

Assessing Hydrological Dynamics in A Tropical Watershed: A Swat-Based Approach Using the Priestley-Taylor Method

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Abstract: Potential evapotranspiration (PET) and evapotranspiration (ET) are vital components of the hydrological cycle, particularly in tropical watersheds where water management relies on accurate predictions of water availability. This study employed the Priestley-Taylor method within the Soil and Water Assessment Tool (SWAT) to model long-term PET and hydrological responses in the Oyun Watershed, Kwara State, Nigeria, over a 30-year period (1991–2021). The model was parameterized using a 90-meter Digital Elevation Model (DEM), land use and soil maps, and daily climate data from the Nigerian Meteorological Agency (NiMet). The Priestley-Taylor method was selected for its suitability in data-scarce and humid regions. Model simulations revealed a total PET of 11,807.51 mm over the simulation period, with spatial variation across sub-basins ranging from 596.51 mm to 721.96 mm. Groundwater recharge was estimated at 8,050.46 mm, while surface runoff was 3,469.06 mm. Land cover, slope, and soil permeability significantly influenced the spatial variability of these outputs. Calibration and validation results demonstrated satisfactory model performance, with Nash-Sutcliffe Efficiency (NSE) and the coefficient of determination (R^2) exceeding 0.7. These findings confirm the effectiveness of the SWAT model for predicting hydrological responses in data-scarce, humid regions, providing critical insights for water management in the Oyun Watershed.

Keywords: Evapotranspiration, Potential Evapotranspiration, Nigeria, Priestley-Taylor Method, SWAT Model, Hydrological Modeling, Oyun Watershed.

I. Introduction

Evapotranspiration (ET) and potential evapotranspiration (PET) are critical components of the hydrological cycle, as they influence key water balance processes such as soil moisture dynamics, surface runoff, and groundwater recharge (Zhang et al., 2016). ET is the combined process of water evaporation from the soil and water surfaces, along with transpiration from vegetation. PET, on the other hand, represents the theoretical maximum evapotranspiration that could occur if sufficient water were available, often under optimal moisture conditions (Allen et al., 1998). These processes are essential for understanding water fluxes within an ecosystem and play a fundamental role in water management strategies (Mekonnen and Hoekstra, 2016).

The proper estimation of ET and PET is vital for accurately assessing the water balance in a given region. This is especially true in regions where water resources are limited or unevenly distributed, such as in the case of many sub-Saharan African countries, including Nigeria (MacDonald et al., 2012). The importance of these variables extends beyond just theoretical hydrological studies; they are directly applicable in practical areas such as irrigation scheduling, drought assessment, watershed management, and flood forecasting (Djaman et al., 2018). In agricultural regions that rely primarily on rain-fed farming, the prediction of ET and PET is crucial to ensuring that agricultural activities are optimized for water availability (Ogunlela and Ogunbodede, 2001).

Accurate predictions enable farmers and policymakers to plan crop schedules effectively, manage water resources sustainably, and mitigate the adverse effects of droughts or floods (Zhao et al., 2020; Ogunlela and Ogunbodede, 2001). Furthermore, understanding these processes aids in ecosystem preservation and the management of water storage systems, such as reservoirs (Zhao et al., 2020; Ogunlela and Ogunbodede, 2001).

A variety of methods exist for estimating PET, and the choice of method often depends on data availability and the specific characteristics of the region under study (Xu and Singh, 2002). The Penman equation, for example, is one of the most widely used methods for estimating PET, as it incorporates key variables such as net radiation, temperature, and wind speed, which are often available from satellite and reanalysis datasets (Donohue et al., 2010). However, while the Penman equation is widely applicable, it can be data-intensive and may not be suitable for regions with limited data availability (Droogers and Allen, 2002). To address this, the Priestley-Taylor method has emerged as a simpler and less data-demanding alternative. This method, which operates on the assumption of a constant coefficient (typically 1.26 for well-watered surfaces), has proven effective in a wide range of ecosystems, including tropical, Mediterranean, and temperate climates (Donohue et al., 2010). The Priestley-Taylor method's simplicity and low data requirements make it particularly appropriate for water-limited regions like sub-Saharan Africa, where there are often gaps in the availability of meteorological and environmental data (Xu and Singh, 2002).

