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RESEARCH ARTICLE

EVALUATION OF THE MULTI-DECADAL CHANGED DYNAMICS OF HYDROLOGICAL COMPONENTS AT THE TAMNE CATCHMENT, GHANA, USING THE WATER BALANCE APPROACH.

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ABSTRACT

The multi-decadal dynamics of hydrological components in the Tamne Catchment of Ghana play a pivotal role in the region's water resource management and agricultural sustainability. This study evaluates these dynamics using the water balance approach, providing a comprehensive understanding of how key hydrological elements, including precipitation, evapotranspiration, runoff, and groundwater recharge, have evolved over several decades. Additionally, the study assesses the inter-annual variability of Potential Evapotranspiration (PET) and Actual Evapotranspiration (ET_a) within the Tamne Catchment over a defined period of 1992-2022. By analyzing long-term climate data, land use changes, and hydrological records, we constructed a detailed water balance model to quantify the variations in each component. The results indicate a marked shift in the catchment's hydrological regime, characterized by increasing variability in precipitation and significant alterations in runoff patterns. Utilizing climate data, soil moisture levels, and vegetation indices, remote sensing techniques were applied to estimate PET and ET_a. The findings revealed significant inter-annual fluctuations influenced by variations in rainfall, temperature, and land cover changes. PET exhibited a general increasing trend, suggesting heightened atmospheric demand due to rising temperatures, while ET_a demonstrated variability closely tied to annual precipitation and soil moisture availability. The discrepancy between PET and ET_a highlights the critical role of water availability in limiting actual evapotranspiration, with implications for irrigation practices and water resource planning in the catchment. These results underscore the need for adaptive water management strategies to cope with the variability in evapotranspiration, ensuring sustainable agricultural practices and water use in the region.

KEYWORDS

Climate, Hydrology, Tamne.

1. INTRODUCTION

Analyzing hydrological processes within a catchment is essential for gaining a clear understanding of how water is distributed, how much is available, and how it can be managed sustainably (Davie, 2019). In areas such as the Tamne Catchment in Ghana's Upper East Region, where water availability plays a vital role in sustaining local livelihoods, understanding how these systems change over time is essential (Gordon et al., 2013). Over the past several decades, the Tamne Catchment has experienced significant environmental and climatic changes that have altered its hydrological balance (Gordon et al., 2013). These changes, driven by factors such as land use alterations, population growth, and climate variability, necessitate a comprehensive assessment to inform water management practices (Bulley, 1996).

The water balance approach offers a robust framework for analyzing the key components of a catchment's hydrological cycle, including precipitation, evapotranspiration, surface runoff, and groundwater recharge (Yang et al., 2021). By assessing the interactions and relative contributions of these components over time, this approach provides valuable insights into how a catchment's water resources are responding to both natural and anthropogenic influences. The Tamne catchment is expected to undergo shifts in rainfall regimes, oscillating between dry and rainy seasons (Kasei, 2010), with even a minor variation in rainfall potentially leading to significant changes in runoff rates (Kpoti et al., 2016). Surface water reservoirs such as lakes, dams, and rivers within the catchment primarily rely on rainfall and local surface runoff (Mbajiorgu 2020). However, the variability of climate change, encompassing temperature, rainfall, humidity, and wind patterns, poses challenges to local hydrological properties, thereby altering water input and output dynamics and precipitating a freshwater crisis (Jyrkama and Sykes, 2007 ; Varallyay, 2011 ; Faramazi et al., 2013).

Hydrological modeling utilizing tools like SWAT can provide insights into future catchment weather conditions and shed light on water availability scenarios (Nyeko, 2015). The semi-arid nature of the Tamne region renders it susceptible to the impacts of global warming and climate change (Okofo et al., 2023). Mirroring similar water crises unfolding in the Sahel regions (Adaawen, 2021). Precipitation, as a fundamental climate component, significantly influences hydrological stability and

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water availability (Tadic` et al., 2016). Affecting surface water resources (Nasta et al., 2020). However, uncertainties persist in predicting precipitation characteristics such as amount, intensity, and distribution necessitating meticulous analysis (Orlowsky and Seneviratne, 2012 ; Nunes and Lourenco, 2015).

Assessing the impacts of climate change on hydrological processes, particularly water availability, using tools like SWAT (Chaemiso et al. 2016). Integrated with the Mann- Kendall test with Sen`s slope incorporated, holds significant value at the catchment level (Nyadzi et al., 2021). Changes in rainfall trends can disrupt hydrological components, leading to adverse effects such as increased evapotranspiration and decreased surface water availability (Konapala et al., 2020). Climate-threatened regions are likely to confront freshwater crises, underscoring the importance of water-related ecosystem services (Pert et al., 2010 ; Nedkov and Burkhard, 2012).

Furthermore, variations in land use or land cover may exert deep impacts on surface and atmospheric systems, influencing surface water availability (Osei et al., 2019 ; Chaemiso et al., 2021 ; Maru et al., 2023). The savanna zone's vulnerability to prolonged droughts amidst increasing global and local water demands accentuates the urgency for proactive water management strategies (IPCC, 2014 ; Dinko, 2017). Predictions of rising global temperatures and their implications for evapotranspiration and precipitation patterns underscore the need for comprehensive assessments of climate and vegetation dynamics within catchments (Trenberth, 2011). Understanding the dynamics of evapotranspiration is crucial for effective water resource management, particularly in regions where agriculture is heavily reliant on rainfall. In the Tamne Catchment of Ghana, evapotranspiration plays a significant role in determining water availability, influencing both agricultural productivity and ecological balance. Emphasis on inter-annual variability of potential evapotranspiration (PET) and actual evapotranspiration (ET_a) within the catchment. Variability in these two parameters can provide critical insights into the catchment's hydrological behavior, particularly under the pressures of climate variability and land use changes. By analyzing long-term climate data and utilizing modeling techniques, this research aims to quantify the fluctuations in PET and ET_a over multiple years, offering a deeper understanding of how these variations impact water resources and agricultural practices in the region. The findings of this study will contribute to the development of more resilient water management strategies in the face of increasing environmental challenges

Recent reports highlighting record-high temperatures and escalating climate change underscore the pressing need to address the nexus between climate dynamics and water resources (Copernicus Climate Change Service, 2023). With anticipated increases in temperatures and evapotranspiration, coupled with shifts in rainfall patterns, the Tamne catchment faces imminent challenges (Gbangou et al., 2020). The evolving climate scenario necessitates a holistic understanding of catchment hydrology, integrating factors such as land use/land cover changes, climate change and unpredictability (Hengade and Eltido 2016).

