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Modeling soil water balance of an agricultural watershed in the Guinea Savannah Agro-ecological Zone; a case of the Tono irrigation dam watershed

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ABSTRACT

Water is the most significant of all the requirements for plant growth and development. Its availability or scarcity in the soil can denote a successful harvest, reduction in yield, or complete failure. Though Tono is a small community in the Kassena Nankana East Municipality in Upper East Region of Ghana, farmers in the area contribute significantly to the availability of food products in neighboring communities, and even in some parts of southern Ghana. However, changing climate and landscape dynamics are perceived to be the primary cause of decreasing water availability and responsible for the dwindling farming fortunes. The study therefore investigated the changes to soil water balance occurring within the Tono dam watershed, as well as changes to the landuse/landcover (LULC) of the area and its impacts on crop production using the Soil and Water Assessment Tool (SWAT). The LULC continues to change through anthropogenic activities thereby causing variations in the hydrological cycle over time. A 30-year period from 1984 to 2014 was used as the simulation period to run the model. Two (2) LULC maps and change scenarios for 1984 through to 2014 were assessed. The results revealed a relationship between landcover and the response to hydrology, in that, a decrease in landcover causes a decrease in surface water, soil moisture, and a corresponding infinitesimal decrease in evapotranspiration. The results showed a 17.6%, 9.6%, and 1.6% decrease in rainfall, soil moisture and evapotranspiration, respectively. The results showed the ability of the SWAT model to reveal spatio-temporal variation of the change in the landscape and the associated changes arising from climate change having significant effects on the Tono catchment.

Keywords: *Landuse/landcover, SWAT, Soil water balance, rainfall, evapotranspiration*

INTRODUCTION

The managed use of water and its application worldwide has been an imperative factor in boosting agricultural productivity and ensuring predictability in outputs (FAO, 2010). Water is necessary to bring forth the potential of the land and to make possible improved varieties of both plants and animals to make full use of other yield-enhancing production factors. By increasing productivity, sustainable water management (particularly when integrated with adequate soil husbandry) helps to ensure better production for both direct consumption and commercial distribution, thereby providing the necessary economic surpluses for uplifting rural economies (Food and Agriculture Organization (FAO) of the United Nations, 2008).

The scarcity or availability of water can denote a successful harvest, or reduction in yield, or complete failure (FAO, 2011). Plants get access to water by way of precipitation, mainly rainfall, in the form of surface water, soil moisture, or groundwater. The flow of water in plants helps to maintain favorable temperature conditions by means of evaporative cooling. Water also serves as a substrate for most plant biochemical reactions (Ritchie, 1998). During seasons of low or no rainfall, it is imperative to support crops by irrigation. However, increase in water demand for all industrial, domestic, municipal and other activities amidst low or no rainfall , hence, the need for good irrigation water management practices (Steyn, 2004). In the application of water management both for irrigated and dry land crops, the water-holding capacity of the soil, together with the available water and field capacities are essential.

The landuse and landcover of an area changes continually overtime in response to evolving economic, biophysical, and social conditions (Roy and Giriraj, 2008). This significantly affects the hydrologic characteristics of the land surface and consequently modifies the rates and pathways of water flow (Walling, 2009). For several years, the most prominent land changes within the Tono catchment have been the kind and amount of grass cover, caused evidently by the building of houses and other infrastructure (Abubakari, 2014). Consequently, this has affected the climatic conditions, soil, and hence, agricultural activities in the area (Fall *et al.*, 2014). Inappropriate agricultural activities such as intense cultivation and mono cropping directly/or indirectly impact the soil and water resources, though this depends on micro- and macro-scale factors such as climate, landscape, topography, and landuse of the watershed (Arnold *et al.*,2014).

Though water is essential for all forms of life on earth, its availability and distribution all over the world, even at the same locations is not uniform throughout the season. Some parts of the world experience drought while other parts face the challenge of optimally managing their abundantly available water resources (Abubakari, 2014). Plants require not just water, but adequate amount of water to survive. To ensure adequate food crop production, good agricultural practices including proper irrigation system have to be employed under very favorable climatic conditions.

This study therefore focused on assessing the impact of landuse/landcover changes on soil water balance and its effect on crop cultivation within the Tono watershed which is believed to help in managing the water resources**.** The objectives of the study were: i) to assess the landuse/landcover changes over the past 30 years (1984 to 2014), ii) evaluate the impact of landuse/landcover changes on evapotranspiration and soil moisture, iii) estimate the water balance of the watershed and iv) quantify the soil moisture content of the sub-basin within the watershed from 1984 to 2014.

MATERIAL AND METHODS

Study Area

The Tono irrigation dam is located in the Kassena-Nankana municipality district of the Upper East Region of Ghana between latitudes 10°56' and 10°51' North and longitude 1°8' and 1°12' West (Figure 1). It is about seven (7km) kilometers from Navrongo, the district capital. It has a watershed area of about 60,260 ha. The dam embankment wall is about 3.2 kilometers long and serves eight (8) villages (command areas) namely Yigwania, Bonia, Wuru, Chuchuliga zone A and B, Gaani, Yigania and Korania (Asaana and Sadick, 2016). The Water from the dam can be used to irrigate about 2,490 ha of land. Tono River is the main source of water for the dam. The potential irrigable area of the dam is approximately 3,840 ha out of which 2,490 ha is developed. The dam has a water storage capacity of 9.26 x 10^7 m^3.