Despite its advantages, there is a noticeable gap in the application of the Priestley-Taylor method for PET estimation in Nigerian watersheds, particularly in the Oyun Watershed of Kwara State. Most existing studies in Nigeria have focused on modeling hydrological processes such as runoff and sediment yield, primarily using the Soil and Water Assessment Tool (SWAT), with limited emphasis on PET and ET as the main outputs (Githui et al., 2009; Arnold et al., 2012; Alemayehu et al., 2009). Moreover,

the majority of the research on Nigerian watersheds has not fully explored the spatial and temporal variability of PET and its impact on water management, even though these factors are critical for understanding how climate change, land use changes, and population growth may affect water resources (Li et al., 2009; Andersson et al., 2009; IPCC, 2021).

Additionally, the Oyun Watershed, a sub-catchment of the larger Niger River Basin, faces significant challenges related to land cover changes, deforestation, population growth, and climate variability (Buytaert et al., 2006; Li et al., 2009; IPCC, 2021). These factors have placed increased pressure on traditional water management practices, which are often based on outdated methods and assumptions (Cai et al., 2003). There is a pressing need for innovative approaches that can provide accurate, timely, and reliable hydrological forecasts, particularly with respect to evapotranspiration, in order to facilitate adaptive water management strategies in response to changing environmental conditions (Katerji and Rana, 2011).

In Nigeria, most SWAT-based hydrological studies have focused on runoff and sediment yield, with limited emphasis on evapotranspiration and potential evapotranspiration as primary outputs (Githui et al., 2009; Alemayehu et al., 2009). This is a critical gap because accurate PET estimation is essential for irrigation planning, drought monitoring, and water resource management in predominantly rain-fed agricultural systems. Although the Priestley–Taylor method is well suited for humid, data-scarce regions, its application in Nigerian watersheds has been underexplored. To address this gap, this study applies the Priestley–Taylor method within SWAT to estimate PET and evaluate hydrological responses in the Oyun Watershed, Kwara State, Nigeria, over a 30-year period (1991–2021).

II. Materials and Methods

Description of Study Area

The Oyun Watershed is located in the North-Central part of Nigeria in Kwara State and is surrounded by the latitude of 8°00'N and 9°00'N and longitudes 4°30'E and 5°00'E. It borders sections of East Ilorin, South Ilorin and the Oyun local Government Area. Hydrologically, this watershed is part of the most widely spread and ecologically valuable transboundary river, the Niger River Basin in Africa, thus inherently affecting the realm of water management, conservation of biodiversity and climate-adaptation policies in the region (UNESCO, 2012; FAO, 2020).

The topography of the watershed mostly covers gently rolling hills with some having an altitude of about 200 meters to 465 meters above sea level. These gradients control surface-runoff processes and decide on the division of the watershed into individual hydrologically homogenous sub-basins, which is an obligatory component in the context of spatially distributed modelling, and efficient water-resources management (Maidment, 2002).

The climatic conditions in the region are tropical savannah in nature showing pronounced wet and dry seasons that experience typical rainfall of 1,100 mm to 1,500 mm annually. These precipitation levels are enough to sustain seasonal farming and keep shallow ground water charged even with the very high inter-annual variation (Peel et al., 2007). An image showing a schematic distribution of River-case Oyun and the other large tributaries is seen in figure 1. Was used to extract the watersheds and the drainage network, a 90-metre resolution Digital Elevation Model (DEM) that was provided by the Satellite radar (SRTM) was used to get the watersheds and the drainage network. Such spatially derived data were treated in Map window GIS and were later prepared to be used in an integrated platform of soil and water assessment tool (SWAT), which is a process-based hydrological simulation at the sub-basin scale (Arnold et al., 2012; Winchell et al., 2010).

