low WUE levels suggest that vegetation is not using water efficiently. These regions are producing

biomass with inefficient use of water resources. Water stress can affect ecosystems, and evapotranspiration can cause more water loss than benefits. Giving water-saving technologies and increased irrigation efficiency top priority. Calls for actions to cut down on over-extraction and water waste. To improve WUE, reforestation or vegetation restoration may be an option.

Very low/Critical WUE (Water-Stressed Areas)

Severe water stress is indicated by regions with exceptionally low WUE values. Water scarcity poses a serious threat to these regions, which might degrade ecosystems and lower agricultural output. Addressing the problems with water resources requires immediate action. Put water management and conservation measures into action right away. It is important to investigate options for replenishing water resources, such as groundwater management and rainfall collection. It is necessary to create climate resilience adaptation methods.

4. RESULTS AND DISCUSSION

Results

Ghana's Ecosystem Water-Use Efficiency (WUE) Spatial Distribution

As seen in Figure 4 and Figure 5, the evaluation of Ecosystem Water-Use Efficiency (WUE) in Ghana, which was carried out through meticulous geographical analysis utilizing satellite remote sensing data, has provided important new information on how water stress is distributed throughout the country [25], [26], [27]. Interestingly, it was found that a sizable portion of Ghana, 4090750ha, had noticeably low WUE values, which are an indicator of ecosystems under stress from water. Different patterns surfaced throughout this vast area, reflecting the difficulties Ghana's varied terrain faces. In the Upper West and Savannah regions of Ghana, the analysis revealed the highest coverage of 605650ha and 1263150ha of water-stressed vegetation, primarily concentrated within the grasslands, as shown in Figure 5.

The vulnerability of these regions to water stress underscores the importance of sustainable water resource management practices to safeguard both ecological integrity and the livelihoods of local communities. The Bono region exhibited a similar trend, with the Savana land use and land cover (LULC) category registering the highest prevalence of water-stressed areas, as shown in Figure 5. This finding underscores the need for targeted interventions in this region to mitigate the adverse impacts of water scarcity on agricultural productivity and ecosystem health. In the OTI region, a significant portion of the Savannas and Woody Savanna LULC types displayed signs of water stress. Additionally, the vegetation surrounding the Volta River exhibited susceptibility to water stress due to excessive water levels, as shown in Figure 5. This observation highlights the intricate interplay between water abundance and water stress, emphasizing the need for adaptive water management strategies in riverine ecosystems.