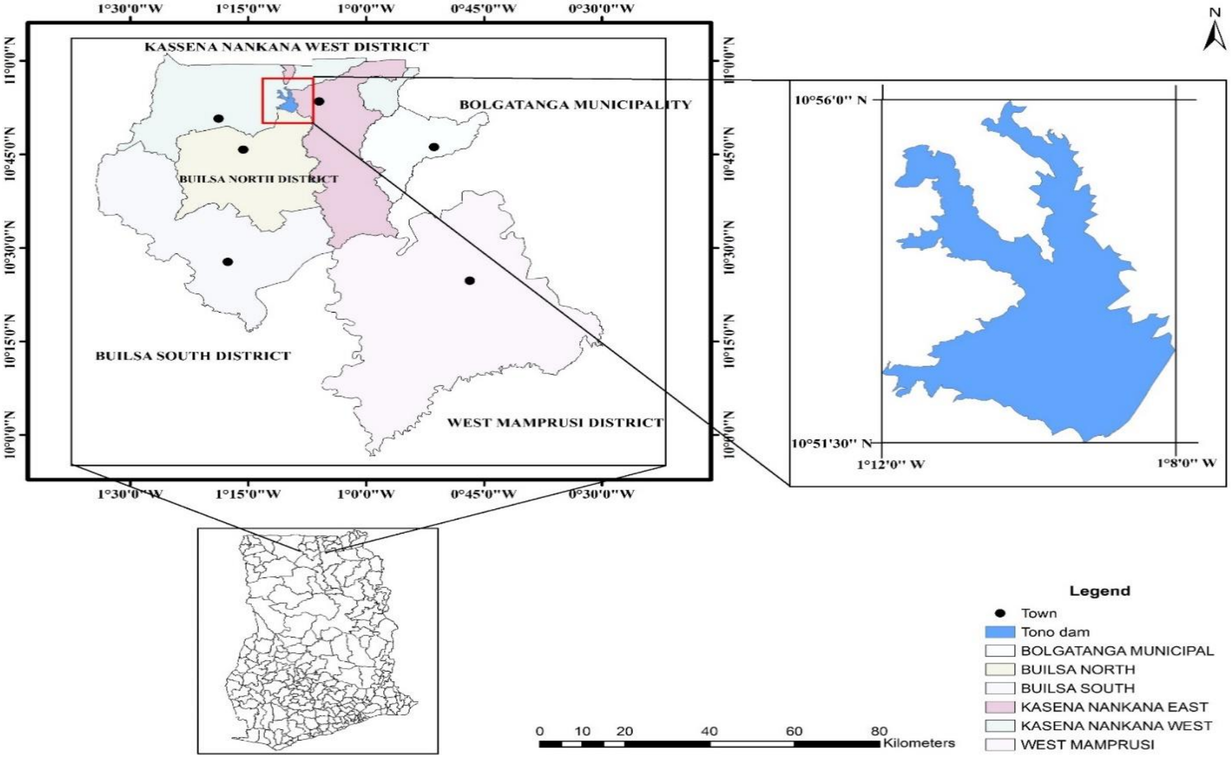

FIGURE 1. **A map of Ghana showing the location of the study area**

Materials and Software Used

A one arcsecond (30m) resolution DEM from Shuttle Radar Topography Mission (SRTM) was used for the study to generate information on elevation (Figure 2). The DEM was used to delineate the watershed and, in so doing, derive significant parameters and stream network attributes such as length, width, and channel slope. One important factor which affects the surface runoff and evapotranspiration of an area is its landuse and landcover. Two years, 1984 and 2014, 300 m resolution LULC data downloaded from European Space Agency (ESA), Climate Change Initiative (CCI) website was used in this study. Having reclassified the maps to simulate the actual landuse based on specific landcover characteristics, nine (9) classes were identified (Figure 3).

Soil data used in this study was digitized from the FAO digital soil map of the world. Four (4) different soil classes were identified in the study area. Luvisol is the dominant soil type in the study area followed by Gleysol, Lixisol, and Fluvisol.

Data such as rainfall, minimum and maximum temperatures, solar radiation, relative humidity, and wind speed were used as weather input to run the model. The data can be obtained from existing records, measurements, or generated using monthly average values by a weather generator model (WXGEN) integrated into SWAT. Daily precipitation and minimum and maximum temperature data from 1984 to 2014 for two weather stations were obtained for use from the Ghana Meteorological Agency (GMet). The main software used for this work is the ESRI ArcGIS 10.1® with its extension ArcSWAT®.