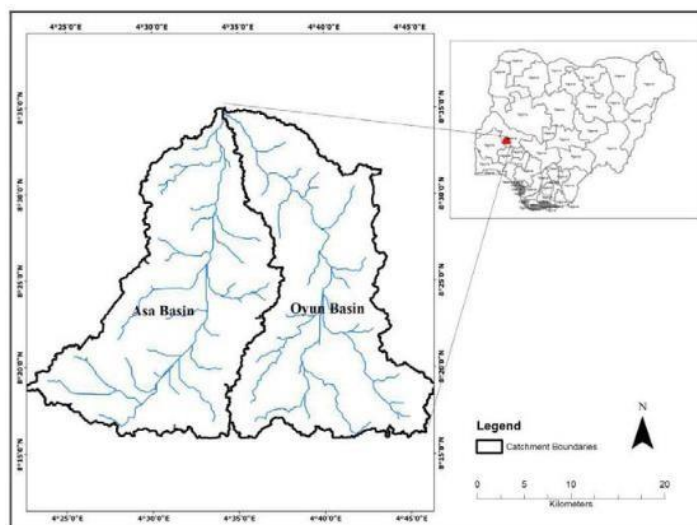


Figure 1: Map of Oyun River basin of the study area. Derived from Shuttle Radar Topography Mission (SRTM) data (Farr et al., 2007) and processed using MapWindow GIS.

Model Selection and Description

The calculation or simulation of hydrological processes in the Oyun Watershed was carried out through the application of Soil and Water Assessment Tool (SWAT), which is a physically based, semi-distributed model to assess land use, soil, slope and climatic effect on water cycle. With the daily time step, SWAT measures significant water balance parameters including surface runoff, infiltration, base flow, and evapotranspiration which makes it perfectly applicable to catchment-based analysis (Neitsch et al., 2011).

In order to capture the spatial heterogeneity, watershed was divided into several sub-basins and again into Hydrological Response Units (HRUs). These HRUs are characterized by distinct sets of land use, soil type and slope class and through this the model is able to discriminate between localized hydrological responses in complex terrain (Gassman et al., 2007). The layer by layer model structure is advantageous in improving the accuracy of the models in terms of reflecting the runoff generation/evapotranspiration variability of different physiographic zones.

MWSWAT (a customized interface built into MapWindow GIS environment) implemented a model set up and has the ability to preprocess the data and configure the model. Topography based on a 90-metre resolution Digital Elevation Model (SRTM) and land use and soil data, as well as climate input data with daily meteorological data temperature and days-long solar radiation were also used as inputs. MWS was aligned to all these inputs on space and times and within MWSWAT, they were integrated with ease within the simulated framework of SWAT (Winchell et al., 2010; Githui et al., 2009).

Because of the occurrence of missing long-term, ground-based meteorological data in the area, the Priestley Taylor method was used to come up with actual potential evapotranspiration (PET).

Modelling Input Data

Digital Elevation Model (DEM)

A 90-m resolution Shuttle Radar Topography Mission (SRTM) DEM was used to delineate watershed boundaries, extract stream networks, and classify slopes in the Oyun Watershed. These topographic inputs supported flow routing and hydrological response unit (HRU) definition within the SWAT model (Farr et al., 2007).