This study aims to evaluate the multi-decadal dynamics of hydrological components at the Tamne Catchment using the water balance approach. By analyzing long-term hydrometeorological data, the research seeks to identify trends and shifts in the catchment's hydrology, offering a clearer understanding of the factors influencing water availability. The findings will contribute to developing strategies for sustainable water resource management in the Tamne Catchment, ensuring that the needs of both current and future generations are met amidst ongoing environmental challenges.

2. Materials And Methods

All the Tamne catchment characteristics within a boundary of 880km2 have been modelled using the hydrologic model, soil and water assessment tool (SWAT). Due to the lack of adequate ground-point or station-gauged data in the Tamne catchment and the presence of inherent data errors in available climatic data, global atmospheric reanalysis geospatial data and weather data with sources outlined in (Table 1) were utilized as input variables. The ArcGIS10.3® using Landsat imagery with ArcSWAT® extension have been employed for digital elevation model (DEM), LULC mapping, Soil classification as well as hydrological measurements. These approaches were adopted to meticulously understand the LULC dynamics, and the trends in the hydro-climatic data.

The topographic data used for the digital elevation model and satellite imagery for land use and land cover (LULC) maps were both extracted from [USGS Earth Explorer] (https://earthexplorer.usgs.gov), while weather data was generated from [Global Weather - Texas A&M University] (https://globalweather.tamu.edu/). Soil grid data for soil mapping was obtained from [FAO GeoNetwork] (http://www.fao.org/geonetwork/srv/), which makes available access to interactive maps, satellite imagery, and spatial databases (Thakuri et al., 2022), maintained by the Food and Agriculture Organization (FAO). Additionally, in-situ river discharge data from Global Runoff Data Center (GRDC) (https://www.bafg.de/GRDC/EN/Home/homepage_node.html) were used for model calibration and validation. This multi-model-based assessment of temporal patterns of key climatic and hydrological variables across different time scales in the catchment is employed as part of the research design in (Figure 3) and the modules explained in Table 3 Land use types delineation and classification using Landsat imagery in ArcGIS® 10.3 with ArcSWAT® extension were conducted to realize the consequences of changing patterns relative to land use or land cover (LULC) on the hydrology of the Tamne zone (Mutayoba et al., 2018).

Additionally, time series trend analysis incorporating the Mann-Kendall test with Sen's slope over a 31-year period from 1992 to 2022 was performed to assess water availability and water balance components using SWAT model outputs from the ArcSWAT® interface. The analysis utilized ArcGIS® with ArcSWAT® extension to generate daily, monthly, or yearly time series of catchment-based climatic variables for climate-hydrological simulation, along with the XLSTAT interface for Mann-Kendall test and Sen's slope estimation.

2.1 Description of the Tamne catchment

The Tamne catchment is predominantly drained by the Tamne River, located in the Upper East Region within the White Volta basin as shown in Figure 1. It spans across the Garu and Tempane districts, sharing boundaries with the Bawku Municipality and Binduri districts, situated in the Northern Savanna Agro-Climatic Zone of Ghana. Renowned for its natural beauty, the Tamne catchment has a river system, reservoir, and fertile arable land, making it a valuable landscape in the northern part of Ghana.

The Tamne reservoir, an important feature of the catchment, is estimated to hold approximately 179036,094.26 m3 (6322,600,000 ft3) of surface water. Initially designed to irrigate 1,500 hectares (equivalent to 3,706.58 acres) of land, the current operational area under irrigation spans 799.98 hectares (1,976.8 acres), as reported by the Ghana Irrigation Development Authority (GIDA, 2022). Covering an approximate land area of 880 km2, the Tamne sub-catchment accounts for 71.54% of the total land area of 1,230 km2, extending across the Garu and Tempane districts. Geographically, it lies between latitudes 10°50'N and 11°18'N, and longitudes 0°08'W and 0°30'W. According to demographic data from the Ghana Statistical Service (GSS, 2021PHC), the population of the study area is estimated to be 158,767. With an altitude ranging between 120m and 150m above sea level, the Tamne catchment is susceptible to flooding during the rainy season, highlighting the seasonal hydrological dynamics and challenges faced by the local communities (Okofo, 2023). Tamne River and reservoir (dam) are both serving as natural and artificial sinks created to hold water for conservation of aquatic natural habitats and its valley for lowland agricultural production and other economic uses.

