INFLUENCE OF TEA, FOREST AND MIXED FARMING LAND USES ON STREAM FLOW AND SEDIMENT FLUX IN SONDU MIRIU RIVER BASIN

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DECLARATION

I understand that plagiarism is an offence and I therefore declare that this thesis is my own original work and has not been submitted to any other university for any other award.

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DEDICATION

This thesis is dedicated to my family members (Shadrack, Amos, Tunu), friends and colleagues for the great support offered during the thesis development period.

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ABBREVIATIONS AND ACRONYMS

ADCP	**:**	Acoustic Doppler Current Profiler
ALPHA_BF	**:**	Baseflow alpha factor
ALPHA_BNK	**:**	Baseflow alpha factor for bank storage
APHA	**:**	American Public Health Association
CH_K	**:**	Channel hydraulic conductivity
DEEPST	**:**	Initial depth of water in the deep aquifer
DEM	**:**	Digital Elevation Model
EPCO	**:**	Plant Uptake Compensation Factor
ESCO	**:**	Soil Evaporation Compensation Factor
ESRI	**:**	Environmental Systems Resources Institute
GIS	**:**	Geographical Information System
GPS	**:**	Global Positioning System
HRU	**:**	Hydrologic Response Units
IDW	**:**	Inverse Distance and Weighting
ITCZ	**:**	Inter-tropical Convergence Zone
KMD	**:**	Kenya Meteorological Department
KNBS	**:**	Kenya National Bureau of Statistics
LVEMP	**:**	Lake Victoria Environmental Management Project
MUSLE	**:**	Modified Universal Soil Loss Equation
NSE	**:**	Nash- Sutcliff Efficiency
NTU	**:**	Nephelometric Turbidity Unit
$\mathbf{R^2}$	**:**	Coefficient of Determination
RCHRG_DP	**:**	Deep aquifer percolation fraction
REVAPMN	**:**	Threshold depth of water in the shallow aquifer
RGS	**:**	River Gauging Station
SDG	**:**	Sustainable Development Goal
SLSUBBSN	**:**	Slope Subbasin -Average slope length
SOL_AWC	**:**	Available water capacity of the soil layer
SOL_BD	**:**	Moist bulk density

STRIP_ C	**:**	Strip USLE cropping factor
STRIP_CN	**:**	Strip SCS curve number II value for strip cropped field
STRIP_N	**:**	Strip vegetation parameters such as manning's roughness coefficient for overland flow
STRIP_P	**:**	Strip USLE practice factor
SURLAG	**:**	Surface runoff lag coefficient
SWAT	**:**	Soil and Water Assessment Tool
TERR-CN	**:**	Terrace Initial SCS curve number for terraces
TERR-P	**:**	Terrace USLE practice factor
TERR-SL	**:**	Terrace average slope length
TSSC	**:**	Total Suspended Sediment Concentration
UN	**:**	United Nations
USGS	**:**	United State Geological Survey
USLE	**:**	Universal Soil Loss Equation
USLE_K	**:**	USLE equation for soil erodibility
VFSCH	**:**	Fraction of the flow of filter strips which are channelized
VFSCON	**:**	Fraction of filter strips
VFSI	**:**	Vegetative filter strip simulating filter strips
VFSRATIO	**:**	Ration of the field area to filter strip area
WMO	**:**	World Meteorological Organisation
WRA	**:**	Water Resources Authority

ABSTRACT

The changing patterns of land cover and land use in the tropical river basins over time are critical. However, there is limited data and information on the extent to which land use types in tropical regions affect hydrological processes particularly in terms of stream flow and sediment transport. The magnitude to which stream flows and sediment flux differ in tea plantations, forests and mixed farming land covers has not been determined adequately in tropical river basins. The main goal of this study was therefore to determine the influences of different land covers tea plantations, forests and mixed farming on magnitudes of stream flow and sediment flux variability. The study was undertaken in three sub basins namely Timbilil sub basin dominated by tea plantations, Kiptiget sub basin dominated by forests and Kipsonoi sub basin dominated by mixed farming at the upstream of Sondu Miriu River Basin located in the Western Kenya region in period from 1960-2021. Field-based investigations was done using a depth integrated sampler to collect samples for Total Suspended Sediments Concentrations (TSSC), Acoustic Doppler Current meter and Seba current meter were used to measure flow velocities and river gauges were used to measure water levels in the sub basins. Turbidimeter was used to determine turbidity levels in the rivers draining the sub basins. Laboratory analysis and hydrological modelling were used to determine response of hydrological components in dominant land cover types. Spatial data used were obtained from the USGS and FAO databases, while temporal data used were obtained from Kenya Meteorological Services (KMS), Water Resources Authority (WRA) and Ministry of Water, Sanitation and Irrigation. Regression and correlation techniques were used to determine relationship between stream flows and sediment yields. Scenario analysis was carried out to test the effectiveness of various catchment management structures in the sub basins with high sediment generation. The findings of this study showed that the forest land cover in the sub basins dominated by tea plantation and mixed farming land covers declined by 8.4% (4 km^2) and 0.3% (26 km^2) respectively in the period from 1975 to 2021. Tea plantations land cover showed an increasing trend in all the three sub basins under study from 1975 to 2021. In the sub basin dominated by tea plantation an increase of 7% (24 km^2) was observed while in the sub basins dominated by forest and mixed farming land cover, tea plantation increased by 15.2% (23.1 km^2) and 6.4 % (101 km^2) respectively. The mixed farming land cover portrayed a decline in the sub basins dominated by mixed farming and forest land covers by 6.1 % (96 km^2) and 15.4% (23.4 km^2) respectively. At the basin scale it was revealed that forest and mixed farming land cover reduced by approximately 16.9% (84 km^2) and 3.6% (93 km^2) from 1975 to 2021. While the area under tea plantations in the river basin increased by 44% (177 km^2) in the same period. It was observed that the sub basin dominated by mixed farming generates high surface runoffs with average of about 30 m^3/s compared to average surface runoffs of approximately 4 m^3/s generated by sub basins dominated by forest and tea plantation. The sub basin dominated by mixed farming land cover exhibit high turbidity and TSSC levels of about 620 NTU and 630 mg/l in wet seasons. The relationship between TSSC and turbidity in sub basin dominated by mixed farming was positive with coefficient of determination R^2 of 0.97. While low levels of turbidity and TSSC of less than 30 NTU and 20 mg/l were observed in the sub basins dominated by forest and tea plantations land cover in wet periods. The sediment loads in the sub basin dominated by mixed farming land cover in the pre planting period were about

900 tonnes/day. The sub basin dominated by the forest and tea plantations land covers exhibited relatively lower sediment generation ranging between 2 and 7 tonnes/day. The sediment loads at the downstream of the river basin ranged from 150 to 600 tonnes/day during the pre-planting and post harvesting periods. The SWAT model simulated the stream flows and sediment yields in the three sub-basins with dominant land covers quite effectively with R^2 of 0.8 and Nash–Sutcliff Efficiency (NSE) of 0.78. The SWAT model showed that the mean annual sediment yield in the larger Sondu Miriu River Basin was about 140 tonnes/ha. The identified hotspots' areas of the sediment generation in the river basin were Kuresoi at the upstream, Ndanai at the middle part and near Sondu market at the downstream. The mean annual evaporation and transpiration was high in the sub basins dominated by tea plantations and forest land covers ranged between 800 mm/a and 1000 mm/a compared to the sub basin dominated by mixed farming land cover with less than 800 mm/a. The relationship between sediment yields and stream flows in the sub basin dominated by forest and tea plantations land covers was weak with R^2 of less than 0.24. Whereas a strong relationship between sediment yields and stream flows with R^2 of 0.84 was observed in the sub basin dominated by mixed farming land cover. Forest and tea plantations land covers were found suitable for sustainable stream flows and sediment reduction. Also, the terraces, strip cropping and vegetative filter strips were found ideal structures for conserving soils in the sub basin dominated by mixed farming especially the hotspot areas. This study therefore recommends integration of tea plantations and forest land covers to be practiced in the sub basins of the Sondu Miriu River Basin. However, mixed farming should not be replaced completely because it will affect food security in the river basin. Alternatively appropriate soil water conservation measures terracing and strip cropping are recommended to be adopted in mixed farming land uses. This study creates awareness to basin communities, water users and water managers in both County and National Governments on the appropriate land cover and land use that will ensure sustainable availability of water with high water clarity.

CHAPTER ONE

1.0 INTRODUCTION

Land cover and land use changes contribute to the dynamics of the hydrologic responses in a tropical river basin. This study focused on the determination of the hydrologic response of the three sub basins with dominant land cover and land use types located in the Sondu Miriu River Basin in Western Kenya. The Sondu Miriu River Basin is among the river basins in Kenya that have experienced significant changes in land cover and land use due to expansion of settlement and agricultural fields including introduction of exotic tea plantations. The study on the hydrologic responses of these specific land cover changes is limited in Kenya and Africa. This chapter provides the background information on the study, the statement of the problem, objectives and hypotheses of the study. Also included in the chapter is an elaboration of significance and justification of this study.

1.1 Background to the Study

Understanding the changing pattern of land cover and land use in the river basin over time is critical. The hydrological phenomena at basin and sub basin scale are affected positively or negatively by dynamics of the land cover and land use patterns (Olang and Fürst, 2011). Hence identifying causes and driving factors aid in taking appropriate measures to avert the impacts. This key information on the changes of land covers patterns over time and possible factors contributing to the changes especially at the sub basin level is scarce in most river basins in Kenya such as the Sondu Miriu River Basin. Alteration of the land cover and land use in the river basin can transform the behaviour of the stream discharges and sediment yields (Choto and Fetene, 2019). Hence assessment of the effects of land cover change on hydrologic response is crucial. Several studies have been undertaken to determine the extent to which land uses and land covers affect surface run offs (Kundu and Olang, 2011; Tundu *et al*., 2018). However, assessment of the contribution of individual land use and land cover on variations of stream flows and sediment yields is very important, this issue has not received adequate attention in the past studies. In many tropical river basins, there is limited knowledge on the influence of specific dominant land use and land cover on stream flows and sediment yields (Masese *et al*., 2012). The Sondu Miriu River

Basin in Lake Victoria basin is characterized by three major land covers i.e., forest, tea plantation and mixed farming. The extent to which these specific land uses affects the flow and sediment loads of Sondu Miriu River Basin is not well known. The mixed farming in this study referred to food crops (maize, sorghum, millet, sugarcane, potatoes, tomatoes, vegetables, grazing grounds, beans, pineapples and fruits trees).

Forest land cover has been known to be important factor in the regulation of the hydrologic components of the river basins (Guzha *et al*., 2018). However, transformation of forested land covers into other uses is believed to affects response of hydrological components uniquely in different river basins and sub basins. Further, seasonality of river discharges has been associated with reduced forest cover (Chandlera *et al*., 2018). However, understanding hydrological processes which are connected to the changes in the stream flows in deforested sub basins are limited. The sediment inflow into the reservoirs due to the soil erosions was reported to cause water quality reduction (Tundu *et al*., 2018). But the routing of sediment transport to understand the dynamics of land cover which triggered soil erosion is limited in the tropical river basins.

Knowledge on the effect of forest land cover on stream flows and sediment yields is limited in the tropics compared to the temperate region. For example, study conducted in Western Europe, Southwest China and upper Yellow River showed that deforestation at the catchment level increases sediment flows and reduces stream flows (Bussi *et al*., 2016; Bieshenk *et al*., 2018; Tian *et al*., 2019). Most studies conducted in tropical river basins have not considered the effects of deforestation on river discharges and sediment yields (Gathagu *et al*., 2017; Ochieng *et al*., 2019). Therefore, conservation of forests has not taken into account the important role forests play in the sustainability of the river discharges (Masayi 2021; Ndungo, 2021). Reduction of the forest land cover in river basins might have negative impact on the hydrology of the rivers (Mekuriaw, 2019). There is therefore a need for further studies to provide data and knowledge on the influence of forest land cover on hydrologic response of the rivers (Kundu and Olang, 2011; Omengo *et al*; 2016).

Tea plantations are important land use types in some tropical river basins such as Sondu Miriu River Basin. The effects of tea plantations on the hydrologic response of rivers have not received adequate attention in most previous studies. The effects of tea plantations are thought to be similar to that of tropical forests although lack of data makes it difficult to ascertain whether this is true. The previous study conducted in East Usambara Mountain, Tanzania revealed that tea bushes have effect on water quality especially in relation to oxygen levels affecting aquatic ecosystem (Biervliet *et al.*, 2009). Further it has been believed that replacing forest land cover causes insignificant change on the stream flows and sediment yields in the river basins (Gebrejewergs *et al*., 2020). But the knowledge gap exists on the impacts of the tea plantations on the stream flows, sediment yields in most tropical river basins. The tea plantation occupies a large part in the upstream of Sondu Miriu River Basin. Understanding the impacts of the tea plantations on stream flows and sediment discharges of Sondu Miriu River Basin is important for determining the appropriate land use and land cover for the basin.

Studies have been undertaken to determine the impact of agricultural land conversion on stream flows and sediment yields in the river basins (Mello *et al*., 2018; Baunde *et al*., 2019). Previous studies have shown that agricultural fields create seasonal variations in the amount of sediment yields observed in the river systems. A study conducted through demonstrations on agricultural plots had shown that cultivated fields generate high sediment transport in seasons with less agricultural activities especially when soils are exposed to erosion (Ouma *et al*., 2013; Kertész *et al*., 2019; Uwimana *et al*., 2018). However, the effects of farming at sub basin scale and basin scale especially in Sondu Miriu River Basin has not been conducted specifically on hydrological components. This calls for further assessment on the hydrologic responses in sub basins dominated by the agricultural fields in comparison with response of other dominating land covers such as tea plantations and forest land cover.

Previous studies conducted in river basins in Africa and elsewhere have established that there is need to understand the long-term response of the stream flows and sediment yields in sub basins with different land use and land cover patterns (Addis *et al.,* 2016; Bussi *et al*., 2016; Briak *et al*., 2016: Hallouz *et al*., 2018). For instance, in Little Ruaha River Basin, it was noted that changes in land use and land cover have long term impacts on stream flows and sediment generation (Chilagane *et al*., 2021). However, understanding specific effects of the dominating land cover and land use on stream flows and sediment yields in sub basins and catchment areas is still a gap in most sub basins. In Kenya, tea plantations are one of the important agricultural activities in the upstream reaches of most large river basins including Sondu Miriu River Basin. In the previous studies tea plantations had been clustered as an agricultural field land use lumped with other cash crops and food crops in analysing land use hydrologic response (Nyangaga, 2008; Olang and Fűrst, 2011; Ngeno, 2016; Ndungo, 2021). Simulation conducted in Chinese River Basin on agricultural crops land covers (tea, cabbage and rice) has shown that each crop had different hydrologic responses (Schmalz *et al*., 2015). Therefore, understanding the past, present and future specific effects of tea plantations as dominant land use in the Sondu Miriu sub basins on hydrologic response is important as this will aid in the formulation of policies as the appropriate combinations of land cover and land use type that need to be promoted in the basins in order to sustain stream flows and reduce high sediment loads.

Limited information exists in temperate and tropical regions on the simulated long-term impacts of dominant forest land cover on stream flows and sediment yield (Guzha *et al*., 2018). The simulation studies conducted in the tropical forest in east Africa Montane with limited measured short-term data shown that forest land cover is characterized by low generation of sediment yields and sub surface flow (Kroese *et al*., 2020). The knowledge on the long-term effect of forest land cover on stream flows and sediment yields is important in understanding the hydrologic response of the sub basin facing decline of the forest land cover. Although simulation studies have been conducted in East Africa River basins in short term temporal scales, inadequate data have led to inconclusive research outputs. Hence there is a need for long term simulation to determine the past, present and predict future hydrologic consequences of expanding or decreasing the dominant forest land cover in the river basins (Guzha *et al*., 2018). The Sondu Miriu River Basin is one of the river basins in Kenya with insufficient long term hydrological data for decision making. Therefore, simulation of past, present and future stream flows and sediment yields is crucial for proper water planning and management and for determination of the future hydrologic impacts of different specific land uses or combination of land use and land cover in the basins. Simulation undertaken in Ghaggar River Basin have shown that continuous replacement of natural forest by mixed farming increases stream flows seasonally and also contributes to sediment loads transported by rivers (Chauhan *et al*., 2020). Land use and cover policies changes with time and simulating the past and future hydrologic response on the land use changes will update the governments on possible effects of land use change on water resources (Tram *et al*., 2021). The research gap on simulation of stream flows and sediment yields on mixed farming dominant land use and land cover has led to unidentification of sources of hydrologic response variability.

Understanding hydrologic components of sub basins with dominant land use and land covers is key in achieving the sustainable water resources development (Setti *et al*., 2017). Changes in the land uses and land covers over time affects the natural water balance of the sub basins (Said *et al*., 2021). Therefore, continuous assessment of the behaviour of hydrological components exposes the hydrologic response of a sub basin under influence of main land cover. The hydrologic response of various land use and land cover types can be understood most clearly by examination of the hydrologic cycle theory. Hydrologic cycle theory of a sub basin dominated by forest as presented in Figure 1.1.1 consists of vertical, horizontal and storage components. The vertical components are rainfall, evaporation, infiltration, through fall, percolation and transpiration. The horizontal components are surface runoffs, lateral flow and baseflow. The storage components are interception, surface sinks, soil moisture in unsaturated zone, groundwater aquifer and streams. These components respond differently in sub basins with dominating land uses and covers. In a sub basin dominated by forest land cover, water balance studies have shown that evapotranspiration is the leading hydrologic component consisting approximately 45% of the rainfall input while surface runoffs, lateral flows and baseflow were about 20%. (Setti *et al*., 2017). Study conducted in Buzi sub basin further showed that interception in the forest cover was high compared to other hydrologic components (Chemura *et al*., 2020). Reforested areas in Pakistan sub basin were assessed and revealed that forest cover influences hydrologic components and the water balance. Different land covers respond uniquely to the vertical and horizontal components of the hydrological processes (Saddique *et al.*, 2020). In tropical river basins data and information on the dynamics of hydrological components under different land use types in a sub basin is limited. The lack of data and information has limited the extent to which the sustainable management and development of the water resources in a river basin can be attained.

Assessment of hydrological components and water balance in sub basins dominated by tea plantation is limited. The response of other key hydrological components and water balance in sub basin dominated by tea plantation especially Kenya is unknown. The tea plantation is characterized by low height plants of about 1 m high from the soil surface, thick canopy and bush density. In the water cycle context shown in Figure 1.1.2, tea plantation has thick and dense canopy cover and its impact on the hydrological processes such as interception, transpiration and evaporation of the intercepted water on the leaf surfaces has not been estimated. However, a study to unveil this theory is required especially in sub basin with expanding tea plantation land cover over time. This will aid in understanding effects of tea plantation in the water balance of the sub basin.

Previous studies stated that sub basins with less forest cover experience seasonal variations in horizontal components surface runoffs and stream flows (Lopes *et al*., 2021). However, understanding the effects of mixed farming on horizontal and vertical hydrologic components has been conducted only on surface runoffs (Chauhan *et al*., 2020; Chemura *et al*., 2020; Said *et al*., 2021). The conceptual model Figure 1.1.3 portrays the four temporal scales in sub basin dominated by mixed farming in Kenya. The response of hydrological components and water balance in each temporal scale is unknown in many sub basins dominated by mixed farming. Further the information on the effects of four seasons on sediment transport has not been established. Assessing the response of hydrological components and water balance is very important for water resources planning and management.

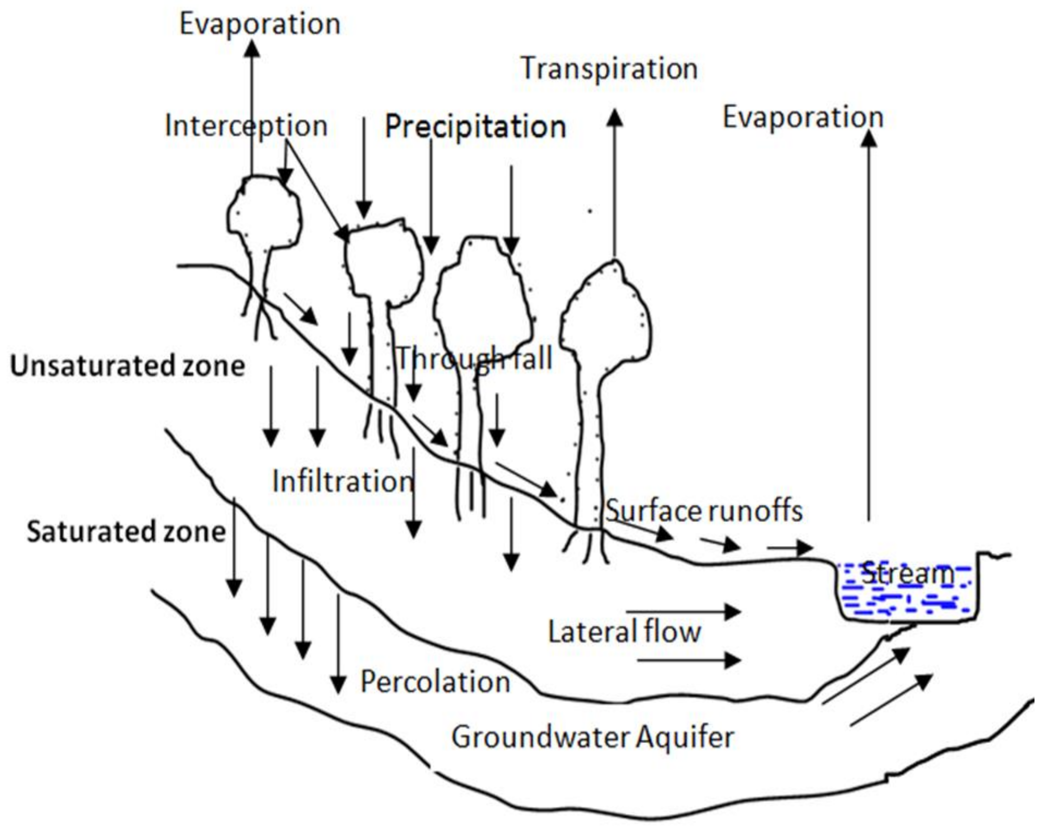


Figure 1.1.1: Water cycle in the sub basin dominated by the forest land cover
(Source: Shiklomanov and Rodda, 2003)

The relationship between stream flows and sediment yields is critical in identifying the genesis of sediment generation. Past study conducted in Lower Tana River showed positive relationship at the onset and negative relationship towards the end of rainy season (Geereart *et al*., 2015). However, information on the causes of the seasonal variations of sediment yields transported downstream was not provided. In order to reduce sediment inflow into the basin, there is need to be identify sources of the sediment generation. This only can be achieved through understanding of the existing relationship between sediment yields and stream flows in sub basins dominated by forest, tea plantation and mixed farming in different seasons.

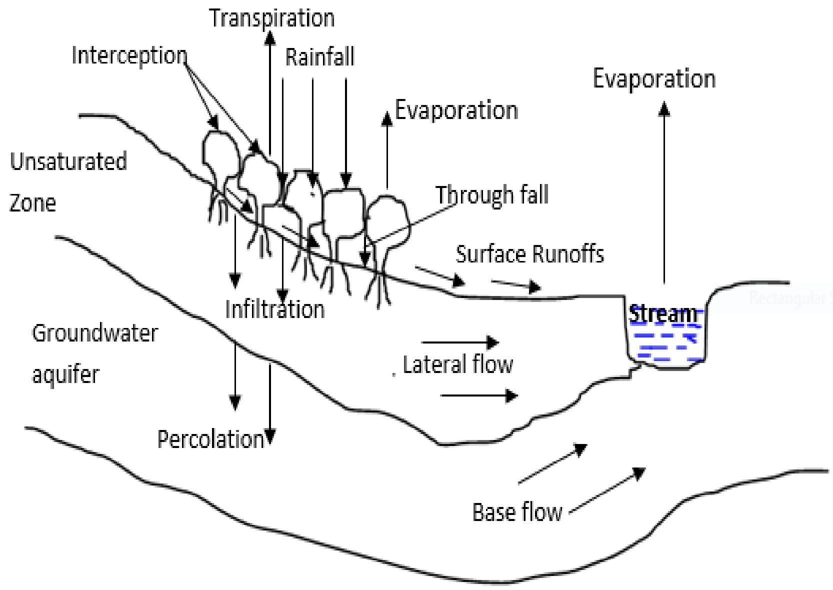
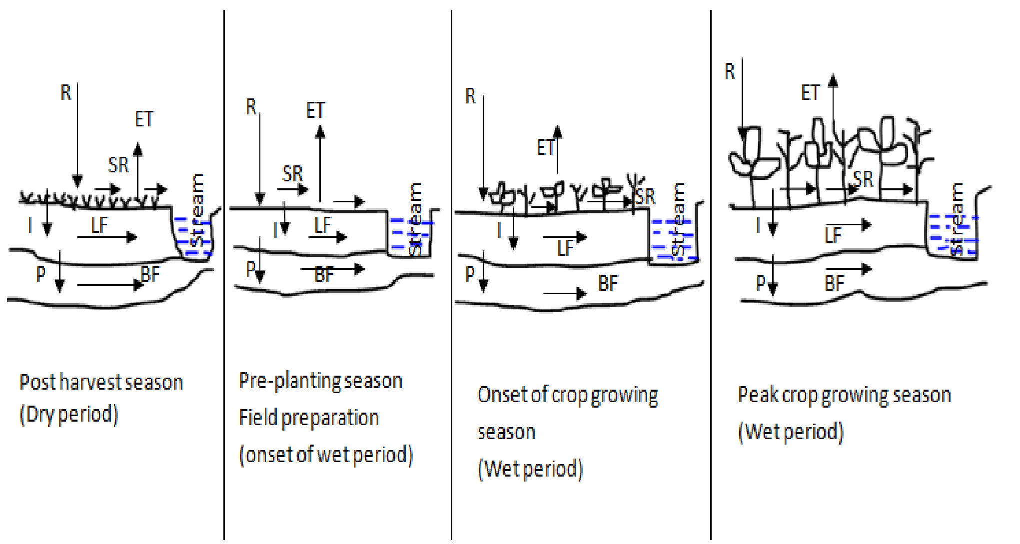


Figure 1.1.2: Hydrologic cycle in the sub basin dominated by tea plantation (Source: Koech, 2021)



Where,
R – Rainfall, ET – Evapotranspiration, SR – Surface Runoffs, LF – Lateral Flow, I – Infitration, P – Percolation, BF – Base flow

Figure 1.1.3:Water cycle in the mixed farming dominant sub basin (Source: Koech, 2021)

The information on the relationship between stream flows and sediment yields in the sub basin dominated by forest land cover in previous studies are limited especially in the tropical river basins. Most studies that have investigated the relationship between stream flows and sediment yields in combined land uses and covers (Fahey and Marden, 2000; Geereart *et al*., 2015; Bathurst *et al*., 2017). Understanding the relationship between stream flows and sediment yields especially in sub basin dominated by forest cover exposes the seasonal variations, causes and sources of sediments transported in the stream network.

The knowledge on the relationship between stream flows and sediment yields in the sub basin dominated by tea plantation is limited. The significant of tea farming in Kenya has led to continuous expansion of tea farms in tea growing zones. The extension of tea plantation in small and large scales interferes with the status quo of hydrologic response. Therefore, understanding the relationship between stream flows and sediment yields in the sub basin dominated by tea plantations exposes the performance of the land cover in the conservation of the soils in the sub basins. This critical information is useful in the sustainable management of the water resources in the sub basins. However, studies which have been conducted in the sub basins dominated by tea plantation have not reported on the possible existing relation between stream flows and sediment yields.

The rise in the population growth increases the demand for food (Elferink and Schierhorn, 2016). This could lead to continuous expansion of agricultural fields to meet the required quantities and qualities of food. Increasing the mixed farming land cover in the sub basins interfere with the natural hydrologic behaviour and response. In mixed farming land cover reduction of vegetative cover occurs especially during field preparation and post harvesting periods. The knowledge on the relationship between stream flows and sediment yields transported downstream in sub basins dominated by mixed farming is very important. Further, the seasonal relationship between stream flows and sediment yields aids in identifying the sources of sediment discharge in the sub basin. Despite the fact that this information is important in the management of water resources and soil nutrients, the gaps exist on the knowledge particularly for the tropical sub basins.

Assessment conducted in the previous study revealed that forest is suitable land use and land cover to improve water quality (Duffy *et al*., 2020). In the tropical sub basins analysis of performance of land uses and catchment management practices is limited especially on the sub basins dominated by the forest land cover. Most studies are conducted on the multiple land uses (Gathagu *et al*., 2017; Djebou, 2018). In Sondu Miriu River Basin, understanding the suitable land uses and land covers in the sub basins helps in ensuring sustainable water resources quantity and quality. The catchment management practices also in the sub basin dominated by the forest land cover have not been revealed in past research studies.

Analysis on the suitability of land use and land cover in the sub basins dominated by tea plantation is scarce. In addition, knowledge on the best catchment management practices which can be implemented in the sub basins dominated by the tea plantation is limited. This information is critical especially in the sub basins where tea plantation is continuously increasing. This will help in understanding the appropriate land use and land cover for improving hydrologic response and right measures to curb the effects of the dominating land use on water resources in the sub basin. Mixed farming has been increasing replacing the natural forest land covers in many sub basins (Hinz *et al*., 2020). Hence the suitable land use and land cover and also best catchment management practices should be identified for the sub basins dominated by the mixed farming land covers and land uses. Previous studies have shown that little has been done in determining suitable land uses and land covers and best practices for managing catchment areas especially in sub basins with dominating mixed farming land covers. Models and ideologies were recommended to balance land cover and land use changes and hydrologic response (Kumar *et al*., 2019; Riddiford, 2021).

1.2 Statement of the Problem

Sondu Miriu River Basin which is located in Western region of Kenya is dominated by the tea plantations, forests and mixed farming land uses and land covers. The river basin has been experiencing low flows during dry periods and high flows during rainy season and high levels of turbidity (Masese *et al*., 2012). The initial natural forest land cover in the basin has been replaced over time due to progressive introduction of tea plantations and mixed farming land covers. This has been due to continuous population growth that had increased the demand for cultivation, settlement and food security. In the recent decades, low flows in the river basin especially during dry periods has been inadequate for sustaining the water demands in the basin (Ochieng *et al*., 2019). These are indications that hydrological patterns of a river basin have been changing not only due to climate change but also due to land cover change.

Introduction of tea plantations to Kenya in 1903 and to Sondu Miriu River Basin in 1924 was done with aim of economic satisfaction. However, its impacts on hydrologic response were assumed to be similar to the forest land cover due to its canopy appearance (Gebrejewergs *et al*., 2020). However, this has not been determined through field-based studies. The similarities and differences in terms of impacts of the forest and tea in comparison with mixed farming is yet to be determined in the basin. Lack of knowledge in the river basin on the impact of forest, tea and mixed farming land covers on the stream flows and sediment yields makes it difficult to recommend suitable land cover that ensures sustainable flow with less turbidity and sediment loads. Continuing with freewill selection of suitable land cover by basin residents might cause future challenges of water shortage and expensive maintenance of water structures along the river networks.

Previous studies have showed that the Sondu Miriu River is already experiencing high turbidity that has reduced the water clarity (Okungu *et al*., 2002; Omengo *et al*; 2016). There is also a high seasonal variations of stream flow (Nyangaga, 2008; Ochieng *et al*. 2019). High turbidity levels make available water unfit for human consumption. It has been suspected that sediment loads transported downstream might be high and this causes long term impact on the hydraulic structures such as water intake structures for Sondu Miriu hydropower plant (Omengo *et al*; 2016). Changes in the lacustrine ecology of Lake Victoria overtime was attributed to inflow of sediments and nutrients from the upstream catchments (Masese *et al*., 2012). However, the quantities and sources of sediment fluxes have not been assessed adequately in the Kenyan part of the Lake Victoria Basin. Further decline stream flow in the river basin has caused conflicts among competing water users (Gathagu *et al*; 2017; Tundu *et al*., 2018). However due to existing gaps in the available information on the link between response of different hydrological components under specific dominant land uses and covers, determination of appropriate land use type has been difficult in the basin. This is also true for other basins in Kenya and Africa at large. Also, inadequate information on hydrologic response of the sub basins under different land uses and covers, proves to be dilemma faced by natural resources managers in the determination land use with minimal impact. Previous studies conducted in the Sondu Miriu River basin failed to demonstrate connectivity between hydrologic response on the sub basins with dominant land uses and land covers (Masese *et al*., 2012; Ochieng *et al*., 2019).

The relationship between sediment yields and stream flows in the Sondu Miriu River Basin has not been identified particularly at the sub basin levels. Also understanding the existing relationship over time step between hydrologic responses on sub basins under different dominant land use types enables tracing of the sediment generation sources and media of sediment transport in the sub basins dominated by specific land uses and land covers. The challenges of turbidity, sediment loads and stream flow variations faced in the river basin are not localized but instead they are transferred into the Lake Victoria. Therefore, solving sediment discharge and stream flow variability at the sub basin levels helps in protecting the Lake Victoria Ecosystem (Okungu *et al*., 2002; Azza, 2006; Kateregga and Sterner, 2009; Isabirye *et al*., 2010).

The challenges of data gaps were addressed in study. These data and information are crucial in identifying suitable catchment management practices in the sub basins to reduce sediment generation and sustain stream flows. This study is key in addressing United Nations Sustainable Development Goal number six that ensure sustainable management and availability of water resources. Understanding the hydrologic response in the sub basins of the Sondu Miriu River Basin is also critical in identifying seasonal variations and long-term behaviour of hydrologic components and sediment fluxes in the Lake Victoria. The study provides recommendations on suitable land use and land cover and catchment management practices to ensure sustainable water quantity and quality for use. The findings of this study also provide options of protecting water from sediment pollution and maintenance of continuous flows all the year round. It aids in providing approaches which ensure availability of good water quantity that boost socio-economic and livelihoods of the basin residents and supports the process of achieving Kenya's vision 2030. Sustainable management and development of water resources is key in the national water policy and strategy. This study helps to provide information for sustainable management of surface and groundwater resources in the basin.

1.3 Research Objectives

1.3.1 General Objective

The main objective of the study is to determine the influence of the dominant tea plantations, forests and mixed farming land covers on hydrologic response such as stream flows, sediment fluxes and water balance components in the sub basins of the Sondu Miriu River Basin.

1.3.2 Specific Objectives

The specific objectives of the study are as follows:

i. To determine patterns of land use changes in the sub basins dominated by tea plantations, forest and mixed farming land covers in the period 1975 to 2021.
ii. To determine the effects of the sub basins dominated by tea plantations, forest and mixed farming on stream flow and sediment load in the period July 2020 – June 2021.
iii. To simulate past, present and predict future stream flows and sediment yields in the sub basins dominated by tea plantations, forest and mixed farming land covers from period 1960 to 2090.

iv. To estimate major hydrologic water balance components in the sub basins dominated by tea plantations, forest and mixed farming land covers from 1960 to 2020.
v. To determine the relationships between stream flow and sediment yield in the sub basins dominated by tea plantations, forest and mixed farming land covers in the period between 1960 and 2020.
vi. To determine the suitable land use types and catchment management practices for sustaining streamflow and reducing sediment transport in the sub basins dominated by tea plantations, forest and mixed farming land covers.

1.4 Research Hypotheses

The following are the null hypotheses:

i. There is no significance change in the areas of the dominant land covers in the sub basins dominated by tea plantations, forest and mixed farming land covers.
ii. There is no significance difference in the stream flows in the sub basins dominated by tea plantations, forest and mixed farming land covers.
iii. There is no major statistical difference in the sediment discharge in the sub basins dominated by tea plantations, forest and mixed farming land covers.
iv. There are no significant differences in the hydrological components of the sub basins dominated by tea plantations, forest and mixed farming land covers
v. There is significant relationship between stream flows and sediment yields in the sub basins dominated by tea plantations, forest and mixed farming land covers.
vi. There is no significant difference in catchment management structures used to reduce sediment yields generated in the sub basins.

1.5 Significance and Justification of the Study

The study on the extent to determines the influence of different dominant land covers tea plantations, forests and mixed farming on magnitude of stream flows and sediment yields in tropical river basins. This study revealed the appropriate land uses and land covers which reduces sediment generation and increases stream flow sustainability. Also, this study was important for formulating policies for implementation of appropriate land uses in tropical river basins. This study also contributes to the data and knowledge on the patterns of dominating land covers in the period of four and half decades. This is useful in understanding the influence of land use and land cover change on the local water cycle of the river basin. The outcome of this study showed the response of hydrologic components under various land use types (mixed farming, forests and tea plantations). This is essential for demonstrating the extent to which various land use types leads to modification of the seasonal variations of stream flow and sediment discharge in tropical rivers. Most river basins in Kenya are experiencing declining stream flows and increasing sediment discharges. However, the specific land use and land cover types that is responsible for this increase is not known. Sustainable Development Goal number six and Kenya's Vision 2030 demands that the country should have attain equitable access to safe drinking water and sanitation to all (United Nations, 2015). In order to achieve these goals, studies have to be undertaken on the water resources to determine the sustainability of the water sources verses increasing water demands. This study provides data and the information on influence of forest, tea plantation and mixed farming land covers on hydrological components which are key in the water resources management in the Sondu Miriu River Basin. In addition, present, past and future trends of water balance components and sediment yields of the basin have been revealed in this study. This information helps the water resources managers to determine if they will achieve the set water sustainability targets on water supply, water resources management and sanitation for all in the basin by 2030.