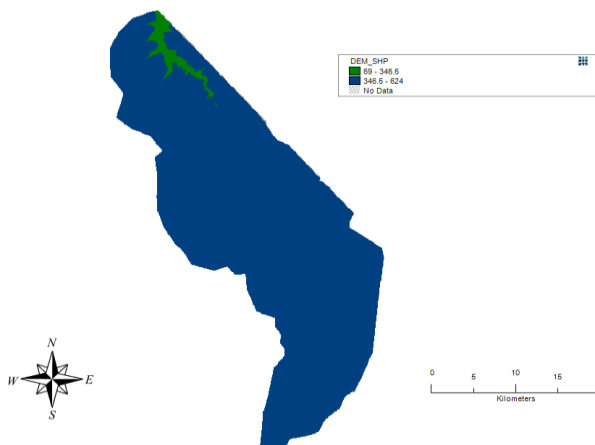


Figure 2: Digital Elevation Model (DEM) of the Oyun Watershed. Elevation data derived from Shuttle Radar Topography Mission (SRTM) at 90-meter resolution and processed using MapWindow GIS. Elevation ranges from 69 to 624 meters above sea level.

Topographic gradients were discretely defined with help of high resolution DEM which facilitated correct knowing of sub-basin outlets, drainage patterns etc. The data of elevation and slope that was obtained as a result of the use of the DEM played a vital role in the moderation of the hydrological pathways and flow routing in the model. Further, the DEM offered the geographical foundation to calculate the flow accumulation areas that were then essential as the key data source in stream networks and watershed structure delineation.

To develop Hydrological Response Units (HRUs) within the SWAT model, the DEM was applied to get the topographic information that was significant. It made sure that the realistic terrain-induced hydrologic behavior, including runoff generation due to different heights and infiltration under the slope effect was replicated via the HRUs (Gassman et al., 2007).

Land Use and Land Cover (LULC)

Land use and land cover data were obtained from medium-resolution USGS satellite imagery and reclassified to match SWAT categories. Major classes included cropland, forest, grassland, and built-up areas, which strongly influence infiltration, evapotranspiration, and runoff dynamics (Arnold et al., 2012; USGS, 2023).

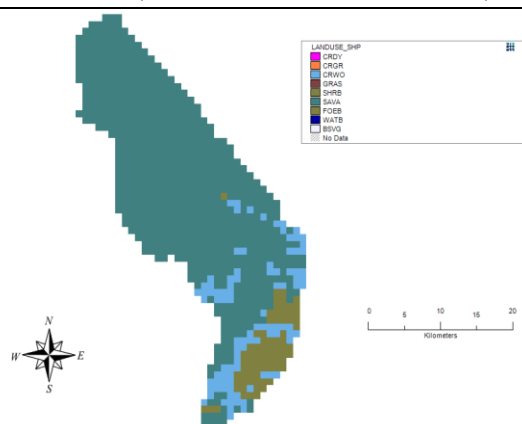


Figure 3: Land Use Land Cover Map of the Study Area

Soil Data

Soil information was sourced from the Harmonized World Soil Database (FAO et al., 2012) and formatted for SWAT compatibility. Parameters such as texture, organic carbon, and hydraulic conductivity were used to define infiltration, percolation, and water storage properties within HRUs (Saxton & Rawls, 2006).

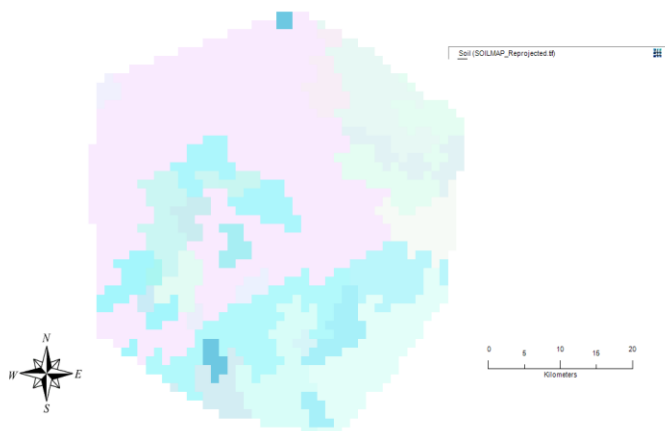


Figure 4: Soil Map of The Oyun Watershed

Following the preprocessing, the soil database was combined with the slope and land use/land cover (LU-LC) so as to create Hydrological Response Units (HRUs). The HRUs are a mixture of soil, land use, and class of slope and each combination forms a unique HRU and thus SWAT can simulate the spatially explicit movement of water, evapotranspiration and sediment transportation in the watershed (Arnold et al., 2012).