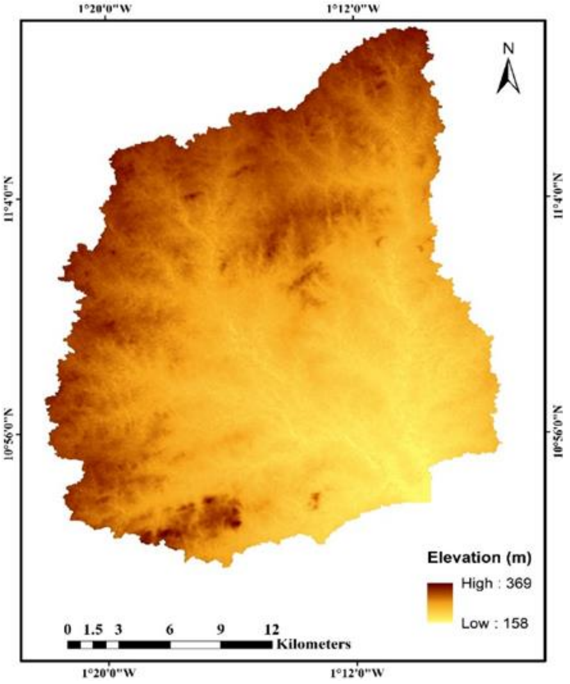

FIGURE 2. **Map showing the elevation of the watershed**

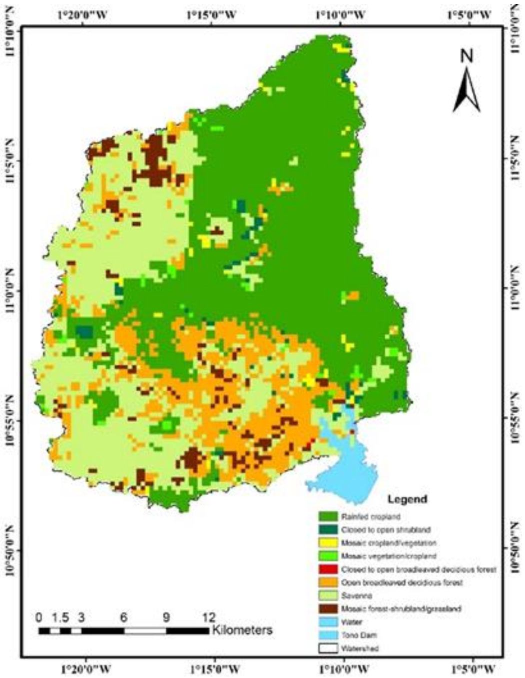

FIGURE 3. **Year 2014 LULC**

Methodology

Soil and Water Assessment Tool (SWAT) is a computationally cost-effective and a physically based model which uses generally available data (Bouslihim *et al*., 2016). This study used ArcSWAT 2012 in a Geographic Information System (GIS) user interface (ArcGIS) to generate a hydrologic model of the Tono watershed.

Water balance within the soil profile at the depth of 15cm is the driving force behind all processes in SWAT (Arnold *et al*., 2012b). The processes simulated by the model include evapotranspiration, infiltration, surface runoff, precipitation, lateral flow, and percolation. Equation (1) depicts the master water balance approach used by the model to determine surface runoff, soil moisture, and peak flows (Kuhn, 2014).

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \qquad \ldots\ldots(1)$$

Where SW_o and SW_t are the initial and final soil water content respectively. Surface runoff in day i (Q_{surf}), Evapotranspiration in day i (E_a), amount of water entering the vadose zone (w_{seep}) and the return flow in day i (Q_{gw}) are all subtracted from precipitation on day i (R_{day}). All parameters are in millimeters except time (*t*) which is in days. The equation can be manipulated to estimate any variable of interest.

Surface runoff can be estimated either by the Green-Ampt infiltration method or the Soil Conservation Service Curve Number (SCS CN) method (Setegn *et al*., 2008). *The* SCS curve number method was used in this study. SCS CN values range from 30 to 100 with lower values representing low runoff potential and higher values representing higher runoff potential, thus, greater ability of infiltration (Hong *et al*., 2016).

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)} \text{ …….. } \mathbf{(2)}$$

Where: Q_{surf} is the accumulated runoff or rainfall excess in mm, R_{day} is the rainfall depth for a specific day (mm), and S is the retention parameter in mm (Hong *et al*., 2016).

SWAT allows for the estimation of potential evapotranspiration using three different options including Priestley-Taylor, Hargreaves, and Penman-monteith methods (Kuhn, 2014). The method to use is based on the availability of data. The Penman-monteith method (Migliaccio and Srivatava, 2007) was used in this study since temperature, relative humidity, wind speed, and solar radiation, the needed inputs were available.