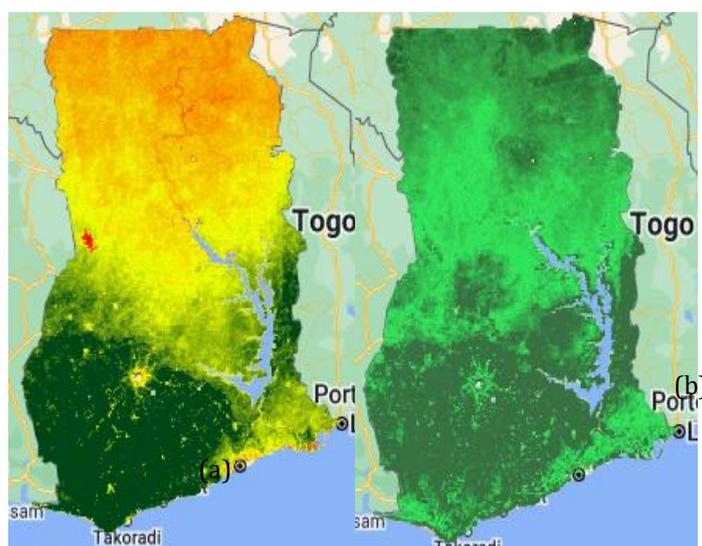


Figure 2. (a) GPP and (b) ET of Ghana Pre-Processed in GEE

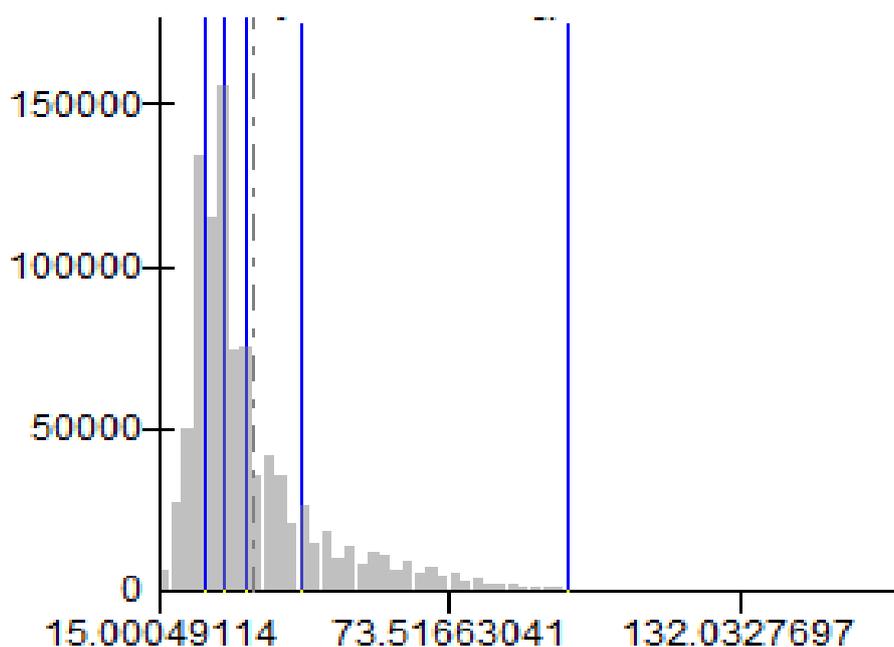


Figure 3. The First Quintile (20th Percentile) Computational Graph in Arcmap

Table 3. WUE Classification based on Threshold Value

WUE Class	WUE range (kgC/m ² /mm/d)
Very Low	15.000 - 24.179
Low	24.179 - 27.851
Moderate	27.851 - 32.441
High	32.441 - 43.455
Very High	43.455 - 97.346

In the assessment of ecosystem water-use efficiency (WUE) in Ghana, a threshold value of 24.179 kgC/m²/mm/d (20th percentile) was computed from the distribution graph Figure 3 as the delineation point to classify WUE into distinct categories. This threshold, representing the first quintile of the WUE dataset, served as a crucial reference point for characterizing the water-use efficiency across different regions of Ghana. Based on this threshold, the WUE values were stratified into five distinct classes as shown in Table 3.

Very Low WUE: This class encompasses areas where WUE values range from 15.000 to 24.179 kgC/m²/mm/d. These regions exhibit the lowest water-use efficiency, signifying a heightened susceptibility to water stress and potential challenges in sustaining ecological and agricultural systems.

Low WUE: Falling within the range of 24.179 to 27.851 kgC/m²/mm/d, the Low WUE class represents areas with slightly improved water-use efficiency compared to the Very Low class. However, these regions still face notable constraints in optimizing water resources for vegetation productivity.

Moderate WUE: Covering WUE values from 27.851 to 32.441 kgC/m²/mm/d, the Moderate class indicates areas where water-use efficiency reaches a more balanced level. These regions strike a better equilibrium between water availability and vegetation productivity.

High WUE: The High WUE class, spanning the range of 32.441 to 43.455 kgC/m²/mm/d, represents areas with a commendable level of water-use efficiency. In these regions, ecosystems efficiently utilize available water resources, supporting robust vegetation growth.

Very High WUE: The top tier, with WUE values ranging from 43.455 to 97.346 kgC/m²/mm/d, includes areas exhibiting exceptional water-use efficiency. These regions are characterized by highly productive ecosystems that effectively harness water for vegetation growth.

The application of this threshold and subsequent classification enables a nuanced understanding of the spatial distribution of WUE across Ghana. Such insights can inform targeted interventions and policy decisions, allowing for the implementation of region-specific strategies to address water stress, enhance agricultural practices, and promote sustainable water resource management in the nation. This classification not only serves as a valuable tool for ecosystem assessment but also aligns with the broader objectives of our study, facilitating the identification of water-stressed areas and the formulation of context-sensitive solutions to bolster Ghana's ecological resilience and socio-economic well-being.