With regard to Oyun Watershed, the soil also played an important role in the shaping of areas with high runoff potential, low-hydraulic conductivity or high evapotranspiration based on the land cover that was above the zone. The stratification of soil types in this way then became the foundation of approximating surface and underground water dynamics under dissimilar forms of terrain and flora (Gassman et al., 2007).

Model Setup and Processing

MWSWAT is a special plug-in within the MapWindow GIS application that was employed to carry out the implementation of the SWAT model configuration of Oyun Watershed. Carrying 90-metre resolution Digital Elevation Model (DEM), the watershed boundary was delineated and sub-basins were defined according to direction of flow and network stream distribution (Winchell et al., 2010). The soil, slope and land-use maps were overlaid to come up with Hydrological Response Units (HRU) which are considered to be spatially distinct of a combination of physiographic factors. The definition of HRU was controlled under the threshold level, such as 10 percent land use, 20 percent soil and 10 percent slope in order to find the tradeoff between spatial detail and computational efficiency (Gassman et al., 2007).

Hydrological Response Units (HRUs) were defined using thresholds of 10% land use, 20% soil, and 10% slope. These thresholds were selected to balance spatial detail with computational efficiency. Previous studies show that very low thresholds increase model complexity and computation time without significantly improving accuracy, while moderate thresholds capture the main variability of land–soil–slope interactions (Gassman et al., 2007; Arnold et al., 2012).

Simulations were created to operate on a daily time cycle so as to incorporate the changes that occur in relation to time in various seasons of the hydrologization process. The daily solution enhances the model sensitivity to the short term climatic variability, seasonal variation of evapotranspiration, runoff and soil wetness (Arnold et al., 2012).

PET Estimation Methods

Priestley Taylor, Penman Monteith and Hargreaves Samani - are three well established method of calculating the potential evapotranspiration (PET), which are all supported by the SWAT model platform (Xu and Singh, 2002). These methodologies very much differ in terms of the data, conceptual, and environmental scope requirements.

In this research, the Priestley Taylor approach, due to its excellent reliability in very humid and sub-humid areas where the effects of aerodynamic resistance are very small on the rates of evapotranspiration (Donohue et al., 2010) was used. This simplification of the Penman Monteith equation assumes that the effect of radiation (wherein the rate of evaporation depends upon the incident amount of radiation, and the amount of energy that can be made use of by the plant and soil surface) dominates, and then scales the radiation term by an empirical coefficient alpha (alpha), which is often set to 1.26 in well-irrigated situations (Priestley and Taylor, 1972).

Owing to the consistent availability of the net radiation and the air temperature from the satellite and also the reanalysis sources, the given method was highly appropriate in the Oyun Watershed. Such conditions fit in the assumptions incorporated in the method and make its results rather certain in terms of long-term simulations (Donohue et al., 2010).

Although the Penman Monteith method is considered as a reference one in agro-hydrology and climatology and physically based, it needs the larger meteorological data set with wind speed, relative humidity, net radiation, and temperature (Allen et al., 1998). They might not be fulfilled or are not supposed to be regularly fulfilled particularly in regions where information is scarce such as the Oyun Watershed that decreases the expectations of the approach and software accuracy on a long-term time scale (Lu et al., 2005).

Hargreaves is a temperature-driven, empirical method of estimating PET by arrival, by use of air temperature minimum and maximum and extraterrestrial radiation (Hargreaves and Samani, 1985). It is however not suitable in humid areas and in areas of complex topography and even though it is computationally efficient it also does not perform well in areas of low data which is characteristic of much of the Oyun Watershed (Droogers and Allen, 2002). This therefore made it suboptimal in this study.