This study also fills the gaps existing in the previous studies conducted in the Sondu Miriu River Basin and other tropical river basins. Further, this study identifies sub basins which generate sediments and peak seasons for stream flows and sediment discharge in the river basin. This information is important for the water resources planning and design of soil and water conservation measures and programmes. In addition, this study identified suitable land cover and catchment management practices to be implemented in the Sondu Miriu River Basin to ensure sustainable stream flows and sediment loads in the river systems by

2030. This study also fills the gap that exists in the management of the Lake Victoria. The Lake Victoria has been experiencing increasing growth of water hyacinth that has threatened aquatic ecosystem in lake. The findings of this study show how change in the land cover from forest to mixed farming is the main cause of continuous flow of high sediment load into the lake water. This study was also important, as it provides long term stream flow and sediment yield data and information that is useful in the designing, sustainable development and management of hydraulic structures. This is particularly important for the two hydro-electric power plants namely Sondu Miriu and Sang'oro Hydropower plants that requires sustainable flows to operate at their optimum capacity. At the same time long term information on sediment discharge and stream flows obtained in this study is important to the Lake Victoria South Water Development Agency in designing of the future hydraulic structures.

The outputs of this study are also useful to government ministries and departments, environmental and water resources development and management agencies, research institutions and universities, among others on the management of water resources. It provides data and information on hydrologic response of specific dominant land use and land cover types in the sub basins of Sondu Miriu River Basin and other sub basins with similar characteristics within the tropics. Land cover and land uses in Africa and Kenya has been undergoing changes in the recent past to meet increasing demands for food, settlement and socio-economic development. Previous studies have shown effects of combined land uses and land cover at river basin level on hydrological components (Masese *et al*., 2012). But gaps exist in identifying impacts of specific major land use and land cover on hydrologic response at the sub basin scale. Also, data and information that can guide design and implementation of projects on sub basin conservation measures is limited. Hence this study determines the most suitable land use and land cover and best catchment management practices which can be implemented to ensure sustainability of quantity and quality of water resources in the sub basins especially with the dominant land use type.

This study also provides information on the pattern and quantities hydrologic components (rainfall, evaporation, transpiration, soil moisture, surface and ground storage, surface runoffs, base flow and subsurface flows) in sub basins dominated by tea plantation, forest and mixed farming land covers and land uses. It is also necessary to understand the genesis and pattern of the land cover changes in the river basin. This information is crucial in the designing of sustainable catchment management strategies of the sub basins in order to avoid adverse effects of land degradation. This study also fills this gap by providing knowledge on the patterns of land cover changes from 1975 to 2021 in sub basins dominated by forest, tea plantation and mixed farming land covers. The fields surveys conducted in the basin showed that the stream flows in the Sondu Miriu River are turbid due to high concentrations of suspended sediments (Ochieng *et al*. 2019). The sources of these sediments are not known in the case of the Sondu Miriu River Basin. The discharge of sediments in the Sondu Miriu River is a serious threat to the public health and has potential of negatively impacting the biodiversity of the Lake Victoria (Ouma *et al*., 2013; Mbaka and Mwaniki, 2017; Kanangire *et al*., 2018).

The information of the water balance of sub basins is very important in the water resources management of a river basin. No studies on water balance components have been undertaken in the Sondu Miriu River Basin. Therefore, this study provides data and information on the water balance components of the basin for the period of six decades. This data is important for planning and management of the water resources in the river basin. The study also identifies the relationship between stream flows and sediment yields in sub basins with three dominant land uses and land cover types. In order to determine the sources of sediment discharged by the rivers in the three sub basins, the relationship between stream flows and sediment loads was determined. The identification of sediment sources is important for directing specific soil and water conservation strategies in those areas.

This study is also important in that it provides data and information on the suitable land cover and appropriate catchment management practices in the river basin. In addition, this study contributes in establishing the effects of forest, tea plantation and mixed farming on the stream flow and sediment transport in a tropical river system. Furthermore, the study contributes original knowledge in the field of hydrology by filling existing research gaps particularly on the effects of tea plantation, forest and mixed farming land covers on hydrologic response of tropical river basin such as Sondu Miriu.

1.6 Scope of the Study

This study focused on the influence of dominant land cover and land use on the hydrologic responses in the three sub basins found in the Sondu Miriu River Basin. These sub basins include; Timbilil Sub basin dominated by tea plantation land cover with an area of 315 km^2, the Kiptiget Sub basin which is dominated by forest land cover with an area of 152 km^2 and Kipsonoi Sub basin dominated by mixed farming land cover with an area of 1582 km^2. The study examined the responses of the river basin with surface area of 3450 km^2.

This study also focussed on the analysis on land cover and land use patterns in the periods between 1975 to 2021 in the three sub basins dominated by different land covers and land uses types. This study period was chosen due to the availability of the land use remote sensing data that started in 1973. The influence of dominant land uses and land covers on the hydrological components and sediment flux was done using historical data covering the period of six decades from 1960 to 2020. The hydrological components investigated include; rainfall, evaporation, transpiration, soil moisture, surface and ground storage, surface runoffs, base flow and subsurface flows. The study examines both seasonal and inert annual variation of stream flows and sediment loads from the three sub basins. The seasonal variations were for the period between July 2020 and June 2021. The inter annual variations were determined in the period between 1960 and 2021. Similar periods were applied in assessing the downstream hydrologic response of the river basin. This study investigated the influence of dominant land cover and land use forest, tea plantation and mixed farming on stream flows and sediment yields on three sub basins. The physical water quality parameters analysed in this study were turbidity, total suspended solids concentrations and sediment yields.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Introduction

The study aims at determining the hydrologic response of catchments and sub basins dominated by tea plantations, forest and mixed farming land covers and land uses. The hydrologic response is in terms of output of stream flow and sediment loads in areas dominated by the above land cover and land use types. The purpose of this chapter is to review studies that have been undertaken in different tropical river basins of the world. The chapter also provides details on the studies done on global, regional, national and local levels. Literature review was undertaken to address each of the specific objectives of the study. The chapter was prepared using information obtained from various published sources such as scientific journals, technical reports, university theses open online sources and university repositories, among others.

2.2 Patterns of land cover and land uses changes in river basins

Studies have been undertaken in river basins to understand the patterns of land covers and land uses (Mayaux *et al.*, 2005; Drigo *et al.*, 2009; Prokop, 2018). These studies have shown that over a period of time, the patterns of land cover and land use changes depend on the land use demands. Further observations showed that temporal resolutions of ten years result in a significant change in land use and land cover patterns. In these studies, conclusions were made that changes in the land cover and land use patterns over time were triggered by population growth and socio-economic development. Tea plantation in the historical and recent periods has created impact in the patterns of original land cover and land use within the tropics. For example, a study conducted from 1874 to 2010 showed that tea plantation increased by about 30% causing decline in the forest land cover by approximately 70% in Eastern Himalayan region (Prokop, 2018). This declined in the forest cover was also linked to the population increase. This observation revealed that there is need to understand effects of tea plants on the initial land cover of river basins experiencing continuous increase of tea plants.

In 1990 the spatial coverage of tropical forests was around 11.5 million km^2 (Mayaux *et al*., 2005). The annual reduction was estimated to be 81,000 km^2 while efforts of reforestation have been done in many regions. However, it was realized that the forest pattern varies between the primary forests and secondary forests (Mayaux *et al*., 2005). The forest land cover in the different river basins have been undergoing changes due to manmade and natural activities. A study was conducted in a period of 13 years from 1997 to 2010 and established that the forest land cover increased by 4% (Spruce *et al*., 2020). While in Tano-Offin reserve the dominating forest land cover showed a declining pattern from 1987 to 2017. The decline was observed in two scales of 15 years and realized that forest decreased almost two times the initial forest cover. Similarly, in the next time scale of 15 years forest land cover decreased by almost 1.5 times the initial forest land cover (Appiah *et al*., 2021). In contrary study conducted within the tropics from 1980 to 2000 revealed that the pattern of the forest land has been declining with a negative trend (Drigo *et al*., 2009). These indicate that at global scale primary forest land cover has been interfered by anthropogenic activities and efforts which have been made to restore through secondary forests have not achieved the initial pattern and original canopy cover. This calls for assessment to ascertain the changing rates of forest covers vis-à-vis the upcoming land covers and uses.

Agricultural land cover has been replacing the natural land covers especially in river basins inhabited by people. For example, a study conducted showed that in one decade from 2003 to 2014 the pattern of the land cover changed by increasing agricultural fields by approximately 28% (Liping *et al*., 2018). This was reported as the cause of declining trends in the forest land covers in many tropical river basins (Hassan *et al*., 2016). This reveals that rise in populations will lead to demand for more food crops and settlement resulting in continuous reduction of forested lands. In India mixed food crops in highlands were found to be expanding faster than in protected and reserve areas to enhance food security (Semwal *et al*., 2004). Accordingly in humid and semi humid areas mixed agricultural crops were increasing at expense of other land uses (Majule, 2013). This showed that in Africa population growth has triggered the increase in demands for food and socio-economic development. For instance, a study conducted between 1990 and 2010 showed that forest land cover reduced by almost 50% in a period of 20 years through deforestation (Addo-Fordjour and Ankomah, 2016). While in East Africa, forest cover declined by 43% in three decades due to expansion of fields for farming and settlement (Bullock *et al*., 2021). Further it was observed that forest land cover pattern decreased by 21% and it translated to losing forest cover of about 5 hectares. This significant decrease in the forest vegetation has serious impacts on hydrological processes of a river basin (Brink and Eva., 2008). In tropical highlands similar declining forest patterns was observed in a study conducted from 1990 to 2017. The change of forest land cover pattern was attributed to fires and deforestation. In addition, inadequate policies were identified as main cause of slow reforestation process especially in the tropics within the African continent (Alemneh *et al*., 2019).

The patterns of land use and land cover change were assessed from 1990 to 2016 and showed that mixed farming increased by 11% reducing wetlands by about 13% (Msofe *et al*., 2019). Similar observations were reported in sub basins with rising population densities. For example, the densely populated areas in 2013 were occupying an increased land coverage of 628, 000 km^2 compared with the area occupied in 1975 (Herrmann et al., 2020). The patterns of land use and land cover change assessed from 1990 to 2016 showed that mixed farming increased by 11% reducing wetlands by about 13% (Msofe *et al*., 2019). The 57% increase in agricultural crops and expansion of farms decreased forest cover by 21% and it translated to losing forest cover of about 5 hectares. This significant decrease in the forest vegetation had serious impacts on hydrological processes of a river basin (Brink and Eva, 2008).

In Kenya patterns of land covers has been changing over time due to anthropogenic pressures. This was confirmed by studies conducted in the sub basins within the country. The patterns of the land cover changes done from Landsat images 1977 to 2019 showed increasing tea plantation pattern with increase of 18% (Masayi *et al*., 2021). The patterns of tea plantation land use and land cover has not been assessed in relation to other land covers despite its continuous extension of land under tea plantations especially in the Kenyan highlands. Assessment of patterns of the land cover changes was done in the slopes of Mt. Elgon from Landsat images 1977 to 2019. It was reported that the forest land cover declined by 18% resulting in the increase of tea plantation and mixed farming by 0.13% and 29% respectively (Masayi *et al.*, 2021). A study carried out from 1987 to 2017 portrayed reduction in forest cover by 0.5%. This decreasing pattern of forest land cover was attributed to population growth and rising demand for food and socio-economic development (Maina *et al.*, 2019). Also, in Western Kenya patterns of land cover and land use changes over time was evaluated and established similar observations like other river basin in the country. Deforestation was key land cover and land use pattern reported (Kogo *et al.*, 2019). Conversion of primary forest land cover patterns into other land uses has decreased the spatial pattern of the forest land cover in the sub basins (Chebet, 2013). Degradation witnessed in slopes of Mt. Kilimanjaro exposed a decreasing pattern in forest ecosystem and pointed out the need to implement policies on reforestation (Ndalilo *et al.*, 2021).

Agricultural fields with mixed food crops land cover pattern assessed from 1987 to 2017 showed an increase of 1.5% (Maina *et al.*, 2019). Also, in Western Kenya mixed food crops had replaced forest land cover as the sub basins (Kogo *et al.*, 2019). Since 1950s sub basins switched the primary land cover patterns to mixed cash crops causing significant increase in mixed farming over decades (Imbernon, 1999). In densely populated areas mixed food crops land cover pattern has been witnessed as dominant land use due to high demand for food production (Musa and Odera, 2015). However, studies have not been done in a number of river basins in the country despite annual increase in demand for food and socio-economic development. Also lack of adequate data has led to short term analysis of land use and land cover changes in the river basins (Ndalilo *et al.*, 2021).

In the upstream part of the Sondu Miriu and its neighbouring Nyando River Basin, tea plantations cover a significant parcel of land bordering the forest cover. While at the mid and downstream the river basins are covered by mixed cash and food crops. However, land cover and land use patterns interconnected the short- and long-term change has not been investigated. An attempt was made in the period from 1979 to 2015 in the neighbouring sub basins in Mara River Basin (Mwangi *et al*., 2016). In a period of 36 years, it was realized that forest land cover has declined by around 55% (Ndungo, 2021). Although the changes in other land uses was not examined. The continuous shrinkage of the forest land covers in the sub basins of Lake Victoria Basin Kenyan side was reported based on Landsat images from 1978 to 2018 (Onyango *et al*., 2021). In Kapkatet location in Sondu Miriu mixed food and cash crops were monitored for a period of three decades from 1986 to 2019 and found that mixed farming had increased with a rate of almost 25% (Kibet *et al*., 2021). The study did not state the impact of the increase in mixed farming on the pre-existing land covers. Previous studies have tried to understand different land use patterns in the neighbouring sub basins mainly forest and mixed farming but little is known especially in the Sondu Miriu River Basin. Hence this study has filled the gap by examining long term patterns of dominate land covers and land uses and showing the cause of the changes in each land cover and land use.

2.3 Influence of land cover and land use types on hydrologic response

Studies conducted in sub basins dominated by different land uses and land covers showed that river basins portray hydrologic response in spatial and seasonal variations. A significant seasonal variation in sediment yield was observed in the upstream compared to the downstream (Kemper *et al*., 2019). In extreme high rainfall seasons small rivers carry high sediment loads compared to dry periods (Sun *et al*., 2020). Analysis was done using 1358 stations globally and revealed that 8.8% of degraded lands yields about 69.1% of the sediment transport while non-degraded areas generate approximately 4.2% sediment yields (Phuong *et al*., 2017). Despite numerous studies conducted on the influence of land use and land cover change in decades, effects of tea plantation specifically on-stream flows and sediment loads has been rarely investigated at the global scale.

Alterations of natural forests cover can reduce or increase sediment transport in a river basin (Pacheco *et al*., 2018). A study conducted in a degraded sub basin revealed that forest reduction has an impact on sediment transport (Zhou *et al*., 2019). On contrary, conversion of bare land into forest land weakens sediment delivery function at the catchment hence reducing the quantity of sediments being transported into the river (Abera *et al*., 2019). This was confirmed in scenario analysis that the reduction of forest land cover by 75% increased stream flows during wet periods by almost 80% while sediment yields increased by almost 200% while expansion in the forest land cover yielded a vice versa scenario (Khanal and Parajuli, 2013). Further analysis revealed that the impacts of declined forest cover on stream flows and sediment yields was realized with more than 20% forest cover reduction (Khanal and Parajuli, 2013). According to the observations made it was noted that change of forest cover affects peak flows in small to moderate downpour (Bathurst *et al*., 2017).

Introduction of the secondary forest covers on the affected sub basins initially dominated by forests reduced stream flows and sediment yields (Kebede *et al*., 2020). In a study conducted in Rhine River Basin from 1993 – 2003 revealed that sparsely forested areas of the upstream received high stream flows compared with forested areas (Hurkmans *et al*., 2009). In Germany it was found that the agricultural fields increased stream flows by approximately 14% while meadows have decreased by about 18% from 1750 to 2005 (Mello *et al*. 2018). The conversion in land cover/use from meadows to mixed farming loosens the soil structure leading to increase in soil and sediment transport into the river channels (Baude *et al*., 2019). Similarly, expansion of arable land by 70% observed in Thames River Basin revealed an increased of sediment transport in the basin by 12% downstream (Bussi *et al*., 2016). However, different land cover/uses have different relationship with sediment transport in various geographical regions (Zorzal-Almeida *et al*., 2018). Dominant land cover contributes to dynamics of hydrologic response. For example, mixed farming land cover comprising of clover and potato in Niğde-Akkaya Dam River Basin, Turkey found that clover was effective in reducing sediment transport compared to potato (Korkanc, 2018). The extension of agricultural fields increases stream flows and sediment yields almost one and a half times (Kebede *et al*., 2020).

The land cover canopy affects the performance of sub basin in regulating quantity and quality of water resource (Abera *et al*., 2019). Previous studies showed that interfering with the forest cover in any elevation leads to negative effects. Hence restoration of forest land covers in the deforested sub basins yields to positive response (Bonilla and Johnson 2012; Woldensebet *et al*., 2018). Human activities in the sub basin are causes of sediment generation. For example, continuous deforestation for creating arable lands, settlement places, urban centres, operating earth moving machinery and mining among others destabilizes soil structure (Mirzabaev *et al*., 2015). Seasonal variations of stream flows and sediment transport in South Africa were assessed and about 79% of the sediment flows were observed in the sub basins during the wet seasons. Despite climate change was attributed to the increase in sediment fluxes, decreasing forest land cover exposes the sub basins to chemical, physical and biological interactions. Reduction of the natural canopy has accelerated weathering of rocks and soil erodibility (Grenfell and Ellery, 2009).

Conversion of savannah into crop farming and urban centres indicated that changes in savannah land cover increased flows by 17% while decreasing evaporation by 5%. This increased stream flows resulted in the downstream high volume of discharges in wet season and water shortage in dry months (Yira *et al*., 2016). The conversion of natural land covers into cultivated field in Gojeb River Basin, Ethiopia resulted in increase of stream flows by 15% and sediment yield (Choto and Fetene, 2019). Land use/cover plays significant role as drivers of sediment transport especially in mixed farming land cover on a hilly slope (Hernandes *et al*., 2018; Uwimana *et al*., 2018). Hence soils with high content of sand and silt can be removed easily from the land by moving water and passing wind. Investigation of the fingerprints revealed that about 75% of the peak flows and sediment yields originate from the mixed farming land cover (Kroese *et al*., 2020). In Congo River Basin suspended sediment transport and stream flow variations were monitored in the sub basins dominated by mixed farming for a period between 2 to 6 years. The results revealed that sediment transport peak occurs at the wet season and decline during dry season (Coynel *et al*., 2005).

Tea plantation in Kenya started 1903 and plays a key in contribution to the national economy. In most highlands continuous expansion of tea plantations was reported (Masayi *et al*., 2021). Although tea plantation has replaced forest cover, the effect on hydrologic response especially stream flows and sediment yields have not been investigated. A study conducted to determine effect of mixed land cover on stream flows noted that the removal of the dense vegetation cover has raised stream flows through surface runoffs (Sutherland and Bryan, 1990). The Montane forests cover in Marsabit was reduced by about 52%, exposing soils to be transported hence increasing sediments in the stream networks (Muhati *et al*., 2018). Further sediment transport in deforested areas was high compared to shrub lands (Hulsman, 2015). In lower Tana at the creek sediment yields of approximately 24,322 tonnes/year was reported (Kitheka *et al*., 2004). Intensive deforestation exposes soil surface to erosion during wet days into the river system (Nadal-Romero and Garcia-Ruiz, 2018). Assessment conducted in Thika Sub basin revealed that replacing the existing land cover and land use in the sub basin by 20% with mixed farming raised the quantity of sediment generated by 40% (Karanja and Gathenya, 2010). Given the continuous transformations of land covers in different river basins, limited studies have been conducted at national scale to determine the effects of sub basin dominated by mixed farming on stream flows and sediment transport (Swart, 2016; Masayi *et al*., 2021).

In Sondu Miriu River Basin and the neighbouring river basins, the effect of tea plantation on the stream flows and sediment flux is key to the local hydrology of the sub basins. Studies which have been conducted in the local hydrology and land use have not considered tea plantation as a dominant land cover that requires investigation (Masese *et al*., 2012; Ochieng et al., 2019). Intensive deforestation exposes soil surface to erosion during wet days into the river system (Nadal-Romero and Garcia-Ruiz, 2018; Dutton *et al*., 2019). A study done in tropical sub basins in Mau complex revealed that the declined of the forest cover by about 1.2% led to low stream flows in dry periods and high peak flows in wet periods (Ngeno, 2016). According to the study done, it was noted that bushlands and natural forestland in the Sondu Miriu River Basin has been reducing since 1980s (Masese *et al*., 2012). It was suspected that the cause of turbidity in the downstream of Sondu Miriu

River Basin was due to the decrease in forestland cover upstream by about 20% (Masese *et al*., 2012). Hence, there is need to maintain the indigenous trees of every ecosystem especially riparian lands in order to receive key ecosystem services (Schmitt *et al*., 2019). The existing ten-year forest restoration plan should be implemented to secure the lost ecosystem (Muhati *et al*., 2018; Odongo *et al*., 2019). Also, in the downstream it was observed that deforestation could have resulted in the increase of suspended sediments to about 109±94 mg/l (Njue *et al*., 2021). These analyses were done in sub basins with mixed land uses. Therefore, to understand better the effects of forest land cover on stream flows and sediment yield, there is need to conduct analysis in the sub basin with forest dominant land cover.

Mixed farming in neighbouring sub basin of Mara River Basin showed that an increase of 9% resulted in high flows during wet season and low flows in dry periods (Ngeno, 2016). Also, it was found that sediment transport was high in fields under mixed farming (Hulsman, 2015). In the Ainapkoi tributary, it was realized that replacing natural forest by settlements and subsistence crops has contributed to increase of sediment discharge in the basin (Ouma *et al*., 2013). It was revealed that high sediment transport occurs in seasons with less agricultural activities because the fields were bare and loose soils were easily eroded (Ouma *et al*., 2013; Uwimana *et al*., 2018). However, study tried to understand the seasonal variations for the sediment fluxes and stream flows in the sub basins with dominant land use and entire river basin.

2.4 Simulation of stream flows and sediment yields under different land use types

Simulation of past, present and predict future stream flows and sediment yield in sub basins dominated by tea plantation land cover aid in decision making on the viability of the tea crop in hydrology of the river basin. However, previous studies have considered mainly mixed crops land uses without attention to the dominance of the specific land covers (Schmaz *et al.*, 2015; Shivhare *et al*., 2018; Worqlul *et al*., 2018). Studies on spatial stream flows and sediment yields in sub basin dominated by the forest cover conducted in temperate climate showed that forest cover generates low quantities of sediments of less than 0.2 tonnes/ha. /annum (Schmaz *et al*., 2015). Although perennial forest land cover exists in pockets within the tropics, limited studies have been done to expose the effects of forest land cover on stream flows and sediment yields in past and future decades.

Simulations of stream flows and sediment yields in the mixed land uses in the temperate climate revealed that sediment yields generated in the bare fields were about 37 tonnes/ha (Schmaz *et al*., 2015). Further, projections observed in a tropical river basin revealed that future stream flows will be increasing due generation of surface runoffs by the open fields (Memarian *et al*., 2001). For example, analysis of sediment loads in the Upper Blue Nile revealed that in the past the sediment loads and surface runoffs were low while future predictions indicated significant increase in surface runoffs and sediment loads (Memarian *et al*., 2014). Despite few studies were conducted at global scale on the simulation of the past, present and future stream flows and sediment yields within the tropics, more needs to be conducted because crops characterized and clustered as mixed farming differ from one sub basin to the other.

A study conducted in the Upper Blue Nile River basin revealed that in the future reduction of the forest land cover might increase the stream flows by approximately 3%. In addition, the future sediment discharge will rise with reduction of forest cover by approximately 8% (Nadew, 2018). Changes of land cover have been taking place in the sub basins dominated by the forest land cover over decades. This calls for more studies to predict future scenarios on the effect of forest land cover in the past and future stream flows and sediment yields. Predictions of stream flows and sediment yields in the sub basins dominated by the mixed farming are limited. However, most simulated which have been conducted was to test the performance of the models to simulate well the stream flows and sediment yields (Shivhare *et al*., 2018; Worqlul *et al*., 2018; Daramola *et al*., 2019).

Scenario analysis in Nzoia River Basin showed that decline of vegetation cover by 5% causes an increase of stream flows by 13% (Githui *et al*., 2010). Although forest land cover in many river basins is under threat, some sub basins are still dominated by the forest land cover. Future projections of impacts of forest land cover on stream flows and sediment yields in sub basin dominated by forest land cover needs to be done. Long term stream flows were generated using the hydrological model and realized that conversion of land cover from natural state increases stream flows (Kimaru *et al*., 2019). Mixed farming practiced in Nzoia River Basin indicated that stream flows by 20% (Githui *et al*., 2010). This shows that more studies need to be conducted in different sub basins to determine how different types of crops in mixed farming affect future stream flows and sediment yields in various sub basins.

Simulations of stream flows and sediment yields in the sub basin dominated by forest land cover are scarce in the Sondu Miriu and neighbouring sub basins. However, an attempt was made in the Mara River Basin where simulation was conducted in the sub basin dominated by Agroforestry. It revealed that agroforestry reduces surface runoffs and stream flows (Mwangi *et al*., 2016). Past and future stream flows and sediment yields in the sub basin dominated by mixed farming are limited in the Sondu Miriu and neighbouring sub basins. Hence more studies are required to determine past and future scenario of stream flows and sediment yields. Little is known at the global scale, at regional level and local studies on hydrologic response in areas with tea plantation dominant land use. This could be due to clustering tea plantation as combined land cover and land use in a river basin. Also, projections of future scenarios and past scenarios with the expansion of land cover under tea plantation has not been fully exposed. This study filled the gaps by investigating past, present and future effects of tea plantations, forest and mixed farming land covers on stream flows and sediment yields in the sub basins.

2.5 Water balance components in different land use types

Understanding the behaviour of hydrological components and water balance in sub basin dominated by tea plantation, forest and mixed farming is important. However, limited studies have been undertaken to estimate hydrologic water balance components in sub basins dominated by tea plantation at the global scale despite tea plants replacing indigenous land covers in highlands within the tropics. Hence there is need to investigate the effects of tea plantation on the components of hydrologic cycle. Conversion of the land cover in sub basin dominated by forest land cover was predicted to increase surface runoffs and reduce base flow (Alibuyog *et al*., 2009). In Benin Owena River Basin effects of catchment degradation on surface flow and base flow was assessed. The results showed that deforestation increases surface run offs approximately 17% though base flow, evaporation and transpiration decreased by around 20%. Therefore, forest cover management helps in regulation of the water resources in the Basin (Aladejana *et al*., 2018; Abera *et al*., 2019). Changes in land cover have been affecting pattern of water resources availability (Hernandes *et al*., 2018). Forest land cover was investigated and reported that forests increase base flow, evaporation, transpiration, percolation and reduces surface runoffs (Chauhan *et al*., 2020). In southern Brazil, it was identified that during rainfall periods evaporation and transpiration counts for about 90% of the received rainfall. On contrary in dry periods showed that evaporation and transpiration reduced to about 60% of the amount of rainfall received (Jerszurki *et al*., 2018).

Evaporation and transpiration are components of hydrologic cycle which depend on land cover changes and affect water resources availability at the catchment area. It was realized that increase in vegetative land cover increases evaporation and transpiration. But conversions of land covers over time affect evaporation, transpiration, base flows and surface runoffs (Tamm *et al*., 2018). Annual stream flows increased with expansion of the land under mixed farming especially during wet seasons. On the other hand, dry periods exposed that stream flows reduced by almost 1.2% while evaporation and transpiration was reduced by about 0.1%. Groundwater and percolation were reported to decline by about 8%. Also, lateral flows reduced during dry periods by almost 4% (Chauhan *et al*., 2020). From the analysis it was concluded that crops with high water consumption and loss through transpiration are not suitable for the upstream catchment area in that it reduces flows affecting downstream water users and ecosystem (Chen *et al*., 2019). Also, it was agreed that changes in land use affect negatively availability of water resources (Ponpang-Nga and Techamahasaranont., 2016).

Forest land cover is significant in regulating hydrological components. A study conducted in Awash Sub basin revealed that forest land cover enhanced groundwater potential (Shawul *et al*., 2019). However, changes in the land cover bring a shift in the hydrological components. A study conducted in Tanzania highlands revealed human activities which transformed the river basin cover affects severely hydrological components (Näschen *et al*., 2018). The Landsat images from 1970 to 2014 shown that groundwater fluxes were influenced by the reduction of the forest land cover (Näschen *et al*., 2018). The decrease in the rainfall received due to the localized weather conditions affected by changes in the land cover patterns over time step impacts negatively on the linked hydrological components (Badjana *et al*., 2017). A study conducted in White Volta River Basin indicated that transformation of the land cover influences surface runoffs, base flows, surface evaporation, transpiration and infiltration (Awotwi *et al*., 2014).

Assessment of hydrological components in sub basin dominated by mixed farming land cover was conducted using data from 2015 to 2017 in Ethiopian Rift Valley. The findings revealed that surface runoffs respond positively to the expansion of mixed farming land cover. During wet periods the surface runoffs increased contributing to rise in stream water levels by 40%. On the other hand, mixed farming land cover exposes surface water to evaporation. Mixed farming land cover was assessed from 1987 – 2017 in Upper Baro River Basin in Ethiopia showed an increase in surface runoffs by 43 mm, reduces base flow by 27 mm and lateral flows by 5 mm. Hence catchment conservation is key in order to restore initial state of hydrological components (Engida *et al*., 2021). Also, seasonal crops result in transpiration. The estimated amount of water loss through evaporation and transpiration counted for almost 70% of the rainfall received. Infiltration reduced in mixed farming by almost 15% compared forested land (Meaza *et al*., 2019). Mixed farming land cover was stated to interfere with infiltration hence reducing subsurface flows and groundwater flows (Shawul *et al*., 2019). Mixed farming land cover was assessed from 1987 – 2017 in Upper Baro River Basin in Ethiopia and it showed an increase in surface runoffs by 43 mm, reduced base flow by 27 mm and lateral flows by 5 mm. Therefore, catchment conservation is key in order to restore initial state of hydrological components (Engida *et al*., 2021).

In a study done in the upstream of Athi River showed that forest cover generates fewer surface runoffs of about 10%. Hence, 75% of rainfall received in the sub basin goes to the evaporation and transpiration. In a forested areas in the river basin, it was noted that evaporation and transpiration were the water main output processes (Mathenge *et al*., 2020). Reduction of forest cover into crop fields and grassland increases surface runoffs by about 10% and 60% respectively (Notter *et al*., 2007). In Nyando assessing the effect of land cover changes on water resources. It was found that catchment degradation has led to conversion of forest cover into agricultural and urban centres. This land use changes have led to increase in surface runoffs and reduces evaporation and transpiration (Opere and Okello, 2011). A study conducted in the upstream sub basins of Lake Nakuru revealed that forest cover generates surface runoffs consisting about 18% while evaporation and transpiration was approximately 74% (Kimaru *et al*., 2019). In study conducted in Naivasha Kenya, the results obtained led to similar conclusions drawn from study done in Heihe River Basin. In Naivasha it was seen that conversion from forest land to mixed farming increases evapotranspiration by approximately 12% during crop growing season (Odongo *et al*., 2019).

Study conducted in Mara River Basin revealed that forest land cover reduces stream flow peaks (Mango *et al*., 2011). Conversions of forest cover into crop fields and grassland increases surface runoffs by about 10% and 60% respectively (Notter *et al*., 2007). In Nyando River Basin assessing the effects of land cover changes on water resources conducted showed that decline in the forest cover led to increase in surface runoffs and reduces evaporation and transpiration (Opere and Okello, 2011). A study conducted in the neighbouring Mara River Basin showed that mixed farming land use and land cover increases trends of surface runoffs (Mango *et al*. 2011). In Sondu Miriu River Basin effects of sub basin dominated by mixed farming on the local hydrological components have not been investigated. Tea plantation is one of the key cash crops embraced in the highland areas. The impacts of continuous expansion of tea plantations on hydrology of the region have not been clearly understood. Tea plantation in Kenyan sub basins has been expanding in coverage due to the need to boost economic development by the communities and companies in the sub basins (Nyangaga, 2008; Mango *et al*., 2011). The tea plantation has replaced the natural forests and this study enables understanding of the behaviour of hydrological components to the change of land cover in sub basin dominated by tea plantation.

2.6 Relationship between stream flows and sediment yields

The knowledge on the relationship between stream flow and sediment yield in the sub basin dominated by tea plantation is limited in the tropics. This shows that there is need to conduct a study to understand the relationship. A study conducted in the upper reaches of the Yellow River revealed that the relationship between the stream flows and suspended sediments was not simultaneous and displayed clockwise and counter clockwise loops and polynomial patterns curves (Fan *et al*., 2013). Most studies have been conducted to determine relation between the stream flows and sediment yield without considering dominant land use and land cover. For example, many studies have established relationship between stream flow and sediment yields without considering the land use and land cover (Gao and Josefson, 2012; Mouri *et al*., 2014; Zheng *et al*., 2019).

A study conducted in Ceyhan sub basin determines relationship in sections of the stream reaches. It was noted that in the sub basin dominated by the mixed farming, the relationship between stream flows and sediment yields was positive ranging from 40% to 90%. The increase in the stream flows and sediment yields apart from land use and land cover was attributed to the size of the catchment (Yüce *et al*., 2018). The knowledge on the relationship between stream flows and sediment yields especially within the sub basins in the tropics dominated by the mixed farming land cover and land use. Assessment of the relationship between stream flows and sediment yields in the sub basin dominated by the tea plantation is scarce in the region. Hence there is need to conduct a study to expose the relationship between stream flows and sediment yields especially in the sub basin dominated by the tea plantation. Little knowledge is known on the relationship between stream flows and sediment yields in the sub basin dominated by forest land cover in the region. Clockwise hysteresis pattern was observed in the Congo River Basin when relationship between sediment discharge and stream flow was assessed (Coynel *et al.*, 2005). Hence there is need to study the relationship that exists between stream flows and sediment in the sub basin with forest being the dominant land use and land cover. Strong positive relationship was established between stream flows and sediment yields were observed in Munyazi sub basin, South Rwanda during low flow periods of up to 93%. However, negative relationship was found during high flows season. The negative relationship during rainy season was reported to be due to field crops which were on the farms which could have reduced the sediment transport into the river system (Uwimana *et al.*, 2018). Also, little is known in the relationship pattern between stream flows and sediment yields in the sub basins within the tropics in the region.

The significant positive relationship between sediment yields and stream flow in the sub basin dominated by the mixed farming land use and land cover was reported (Njogu *et al.*, 2018). The sediment concentrations increase with stream flow reaching the peak at the onset of the rainy periods giving a positive relationship. The sediment concentrations started declining at the mid wet season and showed low concentrations at the end of the wet season while the stream flows observed was at the peak. This revealed that in Lower Tana River Basin the relation between sediment yields and stream flow is complex (Geeraert *et al.*, 2015). Similarly, in Njoro River Basin positive relationship between sediment transport and stream flow was observed (Baker and Miller, 2013). Understanding the relationship between stream flows and sediment yields in the sub basins dominated by the tea plantation, mixed farming and forest cover is limited in the Sondu Miriu River Basin and the neighbouring sub basins. Hence there is need to assess and identify the relationship between stream flows and sediment yields in the sub basin dominated by tea plantation in the river basin. A study conducted in the Sondu Miriu River Basin in Kabianga field experiment dominated by mixed farming revealed the positive relationship between the run offs and sediment yields (Ouma *et al.*, 2013). This study compared sediment generation in the three sub basins with dominant land uses and land covers. This also identified hotspots areas in the entire river basin that was not considered in the previous studies.

2.7 Suitable land use and land cover types and catchment management practices

Investigating suitable land use and best catchment management practices in the sub basin dominated by tea plantation is scarce. This indicates that there is need to identify suitable land use and land cover change in the sub basin. Further the identification of appropriate catchment management practices to reduce surface runoffs and sediment flux in the sub basin should be conducted. Forest land cover has been identified in previous studies as suitable land cover to reduce sediment flux in scenario analysis (Coulston *et al*., 2014; Kulsoontornrat and Suwit., 2021). However, it was done in the temperate zone and might not reflect the scenarios in the tropical zone. The studies on suitable land use and land cover and appropriate catchment management practices in the tropical sub basins dominated by forest land cover are limited.

Catchment degradation has been experienced in various river basins in the world and the Best Management Practices (BMPs) have been implemented to restore water quantity and quality in the sub basins dominated by mixed farming (Qiu *et al*., 2018). In Kwan Phayao sub basin, it was reported that forest land cover was suitable land use to reduce flow of sediment loads into the stream networks (Kulsoontornrat and Suwit., 2021). In catchment areas with sediment discharge due to intense agricultural practices, terraces were stated as the BMP to reduce flow of sediments into the river systems. In Brazil BMPs scenarios were conducted using the SWAT model and it was realized that terraces reduce sediment loads by 40% (Strauch *et al*., 2013). Similarly, it was revealed that in steep slope landscape terraces is the best approach of reducing sediment and nutrient flows in the catchment. Strehmel *et al*. (2016) assessed the catchment management practices of controlling turbidity of the Three Gorges reservoir in China. The cause of turbidity was due to sediment inflow from the degraded catchment in the Three Gorges region. After scenario development, it was concluded that the surface run off rate could be reduced in the region by constructing terraces. The Haean highland, scenarios analysis was conducted to test effectiveness of vegetation filter strip, control of fertilizer inputs and mulching in reduction of sediments and surface run offs. It was concluded that the best alternative is use of vegetation strip that reduces about 16% sediment flow for 1m strip (Jang *et al*., 2017). Also, contour ridges and buffer strips at the Joumine catchment area were reported as effective in reduction of soil erosion (Mtibaa *et al*., 2018).

Tropical sub basins dominated by tea plantation have limited studies on suitable land uses and land covers which can minimize sediment flux and ensure sustainable stream flows. This calls for more studies to identify suitable land cover and appropriate catchment management practices which reduces flow of sediments in the sub basins dominated by tea plantation. Studies which determine appropriate of the land cover and land use types to be practiced in the sub basins dominated by the forest cover within the tropics in the region are scarce. Therefore, there is need to conduct further studies not only on the deforested sub basins but also to the forest dominated sub basins. Also, information on the appropriate catchment management practices in the forest dominated sub basins needs to be identified.