Model Setup

Setting up the SWAT model involves five (5) steps including watershed delineation, definition of Hydrologic Response Units (HRUs), writing input files/tables, sensitivity analysis of parameters, and calibration and validation of the model output. The watershed was delineated into five (5) sub-basins and reaches. The delineation process involves five (5) principal steps (Figure 4**)** including DEM input, stream definition, inlet and outlet definition, selection and definition of whole watershed outlet, and calculation of sub-basin parameters. Using the DEM and threshold based stream definition option; a minimum drainage area of 10 km^2 was defined. In order to adequately analyze the differences in evapotranspiration and other hydrologic conditions for different soils, Landcover, and slopes, it was necessary to divide the sub-watershed into areas with the same soil type, landuse, and slope. In the process, a 10% landuse, 10% soil, 5% slope threshold was applied as suggested by the SWAT users' manual for most applications (Winchell *et al*., 2013). Input data including weather data were further created. To run the model, daily precipitation, temperature, solar radiation, relative humidity, and wind for the period 1984 to 2014 were input into the model. The first three (3) years was used as warm-up period in order to reduce the unknown initial conditions.

The size of a watershed to delineate as well as that of the sub-basins and reaches depends on the set threshold area and placement of the inlet and outlet points. It is also dependent on the stream networks within the area. The total size of the Tono watershed delineated is 60,260 ha.

Delineation involves the DEM setup of the flow direction and accumulation, stream definition through the selection of threshold area which results in the streams and outlets. This is followed by the watershed outlet and inlet definition. The output delineated watershed is used to calculate the sub-basin parameters (Figure 4).

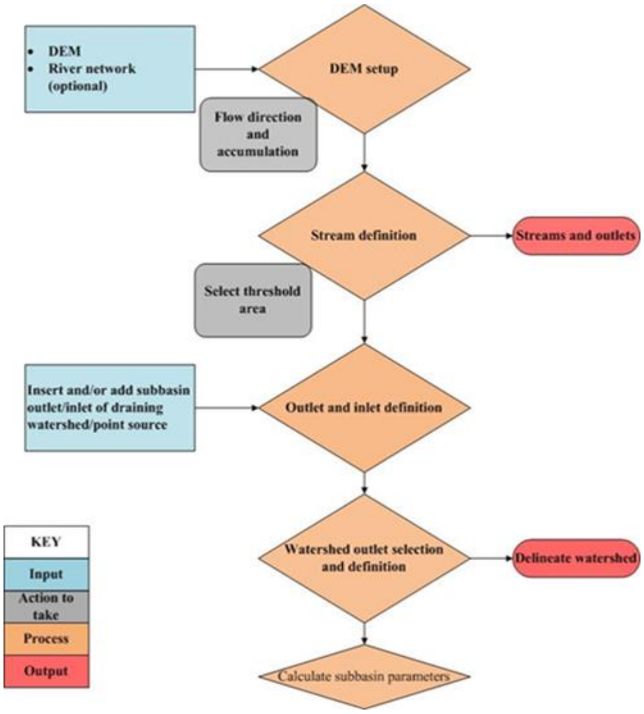

FIGURE 4. **Flow chart of Watershed Delineation**

Results and Discussion

A total of five (5) sub-basins were delineated within the watershed (Figure 6). Their sizes, in square kilometers were 91.5, 154.7, 123.2, 164.2, and 68.9 for sub-basins 1, 2, 3, 4, and 5 respectively, with minimum and maximum elevation ranging from 158m to 212m and 308m to 369m respectively.

LULC maps for the years 1984 and 2014 maps for the watershed (Figure 7 and Figure 8) had nine (9) classes namely, Rainfed croplands, Closed and shrubland, Mosaic croplands (50-70%)/vegetation (20-50%), Mosaic vegetation (50-70%)/croplands (20-50%), Closed and open broadleaf deciduous forest (>5m, >15%), Open broadleaf deciduous forest (15-40%), Guinea Savannah, Mosaic forest –shrubland (50-70%)/grassland (20-50%), and Water bodies.