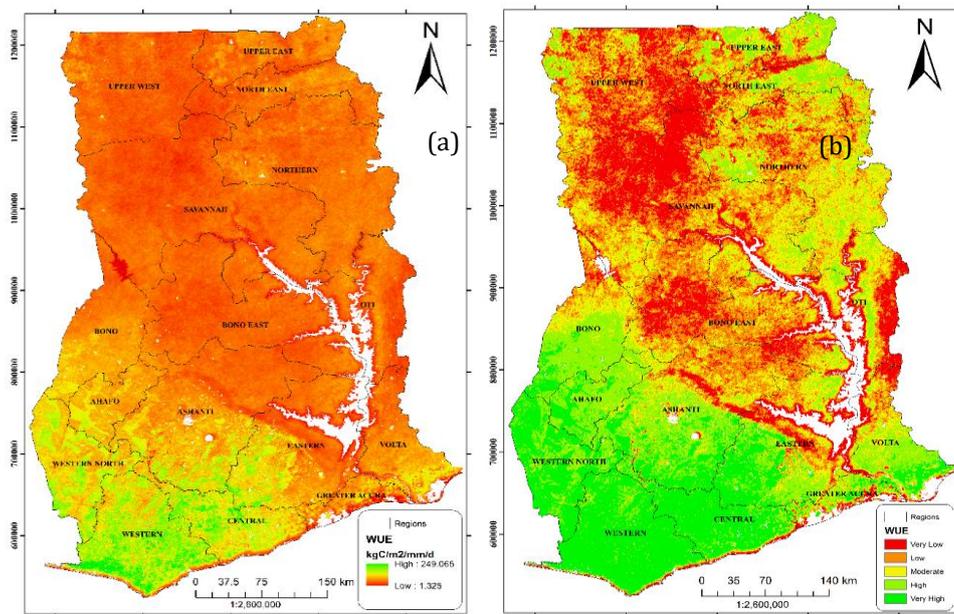


Figure 4. Spatial Distribution of WUE in Ghana (a) Before Threshold (b) After Threshold

