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Satellite Remote Sensing and GIS Based Watershed Analysis: Implications for Soil and Water Conservation Practices in the Denkyira Watershed, Ghana

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Abstract

Land degradation, deforestation and accelerated soil erosion through anthropogenic actions have restricted numerous watersheds and river basins to contribute to agricultural productivity, food security and economic growth. The study examined morphometric characteristics and land use change and their implications for soil and water conservation practices in Denkyira Watershed, Ghana. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data and Landsat images of Multi-Spectral Scanner (MSS) and Enhanced Thematic Mapper Plus (ETM+) were used in generating morphometric and land use data. ERDAS imagine (10.1) and ArcGIS (10.6) software were employed to analyze Landsat and ASTER data. Results revealed that Denkyira Watershed exhibited dendritic drainage pattern, elongated in shape and with high number of first-order streams, an indication of homogenous soil and rock formation, low infiltration rate and high surface runoff. Morphometric analysis further indicated that the Watershed has higher values of drainage density (12.82 km/km^2), drainage texture (5.15), infiltration number (5.13) and ruggedness number (5.16) exposing the Watershed to peak discharge and flash flood risks. Between 1986 and 2015, natural forest, secondary forest and water bodies decreased by 26.08 %, 13.67 % and 237.50 % respectively while degraded lands increased by 91.33 %. Land use and land cover changes in the watershed have triggered mechanical soil erosion and altered hydraulic stream characteristics. Installation of check dams, creation of earth bunds, construction of water absorbing terraces and trenches and valley bottom cropping are the most recommended restoration measures for the watershed. The study concludes that investment in soil and water conservation practices in the watersheds will help to reduce the erosive velocity of surface runoff, mitigate seasonal flooding risks and reclaim degraded farmlands while ensuring agricultural productivity and environmental sustainability.

***Keywords*:** Remote sensing; GIS**;** Morphometric characteristics; Land use change; Denkyira Watershed

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1. Introduction

Land degradation, deforestation and accelerated erosion through anthropogenic actions have limited numerous watersheds and river basins to contribute to agricultural productivity, food security and economic growth. A study by [1] found that declining soil fertility, deforestation and erratic rainfall pattern caused watershed degradation. Also, [2] reported that population growth, poverty and social inequalities contribute to watershed and river basin degradation.

According to [3] watershed degradation occurred mostly through depletion of water bodies, accelerated soil erosion, land degradation, destruction of vegetative cover and infrastructure damages. In Kenya, watershed degradation is exacerbated by rapid population growth, high poverty level, land use and land cover changes and deforestation, leading to land degradation [23]. In general, river basin and watershed degradation caused a long-lasting deterioration of productive land and water resources and drastic reduction in agricultural productivity with negative consequences on livelihoods of the people who bank on land and water resources for their survival.

In achieving Sustainable Development Goal Two (SDG2), i.e. to end hunger, achieve food security, improve nutrition and promote sustainable agriculture, proper evaluation and efficient management of river basins and watersheds are essential components in sustaining food crop production and enhancing food security systems at both household and community level. A study by [4] in Ethiopia noted that quantitative assessment of watershed is of great significant towards watershed conservation and management practices.

In India [5] and Pakistan [6] indicated that quantitative analysis of watershed is vital in understanding hydrological processes such as runoff generation, peak flow and recurrent flooding. Authors, [7] and [8] stated that assessment of land use change is a key in formulating water resources conservation and management strategies at watershed level. In general, watershed analysis creates opportunities for reclaiming degraded lands, mitigating soil erosion effects, improving soil fertility, increasing agricultural productivity and enhancing food security. In Denkyira Watershed, illegal gold mining and deforestation have exposed the watershed to accelerated soil degradation, water resources deterioration and recurrent flooding to the detriment of crop production, crop farmers and ecological conservation.