In the present work, the Priestley Taylor method was selected because it is not very data dependent, performs well in the humid ecosystem, and considers the climatology of the area in which the Oyun Watershed is located. The method was more stable and predictive than other methods among comparable environments, both in terms of similar humidity (Donohue et al., 2010; Zhang et al., 2016).

Model Calibration and Validation

The calibration of the SWAT model using past streamflow and sediment measured data collected by Hydrology and Water Quality directorate of Kwara State Ministry of Water Resources was done. The calibration period was between 1999 and 2014 calendar years whereby important model parameters which determined surface runoff, base flow and evapotranspiration were properly set to reduce the existing variances between actual and computed values (Arnold et al., 2012).

In order to increase the accuracy of parameters, sensitivity analysis and automatic calibration were done using Sequential Uncertainty Fitting algorithm version 2 (SUFI-2), which is incorporated into the tool SWAT Calibration and Uncertainty Procedures (SWAT-CUP). SUFI-2 is an efficient parameter selection tool that considers the uncertainty of parameters and minimizes the multiple objective functions in evaluation of the model performance (Abbaspour et al., 2007). This was used to ensure that the model was better equipped to devise better simulations of major hydrological variables in a more desirable unbiased manor.

The model was validated on the separate the dataset of 2015-2021 and no additional changes to the parameter sets identified in the process of calibration were made. Based on the widely used statistical values, which are the Nash Sutcliffe Efficiency (NSE), Coefficient of Determination (R^2) and Percent Bias (PBIAS), predictive success of the model was evaluated (Moriassi et al., 2007). Both the NSE and R^2 were greater than 0.7 both in evapotranspiration and water yield, meaning that there was a high level of agreement between the simulated and observed performance and it could be used in hydrological forecasting in Oyun Watershed.

III. Result and Discussion

Prediction of Potential Evapotranspiration (PET)

In the estimation of potential evapotranspiration (PET) at the Oyun Watershed, the Priestley Taylor method was used under the model initialization technique where the simulation run in the SWAT was 30 years (1991-2021). This was based on the analysis of long-term climatic inputs such as the temperature, solar radiation, and humidity, most of which were actively sourced to the Nigerian Meteorological Agency (NiMet) with reanalysis datasets fulfilling the needs where it was necessary (Donohue et al., 2010). The MapWindow GIS was used to process and merge the spatial datasets following which the watershed was discretized into sub-basins and further onto the Hydrological Response Units (HRUs) based on soils, the land use and slope (Winchell et al., 2010).

It was estimated that PET on an annual basis of settling on the entire watershed basing on the simulated model was around 11,807.51mm. Still, there was an enormous sub-basin disparity. Let us take an example, Sub-basin 8 had lowest PET reading of 596.51mm and Sub-basin 4 had the highest PET (721.96mm). These divergences were heavily affected by vegetation cover variation, land cover, slope slant and localized climatic condition which influences availability of energy and interactions between the surface and the atmosphere (Mu et al., 2011).

The spatial distribution map (Figure 4.3) pointed out vegetated areas and steep slopes to have a lower PET and it could be attributed to shading and less radiation and surface temperatures. On the other hand, it was discovered that sub-basins that had a low level of vegetation, less exposure to sunlight had high PET. These spatial patterns favor the assumptions under which Priestley Taylor method is developed; namely that PET is controlled by the energy availability as a water supply is non-limiting (Priestley and Taylor, 1972; Wang and Dickinson, 2012).

On the whole, the simulation of the Priestley Taylor method as subsumed in a SWATGIS model validated the use of that method within such data-limited, humid tropical settings as the Oyun Watershed as a definite way to benefit the estimation of PET. PET values produced are also important baseline estimates that will help to divide the water losses in the atmosphere and are baseline data that will be used in further water balance calculations, hydrological modelling and planning of land management in the area (Xu and Singh, 2002; Gassman et al., 2007).