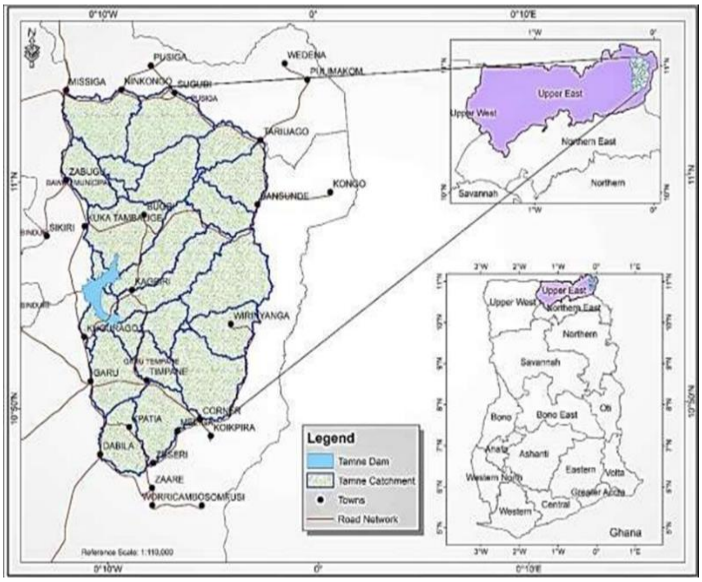

Figure 1: Tamne catchment map showing the river network

Table 1: SWAT input datasets			
Data type	Description	Resolution	Source
Digital Elevation Model (DEM)	Provides data and information on the slope and the river network of the catchment	30x30m	USGS Earth Explorer
Satellite Imagery for LULC Maps	Used for generating HRU in the HRU definition menu	30x30m	USGS Earth Explorer
Soil Map	Used in the generation of the HRU in the HRU definition menu	Scale: 1:5,000,000	FAO GeoNetwork
Weather Data	Daily Precipitation, maximum and minimum air temperature		Global Weather - Texas A&M University
Data of River Discharge	Discharge data used for standardization and authentication of the model		Global Runoff Data Center (GRDC)

2.2 Research Design

Time series trend analysis incorporating decadal proportionality of hydrological indices in percentages over a 31-year period from 1992 to 2022 was performed to assess water availability and water balance components using SWAT model outputs from the ArcSWAT® interface as in Figure 2. The analysis utilized ArcGIS® with ArcSWAT® extension to generate daily, monthly, or yearly time series of catchment-based climatic variables for climate-hydrological simulation, along with the XLSTAT interface for Mann-Kendall test and Sen's slope estimation.

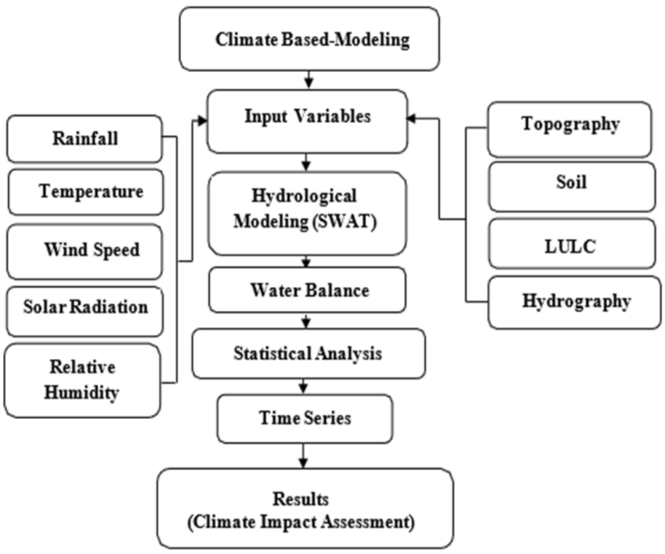

Figure 2: Flow chart for SWAT modelling with Statistical Assessment

2.3 Availability of water and catchment water yield estimation

The Soil and Water Assessment Tool (SWAT®) is a physical model that employs mathematical equations to represent various watershed processes, including hydrology, on a daily time scale. In this study, the SWAT model delineated Hydrologic Response Units (HRUs) based on soil, slope, and using decadal trends in Land Use/Land Cover (LULC) changes and simulated Water Balance Components (WBCs), using daily meteorological indices such as rainfall patterns and temperature for the years 1992, 2002, and 2022. The input data for SWAT were defined at the sub-basin or HRU level, with parameters provided for each feature included in the catchment simulation.

Water balance components typically include precipitation (P), evapotranspiration (ET), river runoff (Qr), surface runoff (Qs), and groundwater flow (Qg). Water balance components include precipitation (P), evapotranspiration (ET), and groundwater recharge with surface runoff estimated using methods like the Soil Conservation Service (SCS) curve number method.

Water loss in the catchment mainly occurs through actual evapotranspiration. The long-term water balance equation for the catchment in terms of rainfall was determined by using parameters such as yearly averages (mm/yr) of rainfall (P), runoff (R), actual evapotranspiration (ET_a), percolation (Wseep), initial soil water (SW_o), and final soil water (SW_a) at the beginning and end of the period.

$$P = R + ET_a + W_{seep} + SW_a - SW_o \quad (1)$$

Equation (1) above indicates that ideally, average precipitation (p) is equal to the sum of average Runoff (R), Evapotranspiration (ET), percolation (W_{SEEP}), and groundwater storage (Gw).

Catchment water yield (WYLD) leaving the HRUs and entering the main channel during the time step (Liang et al., 2020), was estimated using SWAT® model outputs such as surface runoff (SURF_Q), lateral flow (LAT_Q), groundwater contribution to stream flow (GW_Q), and catchment abstraction (C_a) (Sakizadeh and Milewski, 2023; Sisay et al., 2023). The equation for catchment water yield is given below.

$$WYLD = SURF_Q + LAT_Q + GW_Q + C_a \quad (2)$$

2.4 Estimation of Potential Evapotranspiration (PET) and Actual Evapotranspiration (ET_a) using SWAT outputs

SWAT simulations were performed to estimate potential evapotranspiration (PET) using Penman-Monteith as the most comprehensive method. The approach is compatible with the SWAT® model, allowing for the daily estimation of PET using temperature, solar radiation, wind speed, humidity and other factors. After estimating PET at the catchment level, SWAT calculates ETa by considering the availability soil moisture and land use/land cover factors that limit water loss. This involves accounting for the water holding capacity of the soil, plant characteristics, and other environmental conditions. Simulations using the Penman-Monteith method yielded better results in the SWAT model. Additionally, satellite-based actual evapotranspiration (ET_a) analysis for hydrological fluxes, including evaporation, is becoming increasingly reliable.