In the absence of better conservation practices, the challenges of soil degradation and sediment deposition at the downstream have risen and affecting crop production and income levels of the smallholder farmers in the Watershed. Presently, no studies have been carried out to examine drainage and land use systems in Denkyira Watershed. Hence, there is the need to examine land use change and drainage characteristics as well as mapping-out conservation strategies to stem accelerated soil degradation and promote agricultural productivity in the face of climate change.

The study assessed morphometric characteristics and land use change and their implications for soil and water engineering and conservation practices in Denkyira Watershed. The outcome of the study could be useful in designing and execution of environmentally and economically viable soil and water engineering and conservation measures to promote food crop production and enhance household food security system in most river basin and watersheds.

2. Materials and Methods

2.1 Study Area

Denkyira watershed lie within a geographical extent of latitudes 5°30'and 6°00'North and longitudes 1^{o} 00' and 2°00'West in Central region of Ghana. The watershed is characterized by high population density of 155 persons per square kilometer as compared to average of 121 persons per square kilometer for the county. The high population density is attributed to mining activities and these have bearing effects on biophysical conditions in the watershed. Birimian and Tarkwaian formations were the bedrocks found within the watershed with 601.45 km^2 and 537.75km^2 respectively. The average annual temperatures were found to be 29^{o}C on the hottest months and 24^{o}C in coolest months. The rainfall distribution is bimodal (major and minor season). The major rain season is between March and July with peak in June and minor rainy season is between September and November. The mean annual rainfall ranged between 1300 mm and 2000 mm. Cocoa plantation covers about 50 % of the productive lands with cassava, plantain, cocoyam, maize and rice are extensively cultivated in the area**.**

2. 2. Mapping the morphometric characteristics in the Denkyira Watershed

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) image with spatial resolution of 30 m was processed with ArcGIS 10.6 to obtain Digital Elevation Model (DEM) for the watershed. The DEM data was projected to Universal Transverse Mercator (UTM) projection system zone 30 N and datum of World Geodetic System 84 (WGS84). The resulting DEM was used for the extraction of drainage characteristics. Pre-processing was done to fill all sinks. Terrain characteristics such as flow direction and accumulation, stream number, stream order, length, area and slope were retrieved using ArcGIS 10.6. Morphmetric parameters such as bifurcation ratio, elongation ratio, drainage density, drainage texture, infiltration number, stream frequency, form factor, ruggedness number and relief characteristics were calculated using formulas suggested by [9,10] in determining the hydrological processes such as surface runoff, peak flow, infiltration rate and length of overland flow in the Denkyira Watershed.

2.3 Mapping the land use and land cover change in the Denkyira Watershed

The Landsat Multi-Spectral Scanner (MSS) 1986 and Enhanced Thematic Mapper Plus (ETM+) 2015 images from Global Land Cover Facility (GLCF) coupled with Fifty-seven (57) Ground Control Points (GCPs) were used to assess land use and land cover change. Landsat images were imported into ERDAS imagine 10.1 for geometric correction, image enhancement, stacking, mosaicking, sub-setting and image classification. Maximum likelihood classifier (MLC) algorithm was used in supervised classification coupled with the ground control points. Image differentiation tool in ArcGIS 10.6 and change detection option in ERDAS 10.1 were used to compute the extent of land use and land cover change in Denkyira Watershed. The ground control points and Google earth imagery were used to verify land use and land cover classes. Classification error matrix and

KAPPA were used to calculate the producers and user's accuracy level as well as Kappa accuracy level. Handheld Garmin 64 was used to map 126 farmland and 57 ground control points with a positional error of 3 meters.

2.4 Physical soil properties

Soil samples were taken at 0 – 30 cm depth (0 - 15 cm for the topsoil and 15 - 30 cm for the subsoil) using soil auger. The soil samples were air-dried and sieved using a 2 mm sieve and analyzed for pH, CEC and organic carbon at the Soil Research Institute of CSIR, Kumasi. Samples were dried at 105 °C for 24 hours in a forced air oven, weighed and bulk densities calculated as sample dry weight (g) divided by sample volume (cm^3).