Mediterranean Sea is at the threat of eutrophication because of sediments from the sub basins. It was revealed that use of water retention structures and irrigation channels help to reduce flow of nutrients into the sea by more than 50% (Romero *et al*., 2016). Likewise, Lake Victoria is currently suffering from intense growth of hyacinth due to inflow of sediments transporting nutrients from the sub basins dominated by mixed farming of the Lake Basin. In Simiyu sub basin it was indicated that degraded areas could be restored by implementing the appropriate catchment management practices (Kimwaga *et al*., 2012).

Tea plantation in Kenya is established mostly bordering the forest land covers. However, it differs with the forest land cover in the canopy density and tree heights. This indicates that the forest land cover might not have similar catchment management characteristics with the tea plantation. Therefore, there is need to understand the suitable land use and land cover in the sub basin dominated by tea plantation. Apparently, limited information exists on the sub basins dominated by tea plantation. At the same time studies on catchment management practices which are appropriate to reduce sediment flux in the sub basin dominated by tea plantation is scarce. Studies conducted in the sub basin dominated by forest land cover concerns deforestation as the cause of sediment generation. However, they have not revealed the suitable land use and land cover to be implemented in the sub basins (Ayuyo and Sweta., 2014; Eckert *et al*., 2017). Hence, studies on suitable land use and land cover and appropriate catchment management practices in the sub basins dominated by forest land cover needs to be done. Investigations in Kenya found out that the extent of catchment land degradation has increased over time due to human pressures, soil type, slope stability and hydrological processes were reported to be the cause of sediment flux into the water bodies. Mixed farming covering approximately 70% of the sub basin area has replaced the initial forested areas. Therefore, it was recommended that an integrated management approach method could be applied to reduce sediment generation (Waswa *et al*., 2013). In Thika-Chania sub basins, Gathagu *et al*. (2017) conducted scenario analysis to determine the suitable land cover and structural measures to mitigate sediment transport and reduce surface run offs. The results of the study revealed that forest land cover, terraces and grass waterways were the best structures to reduce sediment transport. Terraces reduced sediment flows and surface run offs at sub basins by 81 % and 30 % respectively. The terraces were reported to be enhanced infiltration and increases base flow by 8%. In addition, grass waterways reduced sediment flows by 54%.

Studies on the suitable land use and best catchment management practices in the sub basin dominated by tea plantation in the Sondu Miriu and its neighbouring sub basins are rare. Therefore, there is need to identify suitable land use and land cover change for the sub basins dominated by tea plantation. Moreover, appropriate catchment management practices to reduce sediment flux in the sub basin should be executed. The upstream sub basins in the Sondu Miriu and its neighbouring sub basins are partially dominated by the forest land cover. However, minimal investigations have been conducted to identify suitable land use and land cover and appropriate catchment management practices in the tropical sub basins dominated by forest land cover. This gap was attempted to be filled in this study. The study conducted in the Sondu Miriu assessment noted that the suspended sediments at the downstream noted that high sediment yields observed was due to reduction in the forest land cover upstream. Also, it was recommended that forest land cover was the suitable land cover that reduces sediment transport (Njue *et al*., 2021). Further, it was reported that sub basins dominated by mixed farming generated high sediment loads which affects wetland ecosystem downstream. In order to reduce sediment flux in the Sondu Miriu River Basin and its neighbouring sub basins, it was recommended further studies be conducted to identify suitable land use and land cover and appropriate catchment management practices to be applied in the affected sub basins (Okeyo-Owour *et al*., 2012).

2.8 Identified research gaps

The literature review done revealed existing gaps in knowledge within the tropical river basins especially in Africa. The identified gaps are inadequate information and data on the hydrologic responses of specific land use types especially the influence of the sub basins dominated by tea plantations, forests and mixed farming land covers and land uses. The changes in the land use and cover patterns in the sub basins dominated by tea plantation, forest and mixed farming in decadal scales has not been identified in most sub basins. The past and future response of stream flows and sediment flux in sub basin dominated by tea plantation, forest and mixed farming land cover is limited in the Sondu Miriu River Basin. Further it was noted that knowledge on the influence of change in the land use and land cover on the local hydrologic and water balance components over time step in sub basins dominated by tea plantation, forest and mixed farming land cover and land uses is scarce. Also, little is known on the relationship between the stream flows and sediment yields in the sub basin dominated by tea plantation, forest and mixed farming land cover and land uses. The information on the suitable land cover and uses with minimal sediment discharge and ensure sustainable stream flows on the sub basins dominated by the tea plantation, forest and mixed farming land cover and land uses is limited.

2.9 Conceptual framework

The conceptual framework presented in Figure 2.1 illustrates interrelation between independent and dependent variables in this study. The dominant land covers and population are independent variables while hydrological components are dependent variables.

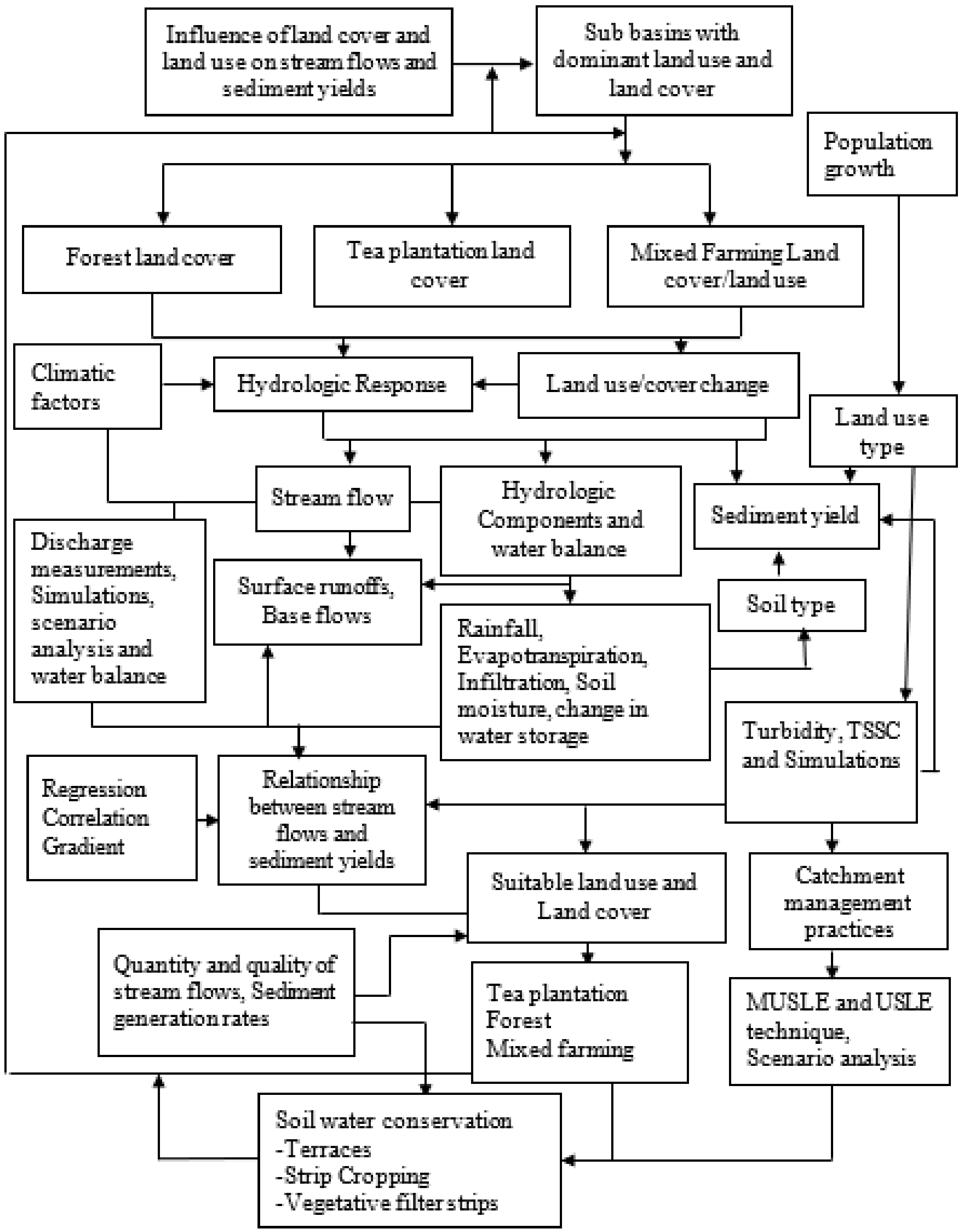


Figure 2.1: Conceptual Framework of this study (Source: Koech, 2021)

CHAPTER THREE

3.0 METHODOLOGY

3.1 Introduction

This chapter provides details on the methodology that was applied in the study. The chapter also provides a description of the study area. The chapter was prepared using data and information obtained from various institutions in Kenya. This study applied standard research methods in the determination of hydrological response of sub basins dominated by mixed arable farms, forests and tea plantations. Both qualitative and quantitative methods of data collection and analyses were applied.

3.2 Description of the study area

3.2.1 Location of Sondu Miriu River Basin

The Sondu Miriu River Basin is located in western region of Kenya (Figure 3.1). Its headwaters are situated in Nakuru and Kericho Counties. The basin is situated within the latitude $0^{o}17'$ and $0^{o}53'$ South and longitude $34^{o}45'$ and $35^{o}45'$ East. It covers a surface area of about 3,470 Km^2 with an altitude ranging from 3000 m above sea level at the Mau Complex to about 1100 m above sea level at the downstream near Lake Victoria (Masese et al., 2012). The basin supports livelihoods in Nakuru, Kericho, Nyamira and Kisumu counties.

3.2.2 Land Cover and Land Use

The Sondu Miriu River Basin is characterized by presence of various land covers and land uses. The main land covers in the basin are natural forest, man-made forest, woodlands, scrubs, rocky/bareland, grassland, tea plantation, sugarcane, subsistence farming (maize, potatoes, vegetables, beans etc), water, sugarcane and settlements as depicted in Figure 3.2. Prior to human interference within the Mau complex natural canopy cover, the total area under forest was approximately 420, 000 hectares (Kroese et al., 2020). The reduction in forest cover has been attributed to encroachment by settlers and farmers (Masese *et al.*, 2012; Nyolei, 2012). The forest cover is the leading land cover in the basin covering a surface area of about 934 km^2. The forests cover approximately 26.7% of the total basin area. The second largest land cover is tea plantations covering an area of 898 km^2 which is approximately 25% of the total basin area. Settlement and sugarcane plantations cover an estimated area of 785 km^2 and 402 km^2, respectively. However in this study land uses and land covers were further clustered into three major groups. These land covers and land uses are tea plantation in Timbilil Sub basin, forest in Kiptiget Sub basin and mixed farming in Kipsonoi Sub basin (see Figure 3.1).

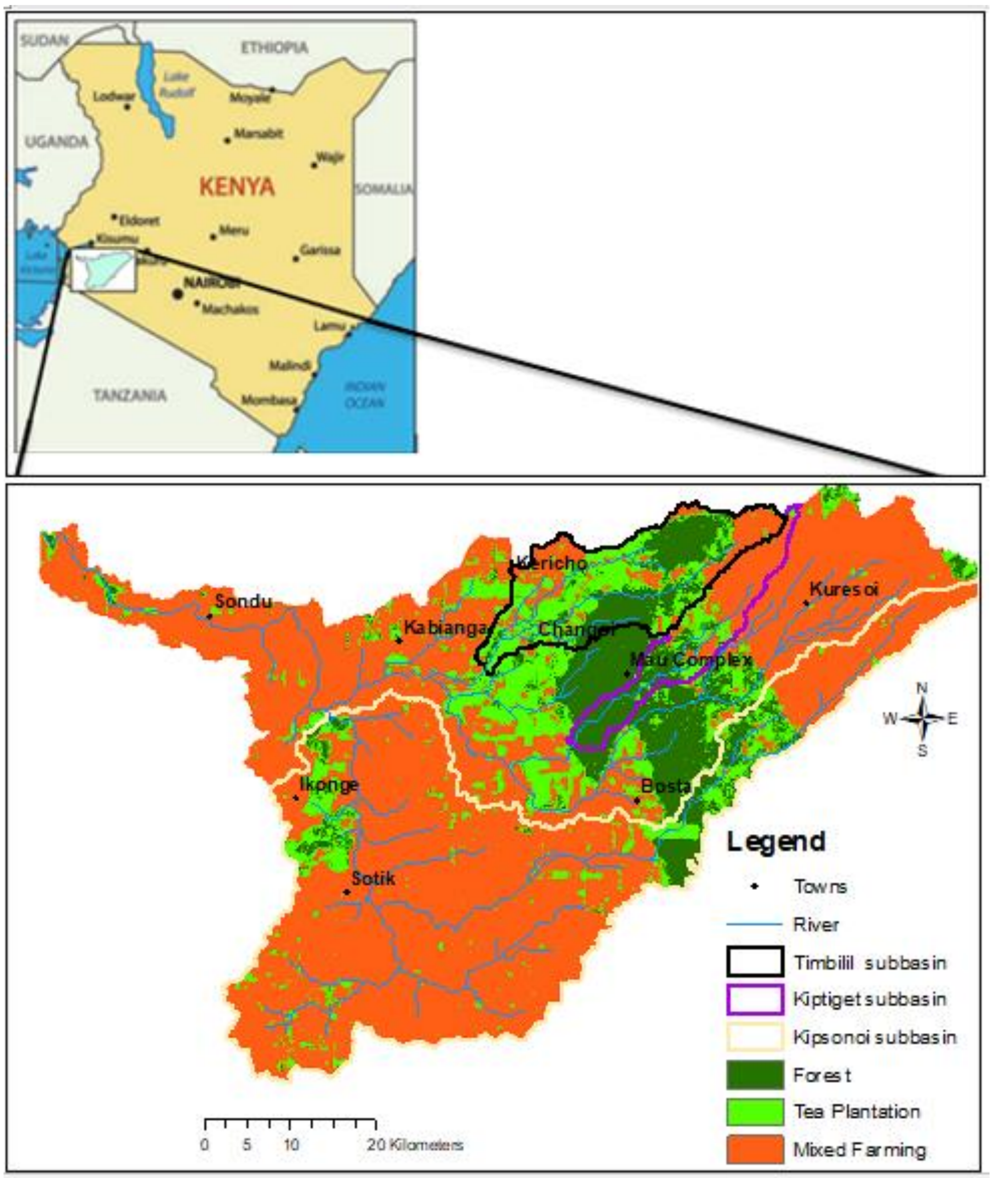


Figure 3.1: The location of Sondu Miriu River Basin in Kenya (Source: Koech, 2021)

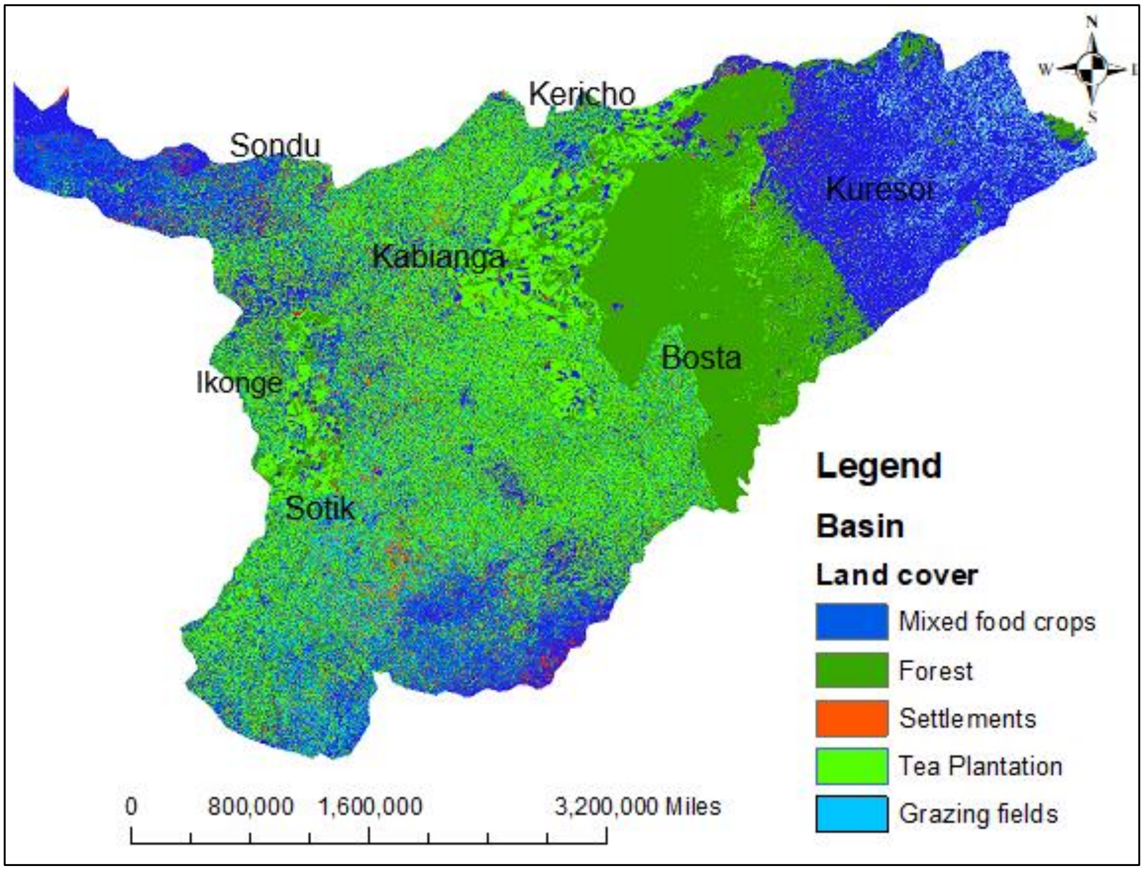


Figure 3.2: Land uses and land covers in the Sondu Miriu River Basin (Source: Koech, 2021)

3.2.3 Climate

The climate of the Sondu Miriu River Basin is influenced by movement of the intertropical convergence zone (ITCZ) leading to bimodal rainfall within a given year. The river basin is characterized by humid and semi humid climatic zones with significant variations in temperature and rainfall. The long rains occurs in the periods between April and July and short rains occurs in the period between October and December (Weeser *et al*., 2018). In the upper region of the river basin, the mean annual rainfall is high as compared to the lower parts of the basin. The upland zones receives mean annual rainfall of approximately 1,800 mm per annum while lowland zones receives about 1,500mm per annum. The temperatures at the upland zones are low with an average of about 16˚C in the periods between June and July. Temperatures are highest about 24˚C in the lowland zones of the basin near Lake Victoria in the period between January and March (Weeser *et al*., 2018: Ochieng *et al*., 2019). The mean monthly rainfall intensity in the basin is about 20 mm/month during dry periods and in wet seasons is about 180 mm/month. The mean annual rainfall ranges from 1140 mm/a to 1800mm/a. The upland zone receives more rainfall than the lowland zone bordering Lake Victoria. Increase of rainfall in wet seasons increases surface run offs and fluvial flooding downstream. The potential evaporation in the lower parts of the basin is 1800 mm/a while at the upland zone is approximately 1400 mm/a (Masese *et al*., 2012; Weeser *et al*., 2018). The relative humidity is about 62% for most days of the year. Climate change based on historical data 1970-2000 shown an incresing trends (Ototo et al., 2022). For example the analysis conducted in Sondu Miriu River Basin showed that temperatures long and short rainy seasons will increased by about 2^{o}C and 3^{o}C respectively under Representative Concentration Pathways 4.5. General Circulation models showed that future rainfall trends will increase especially in long rainy season by about 50 mm and by about 35 mm in short rainy season. The annual rainfall trends showed increased of approximately 18 mm (Ochieng et al., 2021).

3.2.4 Hydrology, Hydrogeology and Drainage

The drainage of the Sondu Miriu River Basin is characterized by dendritic pattern in which tributaries and stream join the river system at an angle of less than 90^{o} (Weeser et al., 2018). The stream and tributaries originates from the springs located in the Mau Forest in Kuresoi and Keringet areas. There are two main tributaries in the upper zone of the basin namely Kipsonoi and Yurith (see Figure 3.3). The Kipsonoi tributary has its headwaters in Keringet areas of Kuresoi in Nakuru County. The tributary traverses Bomet County, Nyamira County and Homabay County. The Yurith tributary comprises Timbilil, Kiptiget and Itare-Chemosit sub tributaries. The Timbilil sub tributary originates from Kuresoi and Mau forest in Kericho County and flows through Unilever Tea zone, Kericho town and Kabianga area. The Kiptiget and Itare-Chemosit sub tributaries originates from Kuresoi and Mau forest in Nakuru County and flows through Konoin Chebangang area in Bomet County. The three tributaries converge at Kabianga tea estate to form Yurith tributary. The Kipsonoi and Yurith tributaries converge at Ikonge tea plantation. The total length of the

Sondu Miriu River is approximately 190 km from its head to the shores of the Lake Victoria. In this study the Timbilil, Kiptiget and Kipsonoi sub basins as shown in Figure 3.3 were considered due to dominant land uses and land covers.

The drainage basin shown in Figure 3.4 enables classification of the stream network into five categories. The stream network in Timbilil has the first and second stream order at the upper region while the lower region of the sub basin has stream order three. The Kiptiget sub basin is characterized by the stream order one and two. Similarly upper part of Kipsonoi sub basin is characterized by stream order one and two. The middle and lower part of the sub basin is characterized by stream order number one to four. The overall stream network of the Sondu Miriu River Basin is categorized into three ones. The upper zone is classified as first, second and third order streams, the middle zone is characterized by stream order one to four and the lower part at the downstream is categorized as stream order five. The mean river discharges is 44.9 m^3/s at the river gauging station 1JG 05 downstream of Sondu bridge (Nyolei, 2012). In 2021, the mean river discharges increased to about 57 m^3/s.

The hydrogeology of the study area depends on the geological formation. The upstream part of the river basin is characterized by phonolites. The groundwater yield in the primary porosity of the phonolites is generally low, water occurs in fissures and other forms of secondary pore space, such as embedded weathered horizons (Mwamburi, 2016). These phonolites with fissures conveys groundwater water movement leading to formation of springs at the upstream areas. Faults near Sondu town were described to be permeable and allow percolation of surface water into shallow and deep aquifers in the area. At Kendu fault outcrops facilitate movement of surface water into the groundwater aquifers (Katsurada et al., 2007). A study conducted in neighbouring river basin Nyando showed that fractured tertiary phonolities at the upstream sub baasins bordering Timbilil Sub basin allows infiltration of surface water into the sub surface and flows along cracks at the joints of the underlying granite rocks towards the downstream and Lake Victoria (Karicho, 2010). This was suspected as the case of groundwater water movement in Sondu Miriu River

Basin since geological characteristsics in the neighbouring river basins are comparable (Geology of Kericho, 1962).

3.2.5 Topography and ecosystem

Sondu River Basin comprises of uplands at the upper catchments and low lands towards the shores of Lake Victoria. Mau Escarpment that occurred due to formation of the rift valley characterizes the upstream part of the basin. The maximum altitude of the river basin is about 3000 m above sea level. The lowest elevation in the downstream zone of the basin is about 1100 m above sea level (Ochieng *et al*., 2019). The steep slope terrains contribute to the increased velocity of the surface run off especially in areas with limited vegetation cover. At the middle zone of the basin, the slope ranges from gentle to flat as it approaches shores of the Lake Victoria.

Sondu Miriu Basin is characterized by reduced land cover, increased sediment and nutrient loadings (Kimwaga *et al*., 2012). Sediments transported in suspension, saltation and dragging cause changes on the river beds and bank. Soil erosion has caused changes in the river beds and banks especially at the downstream (Ochieng *et al*., 2019). The aquatic ecosystem phytoplankton and zooplankton in the river basin and the lake depends on the status of the catchment area and inflow into the river system. Alterations of the land cover affects phytoplankton and zooplankton in the river and the lake (Masese *et al*., 2014). Low flows period reduces supply of nutrients into the river system for the growth of aquatic plants and reduces population of aquatic life (Masese *et al*., 2012). During high flow and peak season nutrients from the catchment areas are transported by floods into the lake increasing bloom of eutrophication such as hyacinth (Masese *et al*., 2014). Consequently, the problem of water hyacinth, deterioration of water quality and massive fish killing may continue to be threat to the health of the Lake ecosystem. In addition, low flows cause shrinkage of lower Sondu Miriu wetland downstream and negatively affects wetland aquatic ecosystem (Gichuki et al., 2001).

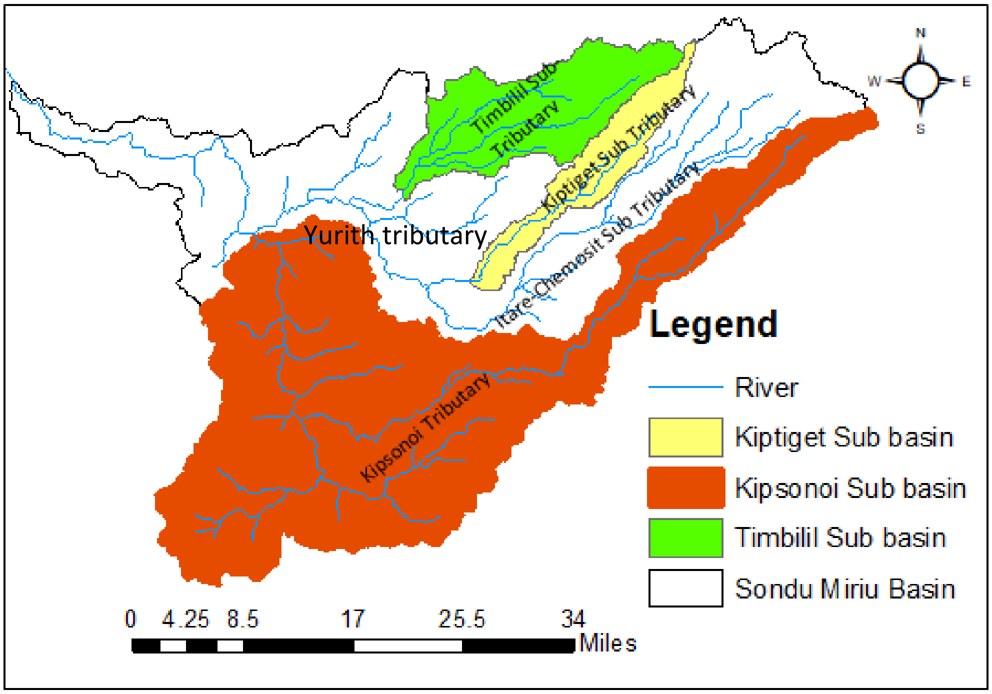


Figure 3.3: The drainage of three sub basins found in the Sondu Miriu Basin (Source: Koech, 2021)

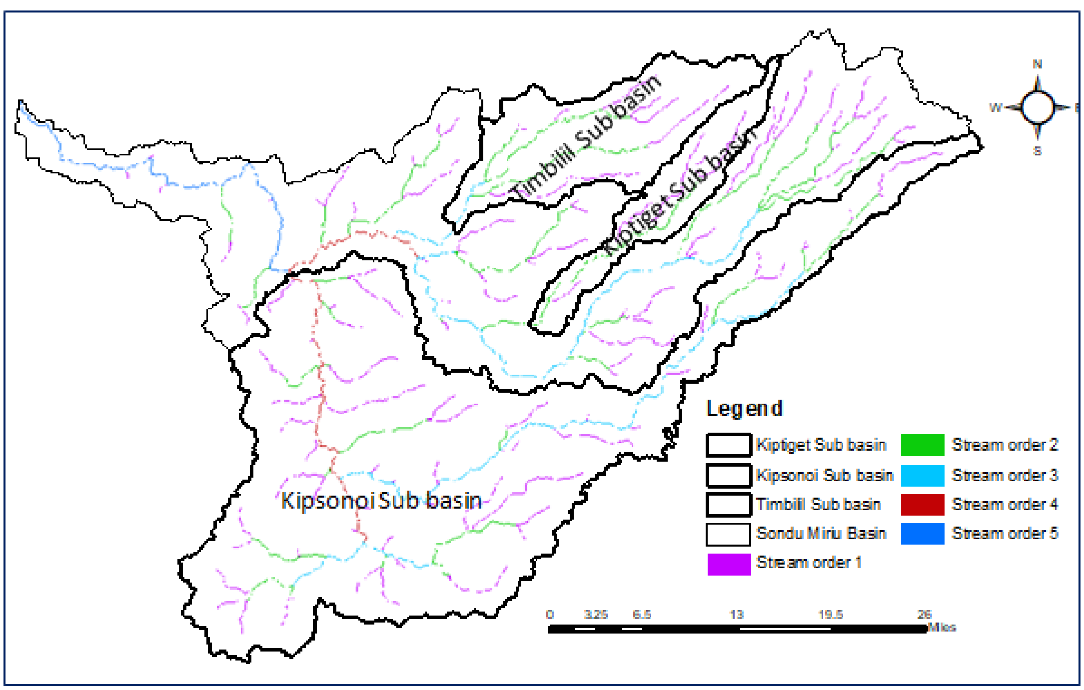


Figure 3.4: Stream order in the sub basins of the Sondu Miriu River Basin (Source: Koech, 2021)

3.2.6 Geology

The geology of the Sondu Miriu River Basin is characterized by volcanic rocks, sedimentary rocks, the Kisii series upper precambrian and Bukoban system such as andesites, rhyolites, basalt and alluvium (Binge, 1962; Opiyo-Aketch *et al*., 2013). The age of rocks in the study area can be traced to Miocene era about 600 million years (Binge, 1962). The volcanic rocks in the study area are mainly phonolites, trachites and tuffs.In the upstream area of Kericho granitoid gneisses of basement complex system are exposed. In Miriu valley, a fault occurred in the Nyanzian and Bukobian rocks (Opiyo-Aketch *et al*., 2013).

The Timbilil, Kiptiget and Kipsonoi sub basins dominated by tea plantation, forest and mixed farming land covers respectively are characterized by Nyanzian system that is folded and has sheared rhyolites with banded ironstones (Schoeman, 1949; Geology of Kericho, 1962; Mwamburi, 2016). The Kericho phonolites has extended in the three sub basins due to lava flow towards Sondu (Ombogo, 2016). Small faults occured in the deep eroded areas of Sondu town and upstream (Harker, 1950). The Bukoban quartzites in the Kipsonoi sub basin are underlain by Bukoban basalts (Opiyo-Aketch *et al.*, 2013). In the downstream areas, erosion has led to the formation 400 feet deep gorges. Massive rhyolites rocks are exposed at Kapruben falls (Pinna *et al*., 2000). The metamorphosized sedimentary rocks are found in areas of Koywalelach. Rhyolites situated in The Kapruben, Kamaget and Chemamul all near Kabianga area (Saggerson, 1952; Pinna *et al*., 2000). The Bukoban basalt underlying quartzites are found in Chepkongo and Marumbasi ridges. The porphyritic felsites overlies basalts and tertiary phonolite at North Sekauani in Kipmulgelwo gorge. In a stretch between Chelemei and Marumbasi coarse grained ophitic are found (Huddleston, 1951; Pinna *et al*., 2000).The Sondu granodiorite (a coarse-grained plutonic rock containing quartz and plagioclase, between granite and diorite in composition) outcrops occured in the Kendu fault. The highly sheared but non-foliated protrusion occured in the Jimo areas (Opiyo-Aketch *et al*., 2013; Ombogo, 2016).

3.2.7 Soils

The main soil type found in sub basins of the Sondu Miriu River Basin are nitisols, andosols, lithosols, greyzems, cambisols, arenosols, phaeozems, planosols, rankers, regosols,vertisols, xerosols and luvisols (Mungai *et al*., 2011). At the upland zone of the basin, phaeozems dominates the sub basins dominated by tea plantation, forest and mixed farming land covers and land uses. The Phaeozems are deep, dark-redish to brown colour soils having clay and thus are able to retain moisture for longer period after the rains (O'Geen and Schwank, 2005) . Also due to high organic matter in the Mau forest, the soils are fertile and attracts agricultural activities. The middle zone of the sub basins dominated by tea plantation, forest and mixed farming land covers and land uses are characterized mainly by nitisols and vertisols soils (Nyaganga, 2008). Other soils in the middle zone of sub basin dominated by mixed farming are Acrisol and Xerosol that are humic and supports forests. In the downstream zone after confluence of Yurith and Kipsonoi tributaries, Regosol soils dominates the area of Sondu and Miriu in Kisumu and Homabay Counties (Nyaganga, 2008). Regosol is weak structured soil type that is easily eroded when they are not covered. High erosion rates in this soils are evidenced by rills and gullies in grazing lands found in Kisumu County (Mungai *et al*., 2011).

Soil texture in the river basin shows that loam soils dominates in the covering 91.1% of the basin area (see Figure 3.5). At the upstream zone north west of Kuresoi (Timbilil and Kiptiget sub basins) clay loam soils covers 0.16% of the basin area. The southern part of the basin in Chebole (Kipsonoi sub basin), clay soils dominates the area covering 5.6% of the total basin area. In the downstream zone the sandy clay loam soils covers 3.2% of the total basin area. The weathered phonolites forms the loamy soils that occupies a larger area in the basin. These soils are favourable for tea plantation and other agricultural crops. The loam soils are easily erodible because of their low permeability but are poorly agreggated and are less resistant to flowing water (O'Geen and Schwank, 2005).

3.2.8 Population distribution

The population size in the Sondu Miriu Basin according to the 2019 national population census was estimated to be approximately 950,000 people. The population sizes in Kericho and Nakuru counties are 520,000 and 170,000 persons respectively. The population in Nyamira and Kisumu counties within the subbasin are 100,000 and 150,000 respectively. The population density in the basin is relatively 300 persons/km^2. The population growth rate based on 2019 data is 2.2% per annum (GoK, 2019). The middle zone of the river basin is densely populated due to gentle to flat terrain that is suitable for settlement, adequate rainfall, fertility of the soils and farming. Socio-economic development has also made upland zones especially those areas around Kericho town, Kuresoi and satelite centres like Chebang'ang and Sondu to be densely populated due to tea plantation, employement and trade opoortunities (Masese *et al*., 2012). Sparsely populated areas are found in the downstream zone towards Lake Victoria due to limited resources, low rainfall, poor soil fertility and challenges of frequent flooding in lowlying areas (Ochieng *et al*., 2019).

3.2.9 Socio-economic activities

The socio-economic activites in the Sondu Miriu River Basin varies from one sub basin to the other. In the upland zone, the main socio-economic activities are tea plantation and mixed farming especially in Kiptiget, Timbilil and Kipsonoi subbasins (Nyaganga *et al*, 2008). At the middle zone of the basin of the river basin, tea and sugar cane plantation are the main cash crops. Mixed farming is also practiced in the middle part of the basin especially in the Kipsonoi and Ainapkoi sub basins. Industrial activities are found in Kericho town and Kapsuser. Mining of rocks and soils in the basin takes place in Kebeneti and Chemamul areas near Sondu Market. In the lower zone of the basin, mixed farming, sugar cane plantation, small scale fishing and hydropower generation are key socio-economic activities. Small scale business enterprises in the basin are spread through the upstream and downstream areas of the basin (Ouma *et al*., 2012).

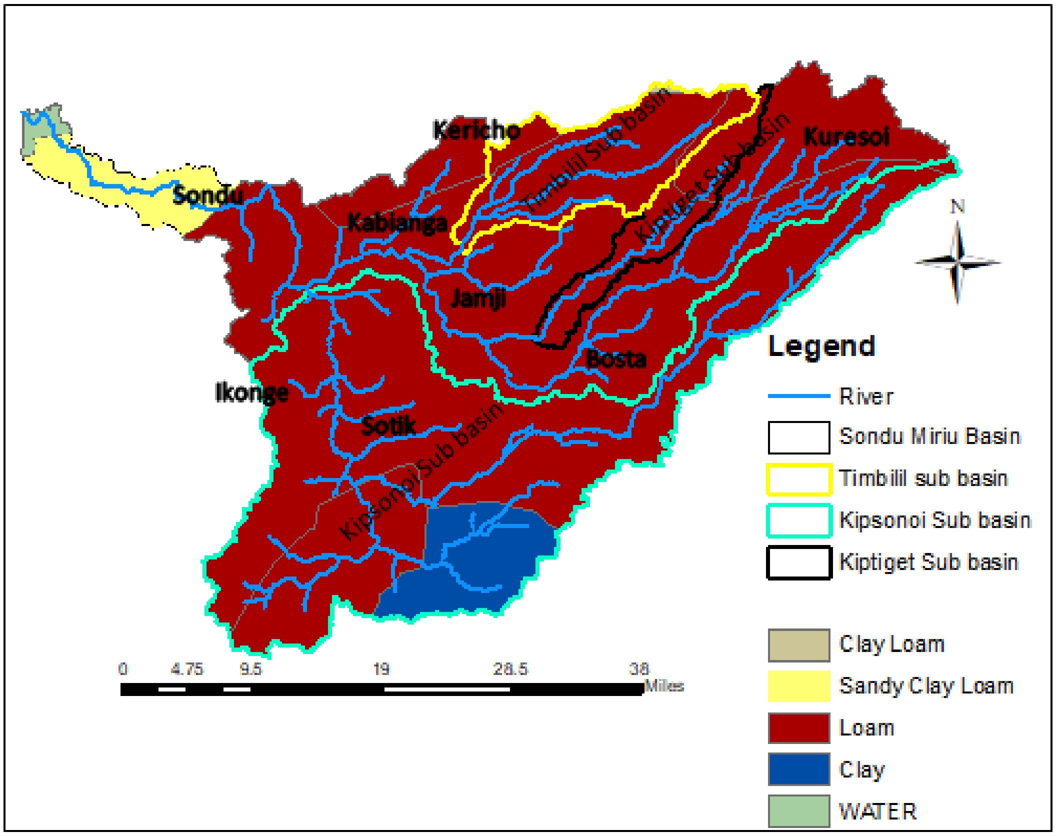


Figure 3.5: Soil texture distribution in the Sondu Miriu River Basin (Source: Koech, 2021)

3.3 Methods

3.3.1 Determine patterns of land cover in sub basins with dominant land use types

The land cover for the Sondu Miriu River Basin and its sub basins were determined from the year 1973 to 2021. This portrayed the changes in the land covers in the river basin in time series of about four and a half decades. This information was important for assessing the effects of land cover/land use change on the hydrological processes within the river basin. The data used and techniques applied are presented in the following sub sections.