3. Results And Discussion

3.1 Analysis of Multi-Decadal Dynamics of Hydrological Components by the Water Balance Approach at the Catchment Scale

The pattern shown in Figure 3 reveals that the time series of key hydrological components simulated by the SWAT model at the catchment scale over the period 1992–2022. The variables analyzed include precipitation (PRECIP), evapotranspiration (ET), surface runoff (SURQ_GEN), groundwater recharge (GW_RCH), and water yield (WYLD).

Precipitation as a key determinant exhibited significant inter-annual and inter-decadal fluctuations, with alternating increasing and decreasing trends. Actual evapotranspiration showed moderate variability, with a peak observed in 2001, 2007, 2013, and 2017, respectively, but a notable fluctuation from 2018 to 2022. Surface runoff and water yield demonstrated a generally declining trend, closely following precipitation variability. Groundwater flow remained relatively stable on an inter-annual basis but showed fluctuations correlated with precipitation patterns.

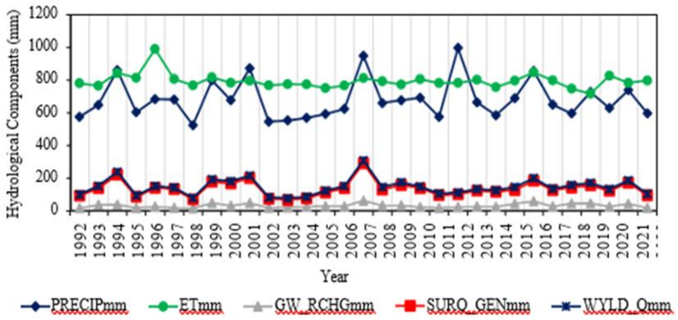

Figure 3 : Time series showing trends of the sensitive hydrological variables

3.2 Multi-decadal proportionality of hydrological indices in percentages for 1992, 2001, 2011, and 2021.

Figure 4 displays pie charts (A–D) representing the proportional contributions of key hydrological variables for the decades 1992, 2001, 2011, and 2021, with 1992 serving as the baseline. Actual evapotranspiration (ET_a) increased from 82% in 1992 to 85% in 2001, then slightly decreased to 84% in subsequent decades. Surface runoff (SURF-CNT) decreased from 9% to 8% between 1992 and 2001, before rising to 10% in 2011 and 2021.Water percolation (Wseep) remained stable at 2% until 2011, dropping to 1% in 2021. Groundwater recharge (GW-RCHG) consistently accounted for 2% throughout the period. Return flow to the root zone (REVAP) varied between 1% and 4% over the decades. Groundwater discharge (GW-Q) remained at 1% until 2011, declining to near zero in 2021. Deep aquifer recharge and lateral flow were negligible (<1%) but deep aquifer recharge increased to 1% in 2021, likely due to the commissioning of the Tamne irrigation dam. Table 2 provides the corresponding volumetric data (H_2O/mm) for these proportions.

The changes in stream flow components such as surface runoff (SURF_Q), lateral flow (LAT_Q), and groundwater contribution to stream flow (GW_Q), translating to water yield (WYLD), and also the impact on evapotranspiration due to LULC were evaluated. As compared to findings on the Black Volta Basin by Kpoti et al., (2016), it was observed that surface run-off (SURF_Q) and lateral flow (LAT_Q) have respectively increased by 27% and 19% while GW_Q decreased by 6% while ET has increased by 4.56%. Implying that, land use and land cover changes integrate climate change impact as a function on the catchment. Despite, stored surface water at the Tamne irrigation dam, evapotranspiration cumulatively decreased by 1.6% serially over three decades spanning from 1992 as a baseline through to 2022. Increasing built and bare soils areas caused an aggregate decrease in actual evapotranspiration by 1.6% in a decadal series from 1992 to 2021 (Table 2). Whiles, grass and shrub lands increased evapotranspiration by 2.1% and agricultural areas caused an increase of 2.2% (Table 2). Even with the decadal increase in built/bare soil size, it has impacted surface flow in the catchment negatively in a reduction of 2.7% while decreased grass/shrub lands caused a decrease in surface flow by 20.7% in aggregation over three decades (Table 2). In decadal series, agricultural areas have decreased over the years yet was responsible for a decrease in surface flow by 20.0%.

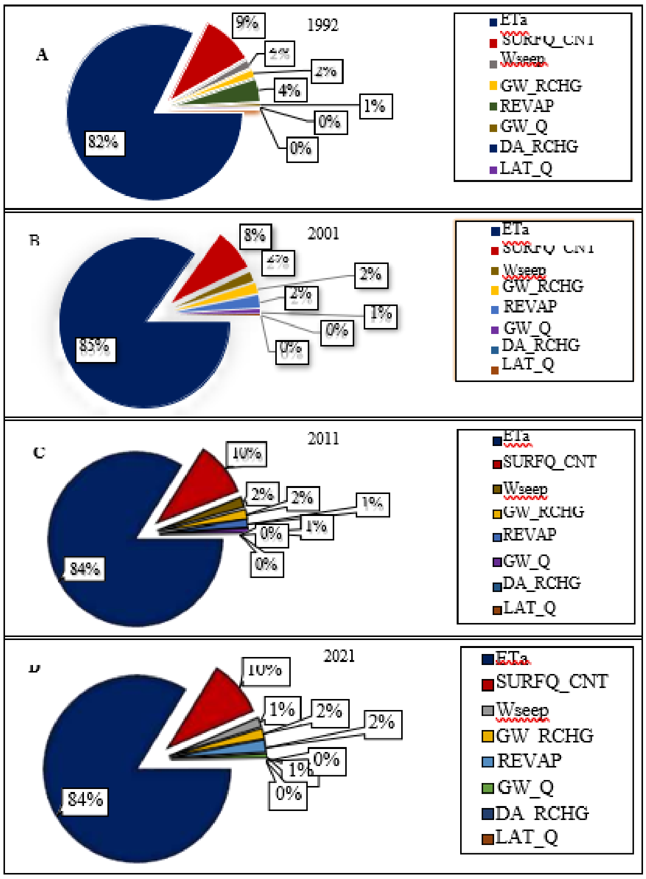

Figure 4 : Multi-charts showing decadal proportionality of hydrological indices in percentage for 1992(A), 2001(B), 2011(C) and 2021(D)