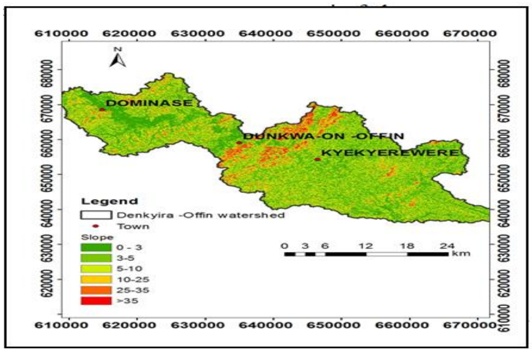
2.5Sampling technique

A multistage sampling technique was used to select sample farm households. One hundred and twenty-six (126) farmers aged between 35 and 50 years from three communities were purposively sampled to collect information on biophysical drivers. Biophysical data were analyzed using Statistical Package for Social Sciences (SPSS) version 20

3. Results and Discussion

3.1 Slope and physical soil properties

The slopes in the Denkyira Watershed were grouped into flat (0-3 %), gentle slopping (3- 5%), sloping (5-10 %), moderately steep (10- 25 %), steep (25–35 %) and very steep >35 % (Figure 1). The steep slopes (>35 %) could restrict soil infiltration and enhance surface runoff leading to recurrent flooding. These conditions call for construction of drainage structures like open channels, storm diversion drains and continuous contour trenches which are efficient in reducing the velocity of runoff, increase land surface storage and promoting safe disposal of excess water. Acrisols, Lixisols and Fluvisols with 981.90 km^2, 120.98 km^2 and 96.12 km^2 respectively were found (Figure 2). Silt loam, sandy loam and sandy clayed loam were soil textural classes identified (Table 1). Silt clay loam and sandy clayed loam were found most in inland valleys which could be suitable for lowland and valley bottom rain-fed rice production.



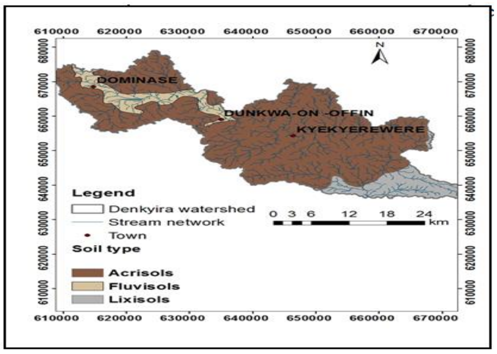


Figure 1: Slope of Denkyira Watershed

Figure 2: Soil type of Denkyira Watershed

The mean soil organic carbon content of 4.4 mgg^{-1} in topsoil and 4.3 mgg^{-1} in subsoil (Table1) were found and these were below recommended value of 17.0 mgg^{-1} desirable for crop production [11]. Soil nutrient management options such as mulching and planting of leguminous crops that have the potential to reduce erosion, increase soil moisture retention capacity and restore soil fertility could be adopted in the watershed. Mean soil bulk density ranged from 1.79 to 1.98 gcm^{-3} and 1.99 to 2.20 gcm^{-3} in the topsoil and subsoil respectively (Table 1). Both mean soil bulk densities of topsoil (1.94 gcm^{-3}) and subsoil (1.99 gcm^{-3}) were high, closed to critical value of 2.1gcm^{-3} [12]. High soil bulk density recorded in the watershed is a sign of compacted soil resulting from adopted land use systems. This could limit crop rooting depth, lower water storage capacity of the soil and reduce food crop yield.

The mean CEC of 4.1 and 4.3 cmol (+) kg^{-1} in topsoil and subsoil were low and found below the critical value of 5 cmol (+) kg^{-1}[13]. The low values of CEC indicate that soil has low ability to hold water and deficient in cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), ammonium (NH_4+), potassium (K^+), hydrogen (H^+), sodium (Na^+), aluminum (Al^{3+}), iron (Fe^{2+}), manganese (Mn^{2+}), zinc (Zn^{2+}) and copper (Cu^{2+}). This observation could restrict nutrient uptake and retention rate in the root zone and call for soil fertility enhancement measures, such as nutrient-fixing plant.