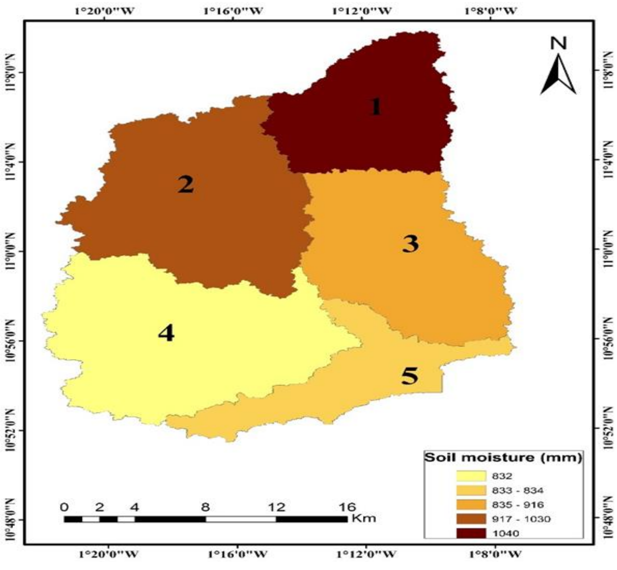

FIGURE 5. **Spatial distribution of Soil moisture in each subbasin**

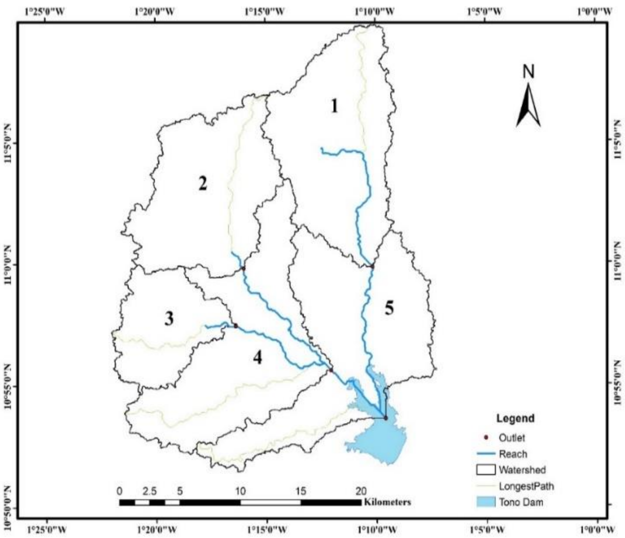

FIGURE 6. **Delineated watershed showing sub-basins and their outlets**

TABLE 1. **Landuse/landcover of 1984 and 2014 and the percentage change**

Landcover	**Area (1984)/km^2**	**Area (2014)/km^2**	**% change**
Rainfed cropland	213.4	285.9	+12
Closed to open shrubland	2.0	7.7	+0.9
Mosaic cropland/vegetation	3.8	5.6	+0.3
Mosaic vegetation/cropland	3.9	5.4	+0.2
Closed to open broadleaved forest	0	0.5	+0.08
Open broadleaved deciduous forest	96.1	96.5	+0.07
Savannah	254.2	172.7	-14
Mosaic forest- shrubland/grassland	25.0	24.8	-0.03
Water	3.8	3.5	-0.05

Rain fed croplands, Open broadleaf deciduous forest, Mosaic forest – shrubland/grassland, and Savannah are the major Landcover types within the watershed. They make up about 85% of the total watershed. Table 1 shows the area and percentage occupied by each landcover type for 1984 and 2014.

A comparison of the two LULC maps shows clearly a decrease in the Savannah, water, and mosaic forest (Figure 7 and 8**)**. These changes could be attributed to growth in intensive agricultural activities. The clearing of Savannah has caused an increase in agricultural lands (rainfed croplands and mosaic cropland/vegetation) by 12.3%. This has affected the amount of water within the watershed, hence, its reduction from 3.8 mm in 1984 to 3.5 mm in 2014 (0.05% decrement). Savannah decreased from 42.2% in 1984 to 28.7% in 2014 (14% decrease). Another very clear change which has taken place is the increase in closed to open broadleaved deciduous forest from 0 to 0.5 km^2. This could be a characteristic of the stress placed on land as a result of increasing population and crave for land for settlement and other artificial activities/infrastructure. Similar illustrations of the conversion of savannah as a result of expanding population and the expansion of agricultural land in such regions has been described by (Yira *et al.*, 2016). Closed to open broadleaved deciduous forest increased by 0.08% (Table 1).

LULC changes greatly affect the spatial distribution of average monthly and annual soil moisture and evapotranspiration. By comparing the annual values of the two parameters for the 1984 and 2014 LULC scenarios, total annual soil moisture decreased from 419.7 mm in 1984 to 346.02 mm in 2014 (Figure 9), about 9.6% decrease. A comparison of the same scenario shows a decrease in evapotranspiration from 354.93 mm in 1984 to 343.79 mm in 2014, approximating 1.6% decrease (Figure 9).

Figure 10 shows that the conversion of savannah to agricultural lands has a higher impact towards the months of high precipitation (June, July, August, September, and October). Hence, peak flows and low evapotranspiration and soil moisture increases with degradation of Savannah. Furthermore, evapotranspiration is controlled by differences in stomatal resistance and leaf area index of a vegetation (Awotwi *et al.*, 2014). Hence, the reduction in amount. Likewise, soil moisture is controlled to a greater extent by precipitation. Thus a reduction in the total annual rainfall from 585.49 mm in 1984 to 410.22 mm in 2014 could be the reason for reduction in soil moisture content between the two LULC scenarios.