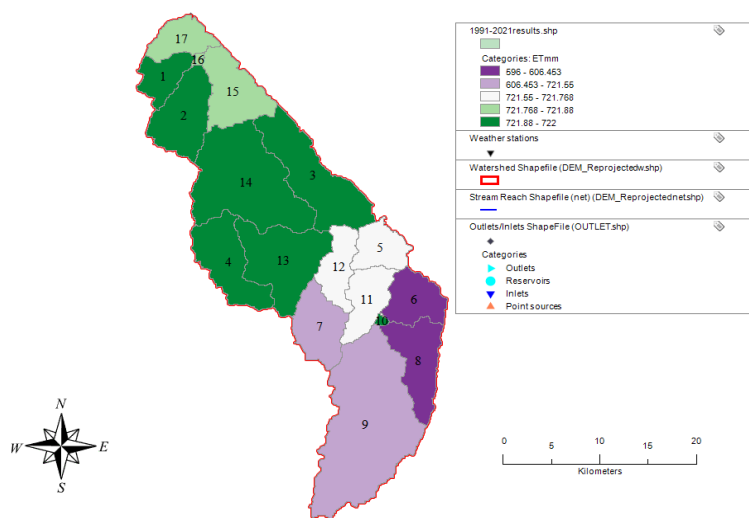


Figure 5: Spatial variation of annual predicted evapotranspiration (1991–2021) across sub-basins of the Oyun Watershed, showing higher PET values in less vegetated areas and lower PET in dense vegetation zones

Prediction of Surface Runoff

Surface runoff is an important part of the hydrological cycle, which determines the amount of the waters entering the streamflow, recharging the aquifers, and transporting the sediments. It has connections to flood risk management, erosion control and water planning in the farming community (Beven, 2012). The SWAT model was applied to simulate long-term surface run off in Oyun Watershed, it used meteorological data of the past 30 years (1991 to 2021) and related spatial data such as land use, soil and topography. Moreover, the discretization of the watershed was performed in such a way that local differences in surface conditions and hydrological responses have been considered (i.e. nine sub-basins were formed and thirty Hydrological Response Units (HRUs)) (Gassman et al., 2007).

The simulation indicated that the average total annual surface runoff over the whole watershed was 3,469.06 mm which was experienced over the 30 years. The sub-basin level of analysis indicated major spatial asymmetries: the least influential (in terms of runoff, i.e. 198.01 mm) Sub-basin was No. 9 whereas the most influential (225.05 mm) one was Sub-basin 6. Altogether these variations were mostly determined by the difference in land cover, soil infiltration capacity and topographic slopes. The steep terrain and sparsely vegetated surface exhibited the most run off since there was less infiltration and over other flows flowed high (Arnold et al., 2012).

The Figure 6 displays the distribution of the surface runoff in space. Relative higher runoff values were recorded in sub-basins in the northeastern and central zones where there are croplands and bare surfaces. These trends indicate that land use change, deforestation and urban expansion have a big influence in the dynamics of runoff due to changes in the permeability of the ground and changes in vegetation cover (Fohrer et al., 2001). The results will enable stating that SWAT model will enable describing the specifics of behavior of the localized runoffs especially when HRUs account the heterogeneity patterns of the reality ones. Such results bear practical application in formulation of land use policy and erosion risk management measures, as well as sustainable watershed planning in the area (Githui et al., 2009; Moriasi et al., 2007).