Table 1: Soil physical properties in the Denkyira Watershed

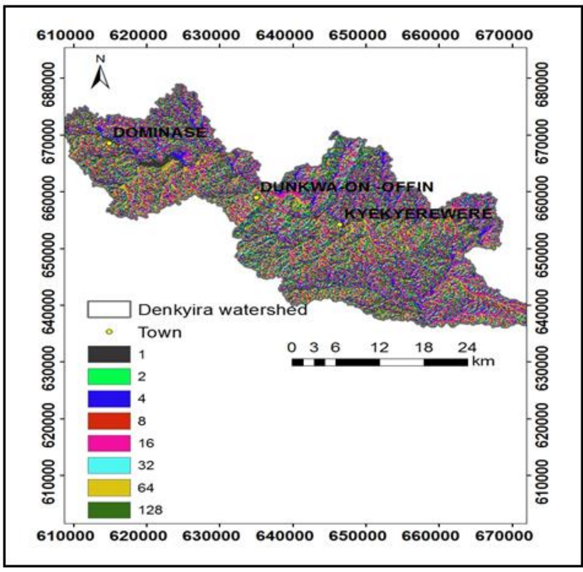
Soil texture	Area (Sq.km) (%)		Topsoil (0-15 cm)		Subsoil (15-30 cm)	
Silt loam	327.12 (27.3)	Soil properties	Ranged	Mean	Ranged	Mean
Sandy loam	471. 34 (39.3)	Organic carbon (mgg^{-1})	5.00 -10.5	5.32	10.30 -2.30	4.61
Sandy clayed loam	227.77 (19.0)	Bulk density (gcm^3)	1.79-1.98	1. 94	1.99 - 2.20	1. 99
Clay loam	66.40 (5.5)	Soil pH	3.36- 7.62	3.65	3.39-7. 69	3.84
Sandy	93.60 (7.8)	CEC cmol (+) kg^{-1}	3.47- 4.63	4.20	4.78- 5.47	4.31

3.2 Morphometric characteristics in the Watershe

Morphometric parameters such as linear, areal and relief characteristics were determined in the Denkyira Watershed

Linear aspects

Linear aspect in watershed is characterized by watershed length, stream order, stream number, stream length and bifurcation ratio. The drainage pattern in the Denkyira Watershed was found to be dentritic in nature characterized by homogenous and uniform soil and bedrock formation. The stream order in the watershed varies from first to fifth (Figure 4) with 481 streams covering an area of 1199 km^2. High numbers of first-order streams were also found in the watershed (Table 3), an indication of low infiltration rates, higher discharge capacity and high surface run off generation. Designing and construction of percolation reservoirs and trenches will help facilitate the storage of runoff.



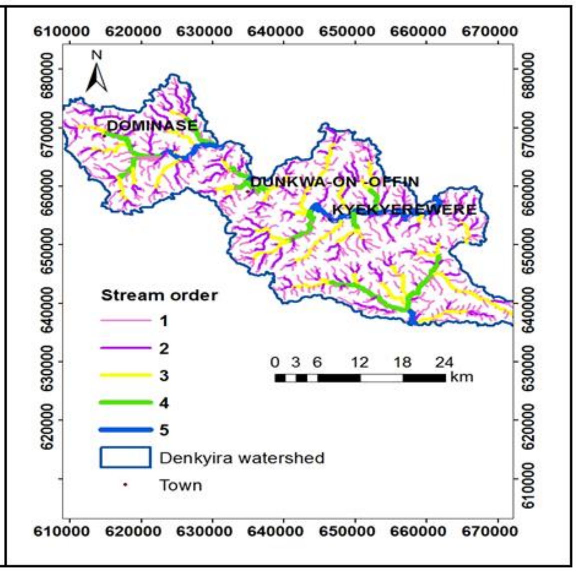


Figure 3: Flow direction of Denkyira Watershed **Figure 4:** Stream order of Denkyira Watershed