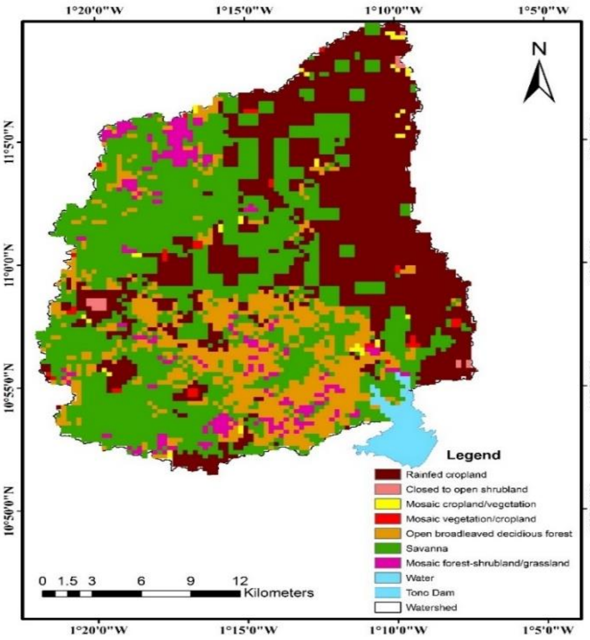

FIGURE 7. **1984 LULC map**

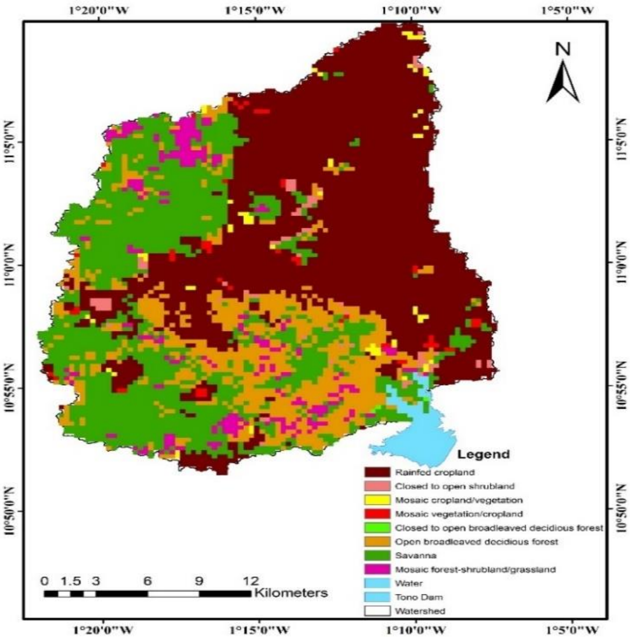

FIGURE 8. **2014 LULC map**

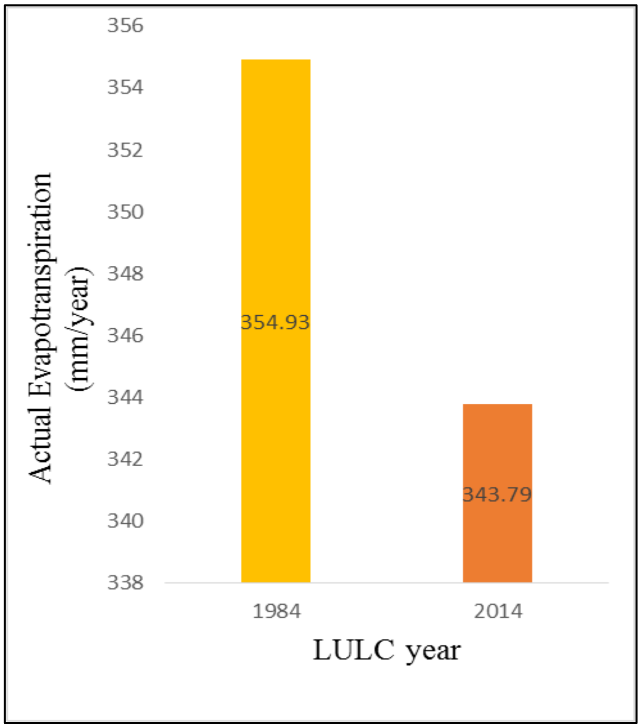

FIGURE 9. **Representation of actual ET for 1984 and 2014 LULC**

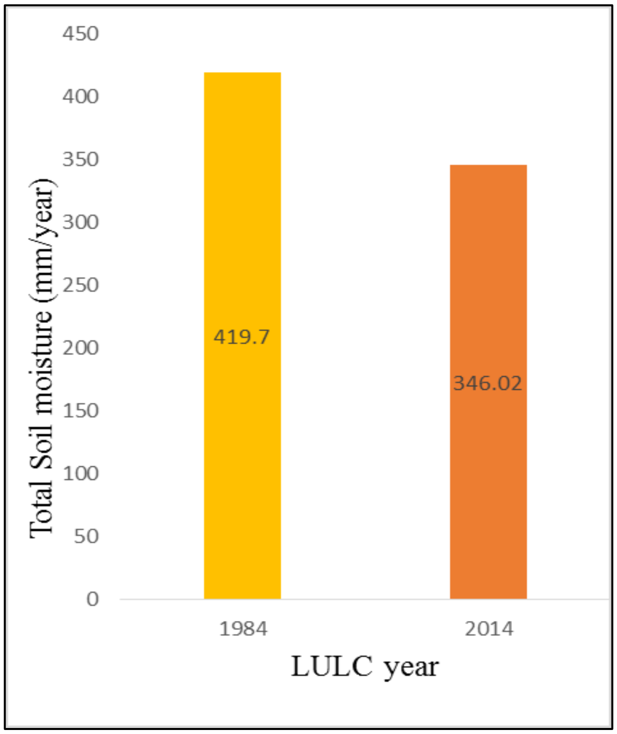

FIGURE 10. **Representation of total moisture for 1984 and 2014 LULC**

Water balance of the Tono watershed

The SWAT model calculated water balance by taking into account the components referred to in the master water balance equation as provided in Equation 2. Surface runoff, lateral flow, actual evapotranspiration, groundwater, and soil water were the most significant water balance components considered in this study.