3.3.1.1 Data Requirement

The data used to determine the change in land use and land cover patterns are spatial data derived from Landsat images especially from the Landsat thematic 4 -5 thematic mapper with bands 1 to 5 and 7. The Landsat thematic 4-5 imagery was obtained from wavelength ranging between 0.45 - 2.35 micrometres and with spatial resolution of 30 m. The Landsat data obtained from USGS database was analyzed from 1973 to 2021 and used to determine change in land cover in the sub basins at interval of 10 years.

3.3.1.2 Arc-GIS and remote sensing

The Landsat satellite images with 30 m spatial resolution were downloaded from USGS database. Similar spatial resolution was used in the previous study and strong relationship was established between the Landsat and ground truthing data (Ramsey *et al.*, 2004). The land use and land cover images with good visibility free from cloud cover and geometrically corrected for the month of January to December were used. Arc-GIS software was used to view the remote sensed data visually. The satellite Landsat images were verified with the historical maps, aerial photographs and field visits.

3.3.1.3 Analysis of land cover and land use data

The land cover classification was undertaken using ArcGIS 10.3 software (Esri, 2015). The cloud free Landsat imageries were used at interval of ten years. The ten-year temporal resolution was selected with assumption that significant changes in the land cover could be visible in a period of ten years and above. The location of the Sondu Miriu River Basin and sub basins with surface area determination of tea plantation, natural forest and mixed farming was conducted. Training samples in the uploaded Landsat imagery were created by drawing polygons. The created training samples were merged to develop a signature file. The maximum likelihood classification was used to define land covers using the signature file. Visual interpretation of sub basins tea plantation, natural forest and mixed farming was conducted per time step. The relationship between land cover and land use changes and population size was conducted using correlation analysis.

3.3.2 Effects of dominant land use types on stream flows and sediment fluxes

The Sondu Miriu River Basin has sub basins dominated by the tea plantation, forest and mixed farming land covers and land uses. It is thought that these influence the hydrologic response of the sub basins. The study therefore aimed at determining the influence of the sub basins with dominant land uses and land covers on the stream flows and sediment fluxes. The output information of this components of the study are important for decision and sustainable management of water resources in the basin.

3.3.2.1 Data Requirement

The data used in this study to achieve the stated objective are mainly primary and secondary spatial and temporal data. The detailed information on the data types and sources are presented in the following sub sections.

a) Primary data

The primary data used comprises of river discharges, Total Suspended Sediments Concentrations (TSSC), sediment loads and turbidity in the period. The temporal scale for these parameters was one year from July, 2020 to June, 2021. These data were obtained from the field and sub basins dominated by tea plantation (Timbilil Sub basin), sub basin dominated by forest (Kiptiget Sub basin) and sub basin dominated by mixed farming (Kipsonoi Sub basin). This data was used to determine sediment flux at the sub basins and stream flows in sub basins and river basin from July 2020 to June 2021. Also, this data was used to determine water quality in terms of turbidity and suspended sediments.

b) Secondary data

The secondary data used in this study consists of spatial surface areas information on the land use, land cover, land areas and topographic information in the sub basins dominated by tea plantation, forest and mixed farming land covers and land uses. The spatial land use and land cover data with a spatial resolution of 30 m was acquired from the United States Geological Survey (USGS) remote sensing database. The land surface areas slope and topography data of the sub basins dominated by tea plantation, forest and mixed farming was obtained from Shuttle Radar Topography Mission (SRTM) 30m spatial resolution Digital Elevation Model (DEM).

3.3.2.2 Location of the sampling stations

The sampling stations used in generation of primary data were mainly the installed River Gauging stations (RGS) located near the outlet of each sub basin. These stations were RGS 1JA02 located at -0.55480 S, 35.25844 E in the Kiptiget sub basin dominated by forest land cover, RGS 1JC02 located at -0.46250 S, 35.17917 E in the Timbilil sub basin dominated by tea plantation, RGS 1JF08 located at -0.51463 S, 35.08010 E in the Kipsonoi sub basin dominated by mixed farming and RGS 1JG05 located at -0.39664 S, 35.01698 E at the downstream of the Sondu Miriu River Basin (see Figure 3.6).

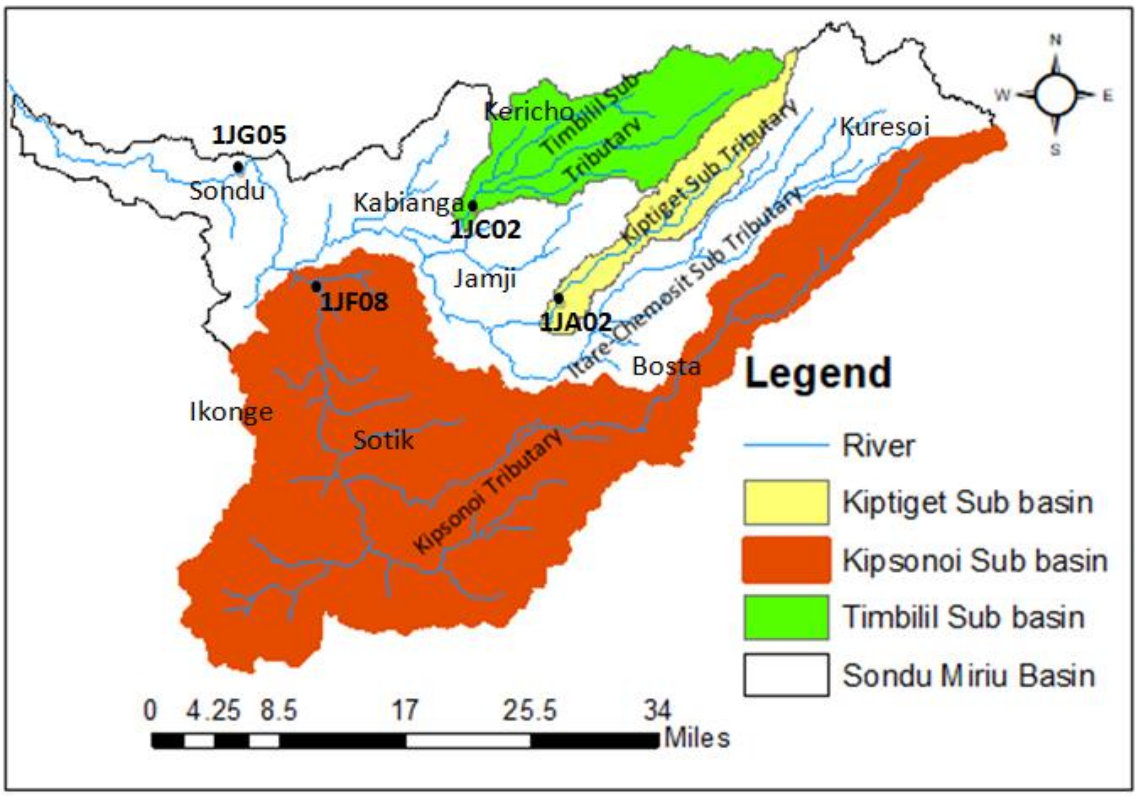


Figure 3.6: Location of sampling stations in the Sondu Miriu River Basin (Source: Koech, 2021)

3.3.2.3 Measurement of river discharges

a) Methods of river discharge measurement

River discharges were measured in the period between July 2020 and June 2021. River discharges were measured at the outlets of sub basins dominated by tea plantations, forests and mixed farming land cover and land uses at RGS 1JC02, JA02 and 1JF08 respectively. The hydrologic response of combined land covers and land uses were measured at the downstream at RGS 1JG05. The staff gauges were used to measure water levels while Acoustic Doppler Current Profiler (ADCP) device (Sontek ®Argonaut SW) and propeller current meter Seba model were used to measure flow velocities in the sub basins.

b) Procedure of river discharge measurement

i) Measurement of water levels

The staff gauges installed at RGS 1JC02 and RGS 1JA02 in Timbilil and Kiptiget sub basins dominated by tea plantation and forest land covers and land uses respectively were non-operational during the period of this study. Hence, this method was only used in the Kipsonoi sub basin dominated by mixed farming at RGS 1JF08 (see plate 3.1). In this method water levels were observed onsite and recorded. The river discharges corresponding to each water level was obtained using rating curve for the station RGS 1JF08 (see Figure 3.7).

ii) Measurements of flow velocities

The flow velocities were measured using Acoustic Doppler current profiler (ADCP) and Seba propeller current meter. The first step was the identification of the suitable site to the measurements. The straight reach of the stream, free from eddies, back flows and dead zone was selected for velocity measurements. At the selected site, width measurement was done from left bank to right bank of the stream as shown in Figure 3.8. The width was sub divided into sub sections which were used to measure vertical depths and velocities. The measurement of flow velocities and depths of the water were done in vertical of each sub section of the cross section as shown in Figure 3.9. The propeller current meter was placed in the vertical to measure velocities by counting revolutions of the propeller for a set duration. The ADCP was placed in water in each vertical (see Plate 3.2) to measure velocities by sending frequency into flowing and echo from the suspended particles in water returns to sensor giving flow velocity of the vertical (Perzyna, 2016). The velocities were measured in two-point depth of the vertical such as 20% and 80% from the water surface towards the stream bed. The average velocity and cross-sectional areas were computed and used to estimate the river discharges.

Plate 3.1: Staff gauges installed in Kipsonoi Sub basin RGS 1JF08 on 16/08/2020 (Source: Koech, 2021)

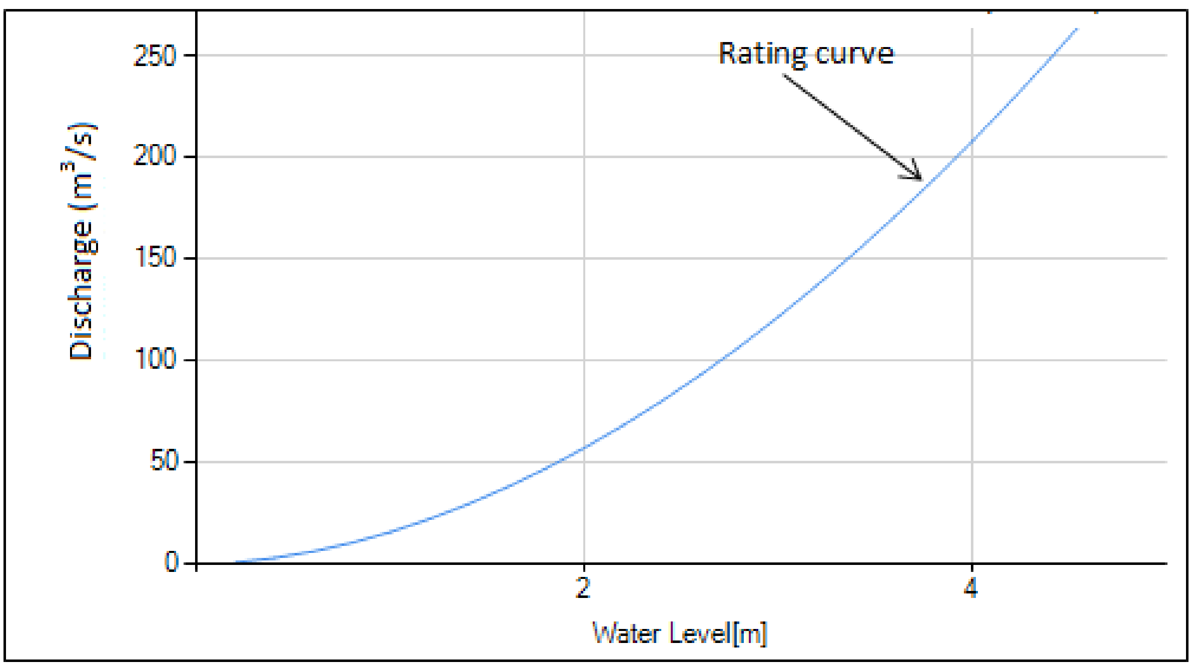


Figure 3.7: Rating curve for RGS station 1JF08 in Kipsonoi Sub basin (Source: WRA, Kisumu)

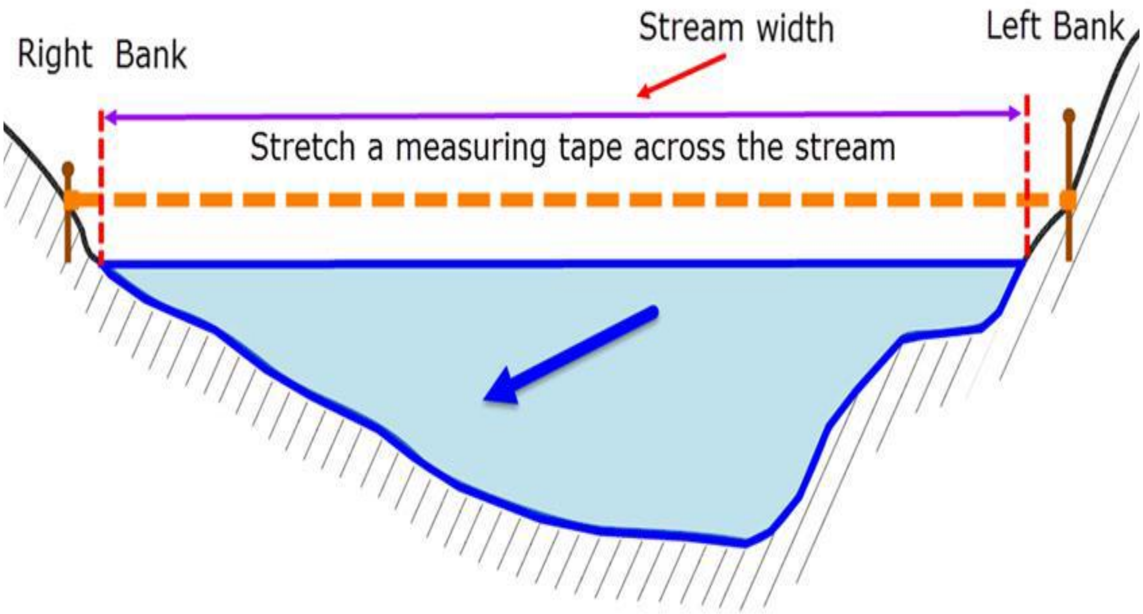


Figure 3.8: Determining cross sectional width of the stream channel (Source: Perzyna, 2016)

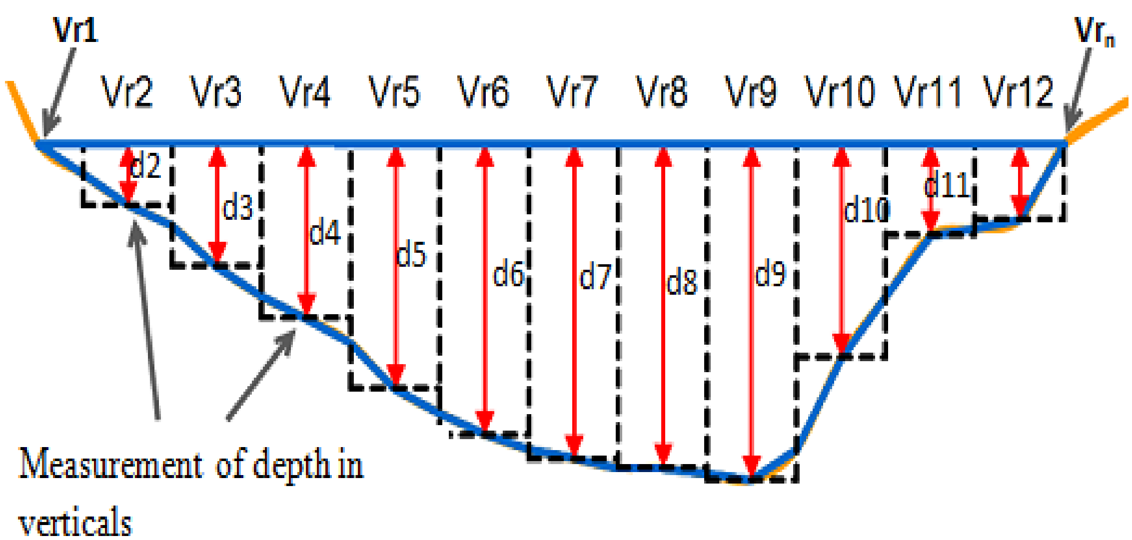


Figure 3.9: Measurement of velocities and depths at the river cross section (Source: Perzyna, 2016)

Plate 3.1: Velocity measurements in Kipsonoi sub basin on 18/10/2020 (Source: Koech, 2021)

b) Computation of river discharges

The cross-sectional area - velocity method was used to determine river discharges at the established river gauging stations located at the outlet of each of the three sub basins. The velocities, depths and sub section widths of the stream cross sections were used to compute discharges in each sub section accordingly USGS (2018).

3.3.2.4 Measurement of sediment flux

a) Turbidity and Total Suspended Solids Concentration sampling

The turbidity levels were determined at the established stations for the period of 12 months from July, 2020 to June, 2021. The sampling stations were established at the outlet of the three sub basins namely Timbilil sub basin dominated by tea plantations, Kiptiget sub basin dominated by forest, Kipsonoi sub basin dominated by mixed farming and at the downstream of the Sondu Miriu River Basin. The stream/river cross section was measured at each sampling station to determine the width. The sub sections of the cross section were selected as sampling points. The depth integrated approach was used to obtained water samples at different depths. The water samples obtained at different sub sections of the stream cross section were mixed and turbidity for the sub basin was measured using calibrated multiprobe meter and expressed in Nephelometric Turbidity Unit (NTU).

The Total Suspected Sediment Concentrations (TSSC) were determined at the sampling stations in the period of 12 months from July, 2020 to June, 2021. The stream/river cross section was divided into sub sections depending on the width. Water samples were collected at each sub sections starting from left bank to the right bank of the river using depth integrated sampler (see Plate 3.3). The pre sampling procedures conducted include preparation of sampling time table according to the nozzle sizes, rinsing of the sampling bottles and fastening of the sampler to the winch prior lowering into the water column. The sampling was conducted by lowering the sampler along the vertical profiles of the river according to the procedures described in the USGS's National Field manual. The collected water samples were stored in the one litre bottles and placed inside the sample storage box. These were transferred to the Kisumu Water Quality Laboratory for analysis.

iii) Laboratory analysis of TSSC

The total suspended sediments concentrations (TSSC) were analysed at the Water Quality Laboratory in Kisumu. In the laboratory collected water samples were analysed in the laboratory using American Public Health Association (APHA, 2005) standard water quality procedures. Whatman GF filters was weighed using a digital scale (Wf) and activated to check tears and holes before using for filtering the samples. The sampled water from each sub basin collected from different width segments were mixed to obtain the total volume (V). The filters were attached into a funnel cup and the water samples were filtered. The retained residues in the filters were placed in 8" x 8" glass pan and dried in an oven for at least 24 hours at temperature of 103ºC – 105ºC (APHA, 2005). The dried sediments in a filter were weighed using a digital balance (Wc) and the total weight of the sediments per sampling site at a given period of time was determined. The total suspended sediment (TSSC) was determined for sampling stations located at the outlet of the sub basins using Equation 3.1.

$$TSSC = \frac{Wc - Wf}{V} \times 10^6 \qquad 3.1$$

Where

TSSC is the total suspended solids Concentration (mg/l),

Wc is the weight of debris and filter (mg),

Wf is the weight of the filter (mg) and

V is the volume of the water sample (litres) (Ouma *et al*., 2013).

The sediment loads were computed using TSSC and river discharge data obtained at the sampling stations. In order to determine the sediment yield, stream discharge at the sampling point was estimated. The annual sediment yields and loads were computed at monthly temporal scale using Equations 3.2 and 3.3.

$$S_l = \left(\sum_i^n TSSC_i \times Q_i\right) \times 8.46 \qquad 3.2$$

$$s_y = \frac{s_l}{A} \qquad 3.3$$

Where

S_y is the annual sediment yield (tonnes/ha),

$TSSC_i$ is the monthly TSSC data in mg/l,

n is the nth month of the data collected and

Q_i is the average monthly stream discharges (m^3/s).

S_l is the sediment load (tonnes/ annum)

A is the area of the sub basin (Hectares)

Plate 3.3: Sampling of TSSC in Timbilil sub basin on 19/7/2020 (Source: Koech, 2021)

3.3.2.5 Data analysis

The data collected from the sub basins dominated by tea plantation, forest and mixed farming land covers and land uses were processed and analysed. The data analysis was done to understand the influence of the sub basins with dominant land covers and land uses on stream flows and sediment fluxes.

a) Hydrological analysis

i) Screening

The visual inspection was conducted to check on the consistency of the collected data and computed data. Time series and graphs were used to visualize outliers in the data series caused by errors in the field. This helped to eliminate errors which might have occurred due to equipment failure and human error during data recording (Danhem and Hall, 1990).

ii) Flow Duration Curve

The flow duration curve was used to determine the frequency and probability of exceedance. The flow duration curve equations were used to compute frequency and probability of the monthly observed hydrological parameters such as stream flow, turbidity, TSSC, sediment yields and sediment loads. Then the percent probability of exceedance was plotted against the hydrological parameters (Danhem and Hall, 1990).

b) Statistical analysis

The study employed various statistical methods for data analysis. The descriptive statistics that were used include mean, standard deviation and variance determined the central tendency of the datasets. Also, the relationship between sediment yields, TSSC, turbidity and stream flows in the sub basins dominated by different land use types were determined using correlation analysis method (Du and Sun, 2016).

3.3.3 Simulation of stream flows and sediment yield in sub basins with dominated land uses

Hydrological modelling was used in this study to understand past and current and predict future scenarios of hydrological events in the Sondu Miriu River Basin. This is to determine the long-term trends of the stream flows and sediment yields. The semi-distributed hydrological model, Soil and Water Assessment Tool (SWAT) was simulated stream flows and sediment yields.

3.3.3.1 Data requirement

a. Spatial Data

The data used in this objective was mainly secondary data acquired from various sources from 1975 to 2020. Land cover and land use spatial data with a spatial resolution of 30 m Digital Elevation Model (DEM) was acquired from the USGS remote sensing database.

These were used to provide land surface areas information such as land cover and use type, topography and slope for modelling. The soils data from FAO database was acquired and used to provide information on soil properties required for hydrological modelling.

b. Climatic and discharge data

Historical observed daily rainfall, minimum and maximum temperature and discharge data for six decades from 1960 to 2020. These data were acquired from WRA, Ministry of Water, Sanitation and Irrigation and Kenya Meteorological Department. The climatic data were used as input into SWAT model and stream discharge data was used to calibrate and validate the model. The SWAT model output data were analyzed together with the land cover and land uses data from 1975 to 2020. This was to understand the response of hydrologic components in relation to changes in land covers.

3.3.3.2 Hydrological Modelling

a) Setting up the SWAT model

The ArcSWAT was used to delineate study area, define stream networks and sub basin outlets and simulate hydrological components and sediment yields in the sub basins dominated by tea plantation, forest and mixed farming land covers and land uses. The threshold percentage of 5% in the model was applied to enable generation of significant HRUs in simulating results hence increasing the model computation efficiency. The daily rainfall, temperature, soils and land use data were inputted into the model for simulation of hydrological components (Arnold and Fohrer, 2005). The Modified Universal Soil Loss Equation (MUSLE) in the model predicts the soil losses from sub basins under specific slopes in different land covers (Briak *et al*., 2019).

b) SWAT Model Calibration and validation

The calibration of watershed, sub basin parameters and land management operations were conducted using the observed stream discharge data from 1960 to 1980. The parameters (see Table 3.1) used in the calibration of the SWAT model were selected based on their performance in simulating stream flows and sediment yields. It was noted that some parameters were sensitive resulting in higher impact in simulation hydrological variables than others.

Table 3. 1: Model Parameters used in SWAT model calibrations

No.	Parameter	Minimum Value	Maximum Value	Fitted Value
1	v__ALPHA_BF.gw	0	1	0.65
2	v__GW_DELAY.gw	30	450	350
3	v__GWQMN.gw	0	5000	3500
4	v__ESCO.bsn	0	1	0.8
5	v__EPCO.bsn	0	1	0.8
6	v__SURLAG.bsn	0.05	24	6.0
7	r__SOL_BD.sol	0.9	2.5	1.2
8	r__SOL_AWC.sol	0	1	0.4
9	v__CH_K2.rte	0.01	500	320
10	v__REVAPMN.gw	0	500	200
11	v__RCHRG_DP.gw	0	1	0.7
12	v__DEEPST.gw	0	50000	20000
13	r__ALPHA_BNK.rte	0	1	0.8
14	v__SLSUBBSN.hru	10	50	14
15	r_ USLE_K.sol	0	0.65	0.2

The watershed parameters evaporation and transpiration parameters (ESCO and EPCO) were used to modify evaporative demand from the basin. Soil compensation factor (ESCO) is a coefficient that ranged from 0-1. The parameter accounts for water lost to atmosphere through capillary action and ground surface openings such as cracks. The default value for the parameter is 1.0 but reducing the value to less than one shows that the model withdraws more water from the lower layers of the soils. The plant uptake factor (EPCO) was used to modify the amount of water lost through stomatal into the atmosphere. This parameter is critical in a dense vegetated land. Transpiration in the river basin plays an important part of the water cycle because of the forest, tea plantation and other food crops land covers. The groundwater recharge coefficient of percolation (RCHRG_DP) for both shallow and deep aquifers was adjusted to allow the model to transfer water from the vadose zone to the saturation zone in the aquifers. The groundwater recharge lag time between the time when water leaves the soil zone and the time the water enters the aquifers. The model was calibrated to factor the base flow delay using GW_DELAY parameter. The number of days taken by the base flow to decline from one unit hydrograph was modified using Alpha factor parameter (ALPHA_BF). The minimum threshold for upward movement of groundwater from the shallow aquifer to the unsaturated zone was controlled in the model by setting minimum height of the water table for revaporation to occur. The coefficient used to meet the threshold was REVAPMN. Also, initial groundwater depth in the deep aquifer to create demand for more recharge from the overlaying aquifer and unsaturated zone was considered in the model adjustment using DEEPST coefficient. This was to allow a good balance of the hydrological parameters (Neitsch *et al*., 2002; Neitsch *et al*., 2005).

The basin characteristic parameters were also used to improve the model performance. The surface water runoff coefficient (SURLAG) was used to adjust the concentration time of surface and subsurface runoffs to reach the downstream river channel from the upstream. The distance of slope length from the catchment area where flows originate from rills to the micro streams was adjusted using slope coefficient parameter, SLSUBBSN. Soil parameters were also modified to balance soil water storage and release. The soil water availability factor (SOL_AWC) was considered to establish the difference in water content between field capacity and wilting point. In addition, soil bulk density (SOL_BD) was used to set the soil moisture in the basin. The ability of soils to be transported by the flowing water from the catchment into the water channels was set based on the soil texture. The parameter used was the soil erodibility factor (USLE_K). Also, the model was calibrated using the river channel parameters. The hydraulic conductivity (CH_K2) that determines surface groundwater interaction and river bank storage factor (ALPHA_BNK) were used to adjust determine channel and bank contribution to the stream flows (Neitsch *et al*., 2002; Neitsch *et al*., 2005).

The coefficient of determination, R^2 and Nash-Sutcliffe Efficiency (NSE) were used to determine a good balance between simulated and observed data (Briak *et al*., 2019). The R^2 summarizes the proportion of variance in the dependent variable associated with the predictor variables. NSE determines relative magnitude of the residual variance compared to the measured data variance (Nash and Sutcliffe, 1970W. Satisfactory performance of about 1 relation between simulated output and observed stream flow data led to SWAT model validation stage. Validation was conducted when the calibrated model showed good performance. The discharge data used in validating the model was from 1981 to 1996. The SWAT modelling process is presented in Figure 3.10.

3.3.3.3 Scenario Analysis

The scenario analysis was conducted in projecting the influence of land cover and land use changes on the stream flows and sediment yields. The baseline land use and land cover data used was for 2020 and was projected for 7 decades. The scenario analysis was conducted in the sub basins dominated by the tea plantation, forest and mixed farming land covers and land uses as displayed in Table 3.2.

Table 3.2: Scenario analysis for sub basins under different land covers

Scenarios	**Description**	**Projected land cover and land use**	**Projection period**
I	Projected land cover and land use in sub basin dominated by tea plantation	-Increase tea plantation by 30 km^2	2020-2090
II	Projected land cover and land use in sub basin dominated by forest	Increase forest by 15 km^2 Decreased forest by 25 km^2	2020-2090
III	Projected land cover and land use in sub basin dominated by Mixed farming	Increase mixed farming by 210 km^2 Decreased mixed farming by 50 km^2	2020-2090

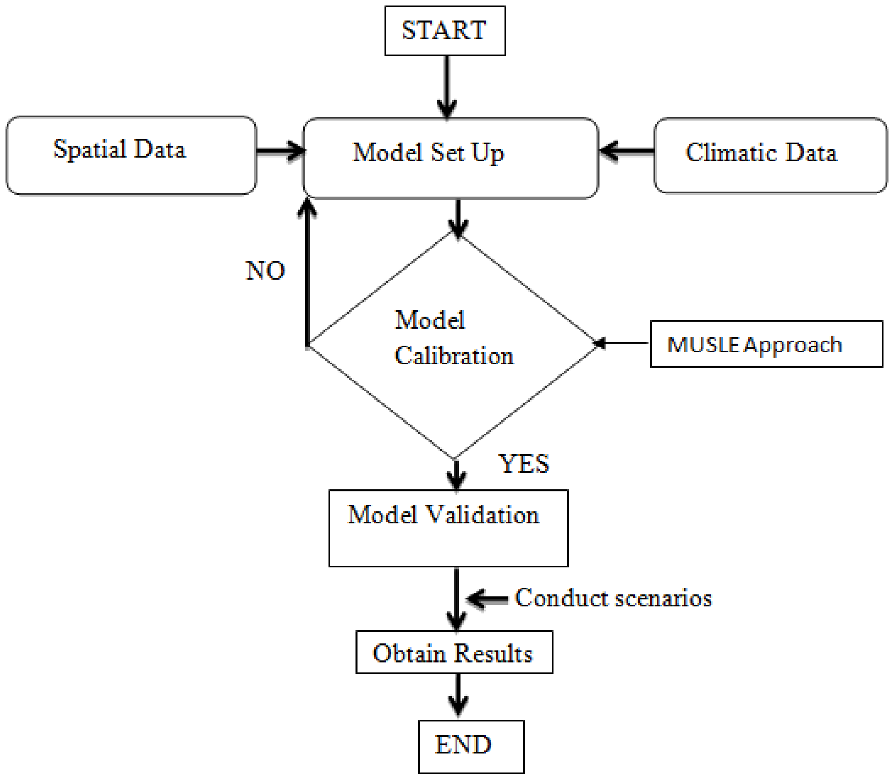


Figure 3.10: A schematic of the SWAT modelling set up and validation (Source: Arnold and Fohrer, 2005)

3.3.4 Estimation of water balance components in the sub basins with dominant land uses

The simulated hydrological components were used to determine the quantities of water in various stages of the water cycle in the sub basins dominated by tea plantation, forest and mixed farming land covers and land uses. The water balance enabled understanding of the water storages within the sub basins in various time steps.

3.3.4.1 Data requirements

The historical observed and SWAT output simulated data for hydrological and water balance components rainfall, evaporation and transpiration, surface runoffs, soil moisture, groundwater recharge, base flows and change in water storage were used. This was conducted in the sub basins dominated by tea plantation, forest, mixed farming and combined land cover and land uses. The obtained data for hydrological balance were compared with the changes in land covers and land uses in the sub basins.

3.3.4.2 Statistical data analysis

The descriptive statistics were used to determine the central tendency of the dataset. The datasets considered in this analysis were evapotranspiration data, rainfall data surface runoffs, soil moisture, ground water recharge, sub surface runoffs, base flows and water storages. The sum, averages, mean, and variance and standard deviation were used to estimate data in monthly and annual time step.

3.3.4.3 Hydrological analysis

The cumulative water volume passing a similar point in the stream flow and rainfall in the sub basin over time was computed. The double mass curve is used to check the consistency of many kinds of hydrologic data by comparing data for a single station with that of a pattern composed of the data from several other stations in the area. The double-mass curve can be used to adjust inconsistent precipitation data. The mean annual value of stream flow, climatic and rainfall data was estimated per station. Then the mean values of data from each station was added cumulatively and then plotted in a graph. The graph of the cumulative data of one variable versus the cumulative data of a related variable in a straight line so long as the relation between the variables is a fixed ratio (Deelat, 2010). Mass curve is the cumulative magnitude of a hydrological event (rainfall, water volume) over time. Equation 3.4 shows mass curve determination for a single gauging station (x) for a period, t. The cumulative data will be plotted against the time to portray curve-showing behavior of the hydrological event. Inconsistency of the data in a station was corrected using the double mass curve Equation 3.5. The hydrological data was presented in flow duration curves.

$$Cummulative\ of\ P_X = P_n + P_{n+1} + P_{n+2} + \cdots P_t \quad 3.4$$

$$Corrected\ P_X = P_X \times \frac{M_c}{M_a} \quad 3.5$$

Where

P_X is observed data in gauging station X,

$\frac{M_c}{M_a}$ is correction factor obtained from the slope of the curve,

M_c is the original slope of the mass curve,

M_a is the adjusted slope of the mass curve and n is the time step (Deelat, 2010)

3.3.4.4 Estimation of the water balance in sub basins

The water balance was determined in the sub basins dominated by tea plantations, forest and mixed farming land covers and land uses. The soil water balance was estimated using Equation 3.6. The soil water balance aid in understanding the soil moisture in the sub basin dominated by tea plantation, forest and mixed farming land cover and land uses. The change in water storage over time in the sub basins was conducted using Equation 3.7 (Savabi and Stott, 1994).

$$SW_t = SW_o + \sum_{i}^{n}(R_d - Q_{surf} - ET_a - W_p - Q_{qw}) \quad 3.6$$

$$\frac{\Delta S}{\Delta t} = \sum_{i}^{n}(R_d - Q_{surf} - ET_a - Q_{qw}) \quad 3.7$$

Where

SW_t is final soil moisture (mm/a),

SW_0 is the initial soil moisture (mm/a),

t is the time (day),

R_d is the rainfall (mm/a),

Q_{surf} is the surface runoff (mm/a),

ET_a is the actual evapotranspiration (mm/a),

W_p is the percolation (mm/a) and

Q_{gw} is the return flow (mm/a).

3.3.5 Relationship between stream flow and sediment yields in the sub basins

The relationship between stream flows and sediment yields was conducted in sub basins dominated by tea plantation, forest and mixed farming land covers and land uses. In addition, at the combined land covers and land uses, the relationship between stream flows and sediment yields were done at the downstream for the entire Sondu Miriu River Basin. This was used to identify sub basins and hotspot areas in the sub basins generating sediments.

3.3.5.1 Data requirement

The data used to achieve this objective were observed and simulated stream discharges and sediment yields data from 1960 to 2020 in sub basins with dominant land uses and land covers. The observed data was collected from WRA and Ministry of Water, Sanitation and Irrigation. The data were used to determine existing relationship between stream flows and sediment yields at the sub basins and the downstream of the river basin.

3.3.5.2 Statistical Methods

a) Regression analysis

The regression analysis was used to determine relationship between dependent variable and independent variables. Simple regression analysis method was conducted to determine the relationship between stream flows and sediment yields/loads. Further, multiple regression analyses (Equation 3.8) were used to determine relationship between sediment load and stream discharges and surface areas covered by specific dominant land use types in the sub basins (Zaid, 2015).

$$y = \beta + (\sum_{i}^{n}(ax_1)) + (\sum_{i}^{n}(ax_2)) + e \qquad 3.8$$

Where

y is the sediment yield,

x_1 is the stream discharge,

x_2 is the land use surface area

a coefficient of regression is,

n is the nth value,

β is the intercept and e is the error (Zaid, 2015)

b) Correlation analysis

The correlation between stream flows and sediment yields was used to determine the influence of stream flows on sediment yields. The relationship was determined using correlation coefficient (r) that provides a numerical summary of the direction and strength of the linear relationship between two continuous variables which are measured on at least an interval scale (Sthapit *et al.,* 2017). The coefficient of determination (R^2) that summarizes the proportion of variance in the dependent variable associated with the predictor (independent) variables, with larger R^2 values indicating that more of the variation is explained by the model, to a maximum of 1 (Gupta and Kapoor, 2014).

3.3.6 Determination of suitable land uses and catchment management practices

The land cover types in the sub basin dominated by tea plantation, forest and mixed farming land covers and land uses were assessed in terms of magnitude of sediment discharge. The land covers and land uses generating less sediment yields were considered suitable to be practiced. However, integration of existing land covers and land uses in the sub basin land cover with catchment management practices was also investigated.

3.3.6.1 Data requirement

Spatial land cover and land use data in the sub basins dominated by tea plantation, forest and mixed farming land covers and land uses. Also, observed and simulated stream flows and sediment yields data in the sub basins dominated by tea plantation, sediment yields and mixed farming land covers and land uses.

3.3.6.2 Assessment of suitable land cover and land uses

The historical and existing coverage of land covers and land uses types in the sub basins dominated by tea plantation, forest and tea plantation were assessed in relation to the stream flows and sediment discharge from 1975 to 2020. The comparisons between the dominant land cover and land use and stream flows and sediment yields were executed in each sub basin. The sub basin with high fluctuations of inter-annual stream flows and high sediment discharge was considered for catchment conservation measures. While the land cover and land use with sustainable inter-annual stream flows and with low sediment flux were considered suitable land cover and land uses.