Bifurcation ratio (R_b) in the Denkyira Watershed ranges between 2.5 and 10 and the mean value of 5.10 (Table 2). High values of Bifurcation ratio in the watershed indicate that drainage pattern is strongly influenced by geological structures and exhibit low permeability which could results in the high stream discharge, peak flow and flooding. High Bifurcation ratio values were found between 4th and 5th orders which shows high overland flow and rapid discharge capacity. The results agree with [4] that high value of Bifurcation ratio indicated strong structural control.

Table 2: Linear characteristics of the Denkyira Watershed**.**

Stream order	Stream number (Nμ)	Stream length (Lu) (km)	Mean stream length (L_{sm})	Cumulative Mean stream length	Bifurcation ratio (R_b)	Mean bifurcation ratio
I	307 (63.83)	8104 (52.72)	26.397	26.397		
II	130 (27.03)	3769 (24.52)	28.992	55.389	2.5	
III	33 (6.86)	2238 (14.56)	67.818	123.208	3.9	
IV	10 (2.08)	912 (5.93)	91.2	214.408	3.3	
V	1 (0.21)	349 (2.27)	349	563.408	10	5.10
Total	481(100)	15372 (100)				

Figures in the brackets are percentages

Areal and relief characteristics in the Denkyira Watershed

The watershed had high drainage density of 12.82 km/km^2 and drainage texture of 5.15 (Table 3), an indication of fine drainage pattern and less permeable subsurface materials resulting into less infiltration rates and higher surface runoff generation causing enhanced soil erosion and land degradation. Land degradation in the form of accelerated soil erosion and declining soil fertility is a threat to agricultural productivity in Denkyira Watershed. A study by [16] opined that high drainage density is an indication of fine drainage texture, low infiltration rate and rapid overland flow. The results agreed with [4] that fine drainage texture coupled with high drainage density suggested less permeable material, low infiltration rate and recurrent flooding.

Stream frequency recorded 0.40 km indicating moderate infiltration and more stream network which could promote inland valley farming activities. Infiltration number of Denkyira Watershed was high (5.13), implying rapid runoff discharge generation. High drainage density, infiltration number, stream frequency and length of overland flow observed in the Denkyira Watershed suggest the influence of structural control, low soil permeability, high surface runoff and flash flooding. Studies by [17] and [18] indicated that, high drainage density; fine drainage and high infiltration number result in frequent flooding.

Areal parameters observed in the Denkyira Watershed generate high surface runoff and induce erosive activity which make the watershed highly sensitive to accelerated erosion and loss of soil fertility. This paper, call for an integrated soil and water conservation measures such as check dams (ditch checks, ditch dikes), broad-based terraces and sediment weirs that have proven to reduce flow velocity, retain overland flow and reduce surface runoff. Adoption of these mechanical practices in the area will have the potential to reduce the runoff velocity, minimize soil erosion and enhance the soil moisture retention capacity.