Table 2 : Analysis of percentage proportion of precipitation for other catchment water balance components from the SWAT model

Year	1992-2001		2002-2011		2012-2021		2022	
Hydrologic Parameter	Annual average (mm)	%	Annual average (mm)	%	Annual average (mm)	%	Annual average (mm)	%
Annual rainfall	571.87	100	542.82	100	992.04	100	593.70	100
Actual evapotranspiration	776.26	82	763.86	85	778.87	84	793.63	84
Surface runoff	89.55	9	72.29	8	98.61	10	92.52	10
Percolation (Seepage)	14.51	2	16.82	2	21.85	2	17.13	2
Lateral flow	0.38	0	0.40	0	0.38	0	0.42	0
REVAP (Shallow aquifer=>Soil/Plant)	40.46	4	21.40	2	11.60	1	20.27	2

Table 2 (cont) : Analysis of percentage proportion of precipitation for other catchment water balance components from the SWAT model

Groundwater recharge	15.16	2	17.29	2	21.74	2	17.13	1
Deep aquifer recharge	0.76	0	0.86	0	1.097	0	0.86	0

3.3 Inter-decadal spatiotemporal analysis of the pattern of PET and ET_a over the 30 years

Model-based analysis of the mean monthly distribution and pattern of satellite-based estimated potential evapotranspiration and evapotranspiration are shown in Figure 5. Potential evapotranspiration (PET) is represented in blue, indicating the demand or maximum quantity of water that would be evaporated if enough water were available (from precipitation and soil moisture), while bars in red represent actual evapotranspiration (ET_a), indicating how much water is actually evaporated and transpired over the period and was limited by the amount of water that was available. Therefore, a time series analysis of the trend for both indicates monthly variability and a continuous trend but not in concurrence.

The temporal patterns of potential evapotranspiration (PET), actual evapotranspiration (ET_a), depending on to their ratios and variations putatively affects soil water. Drawing from overall multi-decadal but monthly distribution indicated that potential evapotranspiration was consistently higher in the dry seasons between November and June ranging 597.07mm/H2O to 787.20mm/H2O in May (Figure 8) due to intensity of wind but lower in wet seasons between July and August ranging from 475.23mm/H2O to 580.07mm/H2O in July (Figure 8) due to leaf index influence. Evapotranspiration on monthly bases on the multi-decadal scale was also constantly higher in wet seasons due to increase in vegetation and soil moisture (Figure 9). The higher values of potential evapotranspiration compared to actual evapotranspiration indicate drought, meaning there was no enough water to be evaporated or plants are unable to transpire maturely and readily (Rind et al., 1990).

This implies, the soil is very dry and may require irrigation for agricultural activities. Potential evapotranspiration (PET) is crucial for determining soil moisture levels as it represents the maximum amount of water that would evaporate if sufficient water sources were available. The PET together with other parameters is then used in estimating actual evapotranspiration (ET_a) as asserted by (Adjei et al., 2023). Conversely, actual evapotranspiration (ET) represents the net result of atmospheric moisture demand from a surface and the surface's ability to supply moisture. This implies that as potential evapotranspiration increases, evapotranspiration tends to decrease. In correlation analysis in this study, potential evapotranspiration showed a strong positive correlation with temperature (r = +0.84), indicating potential evapotranspiration increases as temperature rises, temperature will increase potential evapotranspiration (Milly, 2016; Das et al., 2022). Similar report showed that, PET strongly correlated positively with temperature (r=+0.96) (Asaana et al., 2017). However, potential evapotranspiration strongly correlated negatively with precipitation at -0.72, meaning a decreasing potential evapotranspiration correspond to an increasing precipitation due to LULC changes in terms of vegetative cover and increase in humidity (Asaana et al., 2017). Just as reported, areas with high temperature and solar radiation experienced high ET_a (Nsiah et al., 2021). Also, actual evapotranspiration positively correlated to temperature with a coefficient of 0.70 (Nsiah et al., 2021), indicating increasing ET_a corresponded to increasing temperature. This suggests that, hot air temperature may influence a rise evapotranspiration. But, evapotranspiration relationship with precipitation gave a negative coefficient of -0.41 as calculated, suggesting that, ET_a decreases as precipitation increases resulting in increase in vegetative cover and vice versa probably due to both lower air and soil temperatures (Nsiah et al., 2021).

When potential evapotranspiration (PET) exceeds actual evapotranspiration (ET) in a catchment like Tamne, it suggests that the climatic conditions are favorable for water loss from the land surface, but the actual vegetation and soil in the catchment are not utilizing water as much as they could. This situation can have several implications as follows: Despite favorable climatic conditions for evapotranspiration, if actual ET is lower than PET, it may indicate that water resources are underutilized. This could lead to inefficient water management practices, potentially resulting in water scarcity issues, especially during dry seasons. Also, lower actual ET relative to PET may result in excess water that could potentially contribute to groundwater recharge. However, this may depend on some features like soil properties, land use practices, and the presence of impermeable layers that could inhibit infiltration. Another consequence is that, lower actual ET compared to PET may indicate that crops are not utilizing water efficiently, which could lead to reduced agricultural productivity. Farmers may need to implement more efficient irrigation techniques or adopt drought-resistant crop varieties to mitigate water stress and maintain yields.

If actual ET is consistently lower than PET, vegetation in the catchment may experience stress due to insufficient water uptake. This could lead to reduced plant growth, decreased biodiversity, and increased susceptibility to pests and diseases, ultimately affecting ecosystem health and resilience. Understanding the relationship between PET and ET can provide insights into the resilience of the catchment to climate change. Changes in temperature and precipitation patterns may alter PET, affecting water availability and ecosystem dynamics in the catchment. For water management strategies, identifying areas where actual ET is consistently lower than PET can help prioritize water management interventions, such as improving irrigation infrastructure, promoting water-saving agricultural practices, and restoring degraded landscapes to enhance water use efficiency.