3.3.6.3 Catchment Management Practices

The response of various catchment management practices was determined using the inbuilt soil and water conservation structural measures terraces, strip cropping and vegetative filter strips in SWAT model were applied in the sub basin with high sediment discharges and unsustainable stream flows. Parameters in the watershed management were adjusted in HRUs of the sub basins with high sediment generation, such as average slope length TERR-SL, USLE practice factor TERR-P and initial SCS curve number TERR-CN for terraces were adjusted to determine effectiveness of the terraces in reducing sediment flux and surface runoffs (Arabi et al., 2008). For the strip vegetation parameters such as manning's roughness coefficient for overland flow STRIP_N, SCS curve number II value for strip cropped field, STRIP_CN, USLE cropping factor STRIP_ C and USLE practice factor (STRIP_P). The vegetative filter strip, the parameters used were flag for simulating filter strips VFSI, ration of the field area to filter strip area VFSRATIO, fraction of the HRU which drains to the most concentrated 10% of the filter strips VFSCON and fraction of the flow within the most concentrated 10% of the filter strips which are fully channelized VFSCH. The obtained sub basin sediment yields after applying these operations were compared with the initial generated sediment yields and compute the effectiveness of the structural measure (Arabi *et al*., 2008).

3.3.7 Hypothesis testing

The hypothesis testing to determine significant difference in sediment yields and stream flows in different land use types (tea plantations, natural forest and mixed farming) in the Sondu Miriu River Basin were carried out. Also, statistical difference in the past, present and future seasonal patterns of streamflow and sediment yields was tested. The statistical significance in relationship between stream flows and sediment yields in the sub basins was determined. The significant impacts of catchment management structures on reducing stream flows and sediment transported were conducted. The following are the methods used to test the set hypothesis in this research study. The commonly used methods in test statistics are t test two sample of unequal variance and F test at less than 5% significance level. In this study F distribution method that uses analysis of variance was used due to the large sample size and more than two samples considered.

3.3.7.1 Analysis of Variance (ANOVA)

ANOVA was used for testing the significance and relationship between stream flows and sediment yields in sub basins dominated by tea plantations, natural forest and mixed farming land cover/land use. Also, the statistical difference in the land use/land cover variations and hydrological components in the sub basins. The ANOVA was used to test equality of variances in the three sub basins Equation 3.9. At 95% confidence level, there was enough evidence to accept or reject the null hypothesis by comparing the computed F value and F table value. For example, if the computed F value exceeds the F value in the distribution table of degree of freedom, then the null hypothesis is rejected and vice versa.

$$F = \frac{(S\,S\ between\ groups * df\ within\ groups)}{(SS\ within\ groups * df\ between\ groups)} \qquad 3.9$$

Where

SS is the sum squares of standard deviation,

df is the degree of freedom

F is the ANOVA ratio (Sthapit *et al.*, 2017)

CHAPTER FOUR

4.0 RESULTS

4.1 Introduction

The chapter presents the results of the study which are based on the six main objectives of the study. The results are presented on the pattern of land use change, effect of land cover and land use change on stream flows and sediment transport in the sub basin dominated by tea plantation, forest and mixed farming land cover/land use and simulation of the past, present and future stream flows and sediment loads. Results are presented on the major hydrologic water balance components in the three sub basins. Key findings on the relationship between stream flow and sediment yield in the three sub basins are also presented in this chapter. At the end of the chapter, attempt was made to determine the suitable land use and catchment management practices that are suitable for the basin.

4.2 Patterns of land cover/land use change in sub basins dominated by different land covers/land uses

The changes in the patterns of land covers and land uses in the sub basins dominated by tea plantation, forest and mixed farming in the period 1975 to 2021 are presented in the sub sections below. These results aid in understanding the impact of land cover and land use change on hydrology of the sub basin with specific dominant land cover and land use such as tea plantation, forest and mixed farming.

4.2.1 Patterns of land cover/land use change in tea dominated sub basin

The Timbilil sub basin dominated by tea plantations has area of approximately 315 km^2. The results showed that forest cover decreased from 40.9% in 1975 to 32.5% in 2021. The tea plantation increased from 37.7% in 1975 to 44.9% in 2021. The mixed farming cover increased from 21.4% in 1975 to 22.6% in 2021 (Figure 4.2.1 and Figure 4.2.2). These results indicated that in the period of 46 years, the area under tea plantations and mixed farming increased by 7.2% and 1.2% respectively while forest cover reduced by 8.4%. The result of assessment of changes in the land cover in the sub basin at every decade as presented in Table 4.1. The significant changes in the sub basin occurred in the tea plantations and forests land cover compared to mixed farming in the study period.

In a period from 1976 to 1986, the land under forest land cover increased from 41% to 43% while continuous population growth in the basin increased the area under mixed farming land cover by 2%. This caused decreased in tea plantation by 4%. In the period from 1986 to 1996, the decrease in tea plantations and forest land cover by 0.3% and 2.7% respectively occurred due to expansion of mixed farming by about 3%. However, in 1996 the tea plantation was extended in the areas which were initially covered by forest land cover. The forest land was reduced by 3% while the area under mixed farming increased by 3%. Further decline in forest land cover continued until 2016. In two decades from 1996 to 2016 the deforestation reduced forest cover from 40% to 32%. The land area under tea plantation expanded by 7% in the period of two decades from 1996 to 2016 and the land under mixed farming increased by 1% in the same period. The land area under tea plantation land cover in the sub basin has replaced forest land cover by 9% since 1986. The land under forest land cover in 2021 increased from 32% in 2016 to 33% in 2021.

Table 4.1: Area under forest, tea and mixed farming in the sub basin dominated by tea plantation land cover

Surface Area						
	Forest		**Tea Plantation**		**Mixed Farming**	
Period	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**
1975	128.80	40.90	118.70	37.70	67.40	21.40
1986	135.30	43.00	108.20	34.40	71.50	22.70
1996	126.90	40.30	107.40	34.10	80.70	25.60
2006	107.30	34.10	125.70	39.90	82.00	26.00
2016	101.80	32.30	127.80	40.60	85.50	27.10
2021	102.40	32.50	141.60	44.90	71.10	22.60

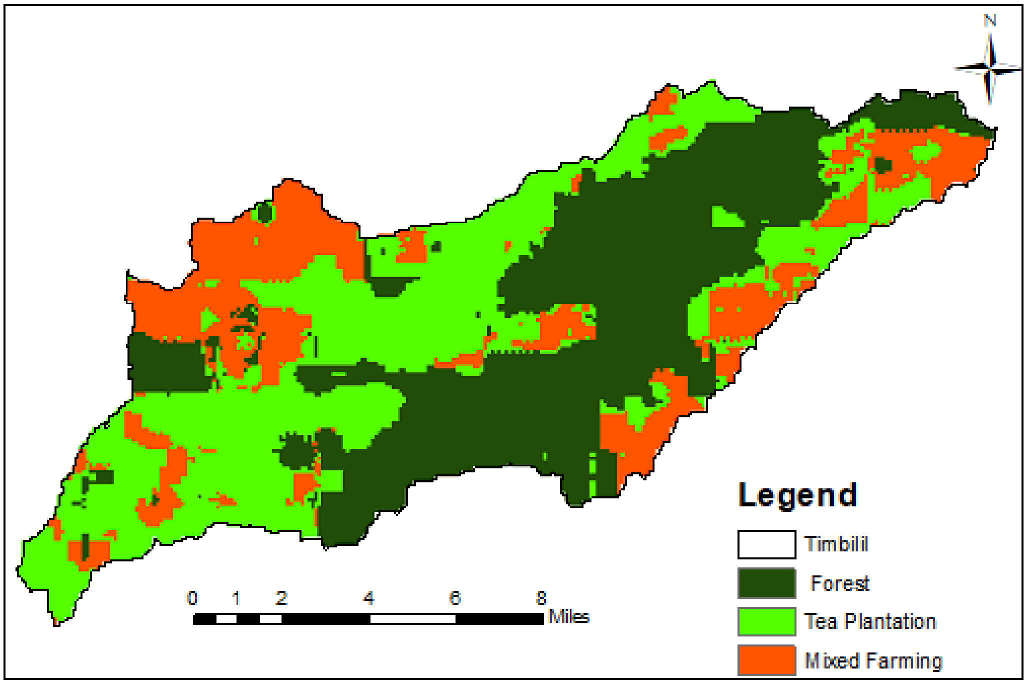


Figure 4.2.1: Land cover distribution in the Timbilil sub basin in 1975 (Source: Koech, 2021)

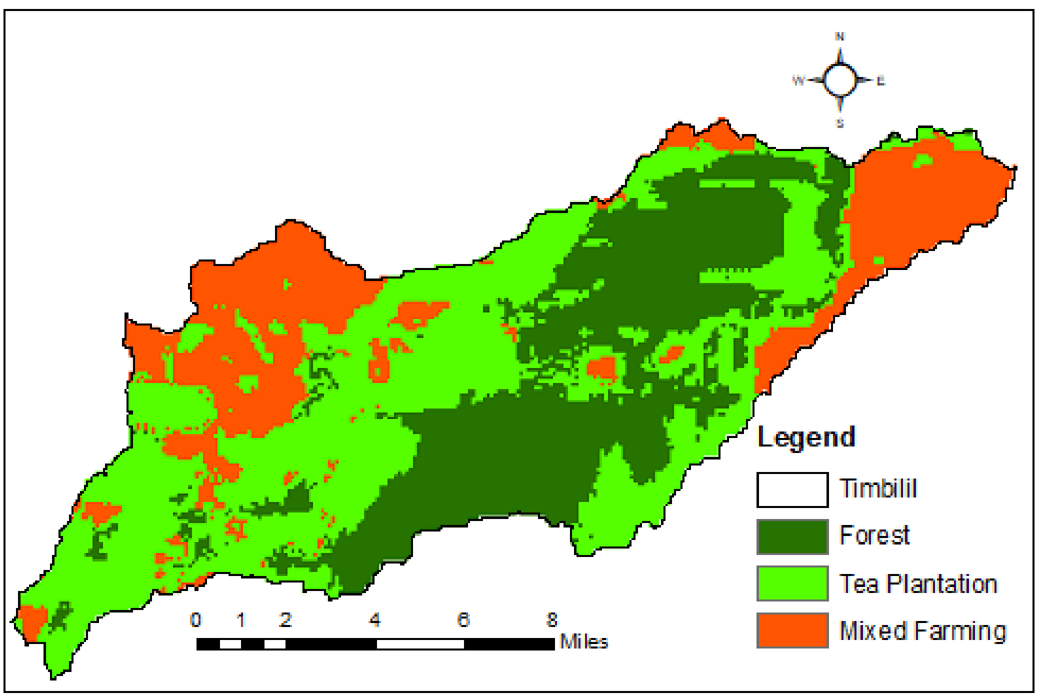


Figure 4.2.2: Land cover distribution in the Timbilil Sub basin in 2021 (Source: Koech, 2021)

4.2.2 Patterns of land cover and land use change in forest dominated sub basin

The Kiptiget sub basin dominated by forest land cover (Figure 4.2.3) had surface area of 152 km^2. The upper part of the sub basin has undergone deforestation and land cover conversion. In period 1975 – 2021 land use patterns showed that the area under forest land cover increased from 35% in 1975 to 36% in 2021. Similarly, the area under mixed farming decreased from 56% in 1975 to 40% in 2021. The tea plantations in the same period increased from 9% in 1975 to 24% in 2021. There was an increase of land in the sub basin under forest by 1% and tea plantation by 15% in a period of 46 years. This caused a decrease of land under mixed farming by 16% as shown in Figure 4.2.4. Analysis of the pattern of land cover in the sub basin are presented in the Table 4.2.

Comparison of the land cover portions in the sub basin dominated by forest land cover in 1975 and 1986 indicates that the forest cover expanded by 7%. While tea plantation land cover increased by 12% reducing mixed farming by 19%. In the period between 1986 and 1996, forest cover and tea plantation reduced by about 11% and 2% respectively. This was caused by increase in mixed farming by approximately 13% (Table 4.2) In the period between 1996 and 2006 forest land cover decreased by about 4.6% while the tea plantations and mixed farming increased by 3.8% and 1.7% respectively.

Table 4.2: Area under forest, tea and mixed farming in the sub basin dominated by forest land cover

Surface Area						
	Forest		**Tea Plantation**		**Mixed Farming**	
Period	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**
1975	53.30	35.10	14.10	9.30	84.50	55.60
1986	64.40	42.40	31.40	20.60	56.20	37.00
1996	46.40	30.60	29.80	19.60	75.80	49.90
2006	38.00	25.00	35.50	23.40	78.40	51.60
2016	57.50	37.80	29.20	19.20	65.40	43.00
2021	53.70	35.30	37.20	24.50	61.10	40.20

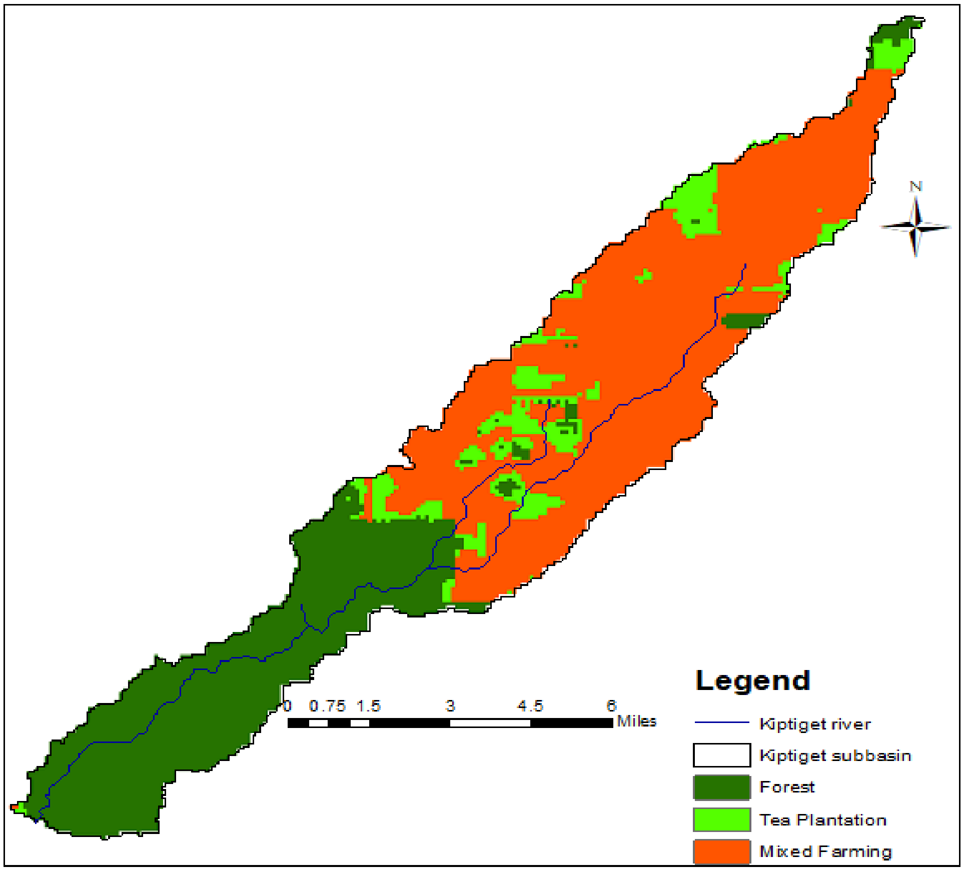


Figure 4.2.3: Distribution of land cover in the Kiptiget sub basin in 1975 (Source: Koech, 2021)

The deforestation of the forest land cover led to an increase in land under mixed farming which was increased from 37% in 1986 to 49% in 1996 while tea plantation reduced by 1% in the same period. The forest cover was reduced in this period to 25% of the total sub basin area. At the same period land under mixed farming increased from 49% in 1996 to 52% in 2006. Also, the land under tea plantations increased from 20% in 1996 to 23% in 2006. The reforestation was conducted between 2007 and 2016 resulting in an increase in the forest land cover from 25% in 2006 to 38% in 2016 (UNEP, 2010). The land under mixed farming and tea land cover decreased by 9% and 4% respectively in the period between 2006 and 2016. However, there was a decline in forest cover in the period between 2017 and 2021. In this three-year period, reduction of the forest land cover by 2% occurred. The decrease of the land under forest cover was attributed to an increase of the tea plantation from 19% in 2016 to 24% in 2021 while land under mixed farming land use decreased by 3% in the same period.

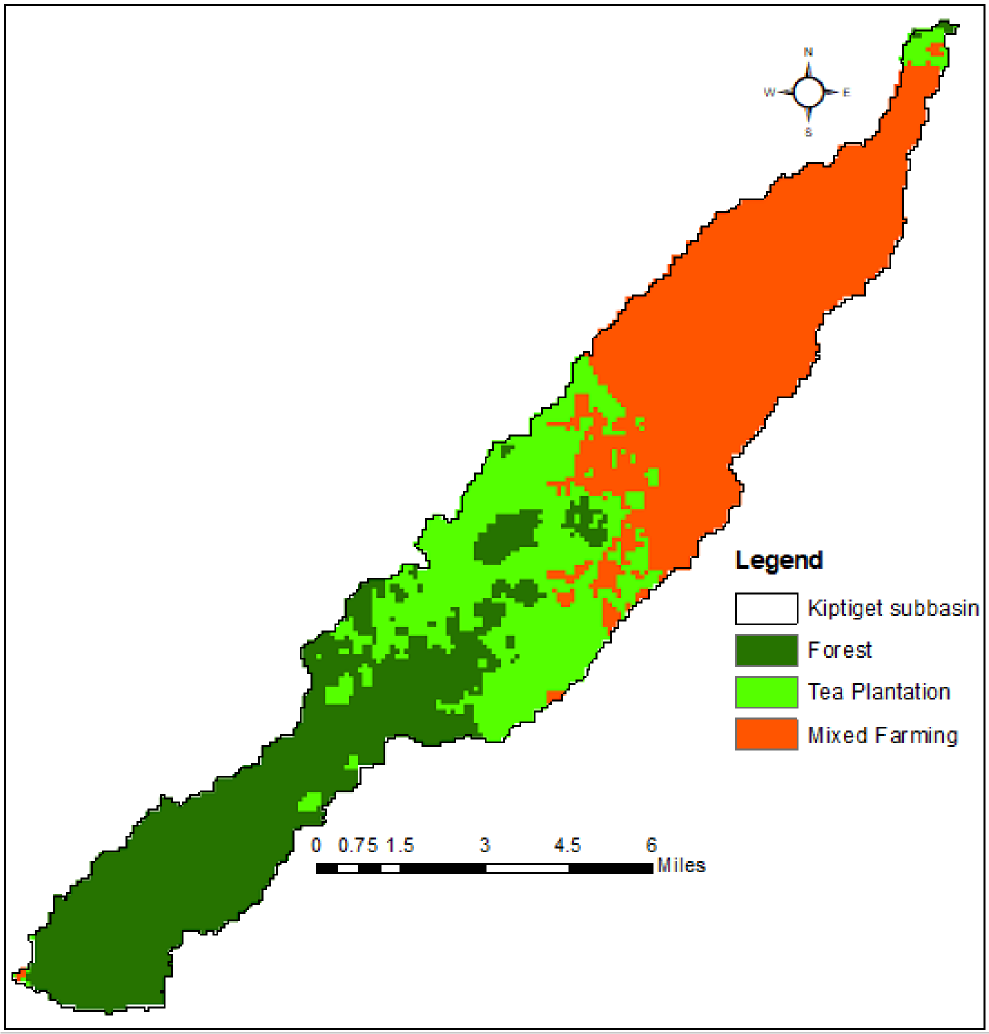


Figure 4.2.4: Land covers distribution in the Kiptiget sub basin in 2021 (Source: Koech, 2021)

4.2.3 Patterns of land use change in mixed farming dominated sub basin

The sub basin dominated by mixed farming is Kipsonoi (see Figure 4.2.5). This sub basin had an area of approximately 1,582 km^2. The sub basin in the period 1975 -2021 showed that the land area under mixed farming covered 91.6% of the total sub basin area. The land area under tea plantations and forest covered 4.1% and 4.3% of the total sub basin respectively. In a period of 45 years in 2021 (Figure 4.2.6), it showed that the land under mixed farming reduced from 91.6% to 85.5%, the land under forest decreased from 4.3% to 4% while the land under tea plantations increased from 4.1% to 10.5% in the same period. Further decadal information is presented in Table 4.3

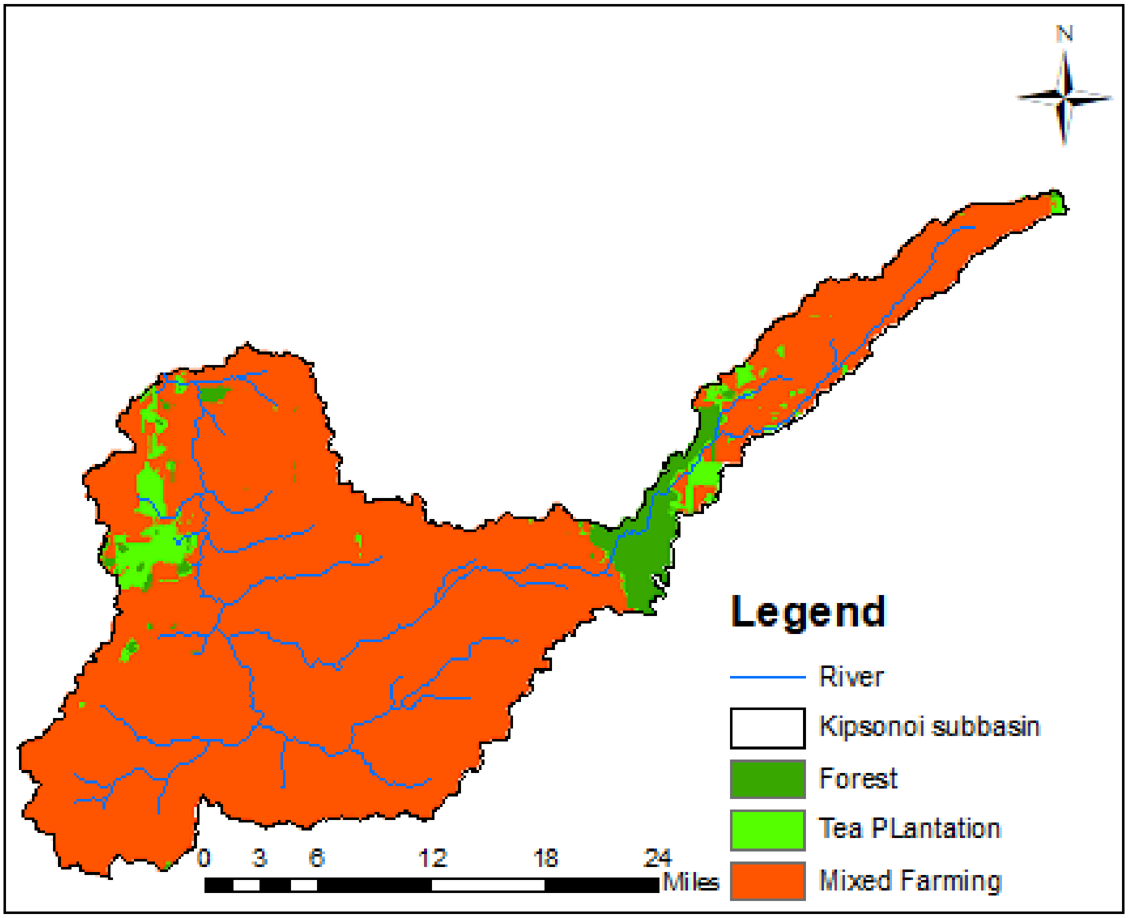


Figure 4.2.5: Distribution of land cover in the Kipsonoi sub basin in 1975 (Source: Koech, 2021)

In Table 4.3 the three land covers forest, tea plantation and mixed farming in the sub basin were compared from 1975 to 2021. The area under forest and tea plantations in the sub basin was about 4.3% and 4.1% respectively. The area of land under mixed farming decreased by about 6.3% in the same period. This could be due to expansion of forest and tea land covers in the same period by 2.4% and 4.3% respectively. In the period between

1986 and 1996 the land under mixed farming decreased by 0.8% while tea plantations increased by 2.4%. The land under forest land cover in the period 1986 to 1996 decreased by 1.6% of the total sub basin area. The land under tea plantation increased over time in the sub basin while forest land cover reduced by 2.7% in the same period. The decline in the forest and mixed farming cover by 1.2% and 1.1% in the period between 1996 and 2006 was due to expansion of the tea plantations in the sub basin by 2.3%. In the period between 2006 to 2021 the land under mixed farming and forest in the sub basin increased by about 2.5% and 0.1% respectively. While the land under tea plantation in the same period decreased by about 3%.

Table 4.3: Inter-decade land cover changes in the sub basin dominated by mixed farming land cover

Surface Area						
	Forest		**Tea Plantation**		**Mixed Farming**	
Period	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**
1975	67.72	4.30	65.32	4.10	1448.96	91.60
1986	106.55	6.70	132.99	8.40	1342.47	84.90
1996	80.99	5.10	170.54	10.80	1330.47	84.10
2006	61.95	3.90	207.55	13.10	1312.50	83.00
2016	89.14	5.60	155.59	9.80	1337.27	84.50
2021	63.14	4.00	166.54	10.50	1352.32	85.50

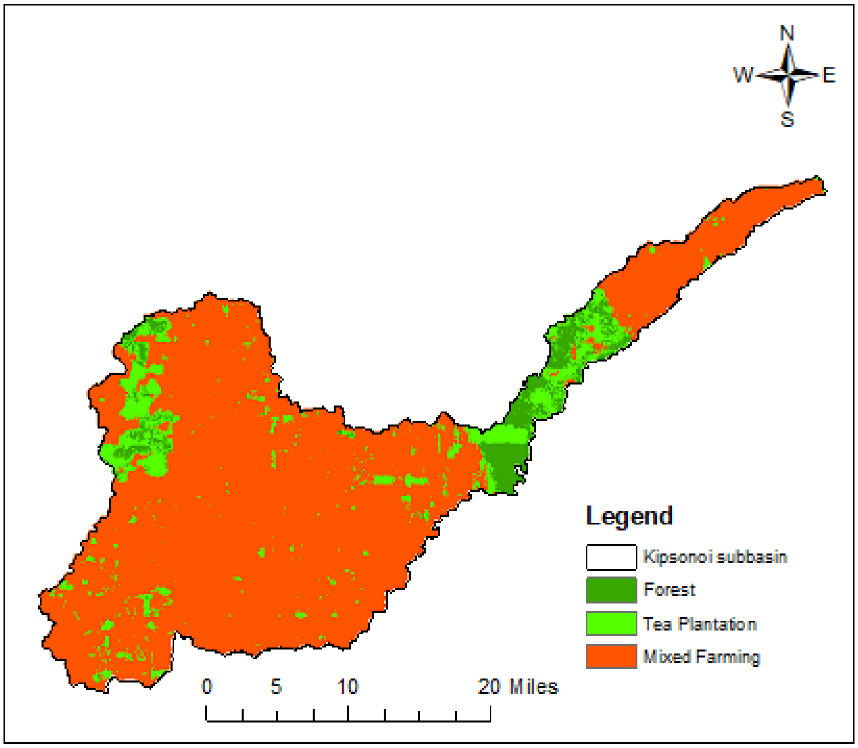


Figure 4.2.6: Distribution of land cover in the Kipsonoi sub basin in 2021 (Source: Koech, 2021)

4.2.4 Patterns of land cover/land use change in the Sondu Miriu River Basin

The Sondu Miriu River Basin comprises of mixed land covers (tea plantations, forests and mixed farming). The area of land under the forest cover in the river basin was approximately 497.3 km^2 which is 14.3% of the entire basin area (see Figure 4.2.7). The forests were found at the upper region of the basin. The tea plantations were located in Kuresoi, Kericho, Bosta and Changoi at the upper region of the basin and also in Sotik in Bomet and Ikonge in Nyamira in the middle region of the basin. The tea plantation covered an area of about 403 km^2 equivalent to 11.6% of the total basin area. The mixed farming land cover occupied area of 2570 km^2 which is equivalent to 74.1% of the total basin area. Land cover changes were assessed in ten years interval as presented in Table 4.4.

In the period between 1986 and 1996, the land area under tea plantation and mixed farming increased by 73 km^2 and 52 km^2 respectively causing decrease forest land cover by 123 km^2 in the same period. The increase in land area under tea plantations by 2.2 % could be due to communities shifting from food crop farming into tea farming as cash crop to help earn livelihoods. The increase in tea plantations between 1975 and 1986 in Sondu Miriu River Basin was also due to the declined in the land under mixed farming land use by 5.2% that is from between 1975 and 1986. This also resulted in the increase in forest cover and tea plantations in one decade by 2.2% and 3.0 % respectively. Further in the period between 2006 and 2021, tea plantations in the river basin declined by 20 km^2 while mixed farming increased by 9 km^2 (Figure 4.2.8). In addition, in the same period land area under forest was increased by 13 km^2. Comparing the land cover changes between 2006 and 2016 (Table 4.4) it showed an increase in the land area under forest by 68 km^2 and the decrease in the land area under tea plantation and mixed farming by 36 km^2 and 52 km^2 respectively.

Table 4.4: Inter-decade mixed land cover changes and population in the Sondu Miriu River Basin in the period 1975 to 2021

The results of the study period 1975 to 2021 showed that the forest land cover has been declining from 497 km^2 to 413 km^2. The main causes of the reduction in the forest were expansion of the tea plantations. There was a continuous increase of the area under tea plantation in the period between 1975 and 2021 (see Tables 4.1 to 4.4). The area of land under tea plantations and mixed farming increased as the population in the basin increases (Figure 4.2.9). The tea plantation covered an average land basin area of 15.3%. This indicates that the tea plantations increased by 177 km^2 in a period 45 years. Comparing the mixed farming land cover area in the periods between 1975 and 2021 showed a decline in the land coverage of about 93 km^2 due to encroachment of tea plantations into the small-scale farms (see Figure 4.2.8). The decline in area under the forest and mixed farming paved way for an increase in the expansion of tea plantations (Figure 4.2.9).

The results showed that in the Sondu Miriu River Basin significant relationship exists between population size and forest cover with correlation r of -0.76 and coefficient of determination R^2 of 0.59 at $p < 0.05$. The relationship between population size and tea plantations was significant relationship with correlation r of 0.49 and coefficient of determination R^2 of 0.24 at $p < 0.05$. The relationship between mixed farming and population size was insignificant with correlation r of 0.3 and coefficient of determination R^2 of 0.1 at $p > 0.05$. This indicates that the land area under mixed farming has not change significantly with rise in population.

Table 4.4: Inter-decade mixed land cover changes in the Sondu Miriu River Basin in the period 1975 to 2021

Land Cover	Forest (km^2)	Tea (km^2)	Mixed farming (km^2)	Population
1975	497.3	403	2569.7	332,426
1986	601.8	477.5	2390.7	465,064
1996	478	550	2442	623,650
2006	401.3	601.1	2467.6	819,477
2016	469.2	565.8	2415	1,035,000
2021	413.1	580.2	2476.7	1,089,441

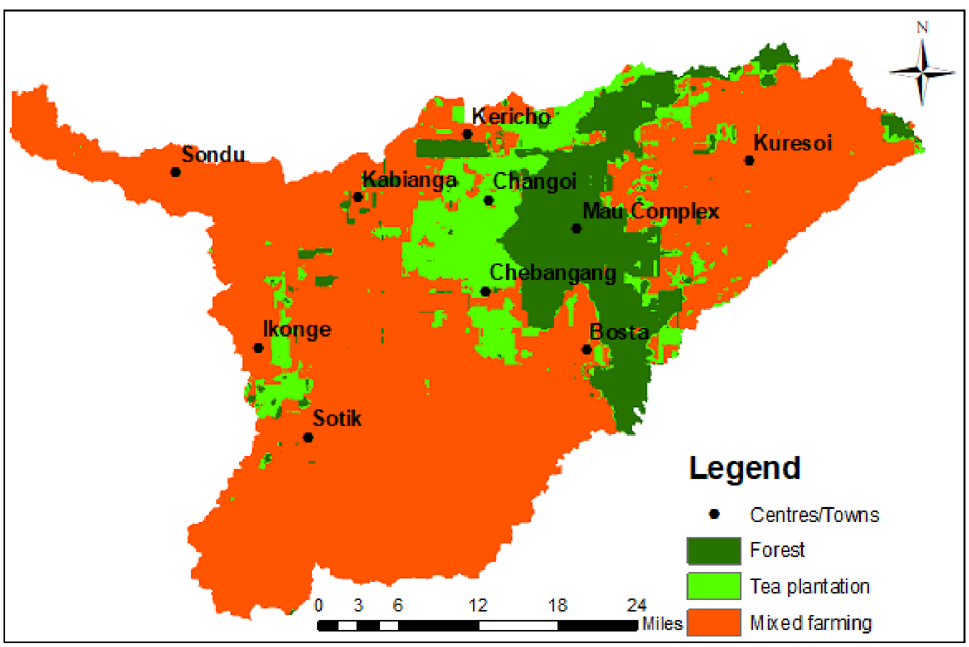


Figure 4.2.7: Distribution of land cover in the Sondu Miriu River Basin in 1975 (Source: Koech, 2021)

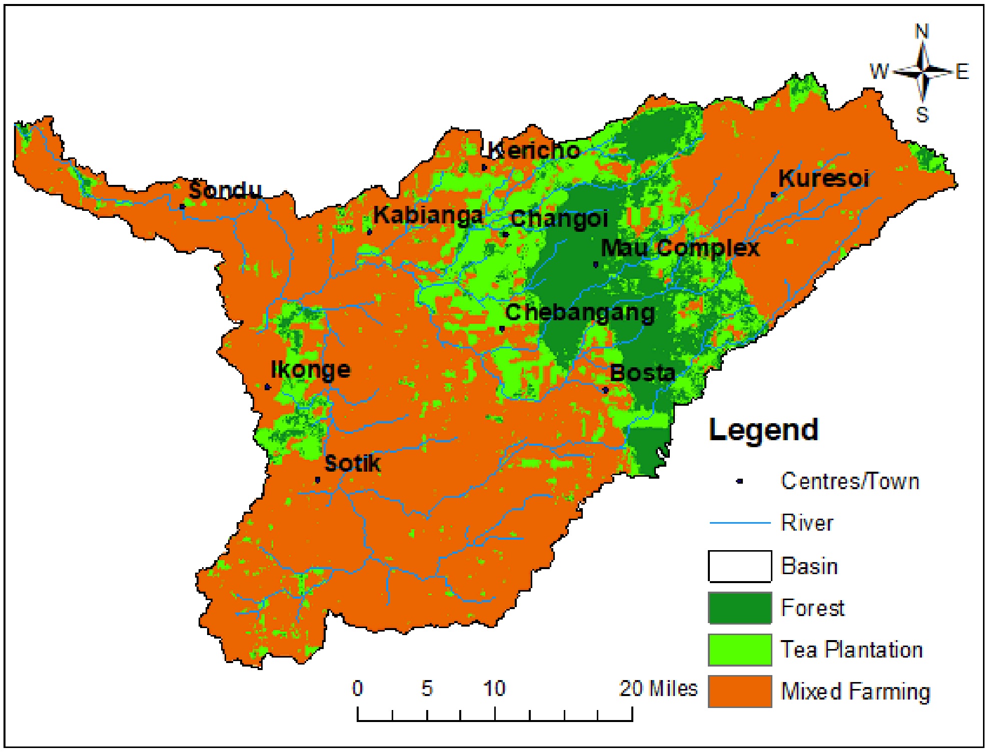


Figure 4.2.8: Distribution of land cover in the Sondu Miriu River Basin in 2021 (Source: Koech, 2021)

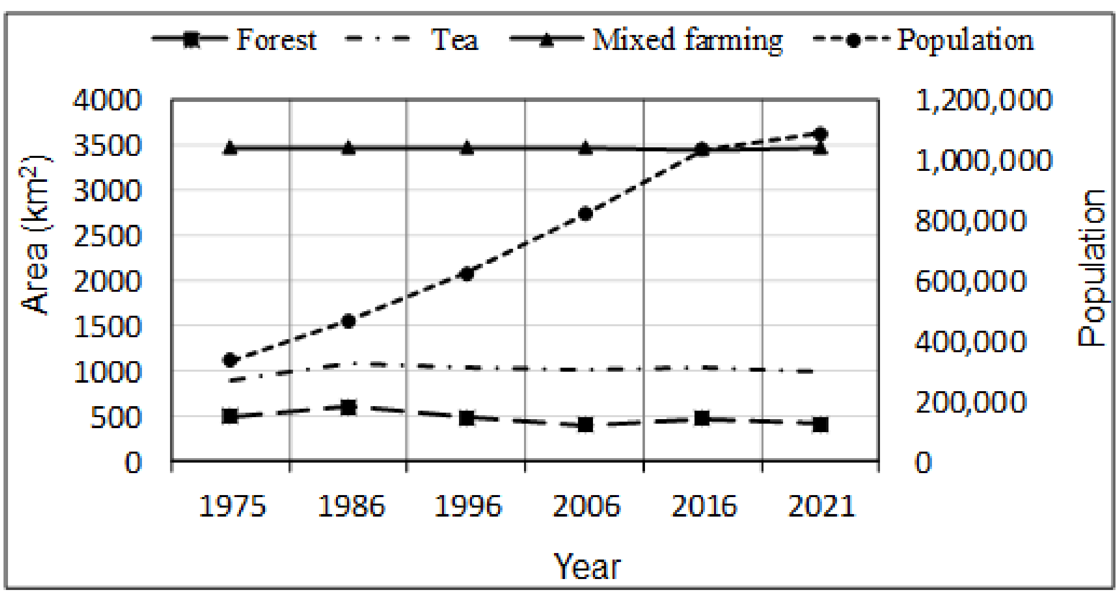


Figure 4.2.9: Area and population of the Sondu Miriu River Basin (1975-2021)

The results were statistically tested with the first null hypothesis that stated there was no significant change in the areas of the dominant land covers and land uses in the sub basins dominated by tea plantations, forest and mixed farming. The ANOVA results showed that at $p<0.01$, the F calculated was 104.1 while the F critical in the table was 3.06. Hence the null hypothesis was rejected.