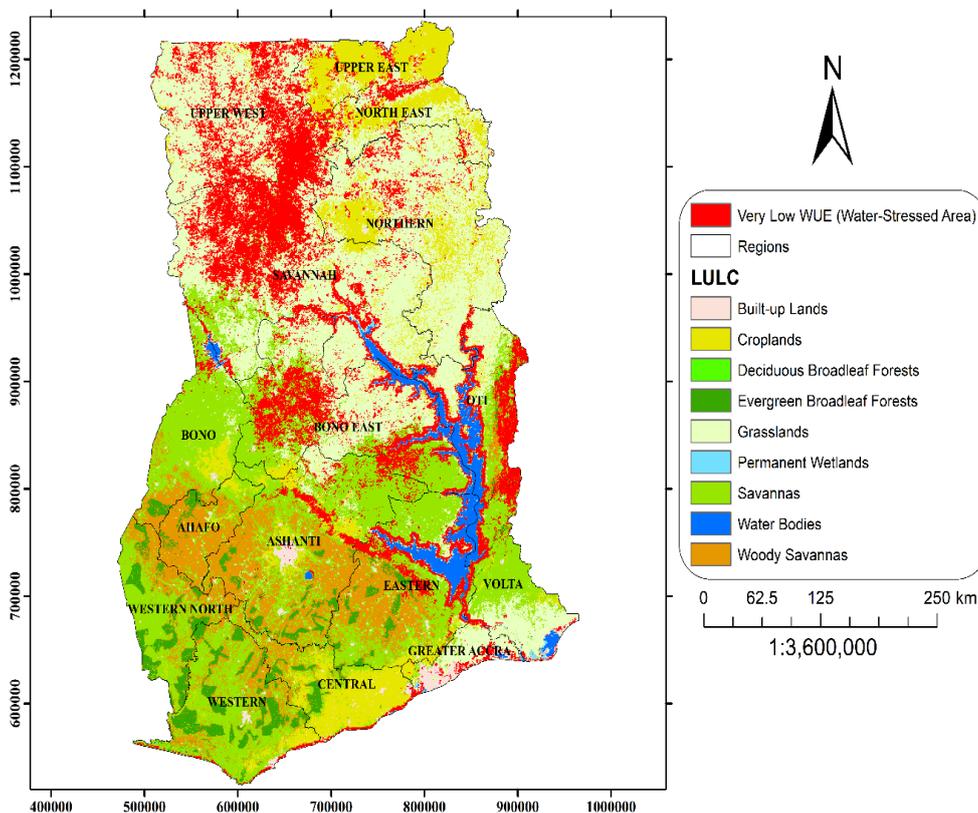


Figure 5. Water Stressed Area (Very low WUE) and LULC in Ghana

Discussion

The results of this spatial analysis align closely with the core objectives of our research. The identification of water-stressed areas in Ghana provides a crucial foundation for understanding the complex dynamics of water resource management and ecosystem resilience. The prevalence of water-stressed vegetation in the Upper West and Savannah regions underscores the vulnerability of these ecosystems to changing climatic conditions and emphasizes the urgency of implementing sustainable land and water management practices. Encouragingly, this knowledge can serve as a catalyst for targeted interventions aimed at enhancing water-use efficiency and bolstering the resilience of these regions.

In the Bono, Upper West, and Savannah regions, where the Savana and grassland LULC category recorded the highest coverage of water-stressed areas, our findings suggest the necessity of region-specific strategies to mitigate water-stress impacts on agriculture, the primary economic driver in this region. By tailoring interventions to local conditions, policymakers can promote sustainable land and water practices that enhance agricultural productivity while conserving vital ecosystems. The OTI region's unique blend of water-stressed Savannas, Woody Savanna LULC, and riverine vegetation highlights the intricate relationship between water availability and water stress. Effective management of water resources in this region should account for the delicate balance between flood and drought conditions, ensuring that both human and ecological needs are met.

5. CONCLUSION

In conclusion, this comprehensive assessment of Ecosystem Water-Use Efficiency in Ghana has unveiled critical patterns of water stress that have significant implications for sustainable water resource management and ecological resilience. The identification of water-stressed areas, spanning regions with varying land cover characteristics, underscores the importance of nuanced, location-specific interventions. These findings not only align with the objectives of our research but also lay the foundation for evidence-based policy recommendations. Prioritizing sustainable water management practices and adaptive strategies tailored to the unique challenges of each region, Ghana can navigate the complexities of water resource management while safeguarding its ecosystems, agricultural productivity, and overall socio-economic well-being.

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Author Contributions Statement

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Jeff Dacosta Osei	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓	
Yaw A. Twumasi	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓
Zhu. H. Ning	✓		✓				✓			✓		✓		✓
Desmond Karikari Osei	✓	✓		✓	✓				✓	✓	✓		✓	
Kingsford Kobina Annan	✓	✓	✓		✓	✓		✓	✓	✓		✓		✓