Addressing the implications of variable and higher PET than ET in the Tamne catchment requires integrated water resources management approaches that consider climatic, hydrological, ecological, and socio-economic factors to promote resilience and sustainable development.

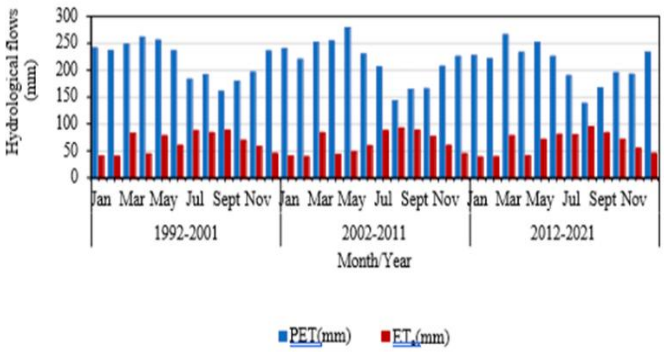

Figure 5 : Decadal mean monthly distribution of Potential Evapotranspiration (PET) and Actual Evapotranspiration (ETa)

3.4 Mean Monthly Levels and Cumulative Distribution of Hydroclimatic Variables

Rainfall Trends (Figure 6) indicates that over the decades, rainfall patterns showed a pronounced dry spell during January, February, March, November, and December recorded zero precipitation respectively. The wet season peaks in August, the month with the highest recorded rainfall, followed sequentially by September, October, July, June, and May. Temperature Variability (Figure 7) shows monthly maximum temperatures from 1992 to 2022 fluctuated between 32.58°C (the lowest) and 42.70°C (the highest). This underscores significant heat variation throughout the year.

Potential Evapotranspiration (PET) (Figure 8) shows that May stands out with the highest potential evapotranspiration, suggesting intense atmospheric demand for moisture. August, on the other hand, records the lowest PET, likely due to high rainfall. March, April, and May show high PET, while February, June, and December present moderate levels. The rest of the months, including August, exhibit relatively low PE values. Actual Evapotranspiration (ET_a) (Figure 9) shows that August has the highest actual evapotranspiration, reflecting both wet and humid conditions. February recorded the lowest ET_a. September, July, and March showed relatively high values, with October, June, May, and November in the moderate range. The driest ET_a period includes December, April, January, and February.

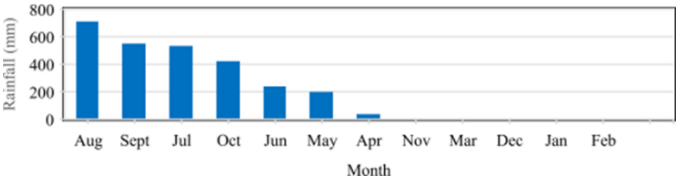

Figure 6 : Cumulative chart of monthly distribution of rainfall from 1992-2022

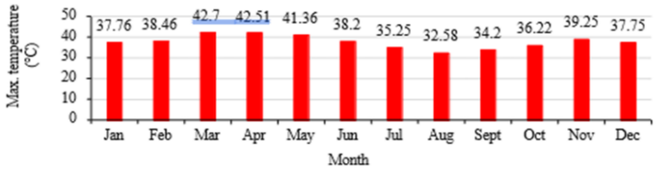

Figure 7 : Mean maximum air temperature 1992-2022

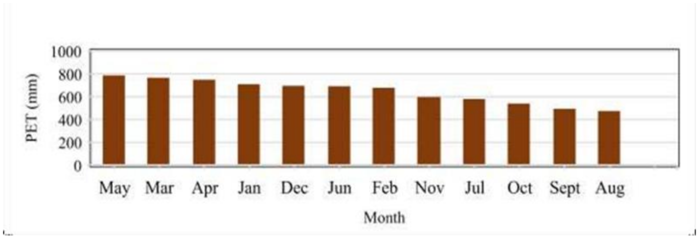

Figure 8 : Cumulative chart of monthly distribution of Potential evapotranspiration (PET) from 1992-2022.

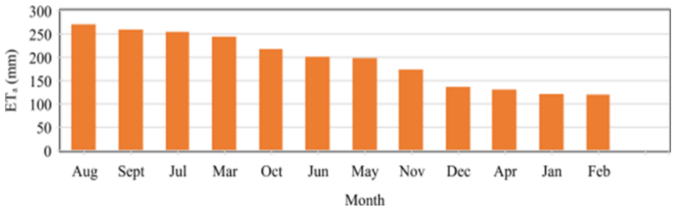

Figure 9 : Cumulative chart of monthly distribution of evapotranspiration (ET) from 1992-2022

3.5 Trend Analysis of Potential Evapotranspiration

In Figure 10, below presents an inter-decadal trend of potential evapotranspiration (PET). In the first decade from 1992 to 2001, PET showed variability, remaining steady from January to February, slightly increasing from March to April, and decreasing from May to September. There was a steady upward trend in October, November, and December. The second decade from 2002 to 2011 in Figure 12, PET dropped in February, then annually increased steadily from March to May, but dipped again from June to August. Observably, it fluctuated slightly upwards from September to December respectively. The third decade, from 2012 to 2021 in Figure 13, exhibits a flat trend from January to February, a rise in March and a fall in April, then fluctuates slightly upwards from May and shows a decrease steadily from June with a dip in August, and a subsequent rise from September and followed by an upward movement through to December. Figure 13 shows a decadal time series trend of a composite curve for 30 years of potential evapotranspiration. The trends are very fluctuating monthly and at inter-decadal scale comparatively. Table 3 shows a decadal mean of potential evapotranspiration (PET), which decreases from 0mm per the base decade to - 3.03mm in the decade between 2002 and 2011 and -3.91mm in the third decade (2012 -2021) over the three decades in series.