TABLE 2. **Percentage averages for water balance components relative to rainfall in the years 1984 - 2014**

	Water balance for major components (%)				
Year	**Surface Runoff**	**Lateral flow**	**Groundwater**	**Soil moisture**	**Evapotranspiration**
1984	25.2	0.51	1.2	6.3	60.6
1985	24.7	0.6	11.3	4.6	51.6
1986	14.9	0.516	4.9	11.5	63.7
1987	28.9	0.612	13	4.3	55.3
1988	20.3	0.71	28.7	3.2	42.8
1989	32.4	0.582	20.7	3.3	40
1990	20.5	0.572	3.2	6.4	67.6
1991	25	0.622	18	4	47.8
1992	22.8	0.544	5.9	6.4	61.5
1993	16.5	0.548	1.1	7.7	72.1
1994	9.2	0.688	11.4	6.7	62.1
1995	12.9	0.682	19	4.9	59.7
1996	30.5	0.492	6.5	4.5	55.5
1997	18	0.555	6	5.3	66
1998	8.4	0.565	0	10.4	82.2
1999	24.8	0.522	0	10.1	65.2
2000	0	0.358	0	0	167.7
2001	11.2	0.5	0	13.5	74.9
2002	7.2	0.504	0	10.6	91.3
2003	21.7	0.52	0	8.6	64.3
2004	0.2	0.435	0	1.1	126.6
2005	1.5	0.456	0	5.6	93.2
2006	27.2	0.584	0	5.1	44.9
2007	23.9	0.555	0.4	6.8	59.7
2008	6	0.593	0.3	9.5	86.3
2009	26.3	0.499	0.4	6.6	60.2
2010	22.6	0.674	14.6	4.6	43.2
2011	15.5	0.592	7	6.4	69.5
2012	12.4	0.663	12.4	5.2	61.5
2013	6.1	0.563	1	8.1	83.8
2014	5.7	0.442	0	18.2	86.7
Average	17.417	0.575	6.233	6.983	72.250

A close examination of the results indicates that evapotranspiration had the largest share of the water balance with values ranging from 40% to 167.7% of the respective annual precipitation. Surface runoff recorded 32.4 % of the annual rainfall. It can be seen that lateral flow falls between 0.40 and 0.70 %. As a percentage of average annual rainfall for the respective years, soil recorded between 0 and 18.2 %. Groundwater on the other hand recorded of 0 and 28.7 % of the average annual rainfall. Table 3 below shows the simulated average annual values for the selected water balance components for 1984-2014.

TABLE 3. **Simulated annual averages of the water balance components from 1984 to 2014**

S/N	Water balance component	Simulated annual average value (mm)
1	Surface runoff	106.99
2	Soil water	33.26
3	Lateral flow	3.11
4	Potential evapotranspiration	2728.0
5	Actual evapotranspiration	318.3
6	Return flow	48.76
7	Percolation (from shallow aquifer)	102.25
8	Revap (from shallow aquifer)	48.66
9	Recharge (to deep aquifer)	5.11

Quantification of Soil Moisture

A simulated total annual average soil moisture content for the sub-basins within the watershed is shown in Figure 12. Soil moisture decreased from upstream to downstream of the watershed. Spatial variation in soil moisture could be attributed to differences in HRUs, rainfall, and LULC changes. Sub-basins 1 and 2 consists of Guinea Savannah and rain-fed cropland as their major landuse and about 70% of their area is made of Plinthic Luvisol, similar slope classes, thus, recording the relatively higher maximum amount of moisture, compared to subbasins 3, 4, and 5 which consist more of Ferric Luvisol which recorded moisture values of 916mm, 832mm and 834 respectively. Sub-basin 4 recorded the least amount of soil moisture of 832 mm. Plinthic Luvisol and Ferric Luvisol are both iron-rich and consist of particles of clay**.** However, Ferric Luvisol is highly susceptible to erosion and has high proportion of sand unlike Plinthic Luvisol hence, the ability of Plinthic Luvisol to hold more moisture and for longer period than Ferric Luvisol (FAO, 2015). This caused sub-basins 1 and 2 to record the highest amount of moisture. Sub-basin 5 however consists of only Ferric Luvisol together with Savannah, rainfed cropland, and open broadleaf deciduous forest, hence, the resulting low amount of soil moisture (Atakora *et al.*, 2019).

Furthermore, soil moisture was lower in the southern sub-basins than in the northern ones despite the almost equal volume of monthly and annual rainfall recorded for the study period. This could be attributed to the shallow soil depth coupled with increasing changes in LULC, as well as changes in rainfall and HRUs, thereby causing more surface runoff at north-east of the watershed (Figure 11).