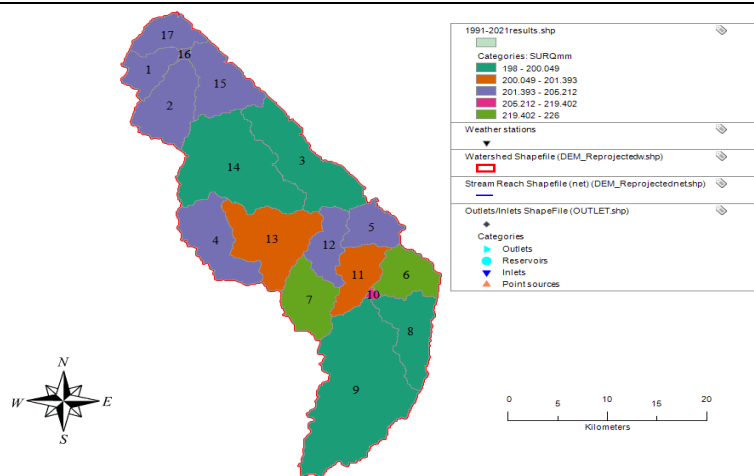


Figure 6: Spatial variation of annual predicted surface runoff (1991–2021). Higher runoff is concentrated in northeastern and central zones dominated by cropland and bare surfaces.

Prediction of Groundwater Recharge

The model estimated that the volume of total annual average proportion of recharge was 8, 050.46-mm in the entire watershed. There was also high variation shown in spatial one: the value of recharge was lowest in sub-basin 5 (444.87mm) and highest in sub-basin 8 (562.74mm). The dominant or paramount causes of such disparities were assumed to be hydraulic conductivity of soil, infiltration capacity and topography of land cover. The recharge was increased in sub-basins that initially had permissible soils and a thicker vegetative cover since there was less surface run off and more infiltration (Healy and Cook, 2002; Dell and Fiedler, 2008).

The results show that the SWAT model has the potential to be of high representational standing to be able to redefine the spatial explicit groundwater recharge. This strengthens the usefulness of the model to determine the sustainability of aquifers, well-siting approach, and mapping groundwater vulnerability in other tropical regions with limited data such as the Oyun Watershed (MacDonald et al., 2012; Moriasi et al., 2007).

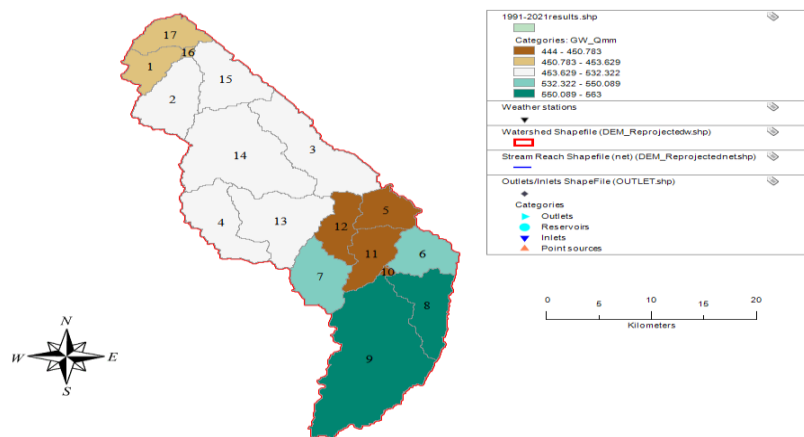


Figure 7: Spatial distribution of annual predicted groundwater recharge (1991–2021) across the Oyun Watershed, highlighting areas of higher recharge in vegetated and permeable soils.

IV. Conclusion

The Priestley-Taylor method proved to be an effective approach for estimating potential evapotranspiration (PET) in humid tropical regions with limited data, such as the Oyun Watershed. Its simplicity and low data requirements make it particularly suitable for areas where high-quality meteorological inputs are scarce. Although the model was not calibrated using observed streamflow or evapotranspiration data, the simulation results are consistent with the hydrological processes within the watershed, suggesting that the model can provide reliable predictions. This study demonstrates the applicability of the Soil and Water Assessment Tool (SWAT) as a robust framework for water resource evaluation at the watershed level, supporting land use planning and sustainable water management practices in the region. Future research should integrate field validation data, climate change projections, and land use change scenarios to improve model accuracy and better inform regional water management policies. Overall, this study serves as a valuable guide for hydrological modeling in tropical watersheds and highlights the critical role of PET forecasting in achieving sustainable water resource management.

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