4.3 Effects of tea plantation, forest and mixed farming on stream flows and sediment fluxes

The sub basins dominated by tea plantations, forests and mixed farming land cover and land uses respond differently in terms of stream flows and sediment fluxes. The results in each sub basin with the dominant land cover and land use are presented in the following sub sections.

4.3.1 Effects of sub basins with dominant land uses on stream flows

4.3.1.1 Effects of tea plantations and forest land cover on stream flows

The stream discharge observed in the study period from July, 2020 to June, 2021 in the sub basin dominated by tea plantations and forest land covers showed variations in wet and dry seasons. In the sub basin dominated by tea plantations the stream discharges in long rainy season (month of April – July) were high ranging between 5 m^3/s and 7 m^3/s. In the short rainy season, (October – December) the stream discharges observed ranged between 4 m^3/s and 6 $m^3/$. During the dry season (February – March) low discharges were observed ranging from 1 m^3/s to 3 m^3/s. The average stream discharge was 4.3 m^3/s, the minimum and maximum discharge was 1.1 m^3/s and 7.2 m^3/s respectively (Figure 4.3.1). The difference between minimum and maximum value implied that rainfall contributes to variations in stream discharges.

In the forest dominated sub basin, the stream discharges observed were lesser than the tea plantations dominated sub basin. In the long rainy season (April – July) the stream discharges ranged between 0.6 m^3/s to 3.5 m^3/s. In the short rainy season (October – December) the stream discharges 1 m^3/s to 3 m^3/s. In dry season (February – March) stream discharges ranged between 0.5 m^3/s to 0.8 m^3/s. Results have shown in sub basins dominated by tea plantations and forest rainfall also contribute to stream discharge variabilities as shown in Figure 4.3.1. The average stream discharge was 2.2 m^3/s, the minimum and maximum discharge was 0.5 m^3/s and 3.8 m^3/s respectively. The stream discharges in dry periods showed that tea plantation land generates higher stream discharges compared to forest land cover with a magnitude of about 0.6 m^3/s.

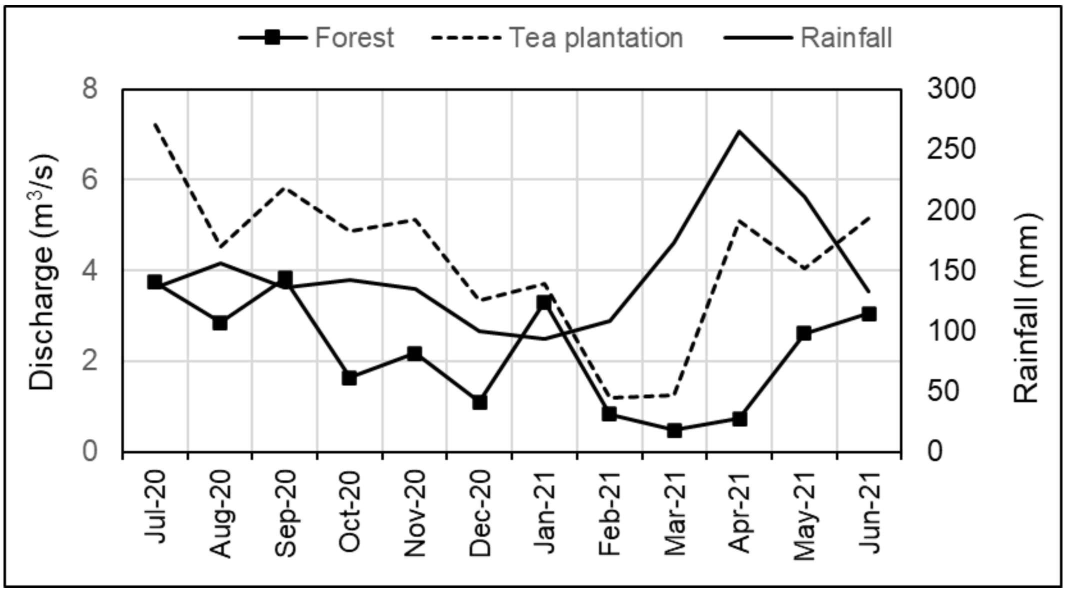


Figure 4.3.1: Discharges in tea plantations and forest dominated sub basins (2020 – 2021)

4.3.1.3 Effects of mixed farming and mixed land covers on stream flows

Stream discharges in the sub basin dominated by mixed farming which occurred in long rainy season (April – July) ranged between 5 m^3/s and 27 m^3/s. In short rainy season (October – December) it ranged between 7 m^3/s and 17 m^3/s and from 5 m^3/s to 7 m^3/s in dry season (February – March). The average stream discharge was 10.4 m^3/s, the minimum and maximum discharge was 5 m^3/s and 27 m^3/s respectively (Figure 4.3.2).

In the mixed land covers, the stream discharges were observed in the downstream of the Sondu Miriu River Basin. The stream discharges in the mixed land covers during long rainy season (April – July) ranged between 34 m^3/s and 40 m^3/s. While in the short rainy season

(October – December), the stream discharges ranged between 20 m^3/s and 45 m^3/s. In dry season (February – March) the stream discharges ranged between 5 m^3/s and 11 m^3/s (see Figure 4.3.2). The average stream discharge was 28.3 m^3/s, the minimum and maximum discharge was 5.8 m^3/s and 45 m^3/s respectively. In March the stream discharges portrayed low values of 5.2 m^3/s and 5.8 m^3/s indicating that mixed farming and mixed land cover have comparable effect on stream discharges. Comparing different land uses and land covers in Figures 4.3.1 and 4.3.2 stream discharges fluctuates higher during wet season in mixed farming land covers than tea plantations and forest land covers.

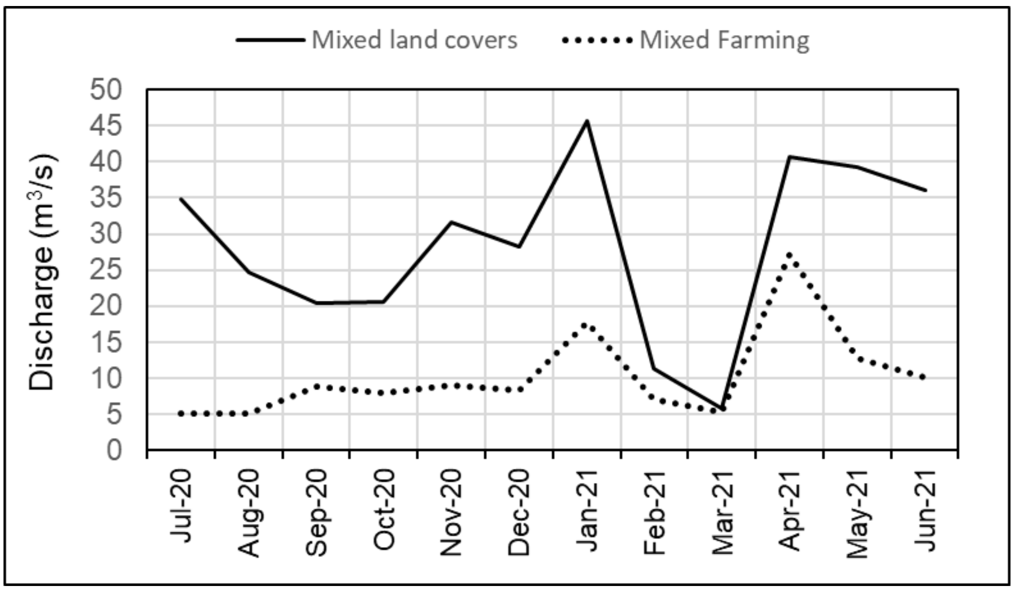


Figure 4.3.2: Discharges in mixed farming and mixed land covers (2020 – 2021)

The flow duration curve at the downstream for the mixed land covers shown in Figure 4.3.3 portrayed gentle slope which is a typical of perennial river system. The high flows were greater than 150 m^3/s and occurred in less 1%. On the other hand, at 99% of the flow duration base flow greater than 26 m^3/s were experienced. The high base flows could be due to infiltration of rainfall in the highly vegetated upper zone of the river basin. At 70% of the time the stream discharges were about 68.3 m^3/s. Less than 5% of the time, the stream discharges observed were about 120 m^3/s.

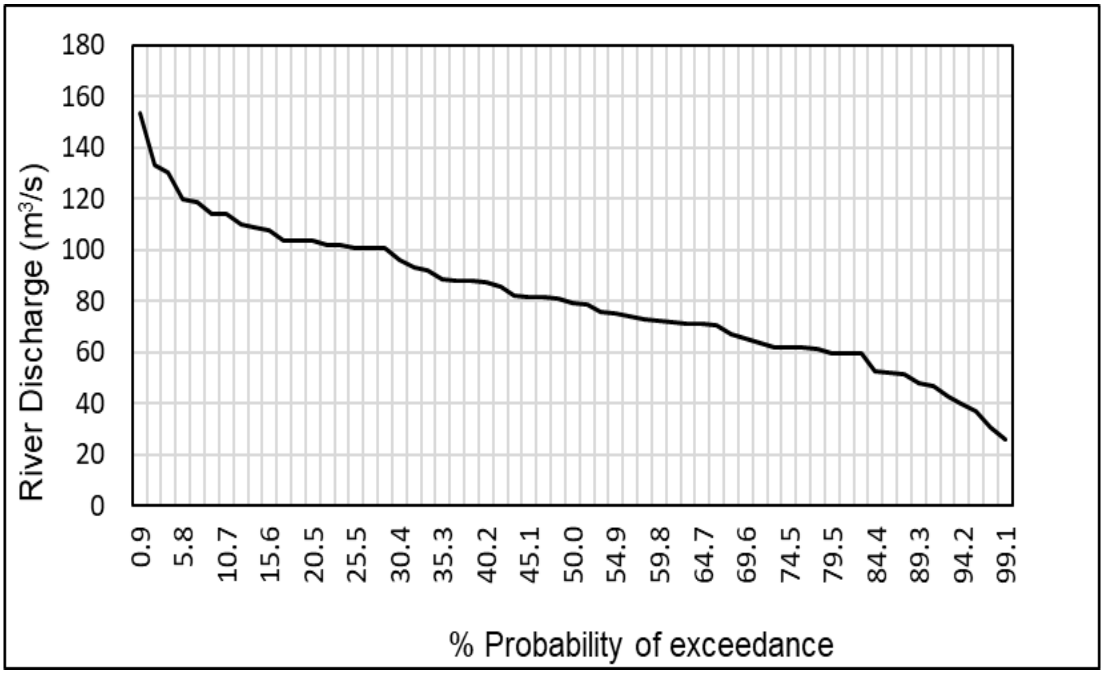


Figure 4.3.3: Flow duration curve in the mixed land covers in Sondu Miriu River Basin

The hypothesis stated that there was no significance difference in the stream flows in the sub basins dominated by tea plantations, forest and mixed farming land covers. The hypothesis was tested using single factor ANOVA at $p<0.01$ and it was observed that F calculated was 330.2 while F critical was 3.05. This indicated that the F calculated was greater than the F critical and the null hypothesis was rejected.

4.3.2 Effects of the sub basin dominated by different land covers and land uses on the sediment flux

4.3.2.1 Effects of the sub basin dominated by tea plantations on sediment flux

a) Turbidity

The turbidity in the sub basin dominated by tea plantations was high in wet seasons specifically during short rainy seasons and was low during dry seasons. In dry periods turbidity levels ranged between 15.24 and 21.8 NTU. During the rainy season (short rains) turbidity levels ranged between 36.17 and 95 NTU. Turbidity levels during the long rains were relatively lower ranging between 18.5 and 21.5 NTU. The maximum turbidity level in the sub basin observed was 95 NTU while the minimum turbidity was 15.2 NTU. The average turbidity level in the sub basin was approximately 29.5 NTU (see Table 4.5). It was also noted that changes in turbidity was ± 5 NTU between the month of September and November 2020. For instance, in the month of September where turbidity increased by around 2 NTU and in November turbidity decreased by about 5 NTU. The turbidity in the sub basin was moderate in the periods of high river discharge during the month May – July long rainy seasons and between November and January short rainy seasons. The turbidity in February and March reduced to less than 20 NTU during dry periods due to low decreased flows in the sub basin (see Figure 4.3.4). The turbidity duration curve indicated that the turbidity levels at 95% of the time was 15.2 NTU which is relatively low. At 50% of the time the turbidity level was 21.5 NTU. This revealed that more than 50% of the time, the turbidity levels were low and water in the river system of the Timbilil sub basin was clear water. At less than 5% of time, the turbidity level was greater than 90 NTU. The maximum turbidity of 95 NTU reported in this study was comparable to turbidity levels observed at Jamji of about 100 NTU (Masese et al., 2012).

b) Total Suspended Solids Concentrations (TSSC)

The TSSC was high during the wet and high flow seasons in the sub basin dominated by tea plantations as depicted in Figure 4.3.4. High TSSC was observed during short rainy season than long rainy season. This occurred specifically between the months of October 2020 and January 2021 with values ranging between 20 mg/l and 40 mg/l. At the onset of the long rainy season particularly in March 2021 the TSSC value of 30 mg/l was observed. However, during dry and low flow seasons, low TSSC ranging between 5 mg/l and 15 mg/l was observed in the sub basin. The maximum TSSC in the sub basin was 40 mg/l while the minimum TSSC was 10 mg/l. The mean TSSC in the sub basin was 19 mg/l (Table 4.5). The TSSC observed in this study were comparable to the TSSC values of about 25 mg/l to 40 mg/l observed in Jamji (Masese et al., 2012).

The TSSC duration curve (Figure 4.3.6) indicated that in the 50% of the time, the TSSC was 17 mg/l. In less than 5% of the duration, the TSSC of more than 40 mg/l was observed.

Further at 70% the TSSC of 15 mg/l was observed and greater than 95% of the time, the TSSC less than 5 mg/l was obtained. A significant relationship between TSSC and turbidity was observed with coefficient of determination R^2 of 0.56 and correlation r of 0.74 $< p$ of 0.05. This showed that turbidity occurred as a result of suspended sediments.

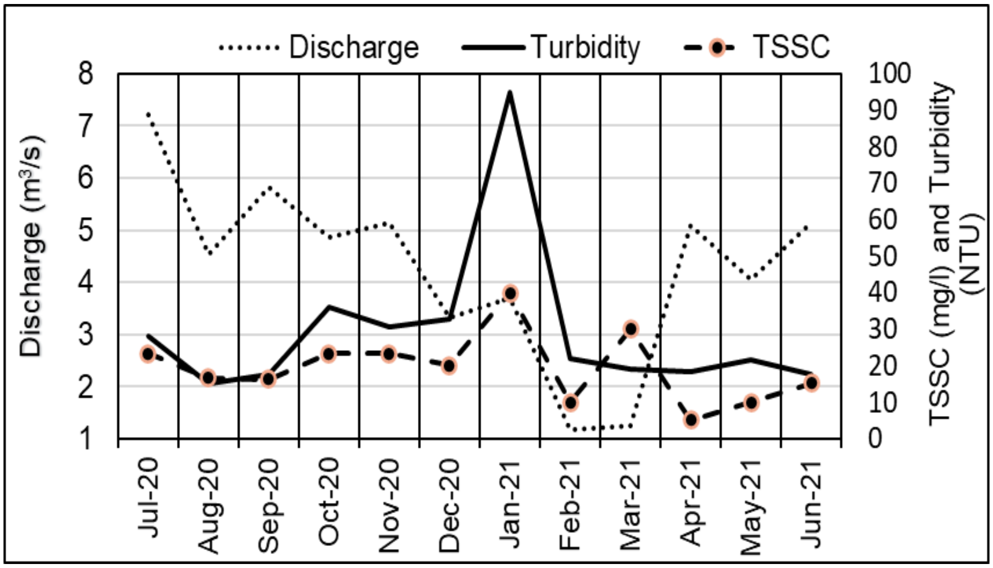


Figure 4.3.4: Turbidity, TSSC and discharge in Timbilil sub basin (2020 – 2021)

c) Sediment loads

The sediment flux in the Timbilil sub basin dominated by tea plantation revealed that sediment loads increased more in the wet seasons than in dry seasons. At the wet season the highest sediment load recorded was 14.5 tonnes/day while the lowest sediment load of 1.02 tonnes/day was observed in dry season. The maximum sediment load was 14.5 tonnes/day in the month of July (Figure 4.3.5). The minimum sediment loads of 1.02 was observed while the average sediment loads in the sub basin was 7.05 tonnes/day (see Table 4.5). The time series of sediment load and river discharges showed positive response. The relationship between sediment loads and stream flows obtained in the study was positive with coefficient of determination R^2 of 0.42 and correlation r of 0.65 at $p < 0.05$. The study conducted in Sri Lanka reported similar observations (Kanakarathna *et al*., 2013). The sediment load duration curve (see Figure 4.3.6) indicated that less than 5% of time the sediment loads in the Timbilil sub basin dominated by tea plantation were greater than 14.5

tonne/day. On contrary, greater than 95% of the time the sediment loads were less than 1.02 tonnes/day. At 50% and 70% of the time, the sediment loads were less than 6.5 tonnes/day and 3.5 tonnes/day respectively. In rare situations that sediment loads greater than 14 tonnes/day were observed. The significant relationship between sediment loads and TSSC was observed with R^2 of 0.94 and r of 0.97 at $p < 0.05$. While relationship for turbidity and sediment load was R^2 of 0.29 and r of 0.54 (Figure 4.3.7).

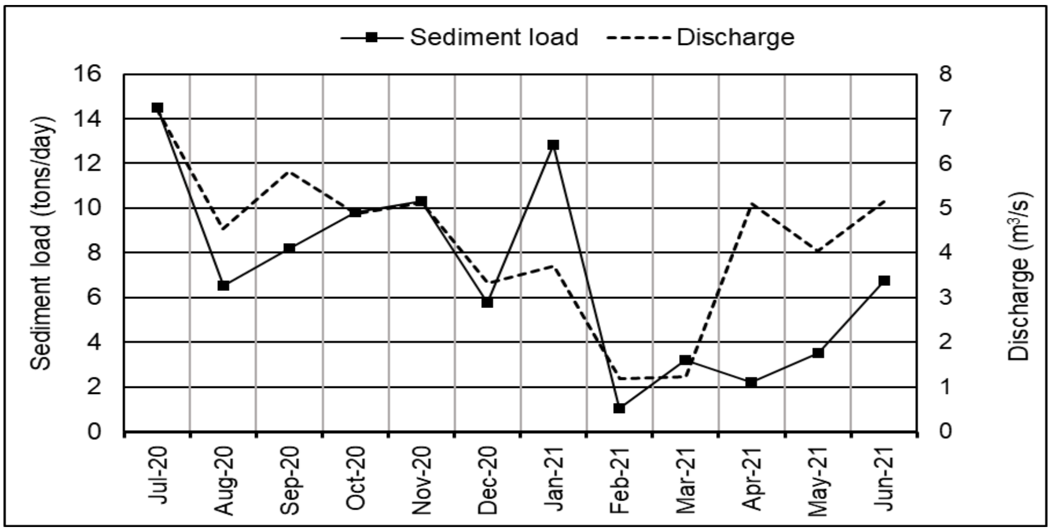


Figure 4.3.5: Sediment loads and discharge in Timbilil sub basin (2020 – 2021)

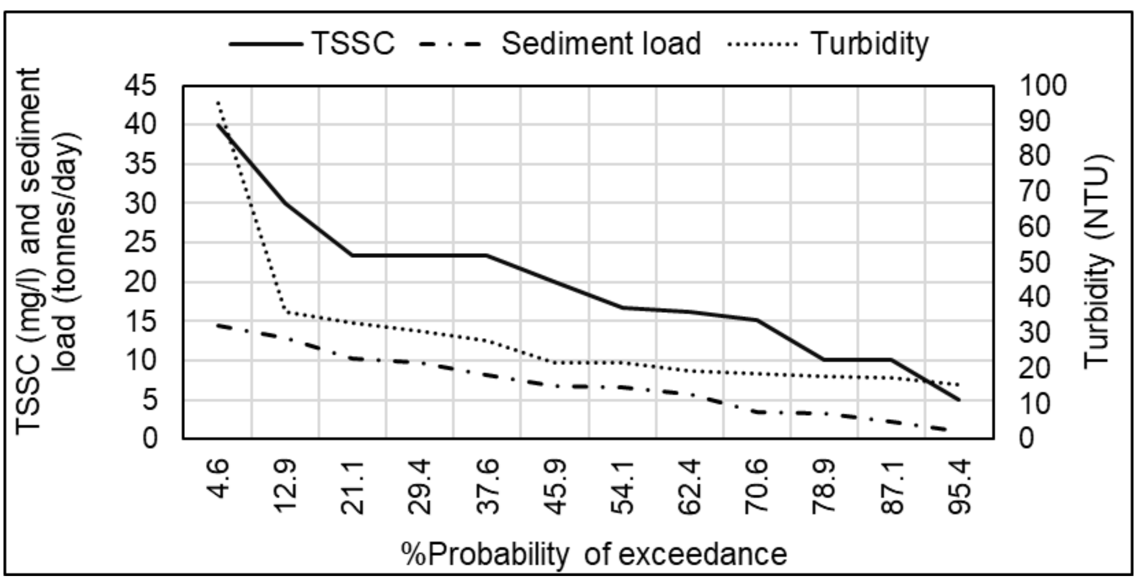


Figure 4.3.6: Duration curves in the Timbilil sub basin (2020-2021)

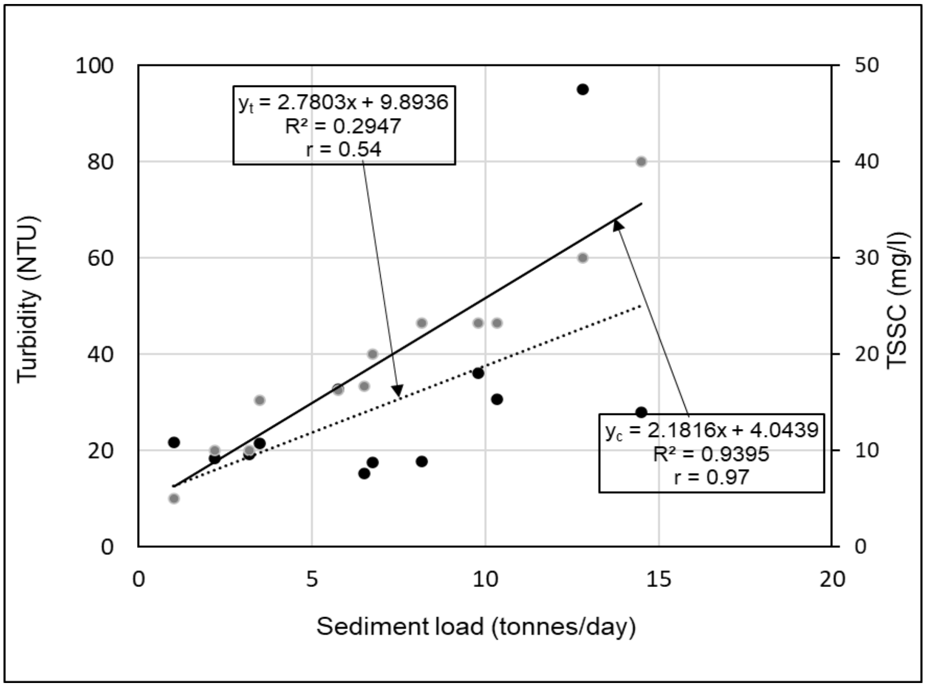


Figure 4.3.7: Relationship between sediment load, turbidity and TSSC (2020-2021)

4.3.2.2 Effects of sub basin dominated by forest land cover on sediment flux

a) Turbidity

The turbidity levels in the Kiptiget sub basin dominated by the forest land cover were high in wet season and low in dry periods. In short rainy season (September-December) turbidity ranged between 15 NTU and 27 NTU while in long rainy season (May-July) it ranged between 18.2 NTU to 18.9 NTU. In dry periods turbidity ranged between 4.3 NTU to 6.9 NTU (Figure 4.3.8). The maximum turbidity in the sub basin was 27 NTU and the minimum was 4.3 NTU. The mean turbidity observed was 17.4 NTU (see Table 4.5). The relationship between turbidity and river discharges in the Kiptiget sub basin was positive with coefficient of determination R^2 of 0.54. The strong positive correlation r of 0.73 at p of 0.05 showed that increase in stream flows raises the turbidity levels. The turbidity duration curve (Figure 4.3.10) showed that in less than 5% of the time in the sub basin the turbidity levels increased to 27 NTU. Further, at 50% of the time turbidity level in the sub basin was 18.2 NTU. In more than 95% of the time in the sub basin the turbidity levels were less than 4.4 NTU.

b) Total Suspended Solids Concentrations (TSSC)

The TSSC in the Kiptiget sub basin dominated by the forest cover showed similar pattern with the pattern of the river discharges (Figure 4.3.8). During the short-wet season, the TSSC observed in the sub basin ranged between 10 mg/l and 28 mg/l. Further in long rainy season the TSSC ranged between 10 mg/l and 25 mg/l. In dry periods the TSSC in the sub basin ranged between 6 mg/l and 10 mg/l. The maximum observed TSSC in the sub basin was 28 mg/l and minimum of 7 mg/l. The mean TSSC in the sub basin was 19 mg/l. The relationship between TSSC and river discharges was positive correlation r of 0.54 and the coefficient of determination R^2 was 0.29 at p of 0.05. The TSSC duration curve (Figure 4.3.10) revealed that in less than 5% of the time the TSSC was 28 mg/l. At 50% of the time 20 mg/l TSSC was observed and at 60% to 70% of the time the TSSC was less than 10 mg/l. The TSSC in more than 95% of the time, the TSSC observed was less than 6.7 mg/l. The relationship between TSSC and turbidity showed positive relation with correlation r of 0.56 and coefficient of determination R^2 of 0.3 at p of 0.06.

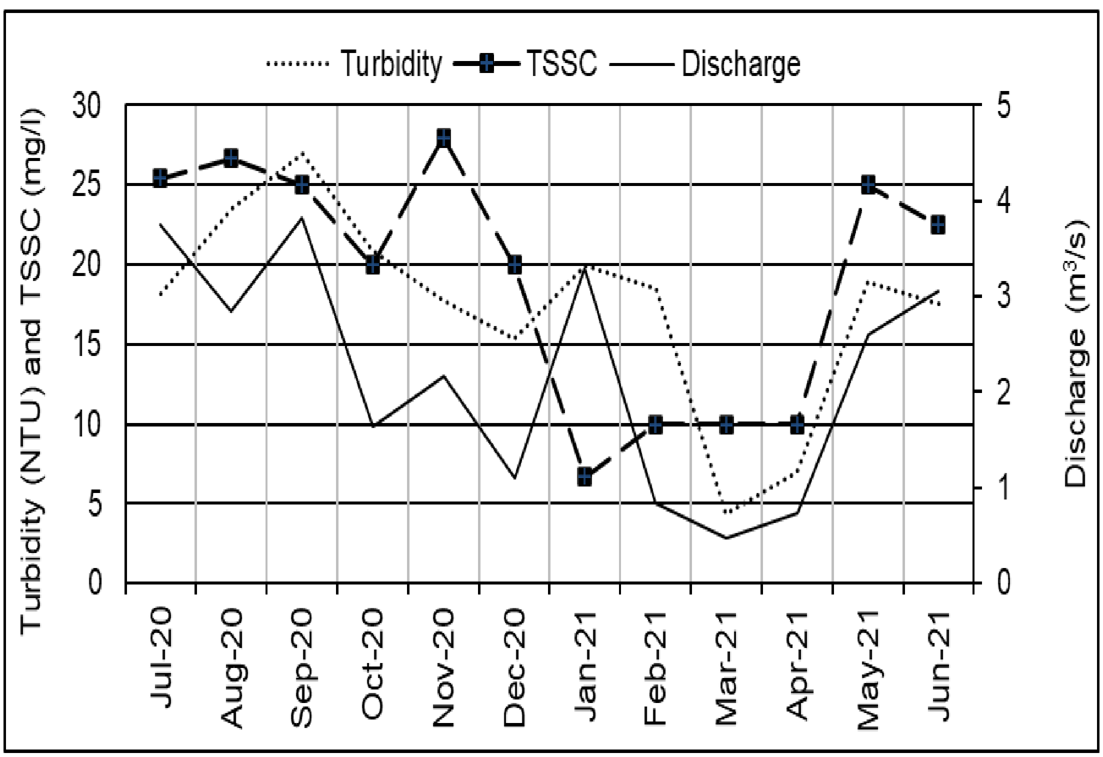


Figure 4.3.8: Turbidity, TSSC and discharges in Kiptiget sub basin (2020 – 2021)

c) Sediment loads

Sediment loads in the Kiptiget sub basin dominated by forest land cover showed that in long rainy season the sediment loads observed ranged between 5 tonnes/day to 8 tonnes/day as shown in Figure 4.3.9. The sediment loads generated in short rainy season ranged 1.9 tonnes/day and 5.6 tonnes/day. In dry months, the sediment loads observed ranged between 0.4 tonnes/day and 1.9 tonnes/day. The maximum sediment load observed was approximately 0.4 tonnes/day. The mean sediment load in the sub basin was 4.02 tonnes/day (Table 4.5). The relationship between sediment loads and the river discharges showed positive relation with the correlation r of 0.86 and coefficient of determination R^2 of 0.74 at $p < 0.05$ This indicates that increase in the stream discharges increases the sediment transport.

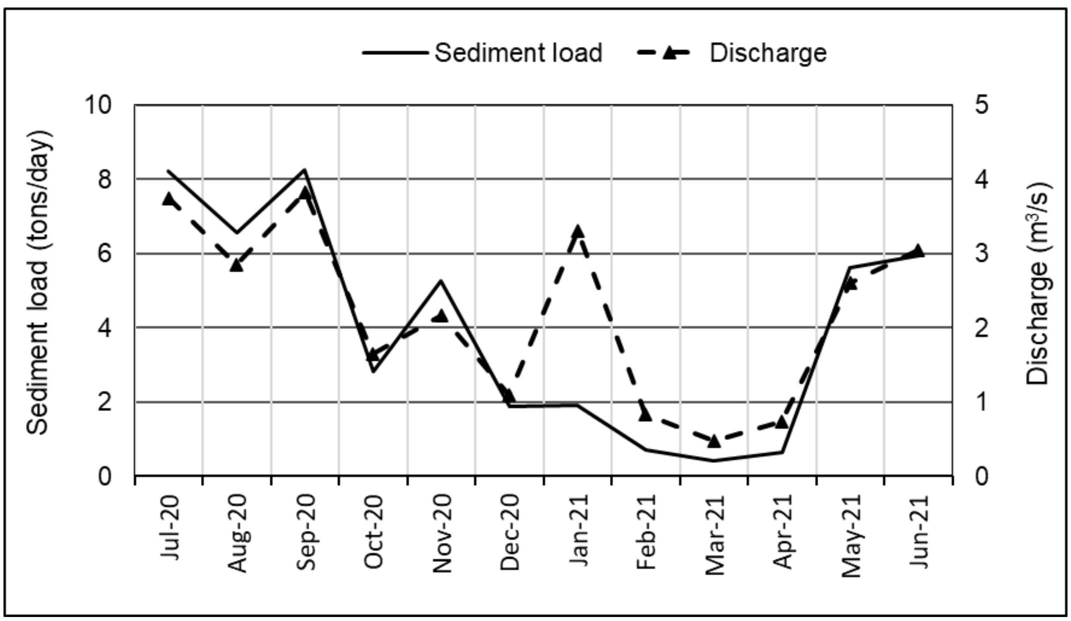


Figure 4.3.9: Sediment loads and discharges in Kiptiget sub basin (2020 – 2021)

The relationship between the sediment loads and turbidity showed positive significant relation with correlation r of 0.67 and coefficient of determination R^2 of 0.44 at $p<0.05$ (Figure 4.3.11). Further the relationship between sediment loads and TSSC showed significant relation with correlation r of 0.85 and coefficient of determination R^2 of 0.73 at $p < 0.05$. These high positive correlation between sediment loads and turbidity and TSSC showed that the surface runoffs transport sediments into the water system in the sub basin. The sediment load duration curves (Figure 4.3.10) indicated that more than 95% of the time, the sediment load observed was less than 0.4 tonnes/day. In less than 5% the time the sediment loads were greater than 8 tonnes/day. In the 50% of the time the sediment loads were 2.8 tonnes/day and 70% of the time the sediment loads observed were 1.9 tonnes/day.

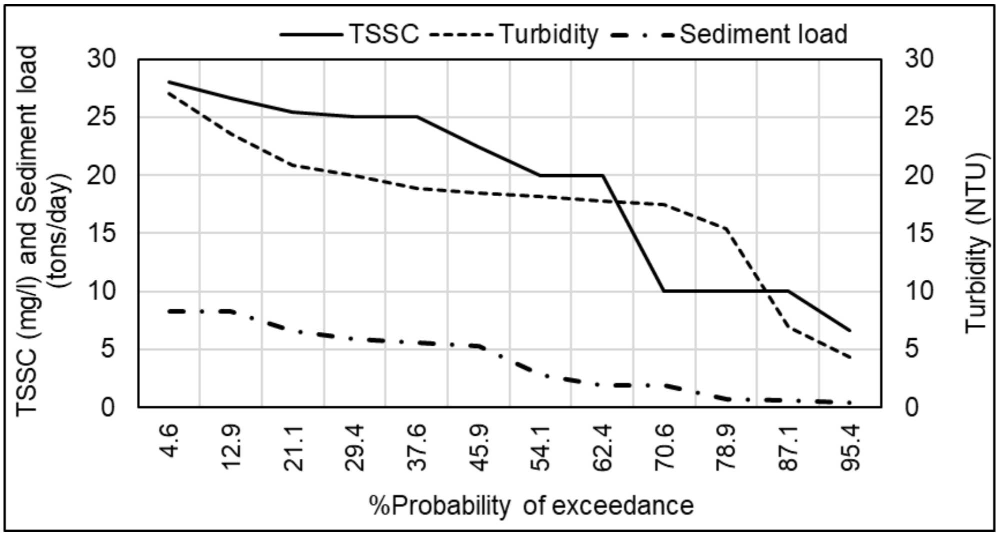


Figure 4.3.10: Turbidity, sediment load and TSSC curves for Kiptiget sub basin

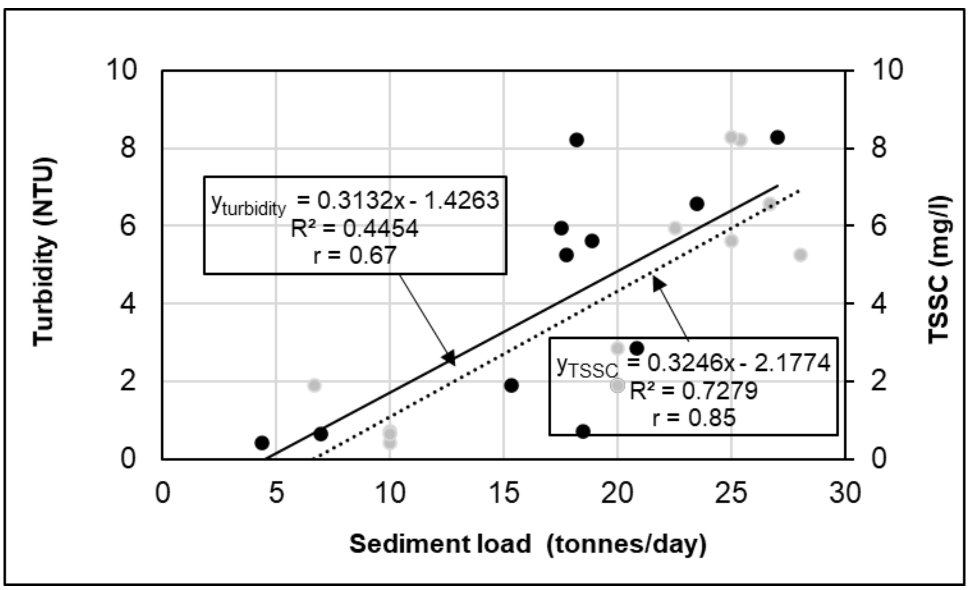


Figure 4.3.11: Relationship between sediment loads, turbidity and TSSC in the Kiptiget sub basin (2020 – 2021**)**

4.3.2.3 Effects of sub basin dominated by mixed farming land uses on sediment yields

a) Turbidity

The patterns of variability in turbidity in the sub basin dominated by mixed farming are presented. These seasons were the post-harvest period (September – December), pre planting period (January – March) and crop growing season (April – August). The turbidity in the post-harvest period ranged between 71 NTU and 112 NTU. The maximum observed turbidity in this period was 112 NTU while the minimum was 71 NTU. The mean turbidity for the post harvest season was 85 NTU. In the pre planting season it was noted that the turbidity levels ranged between 91NTU and 637 NTU (see Figure 4.3.12). The maximum turbidity observed in this season was 637 NTU while the minimum was 91 NTU. The mean value was 335 NTU. In the crop growing season the turbidity levels ranged between 80 NTU and 115 NTU. The maximum observed value was 115 NTU and the minimum was 80 NTU with the mean value of 94 NTU. The overall results showed that in the wet season the turbidity levels ranged between 80 NTU and 637 NTU. In dry season the turbidity ranged between 77 NTU and 279 NTU. The maximum turbidity level in the sub basin was 637 NTU while the minimum was 71 NTU. The mean turbidity level was 151 NTU (see Table 4.5).