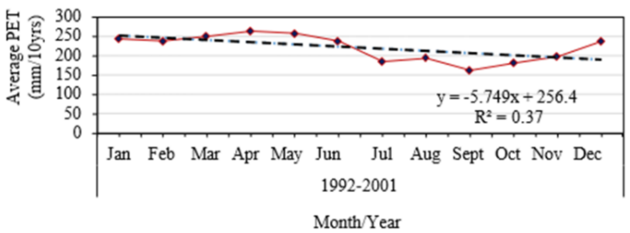

Figure 10 : Decadal trend of monthly cumulative average potential evapotranspiration for 1992-2001

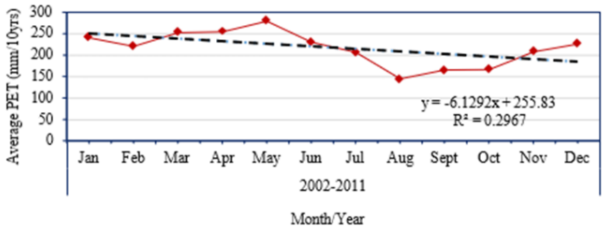

Figure 11 : Decadal trend of monthly cumulative average potential evapotranspiration for 2002-2011

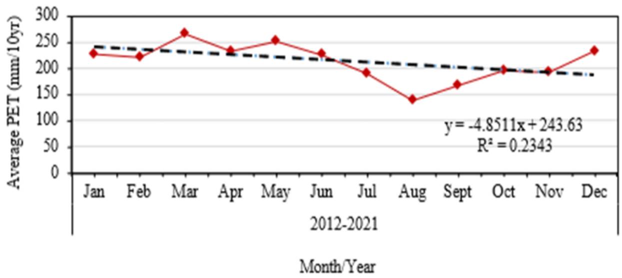

Figure 12 : Decadal trend of monthly cumulative average potential evapotranspiration for 2012-2021

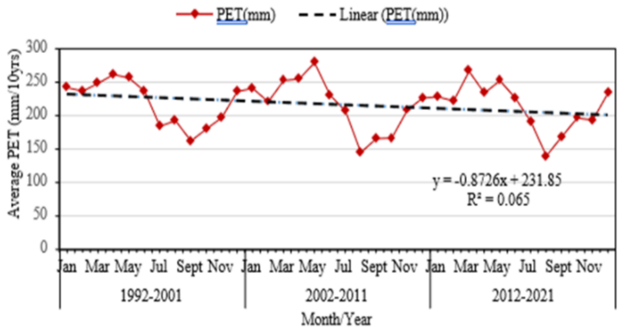

Figure 13 : Inter-decadal trend of monthly cumulative potential evapotranspiration from 1992 – 2021

Table 3 : Basic statistics of Mean of potential evapotranspiration for three (3) break decades

Decade-scale	Mean (mm/10yrs)	Change in Mean (mm/10yrs)
1992-2001	219.03	0.00
2002-2011	216.00	-3.03
2012-2021	212.10	-3.90

3.6 Trend Analysis of Actual Evapotranspiration

Figure 14, depicts a flat evapotranspiration trend for January to February, followed by a rise in March and fluctuations up to September, with a subsequent decrease from October to December, during the decade from 1992 to 2001. In Figure 15, the second decade in series, from 2003 to 2011, showed, there was a flattened trend from January to February, followed by a sharp rise in March, a fall in April, and a subsequent rise from May to August, with a decrease from September to December. Figure 16 represents the third decade between 2012 and 2022 showed a flat trend of evapotranspiration from January to February, a sharp rise in March, and a decline in April, followed by a steady increase from May to August, and a decrease trend again from September to December. In cumulative terms, Figure 17 represents the composite decadal trends in months expressed over the entire 31-year period. The pattern is very variable per average annual monthly evapotranspiration but cumulative. Table 4. illustrates the mean decadal fluctuation, decreasing from 0mm/10yrs to -1.13mm/10yrs over two decades, and then rising by 1.25mm/10yrs between 2013 and 2022.

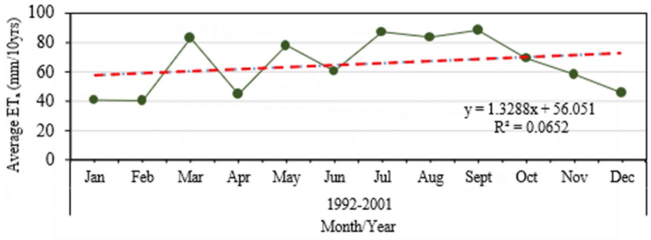

Figure 14 : Decadal trend of monthly cumulative average of evapotranspiration for 1992-2001

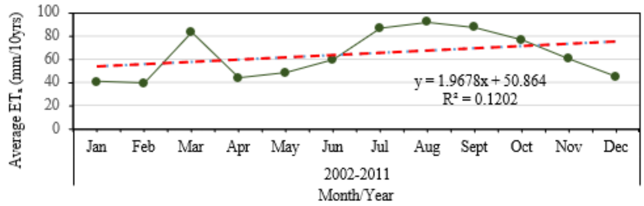

Figure 15 : Decadal trend of monthly cumulative average of evapotranspiration for 2002 -2011

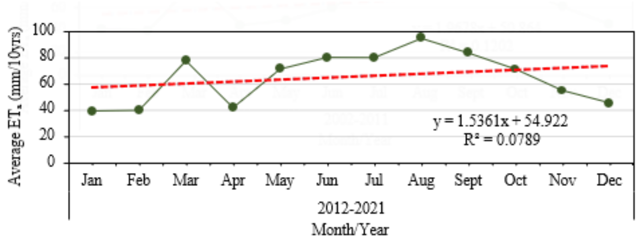

Figure 16 : Decadal trend of monthly cumulative average of evapotranspiration for 2012-2021