Table 3: Areal and relief characteristics of Denkyira Watershed**.**

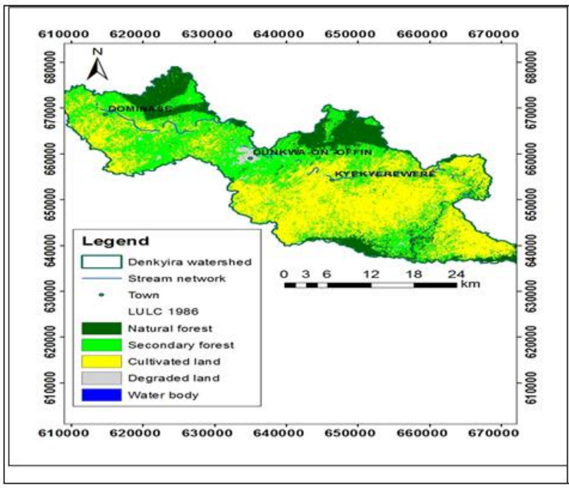
Parameter	Estimated value	Parameter	Estimated value
Watershed area (km^2)	1199	Overland flow (L_g) km	0.16
Watershed length (km)	75	Form factor (R_f)	0.21
Watershed perimeter (km)	283	Circularity ratio (R_c)	0.19
Drainage density (D_d) km/km^2	12.82	Elongation ratio (R_e)	0.52
Drainage texture (D_t)	5.15	Total relief (R) m	250
Infiltration number (I_f)	5.13	Relative relief	0.001
Stream frequency (F_f)	0.40	Relative ratio	0.004
Ruggedness number (R_n)	5.16		

Circularity and elongation ratios are shape characteristics which determine intensity of erosion and occurrence of floods. The values of elongation ratio, circularity ratio and form factor obtained in the watershed were 0.52, 0.19 and 0.21 respectively (Table 3). These values suggest that Denkyira Watershed is elongated in shape, low infiltration capacity and rapid discharge of surface runoff making the watershed more prone to flooding and susceptible to erosion. Elongated shape together with low form factor and moderate overland flow recorded in the area indicates flatter peak flow for longer duration which are conducive for the implementation of physical soil and water conservation structures such as soil and stone bunds, deep trenches, terraces, diversion ditches and tied ridging that have effect to build up organic matter, enhance infiltration rate and increase water holding capacity of the soil.

The total relief and relief ratio obtained indicated moderate relief and could promote lowland rice production. The ruggedness number obtained for the watershed was 5.16 which suggested high rugged topography and high drainage density making the catchment more susceptibility to soil erosion and recurrent flooding [10, 19]. These factors are important in understanding erosion intensity as well as site selection for artificial recharge structures (Tiwari, 2011).

3.2 Land use and land cover change in the watershed

Over the period (1986-2015) natural forest, secondary forest, cultivated land and water bodies have shrunk by 4, 248, 5,036, 2,198 and 190 ha respectively while degraded land increased by 11,672 ha (Table 4) which have led to land degradation, accelerated soil degradation and rapid deforestation. The high soil degradation poses serious threat to farmlands and soil nutrient availability. Accelerated soil degradation in the Watershed has led to the total removal of organic matter and plant nutrients from the fertile farmlands and eventually reducing food crop productivity, increasing food prices and food insecurity (Table 5). Biological measures such as Acacia plantation and Alley cropping which moderate erosion in natural and ecological manner by increasing soil surface roughness, increasing surface storage capacity and intercepting overland flow could be useful soil and water conservation strategies to reclaim degraded lands and improve soil chemical attributes.



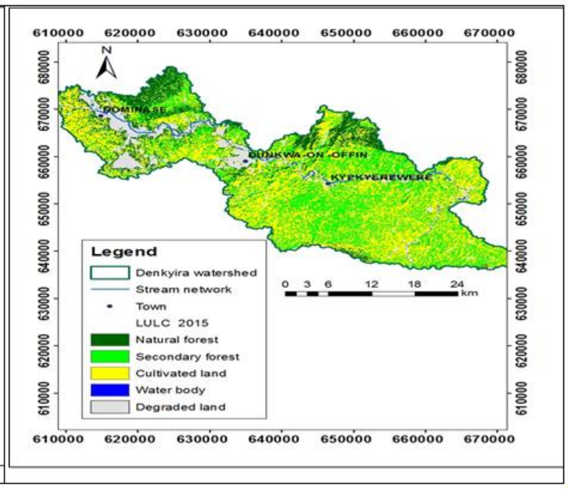


Figure 5: Land use land cover map 1986 **Figure 6**: Land use land cover map 2015

Increased land degradation observed in the watershed have the potential to alter the capacity of the watershed to capture and store rainwater resulting in the high surface runoff, water pollution and recurrent flooding which impacting severely on water quality and food crop productivity (Table 5). Studies by [14, 15] indicated that land use change in watersheds increased runoff generation and water pollution and thus affect water quality and food crop yield.