The relationship between turbidity and river discharge in the Kipsonoi sub basin was positive response with coefficient of determination R^2 of 0.08 and correlation r of 0.28 at $p = 0.05$. The turbidity duration curve indicated that at less than 5% of the duration in the sub basin the turbidity levels were greater than 600 NTU. This was much lower than those reported in the Upper Athi river basin which reaches 1000 NTU (Kitheka et al., 2022). On the other hand, in more than 95% of the time the turbidity levels were less than 71 NTU. In addition, the 50% and 70% of the time the water in the river system in the sub basin experience turbidity approximately 91 NTU and 80 NTU respectively (see Figure 4.3.14).

b) Total Suspended Solids Concentrations (TSSC)

The TSSC in the Kipsonoi sub basin dominated by mixed farming showed high variability in the post- harvest, pre-harvest and active crop growing seasons. This variability had similar pattern with the river discharges. In the post-harvest period, the TSSC ranged between 56 mg/l and 140 mg/l. In the pre-planting period, the TSSC ranged between of 70 mg/l and 620 mg/l. In the crop growing season the TSSC in the sub basin ranged between 100 mg/l and 175 mg/l. The observed maximum and minimum TSSC in the sub basin were 62 mg/l and 56 mg/l respectively (see Figure 4.3.12). The mean observed TSSC in the sub basin was 165 mg/l (see Table 4.5). In this sub basin significant relationship between TSSC and turbidity was observed with coefficient of determination R^2 of 0.97 and the correlation r of 0.98 at $p < 0.05$. The TSSC duration curve (Figure 4.3.14) showed that at less than 5% of the time, the TSSC was greater than 600 mg/l. In the 50% and 70% of the time, the TSSC in the sub basin were 100 mg/l. Further in the time greater than 95% the TSSC was found to be less than 70 mg/l.

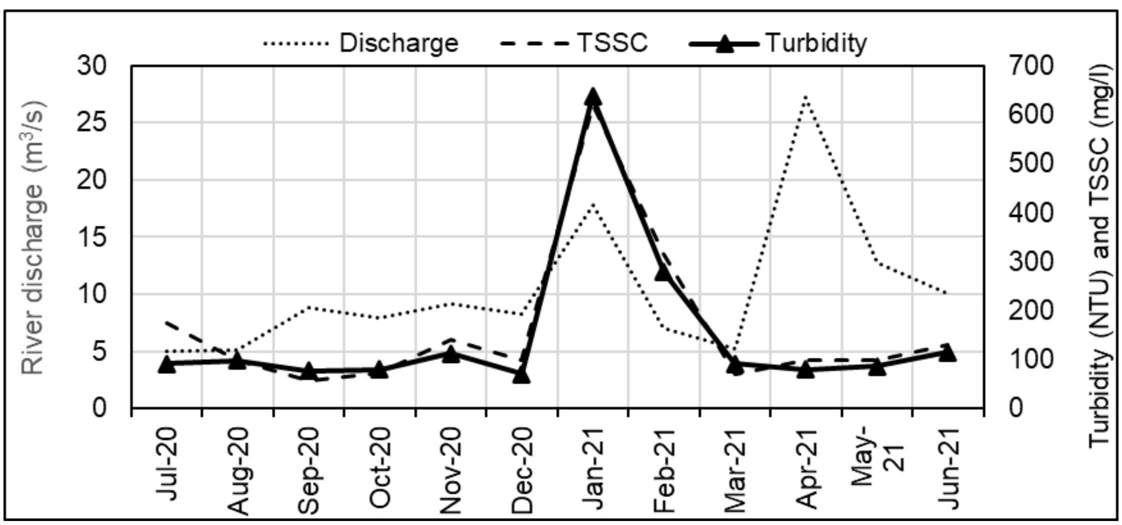


Figure 4.3.12: Turbidity, TSSC and stream discharges in the Kipsonoi sub basin in the period 2020 – 2021

c) Sediment loads

The sediment loads observed in the Kipsonoi sub basin dominated by mixed farming land use showed that the peak sediment load occurred in pre planting season (see Figure 4.3.13).

The sediment loads in the sub basin during pre-planting season ranged between 190 tonnes/day and 952 tonnes/day. In the post harvesting season, the sediment loads ranged between 42 tonnes/day and 110 tonnes/day. During crop growing periods sediment loads observed ranged from 31 tonnes/day to 113 tonnes/day. The maximum sediment loads observed in the sub basin was 952 tonnes/day and minimum sediment load of 31 tonnes/day. The mean sediment load in the sub basin observed was 169.1 tonnes/day (Table 4.5). It was also observed that stream discharges increased with the rise in the sediment loads in the post harvesting and pre planting season while in the crop growing season rise in the stream discharges to 27 m^3/s could not increase sediment loads.

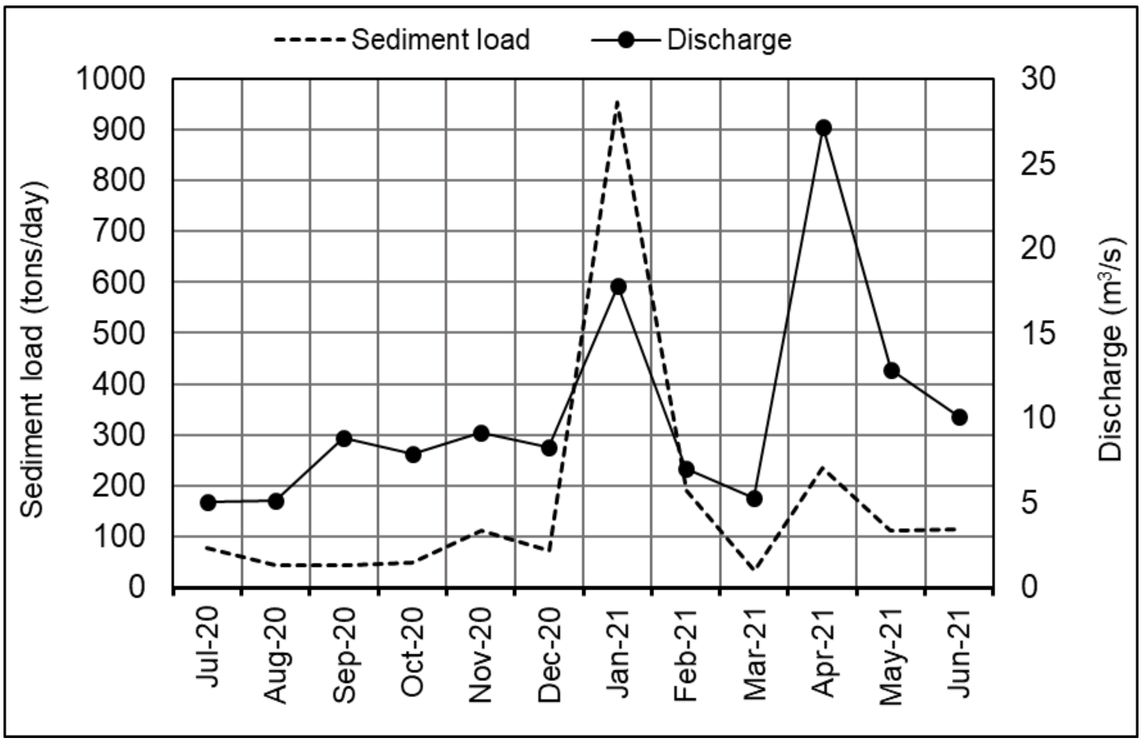


Figure 4.3.13: Sediment loads and stream discharge in sub basin dominated by mixed farming land use (2020 – 2021)

The significant relationship between sediment loads and TSSC was strong positive with values of R^2 of 0.87 and correlation r of 0.93 at $p < 0.05$. Further significant relationship between sediment loads and turbidity showed high positive relation with R^2 of 0.904 and correlation r of 0.95 at $p < 0.05$. This showed that more than 95% of the turbid water in the

Kipsonoi River was caused by suspended sediments. The sediment duration curve (Figure 4.3.14) showed that in less than 5% of the time in the sub basin the sediment loads were more than 950 tonnes/day. Also, the sediment loads at 50% and 70% were 76 tonnes/day and 50 tonnes/day respectively. In more than 95% of the time in the sub basin the sediment loads were less than 32 tonnes/day.

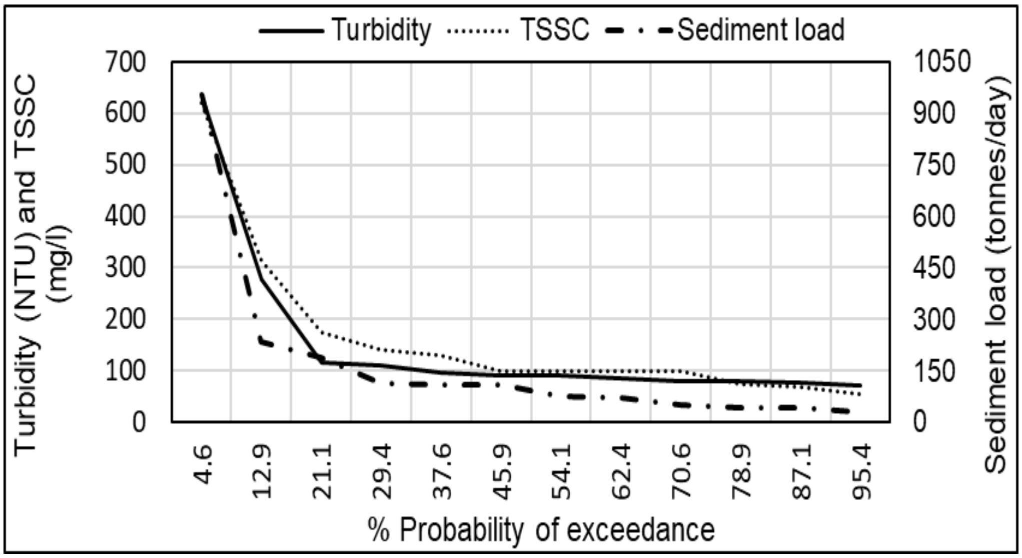


Figure 4.3.14: Turbidity, TSSC and sediment loads duration curve in the Kipsonoi sub basin (2020 – 2021)

4.3.2.4 Effects of mixed land covers/land uses on sediment flux

a) Turbidity

The turbidity in the Sondu Miriu River Basin with mixed land covers/land uses (mixture of tea plantations, forests and mixed farming) showed that turbidity was higher in wet season than dry season. These results were observed at Sondu Bridge and in the long rainy season, the turbidity ranged between 70 NTU and 84 NTU. Further, in the short rainy season the turbidity ranged between 62 NTU and 231 NTU. In the dry periods the turbidity in the river basin ranged between 60 NTU and 68 NTU. The maximum turbidity in the river basin was 231 NTU while the minimum was 60 NTU. The mean turbidity in the basin was 85.1 NTU (see Table 4.5). The maximum turbidity values obtained in this study were slightly higher than 141 NTU observed in Sondu Bridge reported in 2012 (Masese et al., 2012).

The relationship between turbidity and river discharges showed positive relation with correlation r of 0.62 and coefficient of determination R^2 of 0.38 at p = 0.05. The turbidity duration curve showed high variability and in less than 5% the turbidity levels were greater than 230 NTU. At 50% of the time, the turbidity levels were about 67 NTU. In more than 95% of the time, the turbidity levels were less than 60 NTU. Comparing turbidity levels in the sub basins dominated by tea plantations, forests and mixed farming (Figure 4.3.15) showed that mixed farming dominates the Sondu Miriu River Basin with about 700 NTU. The high turbidity values in the mixed land cover were similar to turbidity observed in Itare sub basin by Nyangaga (2008).

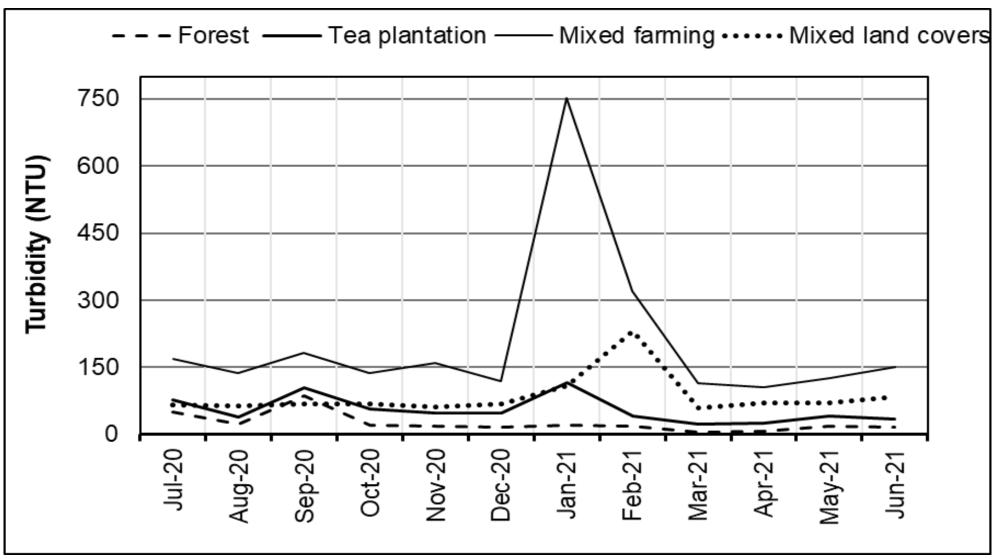


Figure 4.3.15: Turbidity in dominant and mixed land covers in 2020-2021

b) Total Suspended Solid Concentrations

The TSSC in the Sondu Miriu River Basin during dry season ranged between 700 mg/l and 960 mg/l. The TSSC during short rainy seasons in the river basin ranged between 47 mg/l and 260 mg/l. In addition, during long rainy season the TSSC ranged between 76 mg/l and 80 mg/l. The maximum TSSC observed in the river basin was 260 mg/l while the minimum

TSSC was 46 mg/l. The mean TSSC in the river basin was 103 mg/l (see Table 4.5). The pattern of TSSC responded positively to changes of the river discharges during short rainy seasons (April - June). But during long rainy season the TSSC responded negatively to the increase in the river discharges. This study showed that since 2012 TSSC has increased over time from 67 mg/l in 2012 reported by Masese et al. (2012) to 103 mg/l in 2021.

The relationship between TSSC and river discharges in the Sondu River Basin with combined land uses showed negative relation with correlation r of - 0.45 and the coefficient of determination R^2 of 0.21 at p of 0.05. The relationship between TSSC and turbidity was significant with coefficient of determination R^2 of 0.77 and the correlation r of 0.88 at $p < 0.05$. The TSSC duration curve (Figure 4.3.16) showed in less than 5% of the time in the river basin the TSSC observed were greater than 0.26 g/l. At 50% of the duration the TSSC was 0.08 g/l. Further it was noted that at 70% of the time in the river basin, the TSSC was 70 mg/l. In more than 95% of the time, the TSSC was less than 47 mg/l. Comparing TSSC for the sub basins dominated by tea plantations, forests and mixed farming indicated that mixed farming activities causes high transport of suspended sediments in the river basin of approximately 600 mg/l.

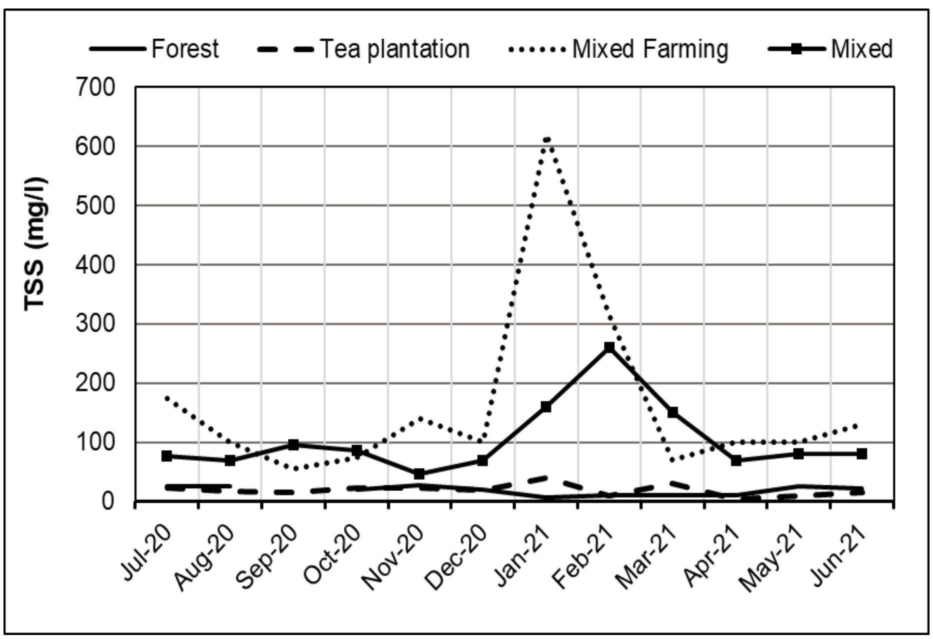


Figure 4.3.16: TSSC in sub basins dominated with tea plantation, forest, mixed farming and mixed land covers

c) **Sediment loads**

Sediment loads in the Sondu Miriu River Basin with combined land covers/land uses showed similar pattern with river discharges except in long rainy season (Figure 4.3.17). The sediment loads during short rainy season between 127 tonnes/day and 631 tonnes/day. In the long rainy season, the sediment loads observed ranged between 246 tonnes/day to 272 tonnes/day. In the dry periods, the sediment loads ranged between 75 tonnes/day and 150 tonnes/day. The maximum sediment load was 631 tonnes/day while the minimum sediment load was 75 tonnes/day. The mean sediment load observed was 227.1 tonnes/day (see Table 4.5).

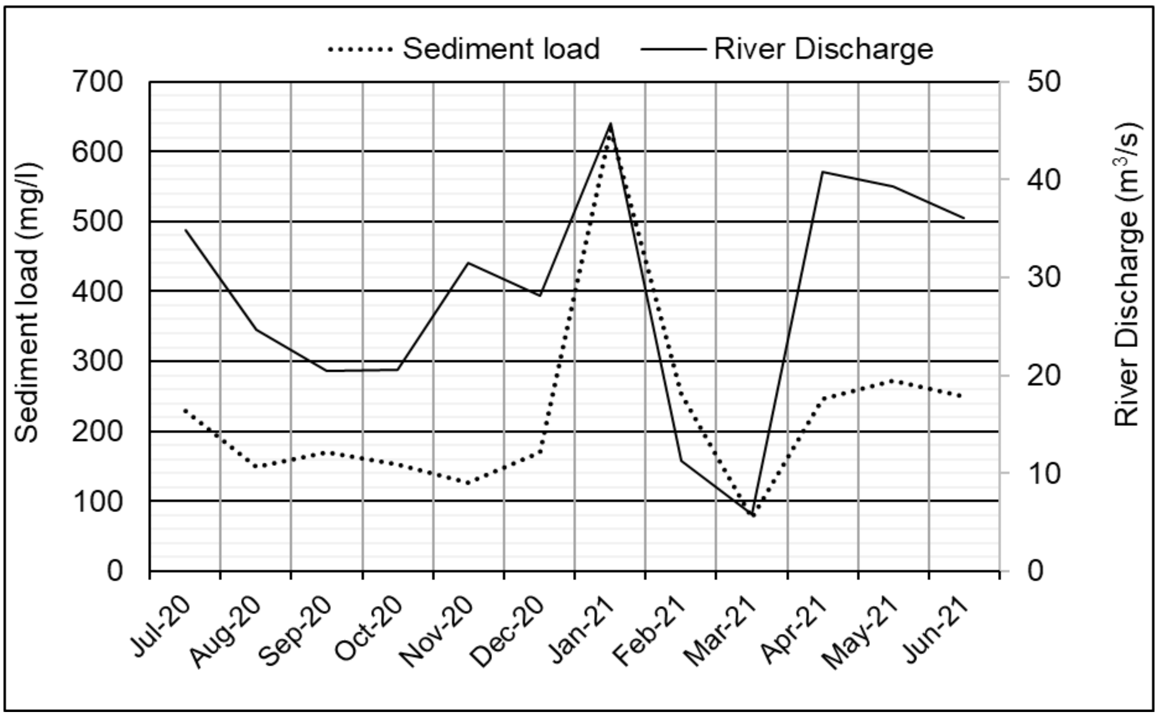


Figure 4.3.17: Sediment loads and river discharges in the Sondu Miriu River Basin in the period 2020 – 2021

The relationship between the sediment loads and river discharges was significant with coefficient of determination R^2 of 0.4 and correlation r of 0.63 at $p < 0.05$. While insignificant relationship was observed between TSSC and sediment yields with the coefficient of determination R^2 was 0.104 and r of 0.32 at $p > 0.05$. Unlike sub basins with dominant land uses, mixed land covers showed insignificant relationship between sediment loads and turbidity with coefficient of determination R^2 of 0.1 and correlation r of 0.32 at $p > 0.05$. Indicating that not all sediments from the upper catchments causes turbidity. The sediment duration curve indicated that less than 5% of the time high sediment loads were transported more than 631 tonnes/day. At 50% of the time the sediment loads were about 170 tonnes/day and at 70% of the time the sediment load was approximately 152 tonnes/day. Further, in more than 95% of the time the sediment loads observed were less than 75 tonnes/day. The comparison between sediment loads generated in different sub basins dominated land uses showed that high sediment loads of about 900 tonnes/da originated from the sub basins dominated by mixed farming land cover in the river basin (see Figure 4.3.18).

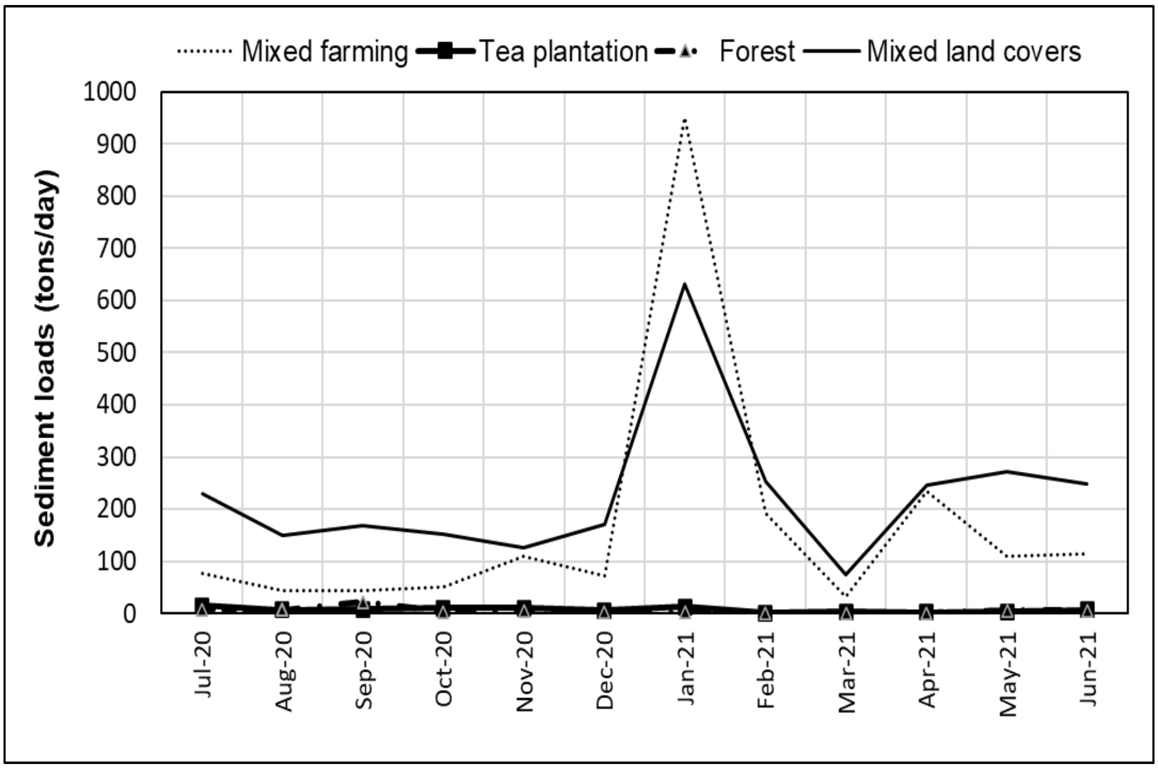


Figure 4.3.18: Sediment loads in sub basins dominated by tea plantation, forest, mixed farming and mixed land covers

Table 4.5: Magnitudes of TSSC, turbidity and sediment load in sub basins dominated by different land uses

Sub basins		Maximum	Minimum	Mean	50%	Remarks
Sub basin dominated by tea plantations	TSSC (mg/l)	40	10	19	16.7	Low TSSC
	Turbidity (NTU)	95	15.2	29.5	21.5	Moderate turbidity
	Sediment (tons/day)	14.5	1.02	7.05	6.52	Low sediment load
Sub basin dominated by forest cover	TSSC (mg/l)	28	7	19	20	Low TSSC
	Turbidity (NTU)	27	4.3	17.4	18.2	Low turbidity levels
	Sediment (tons/day)	8.3	0.4	4.02	2.8	Low sediment load
Sub basin dominated by mixed farming	TSSC (mg/l)	620	56	164	100	High TSSC
	Turbidity (NTU)	637	71	151.4	91	High turbidity levels
	Sediment (tons/day)	952	31.9	169.1	76.4	High sediment load
Mixed land cover Sondu Miriu Basin	TSSC (mg/l)	260	47	104	80	High TSSC
	Turbidity (NTU)	231	60	85.1	68	High turbidity levels
	Sediment (tons/day)	631.5	75.5	227.1	170.4	High sediment load

4.4 Simulation of stream flows and sediment yield in dominant land cover sub basins

The developed SWAT model for Sondu Miriu River Basin was calibrated with daily discharges in the periods 1960 to 1980 while validation period was January 1981 to February 1997. The calibration output showed a good balance between the model generated data and observed stream discharges data (Figure 4.4.1). The model yielded a coefficient of determination R^2 of 0.8 and Nash–Sutcliffe model efficiency value (NSE) of 0.78 which indicated that the model output performance was good. The simulated mean stream discharge at RGS 1JG03 was 60.98 m^3/s while the observed mean discharge was 59.10 m^3/s. This shows that model tended to overestimate the river discharges by an average of 1.88 m^3/s. The standard deviation of the simulated and observed discharges was 51.65 m^3/s and 49.07 m^3/s respectively. The deviations of the simulated discharges from the observed discharges showed standard deviation error of ± 13.1.

The validation of the model in the period 1981-1997 revealed that the peak and low discharges were well simulated (Figure 4.4.2). The relationship between simulated and observed river discharges showed good positive relation with coefficient of determination was R^2 of 0.75 and NSE value of 0.6. The 95% confidence level for the simulated discharges was 7.74 m^3/s that is very close to the observed discharges with its confidence value of 7.48 m^3/s.

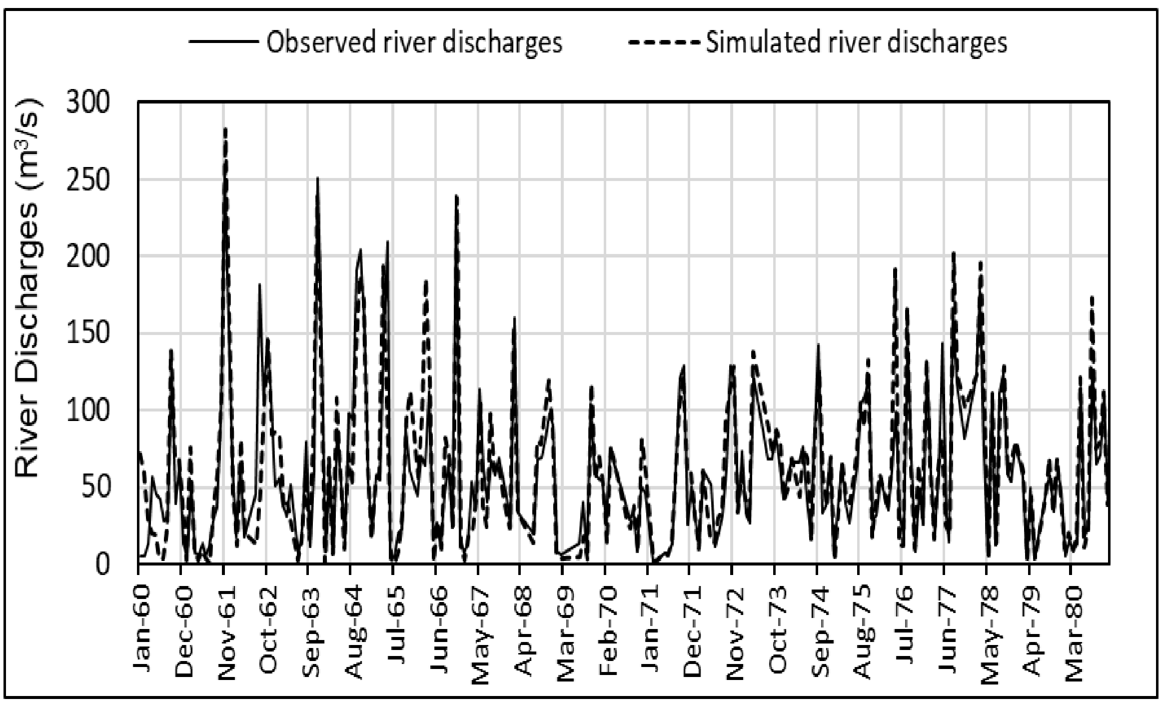


Figure 4.4.1: Comparison between simulated and observed river discharges in calibration (1960 – 1980)

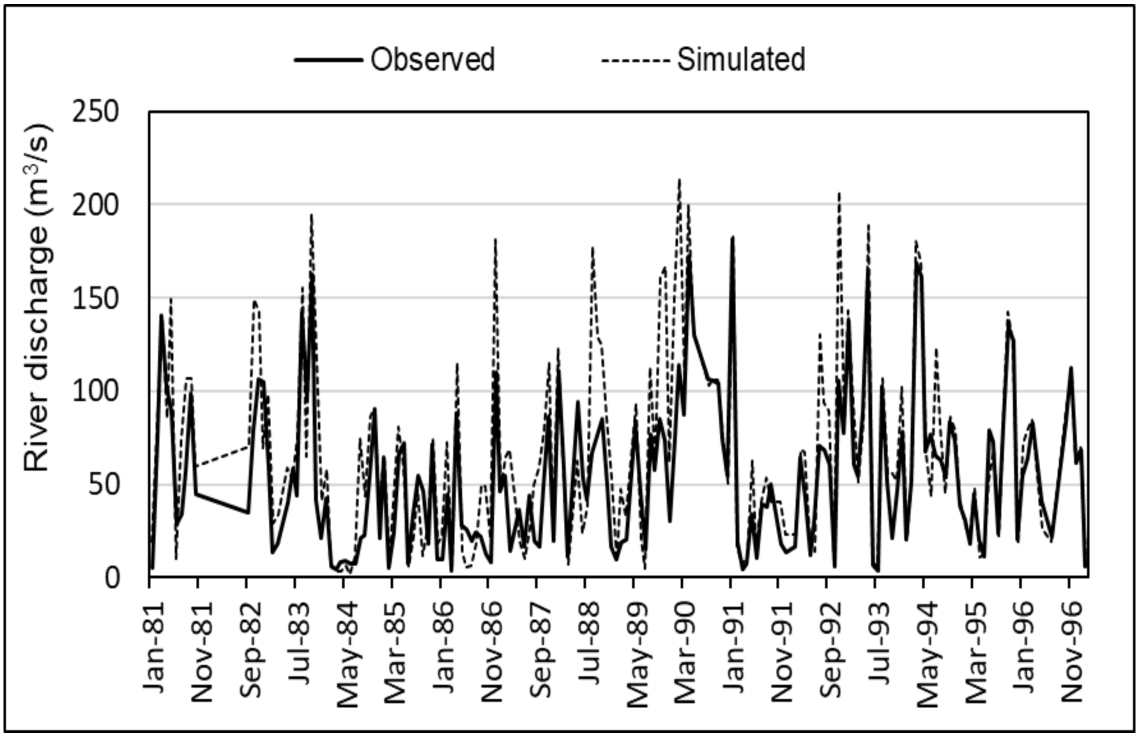


Figure 4.4.2: Simulated and observed stream discharges in validation (1981 – 1997)

4.4.1 Simulation of stream flows in sub basins with dominant land covers

4.4.1.1 Simulation of stream flows in sub basin dominated by tea plantations

Patterns of stream flows and area under tea plantations showed similar trends (Figure 4.4.3). For example, in the period 1975-1990 the discharges and base flows increased especially in 1970s with the increase of the tea plantations land cover. In the 1975 to 1990s an increase in land area under tea plantations by 14 km^2 and rise in stream discharges by 7 m^3/s, surface runoff by 2 m^3/s and base flow by 5 m^3/s. The results in the period between 2000 and 2021 indicated that expansion of tea plantations land cover increases the discharges and base flows. The increasing trends in the discharges and rainfall in the period between 1961 and 1979 indicated that rainfall contributes to changing patterns of stream flows in the sub basin. In the period 1979 – 1988 the discharges decreased by about 3.5 m^3/s, base flow by 2m^3/s and surface runoffs by 1.5 m^3/s despite the increase in the area under tea plantation.

Similarly in the period 1997 and 2018 discharges decreased from 16 m^3/s to 7 m^3/s while area under tea plantations was expanding. Decrease river discharges, base flows and surface runoffs in the periods 1979 – 1988 and 1997 to 2018 rainfall decreased by 300 mm and 700 mm affecting the stream flows. The peak discharges increased from about 10 m^3/s to peak of 17 m^3/s between 1990 and 2020. The maximum discharge was 17.35 m^3/s and it occurred in 1998 during the El Nino period. The minimum discharge was 5.66 m^3/s and it occurred in 1960. The average discharge was 10.8 m^3/s. The future projections of stream flows with the changes in the area under tea plantations between 2020 - 2090 showed continuous expansion of tea plantations by 46%. In this projection period, the discharges increased by about 7.5 m^3/s (Figure 4.4.4).

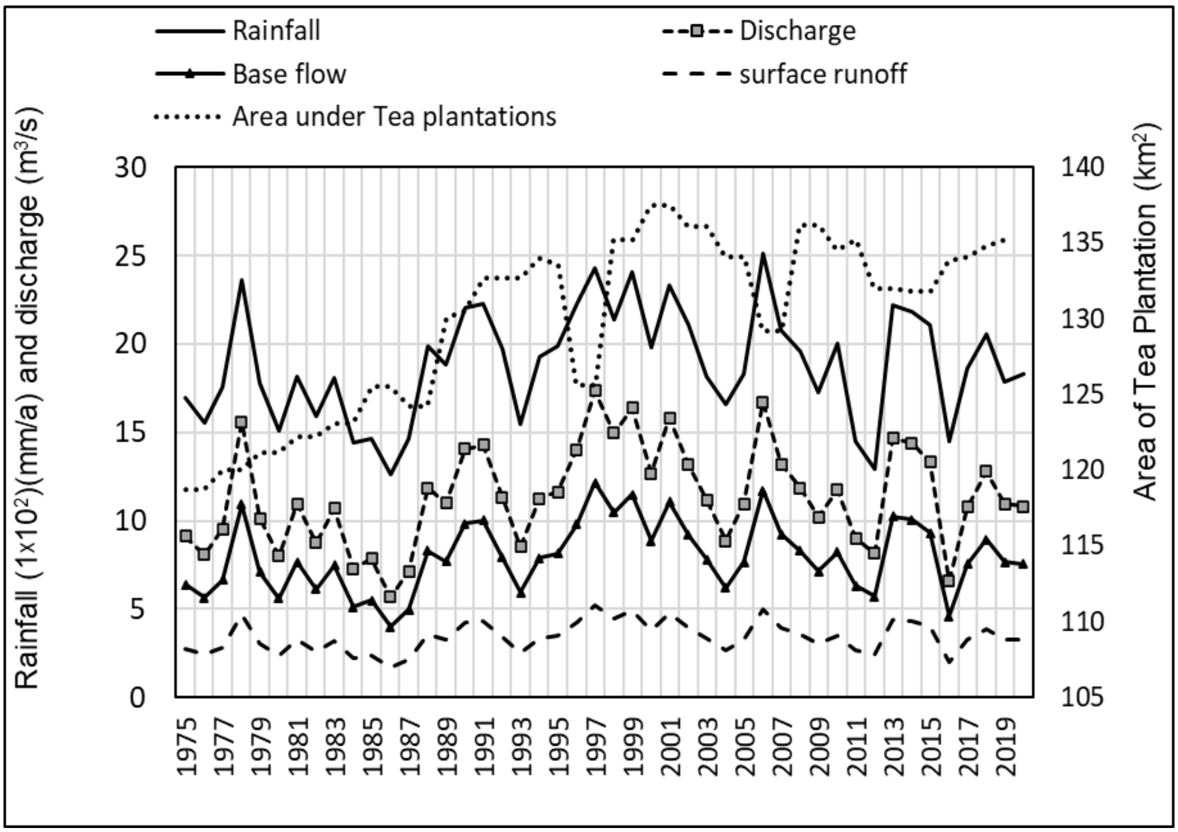


Figure 4.4.3: Rainfall, discharge, base flow, surface runoffs and area in tea dominant sub basin (1975-2020)

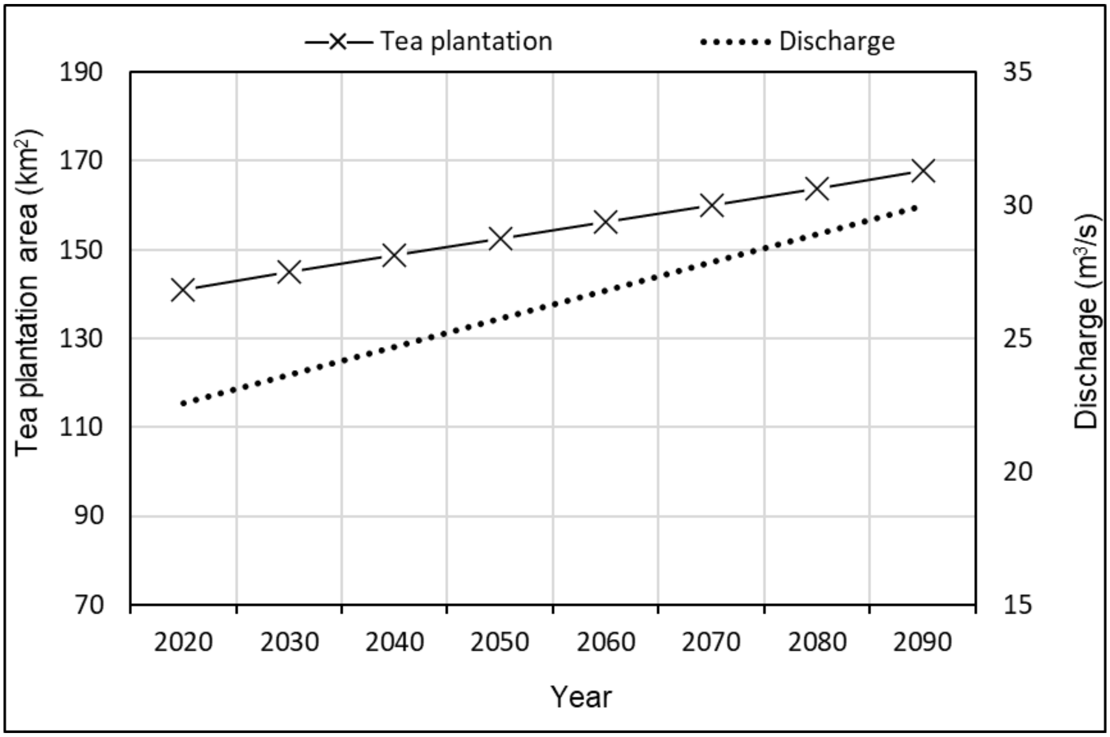


Figure 4.4.4: Projected of discharges and area under tea plantations in Timbilil sub basin in the period 2020 – 2090

4.4.1.2 Simulation of stream flows in the sub basin dominated by forest land cover

The long-term stream flows in the sub basin dominated by forest land cover indicated a decline in the forest land cover from 1985 and led to an increase of surface runoffs and hence raises the discharge peaks as depicted in Figure 4.4.5. In 1971 peak river discharge of magnitude 5.6 m^3/s occurred and the peak return period recurred in 1998 with river discharge of 7.5 m^3/s. In the period 1986 - 2001 decrease in the land area under forest cover by approximately 16 km^2 occurred while surface runoffs increased raising discharges by 5 m^3/s. However, the land area under forest cover was expanded as shown from 2006 to 2014 by approximately 7.35 km^2 caused a reduction in the peak discharges in the same period. The river discharges increased in the period 1986 - 2006 by 5.4 m^3/s, surface runoffs by 2.2 m^3/s and base flow by 3 m^3/s. In the period between 1985 and 1994/1997 there is an increase in stream flows, baseflows while the forest cover was decreasing. In the period between 1997 and 2016 there is a decrease in the discharge by 4.5 m^3/s, baseflow by 2.9 m^3/s and surface runoffs by 1.6 m^3/s. In the period between 1997 – 2008 decline in the forest occurred and the rainfall increased by about 450 mm (Figure 4.4.6). The maximum stream discharge was 7.5 m^3/s while the minimum discharge was 2.02 m^3/s. The mean stream discharge in the sub basin was 4.5 m^3/s. The mean surface runoffs were 1.8 m^3/s consisting approximately 40% of the average discharge and mean base flow by 2.7 m^3/s consisting of about 60% of the mean stream discharge.