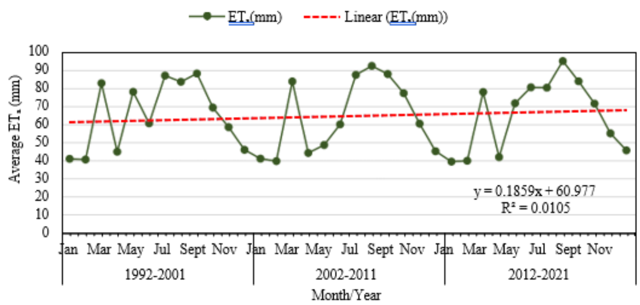

Figure 17 : Inter-decadal trend of monthly cumulative evapotranspiration for 1992-2021

Table 4 : Basic statistics of Mean of evapotranspiration for three (3) break decades		
Decade	Mean (mm/10yrs)	Change in Mean (mm/10yrs)
1992-2001	64.69	0.00
2002-2011	63.66	-1.03
2012-2021	64.91	1.25

3.7 Correlation Analysis

Figure 18 indicates a strong positive correlation between potential evapotranspiration (PET) and precipitation (PPT), with a coefficient of +0.51, and also a high negative correlation with temperature, with a coefficient of (≈-0.71), as shown in Figure 19 below. This suggests that potential evapotranspiration is influenced by high temperatures and sunlight, particularly in March to May. Conversely, it appears to be affected by cold, dry conditions in December to February. The lower potential evapotranspiration observed in July, August, and October could be attributed to relatively high humidity during these periods due to increased precipitation. Figure 20 demonstrates a strong positive correlation between evapotranspiration and precipitation, with a coefficient of (≈+0.49), but a weak negative correlation with temperature, with a coefficient of -0.17, as shown in Figure 21 below.

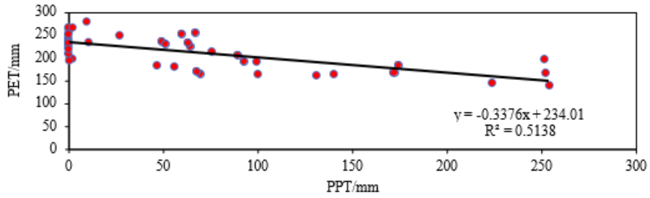

Figure 18 : Correlation between PPT and PET

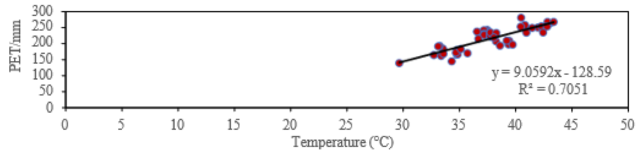

Figure 19 : Correlation between Temperature and PET

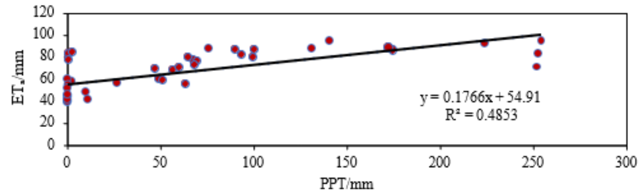

Figure 20 : Correlation between ET and PPT

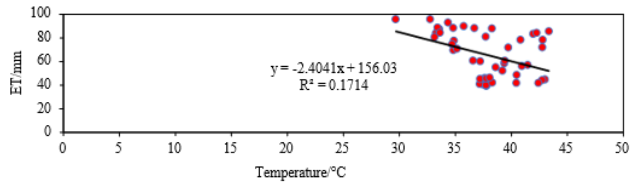

Figure 21 : Correlation between Temperature and ET

5. Conclusion

The conclusion is that unpredictable rainfall and rising temperatures, have altered the Tamne catchment's hydrological components. These changes affect surface runoff, groundwater recharge, evaporation, and other hydrological processes. The results highlight the decreasing trend of hydrological variables, necessitating continuous monitoring and adaptive management to address negative impacts on water distribution across decadal scales.

There were variable changes in the seasonal patterns observed in the hydro-climate, with decadal fluctuations in the hydrological components. Their effects manifest in various ways, with both factors influencing each other over interdecadal scales and leading to annual to decadal variations in rainfall and subsequent changes in hydrological processes. These impacts persisted on a decadal scale.

Recommendation For Research And Adaptation

Research and Data Collection

Research Institutions, Universities, and Government Research Departments should conduct further studies on land use drivers and hydro-ecological impacts in the Tamne catchment. This includes assessing PET and ET_a for crop irrigation, water quality monitoring, and using remote sensing for spatial land cover analysis.

Community Involvement and Field Surveys

Community Leaders, Research Teams, and Local NGOs should involve local communities in participatory research to understand hydrological perceptions and incorporate traditional knowledge. Conduct field surveys to gather data on soil, vegetation, and hydrological features to improve model accuracy.

Ecosystem Services Assessment

Environmental Agencies, and Biodiversity Organizations should evaluate the impact of hydrological changes on ecosystem services, including water supply, agriculture, and biodiversity, to support ecosystem-based adaptation approaches.

Climate-Smart Water Management

Local and Regional Water Authorities, and Climate Policy Departments should implement policies to enhance climate resilience, focusing on surface water storage projects like the Tamne dam to manage water flow variability. Adaptation measures should consider the erratic climate impacts and seasonal fluctuations.

Sustainable Land Use Management

Land Planning and Agricultural Departments should responsibly Monitor and manage land use changes to ensure sustainable agricultural and industrial development. Improve land management to mitigate the impacts of frequent land-use shifts on hydrology in the Tamne catchment.

Agroforestry and Water Conservation Practices

Agricultural Extension Service, and Environmental Agencies should promote agroforestry practices, enhance water conservation, and encourage the adoption of drought-resistant crops. These strategies will protect water resources and increase resilience in local agriculture.

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