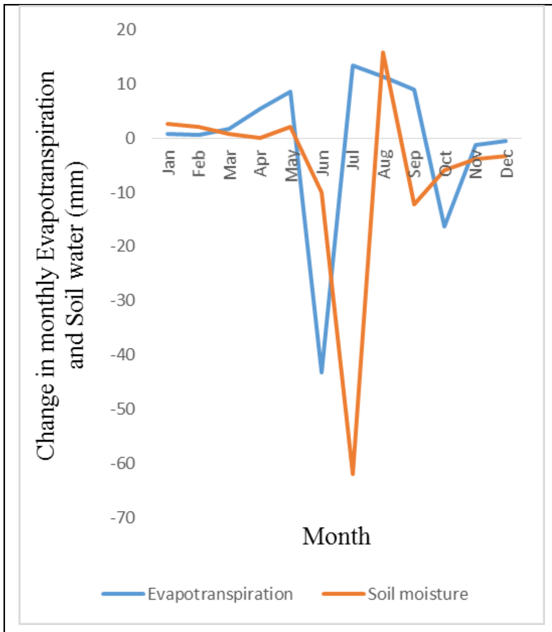

FIGURE 11. **Representation of ET and soil moisture**

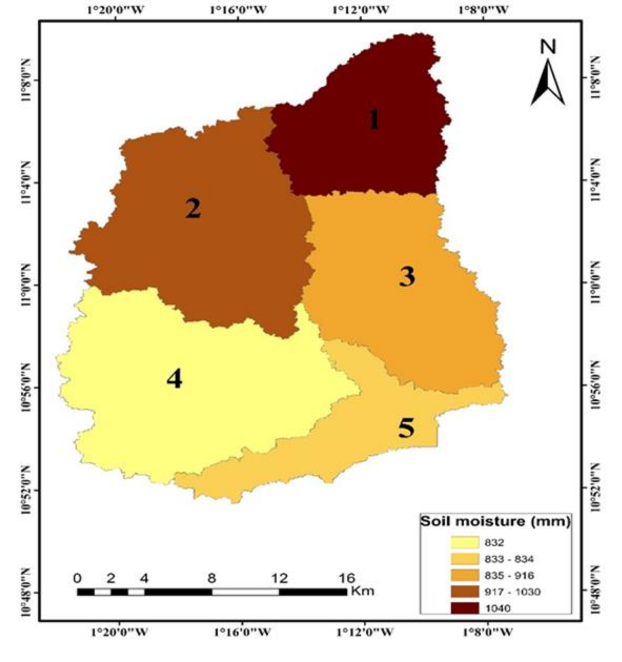

FIGURE 12. **Spatial distribution of surface runoff in each subbasin**

CONCLUSION AND RECOMMENDATION

This study estimated the soil water balance of the Watershed of the Tono irrigation dam and assessed its importance in both crop cultivation and the operation and maintenance of the dam. The SWAT model was used to quantify the soil moisture content in the watershed and assess the impact of LULC changes on evapotranspiration and soil moisture.

Overall, five (5) sub-basins were delineated from the watershed with an area of 602.6km^2. For changes in LULC, agricultural lands (rainfed croplands and mosaic cropland/vegetation) increased by 12.3%, whereas guinea savannah decreased by 14% from 1984 to 2014. The amount of water also decreased by 0.05%. The study thus, showed a decrease in soil moisture by 9.6%, whereas change in evapotranspiration was very minimal though it decreased by 1.6%. In conclusion, changing a Landcover to cropland causes a decrease in soil moisture as is the case of the Tono watershed, and a consequent infinitesimal change in evapotranspiration.

With water balance, the study revealed that evapotranspiration has the largest impact in determining the water balance of the area, with values ranging from 40 to 167.7 %, whereas lateral flow recorded the minimum share of the balance with its values ranging between 0.3 and 0.7 % of the respective annual precipitation. The study successfully simulated annual averages of essential water balance components such as surface runoff, soil water, groundwater recharge, and rainfall to be 106.99 mm, 33.26 mm, 5.11 mm, and 531.30 mm respectively.

The study also indicated that soil moisture was very high in the north of the watershed as compared to the south. Differences in Hydrologic Response Units (HRUs) among the sub-basins were identified to be the major cause for the observed soil moisture distribution.

A good and accurate knowledge of the water balance in the watershed of the dam is key to an efficient management and maintenance of the dam. This could go a long way to ensure continuous successful cultivation of crops in the area. It is recommended that a sound and effective watershed planning and management action be put in place. The participation of the people in the communities around the watershed in the management of water resources is key to establishing equilibrium at the upstream and downstream of the dam. It is therefore recommended that the land users be educated on the negative effects of some landuse practices on the water resource and its consequent impact on crop cultivation. The SWAT model has been shown in this study as a useful scenario modeling system. Thus, it is recommended that further research be carried out, considering scenario modeling projected changes in temperature and rainfall due to climate change, as well as hydrologic responses to different land management scenarios.

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