C : Conceptualization

M : Methodology

I : Investigation

R : Resources

Vi : Visualization

Su : Supervision

- [12] B. Wang, X. Yue, H. Zhou, and J. Zhu, 'Impact of diffuse radiation on evapotranspiration and its coupling to carbon fluxes at global FLUXNET sites', *Agric. For. Meteorol.*, vol. 322, no. 109006, p. 109006, July 2022 doi.org/10.1016/j.agrformet.2022.109006
- [13] C. E. Woodcock, T. R. Loveland, M. Herold, and M. E. Bauer, 'Transitioning from change detection to monitoring with remote sensing: A paradigm shift', *Remote Sens. Environ.*, vol. 238, no. 111558, p. 111558, Mar. 2020. doi.org/10.1016/j.rse.2019.111558
- [14] C. Y. Anani, S. Bonsu, D. Kwayisi, and D. K. Asiedu, 'Geochemistry and provenance of Neoproterozoic metasedimentary rocks from the Togo structural unit, Southeastern Ghana', *J. Afr. Earth Sci.*, vol. 153, pp. 208-218, May 2019. doi.org/10.1016/j.jafrearsci.2019.03.002
- [15] M. K. Gumma et al., 'Mapping Irrigated Areas of Ghana Using Fusion of 30 m and 250 m Resolution Remote-Sensing Data', *Remote Sens. (Basel)*, vol. 3, no. 4, pp. 816-835, Apr. 2011. doi.org/10.3390/rs3040816.
- [16] X. Deng and L. Zhang, 'Spatio-temporal disparity of water use efficiency and its influencing factors in energy production in China', *Ecol. Inform.*, vol. 71, no. 101779, p. 101779, Nov. 2022 doi.org/10.1016/j.ecoinf.2022.101779
- [17] J. Zou, J. Ding, M. Welp, S. Huang, and B. Liu, 'Using MODIS data to analyse the ecosystem water use efficiency spatial-temporal variations across Central Asia from 2000 to 2014', *Environ. Res.*, vol. 182, no. 108985, p. 108985, Mar. 2020 doi.org/10.1016/j.envres.2019.108985
- [18] L. Wang, H. Zhu, A. Lin, L. Zou, W. Qin, and Q. Du, 'Evaluation of the latest MODIS GPP products across multiple biomes using global eddy covariance flux data', *Remote Sens. (Basel)*, vol. 9, no. 5, p. 418, Apr. 2017. doi.org/10.3390/rs9050418
- [19] Q. Mu, F. A. Heinsch, M. Zhao, and S. W. Running, 'Development of a global evapotranspiration algorithm based on MODIS and global meteorology data', *Remote Sens. Environ.*, vol. 111, no. 4, pp. 519-536, Dec. 2007. doi.org/10.1016/j.rse.2007.04.015
- [20] K. De Haan et al., 'Assessment of different water use efficiency calculations for dominant forage crops in the great lakes basin', *Agriculture*, vol. 11, no. 8, p. 739, Aug. 2021. doi.org/10.3390/agriculture11080739
- [21] J. L. Hatfield and C. Dold, 'Water-use efficiency: Advances and challenges in a changing climate', *Front. Plant Sci.*, vol. 10, p. 103, Feb. 2019. doi.org/10.3389/fpls.2019.00103
- [22] J. Elfarkh, K. Johansen, M. M. El Hajj, S. K. Almashharawi, and M. F. McCabe, 'Evapotranspiration, gross primary productivity and water use efficiency over a high-density olive orchard using ground and satellite based data', *Agric. Water Manag.*, vol. 287, no. 108423, p. 108423, Sept. 2023. doi.org/10.1016/j.agwat.2023.108423
- [23] S. Dore et al., 'Recovery of ponderosa pine ecosystem carbon and water fluxes from thinning and stand-replacing fire', *Glob. Chang. Biol.*, vol. 18, no. 10, pp. 3171-3185, Oct. 2012. <https://doi.org/10.1111/j.1365-2486.2012.02775.x>
- [24] Y. Sun, R. Tang, L. Huang, M. Liu, Y. Jiang, and Z.-L. Li, "Synergistic estimates of global 4-day 500 m gross primary production, evapotranspiration, and ecosystem water use efficiency from satellite data," *Journal of Hydrology*, p. 133506, May 2025, doi: 10.1016/j.jhydrol.2025.133506 doi.org/10.1016/j.jhydrol.2025.133506
- [25] R. Guerrieri, L. Lepine, H. Asbjornsen, J. Xiao, and S. V. Ollinger, "Evapotranspiration and water use efficiency in relation to climate and canopy nitrogen in U.S. forests," *Journal of Geophysical Research Biogeosciences*, vol. 121, no. 10, pp. 2610-2629, Sep. 2016, doi: 10.1002/2016JG003415 doi.org/10.1002/2016JG003415
- [26] J. D. Osei et al., 'Vegetation dynamics and surface water infiltration: Addressing hydrological challenges in East Baton Rouge Parish in the Louisiana state of USA using satellite remote sensing', *ISPRS - Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.*, vol. XLVIII-M-5-2024, pp. 139-146, Mar. 2025. doi.org/10.5194/isprs-archives-XLVIII-M-5-2024-139-2025
- [27] J. D. Osei et al., 'Rainfall-runoff modelling for sustainable water resource management in the Louisiana state', *ISPRS - Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.*, vol. XLVIII-M-5-2024, pp. 131-137, Mar. 2025. doi.org/10.5194/isprs-archives-XLVIII-M-5-2024-131-2025

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