Structural measures such as building and rehabilitation of gully structures and biological measures of soil and water conservation that have the potential in reducing the rate of soil erosion and surface runoff should be of priority to practice in the Watershed. For instance, intercropping *Acacia nilotica* with crops such as plantain, yam and the use of nitrogen-fixing tress such as *Leucaena leucocephala* have the effect in reclaiming degraded lands by increasing organic matter content and improving soil moisture availability should be considered in the Watershed.

Biological measures such as planting of *Elephant grass, Eucalyptus saligna*, *Sesbania, Rhodes grass or leucaena*, to stabilize the physical structures to control sediment transport, erosion and increase soil moisture retention in the root zone is highly recommended in the Watershed. Revegetation species for instance, *Becium obovatum, Leucas oligocephala, Euphorbia abyssinica, Acacia etbaica, Opuntia ficusindica, Echinops hispidus, Calpurnia aurea*, *Eucalyptus, Acacia saligna and Dodonaea angustifolia* have proven to reduce surface runoff velocity and accelerated soil erosion as well as increase retention rate of soil and water. Biological conservation measures bind soil particles, slows down the velocity of runoff water and increases the ability of a soil to absorb water.

Table 4: Classified land use and land cover classes (ha) in the Denkyira Watershed (1986-2015)

Land use and land Cover classes	Land use and land cover change		
	1986	2015	1986-2015
Natural forest	20,538 (17.16)	16290 (13.61)	-4,248 (-26.08)
Secondary forest	41866 (34.97)	36830 (30.76)	-5,036 (-13.67)
Cultivated land	55933 (46.72)	53735 (44.89)	-2,198 (-4.09)
Water bodies	270 (0.23)	80 (0.07)	-190 (-237.50)
Degraded land	1,1089 (0.93)	12780 (10.68)	11,672 (91.33)
Total	119,715 (100)	119,715 (100)	

Figures in the brackets are percentages

3.4 Smallholder farmers' response on biophysical changes

Farmers in the watershed identified flooding, pollution of streams and rivers, streams sedimentation, destruction of wetland resources, increase soil surface runoff generation, increase soil erosion and decline in the soil fertility as the main biophysical factors causing watershed degradation (Table 5). These findings supported previous study by [20] in Kenya that land use and land cover change and human induced factors contribute to watershed degradation. The reduction in farmland sizes, accelerated soil erosion and declining soil fertility in the watershed (Table 5) were attributed to land use and land cover changes. These situations have also led to decline in food crop production and rising food prices, with majority of smallholder farmers acknowledging the rising food insecurity.

Table 5: Farmers response on biophysical changes in the Denkyira Watershed**.**

Biophysical changes	Community			Denkyira Watershed
	Dominase	Atechem	Kyerekyewere	
Reduction in vegetation cover	39 (92.86)	40(95.24)	41(97.62)	120 (95.24)
Increase in degraded lands	42 (100.00)	41(97.62)	38 (90.48)	121(96.03)
Increase in soil surface run off	26 (61.90)	34(80.95)	29 (96.05)	89 (70.63)
Increase in soil erosion	34 (80.95)	37(88.10)	27 (64.29)	98 (77.78)
Sedimentation of rivers and streams	42 (100)	42(100)	41(97.62)	125 (99.21)
Pollution of streams and rivers	42 (100)	42(100)	42 (100)	126 (100)
Recurrent flooding	42 (100)	42(100)	42 (100)	126 (100)
Disappearance of water bodies	41(97.62)	39(92.86)	42 (100)	122 (96.83)
Decline in soil fertility	39 (92.86)	27(64.29)	35 (83.33)	101(80.16)
Reduction in farmland sizes	40 (95.24)	28(66.67)	36 (85.71)	104 (82.54)
Destruction of wetlands	42 (100)	42(100)	40 (95.24)	124 (98.41)
Lowering in food crop productivity	40 (95.24)	34(80.95)	41(97.62)	115 (91.27)
High food price/ food insecurity	41(97.62)	42(100)	42(100)	125 (99.21)

3.5 Driving forces of watershed degradation

The mining, deforestation, poor farming systems, poverty, high population density and settlement expansion were major driving forces behind watershed degradation (Figure 7). Similar findings have been reported by [21] in Ghana that mining within river basins in Ghana constituted the major driving force towards soil degradation, dwindling of water bodies and declining soil fertility. In Pakistan, [22] and Kenya [23] identified rapid population growth, poverty, poor land use systems and deforestation as factors leading to food crises and watershed degradation. Rapid population growth, poverty and social inequities contribute to watershed degradation [24].

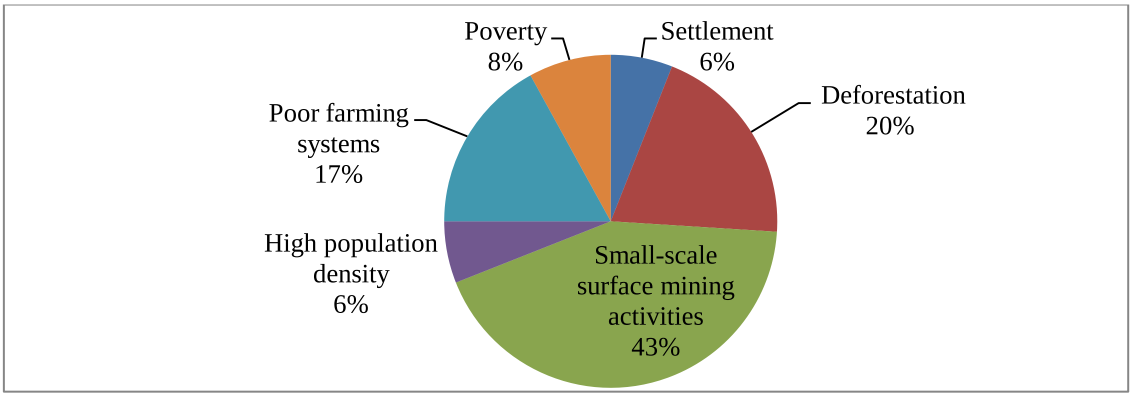


Figure 7: Response of farmers on causes of land use and cover change in the Denkyira Watershed.

4.Conclusion

Drainage density, drainage texture, infiltration number, circularity ratio, elongation ratio, ruggedness number and form factor values recorded in the Denkyira Watershed highlighted low infiltration and rapid stream discharge making the Watershed more prone to high sediment transport, recurrent flooding and more susceptible to accelerated soil degradation. Land use and land cover changes have also exposed the Watershed to accelerated soil erosion, land degradation, deterioration of water bodies with negative impact on soil fertility, reducing farmers' ability to produce enough food, rising food prices and food insecurity.

This paper calls for investment in soil and water conservation engineering structures such as soil bund, water absorbing trenches, stone and earth terraces, earthen check dams and rain-fed valley bottom cultivation that have been established to be effective in reducing the velocity of surface runoff, lessen erosive activity, enhance soil moisture retention rates and promote food crop production among rain-fed farming households.

5. Policy consideration

- Farming methods that retain soil moisture at the root zone, reduce soil erosion and promote high crop yield should be promoted among the smallholder farmers by agricultural extension officers in the watershed.
- Rehabilitation and reclamation schemes to improve and conserve soil and water resources and protect productive farmlands such as agroforestry and climate-smart agriculture technologies against flash flood risks should remain key agenda of the Districts and Municipal Assemblies in the watershed.
- Adoption of inland valleys and valley bottoms cropping systems to improve food crop productivity and household food security in the area.

Acknowledgement

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