The projections in the period 2020 - 2090 revealed that area under the forest cover will decline by 56% if deforestation continuous. In the similar period decline in the forest cover will increase the surface runoffs and discharges by 43% and 42% respectively (Figure 4.4.7). On the other hand, the projected increment of the area under forest cover in the sub basin by 14 km^2 can reduce surface runoffs by 23.8% and peak discharge by 23.6% (Figure 4.4.8).

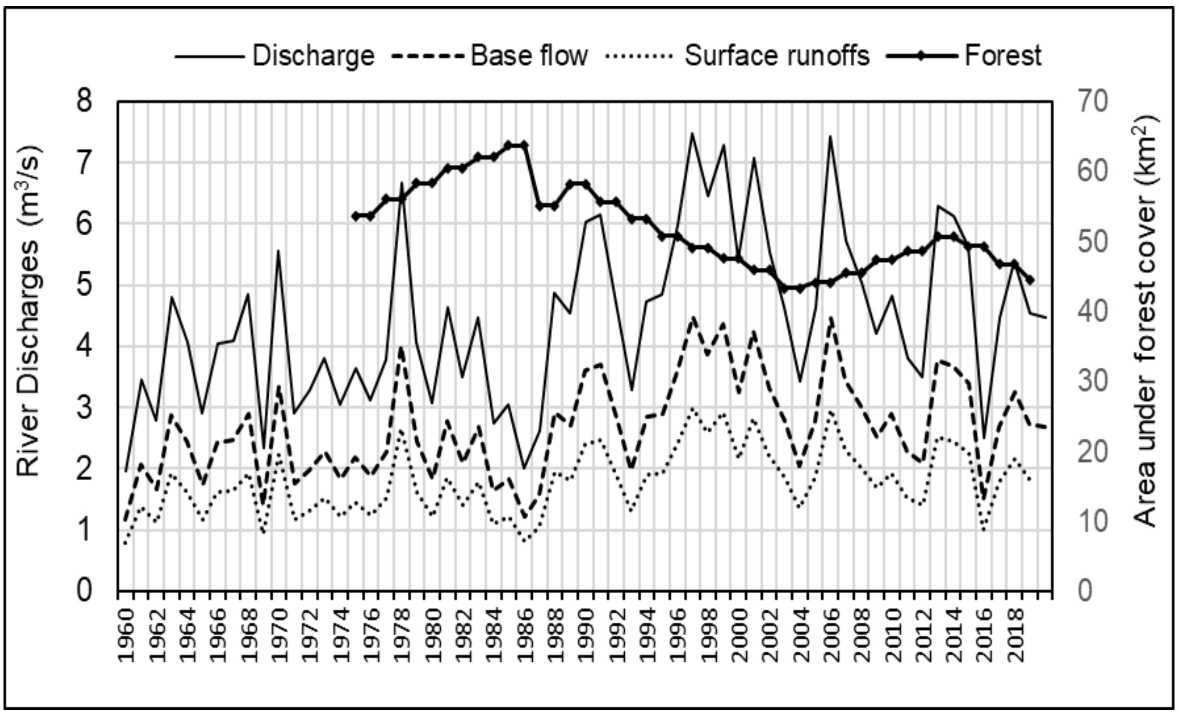


Figure 4.4.5: Stream discharges, surface runoffs and forest cover in Kiptiget sub basin (1961-2020)

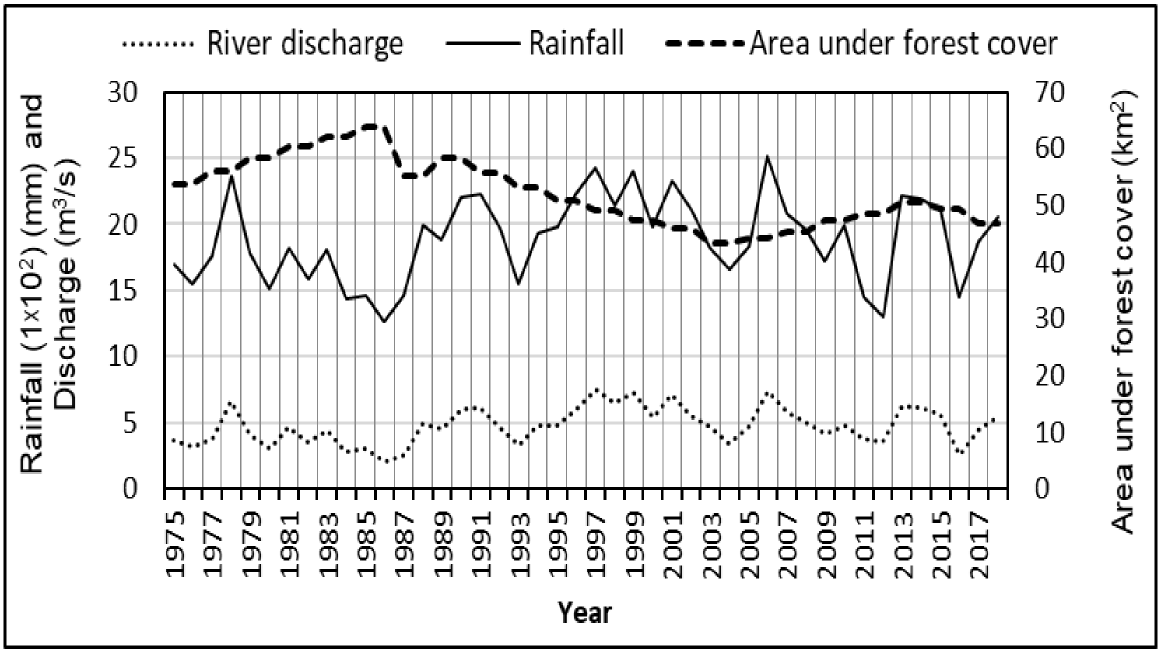


Figure 4.4.6: Stream discharges, rainfall and forest land cover in the sub basin (1975 – 2021)

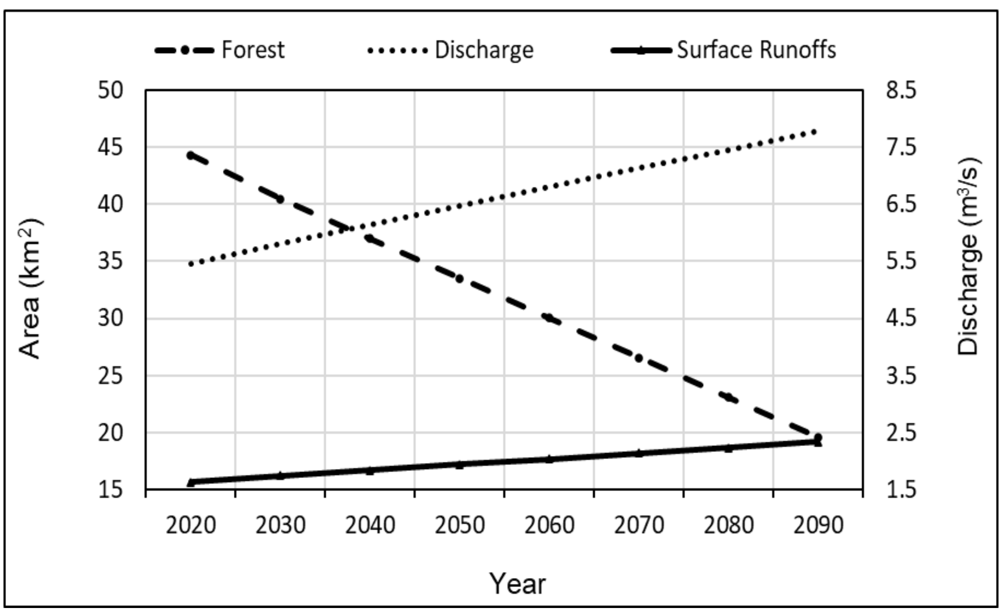


Figure 4.4.7: Projected stream flows, surface runoffs and forest in the Kiptiget sub basin (2020 – 2090)

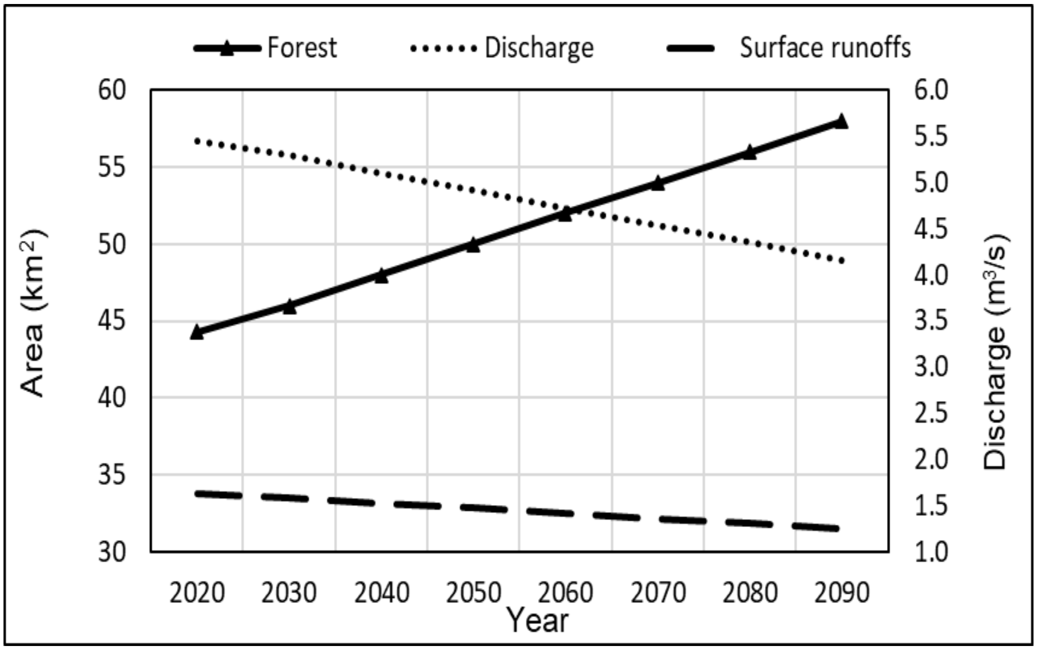


Figure 4.4.8: Predicted stream flows, surface runoffs and forest in the Kiptiget sub basin (2020 – 2090)

4.4.1.3 Simulation of stream flows in sub basin dominated by mixed farming land cover

Stream flows in the sub basin dominated by mixed farming showed significant inter annual variability. There were also significant trends in stream flow in the periods 1961 – 1983, 1986 – 1997, 2001 – 2013 and 2014 - 2020. Attempt was made to relate the observed trends on stream flows to changes in the area under mixed farming. In the period between 1961 and 1983, there was an increase in discharge by about 18 m^3/s and surface runoffs by approximately 10 m^3/s (Figure 4.4.9). In the period 1975 – 1983 there was a reduction of the land area under mixed farming by about 100 km^2 and discharge decreased by approximately 22 m^3/s. In the period 1986 – 1997 there was an increase in the discharges and surface runoffs by 34 m^3/s and 19 m3/s respectively. In this period the base flow increased by 2 m^3/s and the area under mixed farming increased by 56 km^2. from 19 m^3/s in 1986 to 43 m^3/s in 1997. In the period between 2001 and 2013 there was a significant decrease in the discharges in the sub basin by 52 m^3/s. In this period, the change in the area of land under mixed farming decreased by about 22 km^2 and rainfall reduced by 1150 mm

(Figure 4.4.10). Further in the period between 2014 and 2020 the stream flows increased from 13 m^3/s in 2014 to 33 m^3/s in 2020. The maximum stream discharge was 57.2 m^3/s while minimum discharge was 10.89 m^3/s. The mean stream discharge was 32.4 m^3/s. Mean surface runoffs was 28.2 m^3/s consisting about 88% of mean stream discharge while mean base flow was 4 m^3/s comprising 12% of the mean stream discharge. The future projections showed that the land area under mixed farming reduces at a rate of 1 km^2 per annum. In the period 2020 – 2090, the area of land under mixed farming was estimated to reduce by almost 55 km^2 while discharges were expected to decrease by 4 m^3/s (Figure 4.4.11). On the other hand, in the period 2020 – 2090 an increase in the area of land under mixed farming by 194 km^2 will increase discharges by 14 m^3/s in 2090 (Figure 4.4.12).

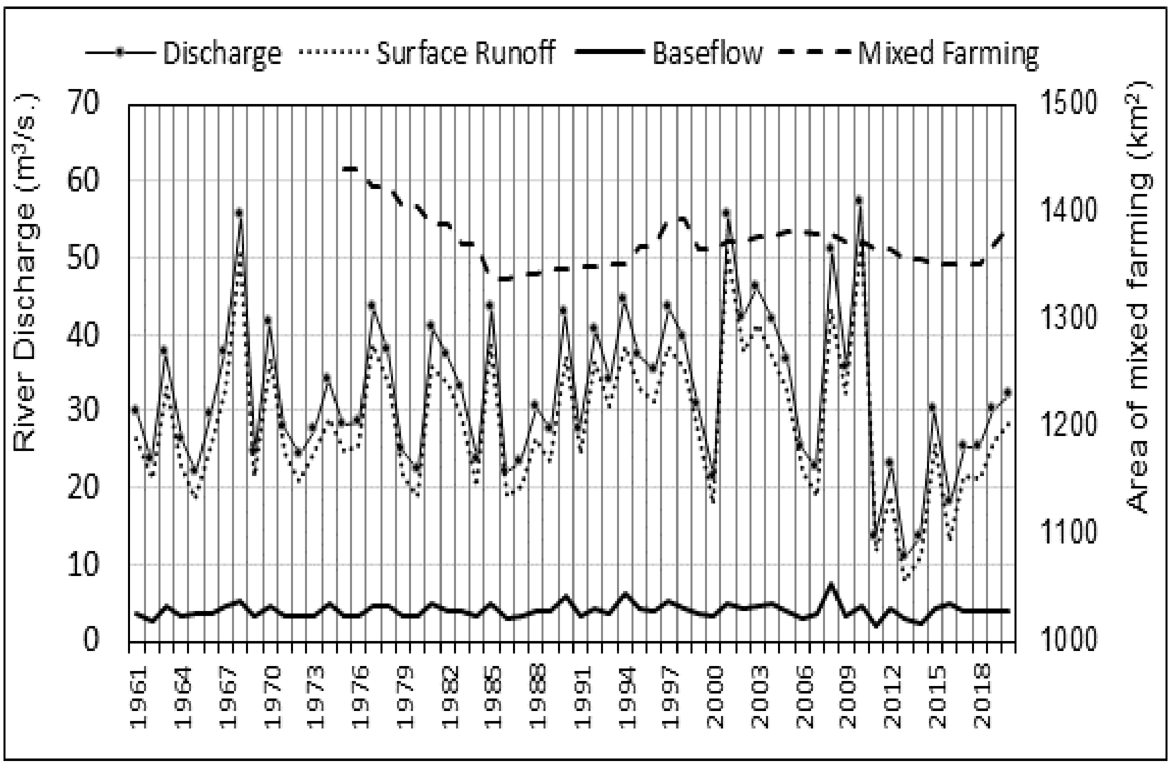


Figure 4.4.9: River discharges, surface runoffs, base flows and mixed farming in the Kipsonoi sub basin (1961 – 2020)

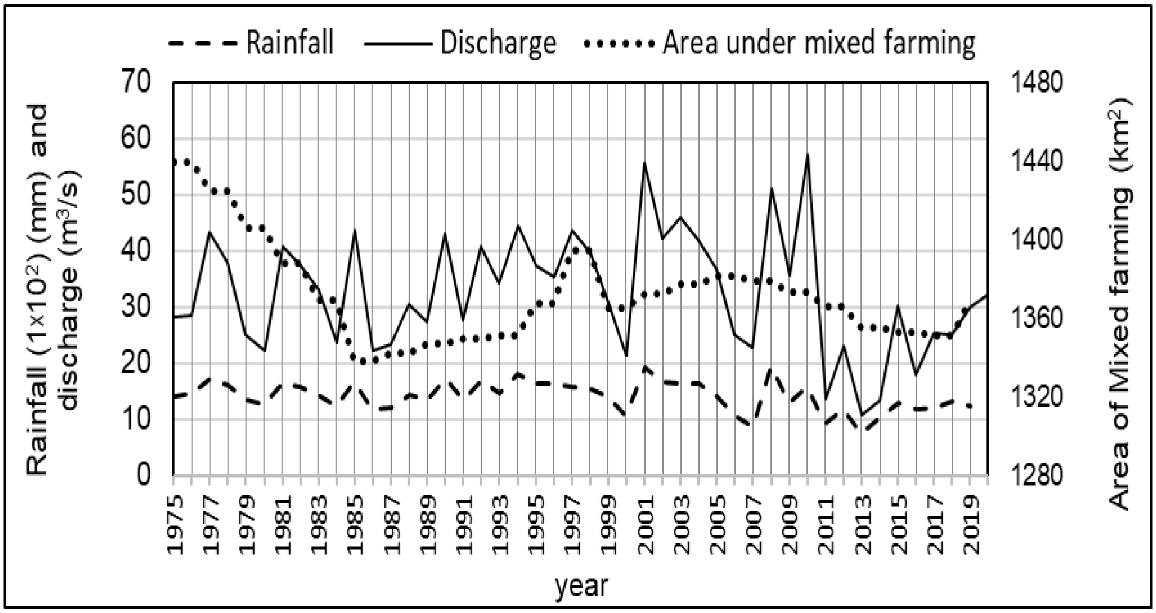


Figure 4.4.10: Mixed farming, rainfall and discharges in the Kipsonoi subbasin in the period 1975 – 2020

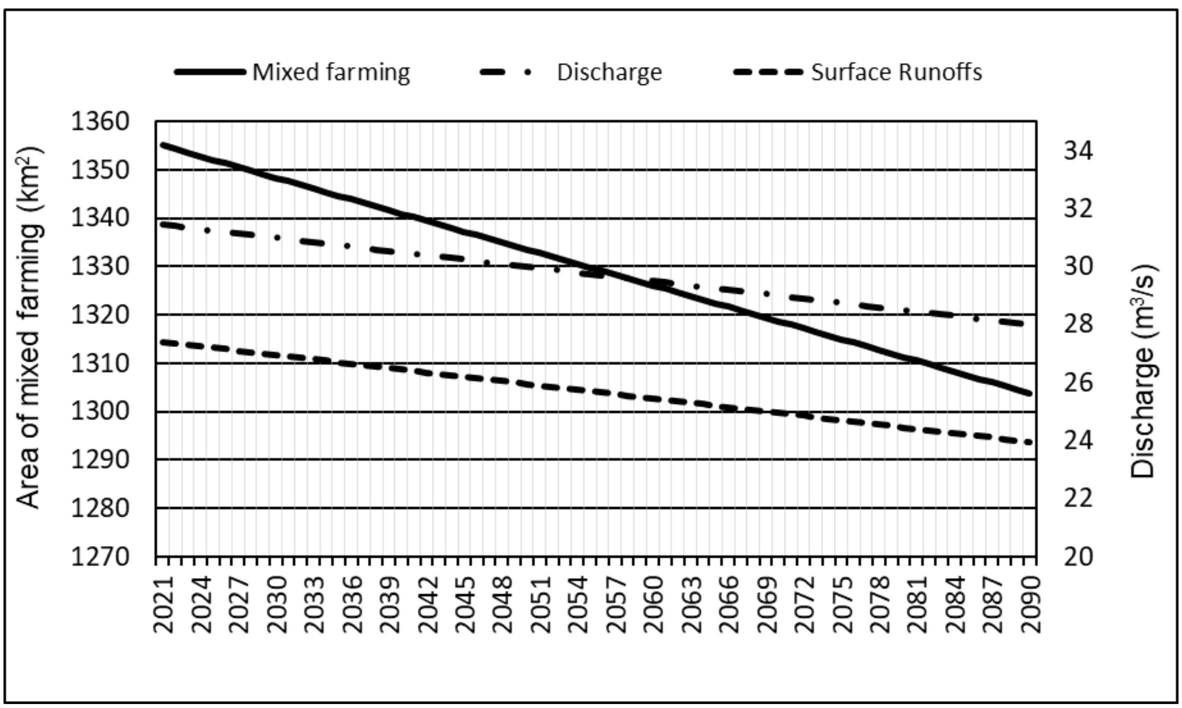


Figure 4.4.11: Forecasted discharges, runoffs and area under mixed farming land cover in the Kipsonoi sub basin (2020 – 2090)

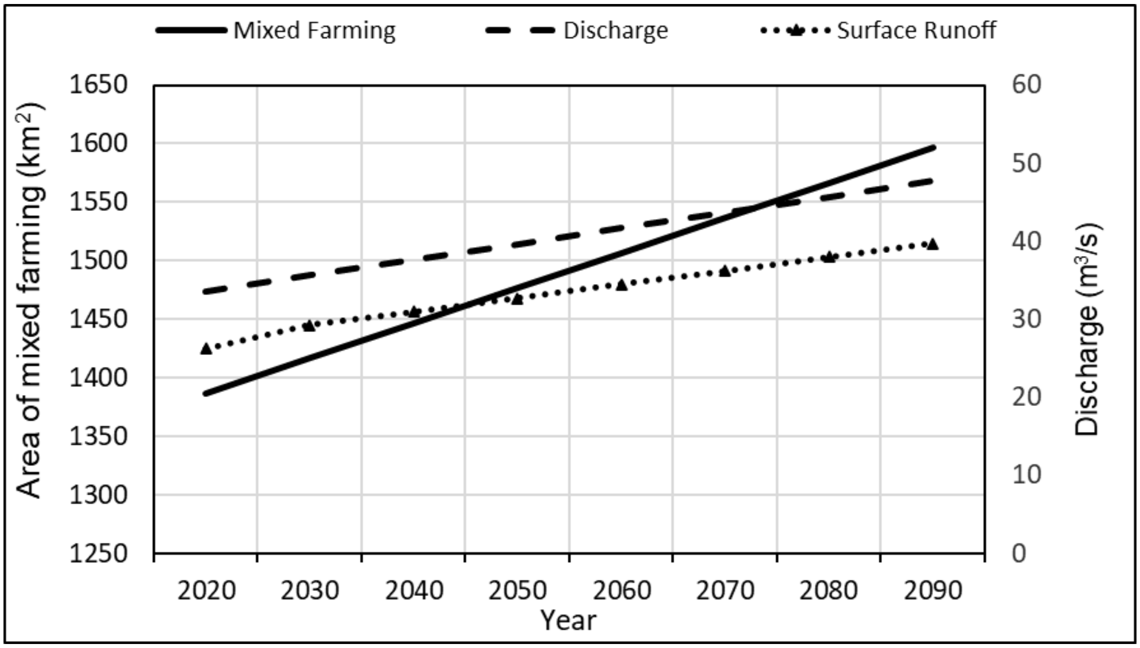


Figure 4.4.12: Predicted discharges, surface runoffs and mixed farming in the Kipsonoi sub basin (2020 – 2090)

4.4.2.4 Simulation of stream flows in river basin with mixed/combined land covers

Simulation of the stream flows in the entire Sondu Miriu Basin with changes in mixed land covers/land uses (mixture of tea plantations, forests and mixed farming) showed a significant impact on the hydrologic response of the sub basin. The outlet for the simulated stream flows for the river basin was at RGS 1JG03 located near new bridge Kendu Bay – Katito Road. The results of simulation studies using SWAT model shows that there are four main stream flow trend periods. These are 1963 – 1970, 1975- 1990, 2001-2013 and 2014 – 2020 (Figure 4.4.13). In the period 1963 – 1970, the discharges decreased from 110 m^3/s in 1963 to 30 m^3/s in 1970. In the period 1975 – 1990 the discharges increased by 120 m^3/s while the area under mixed land cover decreased by 100 km^2. In the period from 2001 to 2013 there was a significant reduction in the discharges from 130 m^3/s in 2001 to 26 m^3/s in 2013 while the area under mixed farming in the river basin increased by 33 km^2. In this period rainfall declined by about 900 mm. In the period between 2014 and 2020, stream flows being increased from 37 m^3/s in 2014 to 81 m^3/s in 2020.

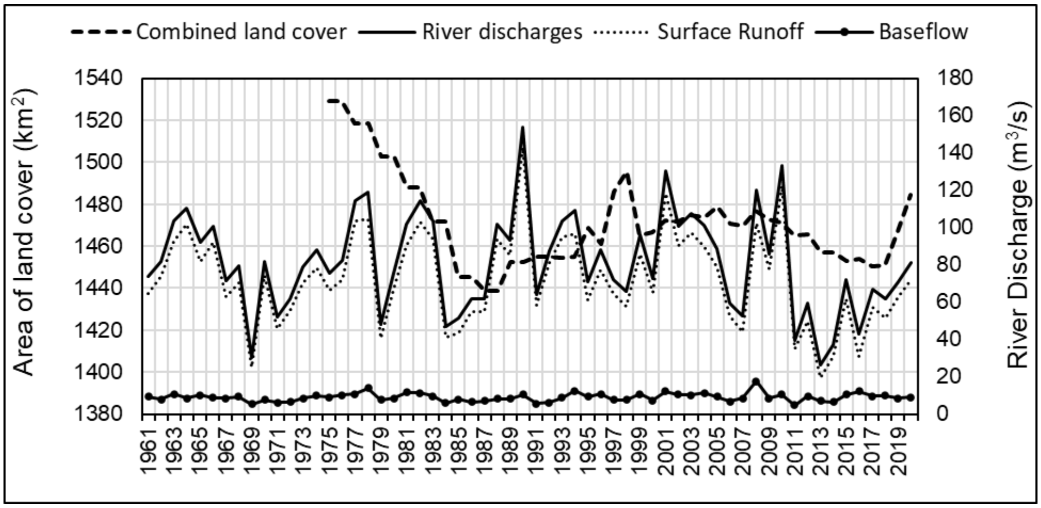


Figure 4.4.13: River discharges and combined land covers/uses in the Sondu Miriu River Basin (1961 – 2020)

4.4.3 Simulation of sediment yields in sub basins dominated by different land covers/land uses types

4.4.3.1 Simulation of sediment yields in the sub basin dominated by tea plantations

The simulation of sediment yields in the tea plantations dominated sub basin showed inter annual variations. The results showed that there were three main periods in which sediment yields in the sub basin showed declining trend. These are the period 1961 – 1985, 1988 – 2000 and 2006 – 2016. During these periods the area under tea plantations increased (Figure 4.4.14). In the period between 1961 and 1985, the sediment yields declined from 12 tonnes/ha in 1961 to 5 tonnes/ha in 1985. This translates to decrease in sediment yields by 7 tonnes/ha in a period of 24 years. During this period the area of land under tea plantations progressively increased from 118.7 km^2 in 1975 to 125.5 km^2 in 1985. In the period between 1988 and 2000, the sediment yields declined from 10 tonnes/ha in 1988 to 6 tonnes/ha in 2000. In the same period the area of land under tea plantations increased from 124.2 km^2 in 1988 to 137.5 km^2 in 2000. In the period between 2006 and 2016, the sediment yields also showed a decreasing trend varying from 10 tonnes/ha in 2006 to 4 tonnes/ha in 2016. During the same period the area of land under tea plantation increased from 129.2 km^2 in 2006 to 133.8 km^2 in 2016. The trend of the simulated sediment yields in the Timbilil sub basin dominated by tea plantations was projected from 2020 to 2090. The results showed that an increase in the area of land under tea plantation by 5 km^2 in a decade will reduce the sediment yield generated by 0.4 tonnes/ha/decade. The seven decades projections from 2020 to 2090 showed that increase in the area of land under tea plantations by 30 km^2 will reduce sediment yields generated in the sub basin by 1 tonnes/ha (Figure 4.4.15).

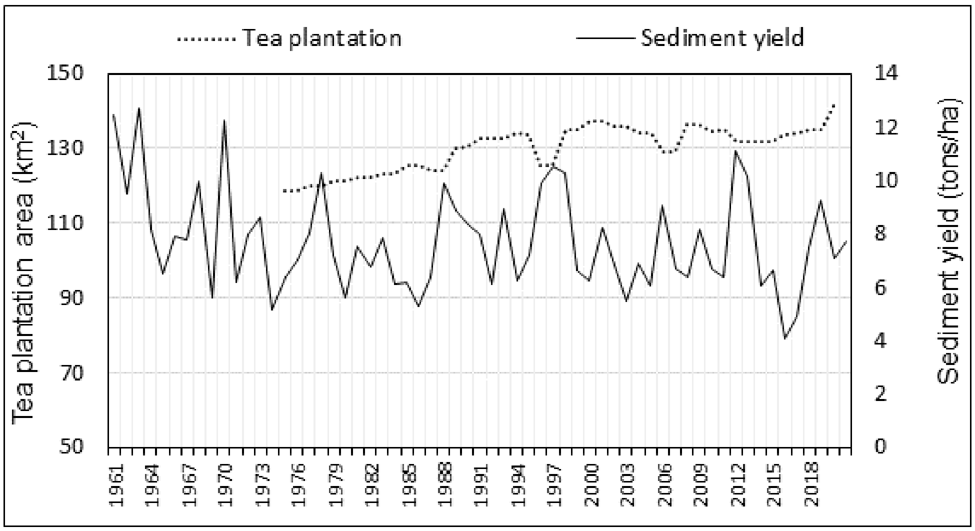


Figure 4.4.14: Sediment yields and tea plantation in the Timbilil sub basin (1960 – 2020)

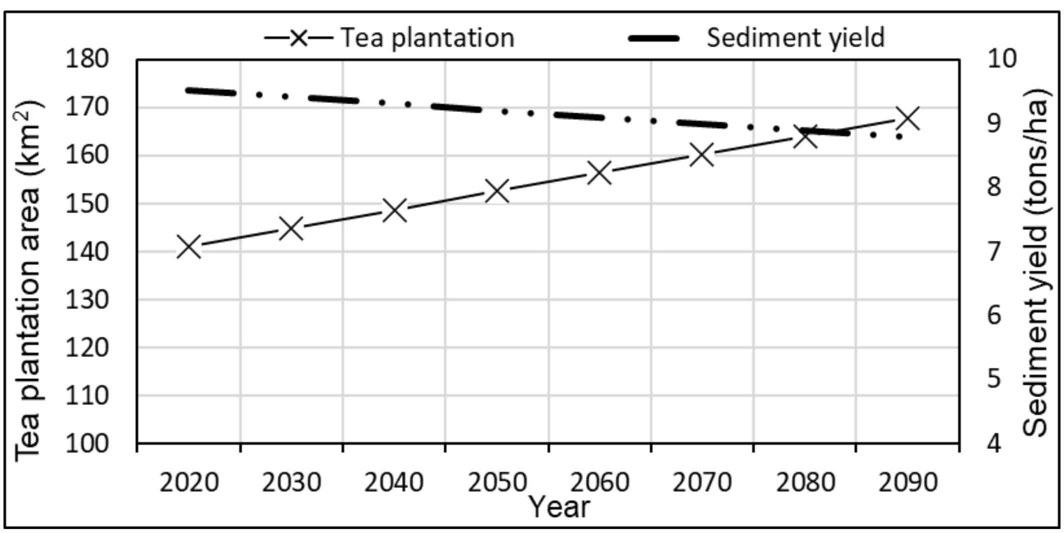


Figure 4.4.15: Projected sediment yields and tea plantation in the Timbilil sub basin (2020 - 2090)

4.4.3.2 Simulation of sediment yields in the sub basin dominated by forest land cover

The simulated sediment yields in the Kiptiget sub basin dominated by forest land cover showed decreasing and increasing trends in three periods. These periods are 1961 – 1985, 1986 – 1998 and 1999 – 2016. In the period between 1961 and 1985, the sediment yields generated decline from 5.6 tonnes/ha in 1961 to 2.4 tonnes/ha in 1985. During the same period, the area of land under forest cover increased from 54 km^2 in 1975 to 64 km^2 in 1985 (Figure 4.4.16). On the other hand, in the period between 1986 and 1998 the sediment yields increased from 3 tonnes/ha in 1986 to 5 tonnes/ha in 1998. Further during this period decrease in the area under forest land cover from 64 km^2 in 1986 to 49 km^2 in 1998 was observed. In the period between 1999 and 2016, the sediment yields decreased from 5.4 tonnes/ha in 1999 to 2 tonnes/ha in 2016. The area under forest cover increased during the same time from 43 km^2 in 1999 and 49 km^2 in 2016.

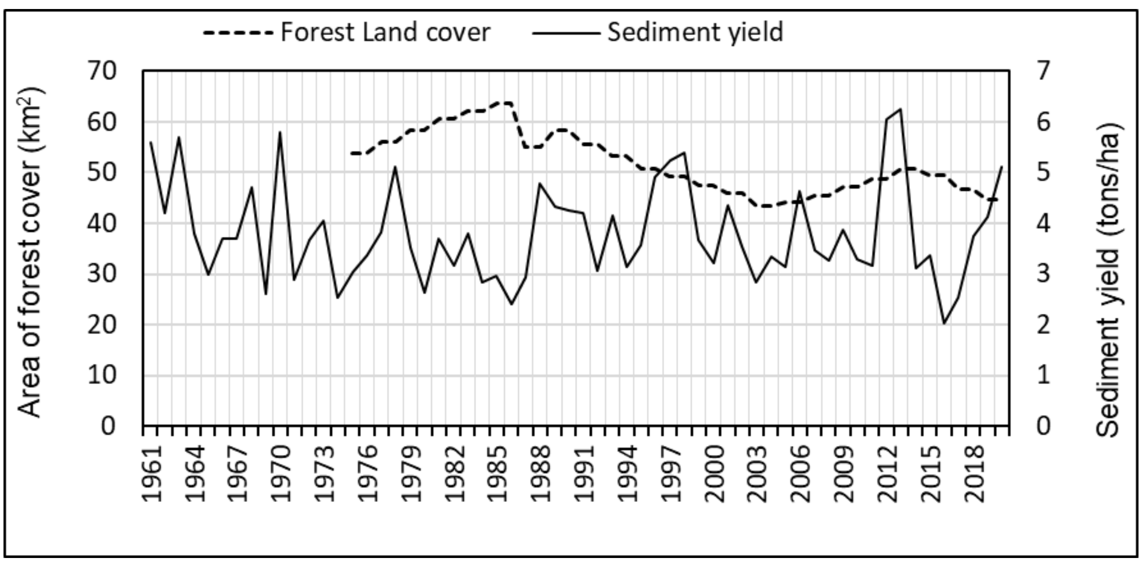


Figure 4.4.16: Sediment yields and forest in the Kiptiget sub basin (1960 – 2020)

The predicted sediment yields in the period 2020 – 2090 showed that in a scenario where area under forest land cover declined, sediment yields generated will increase. For example, reduction of area under forest cover by 25 km^2 by 2090 can increase the sediment yields generated by 0.8 tonnes/ha (Figure 4.4.17). Alternatively in a scenario where the area of land under forest cover increased between 2020 and 2090 by 14 km^2, the sediment yields generated will decrease by about 0.5 tonnes/ha (see Figure 4.4.18).

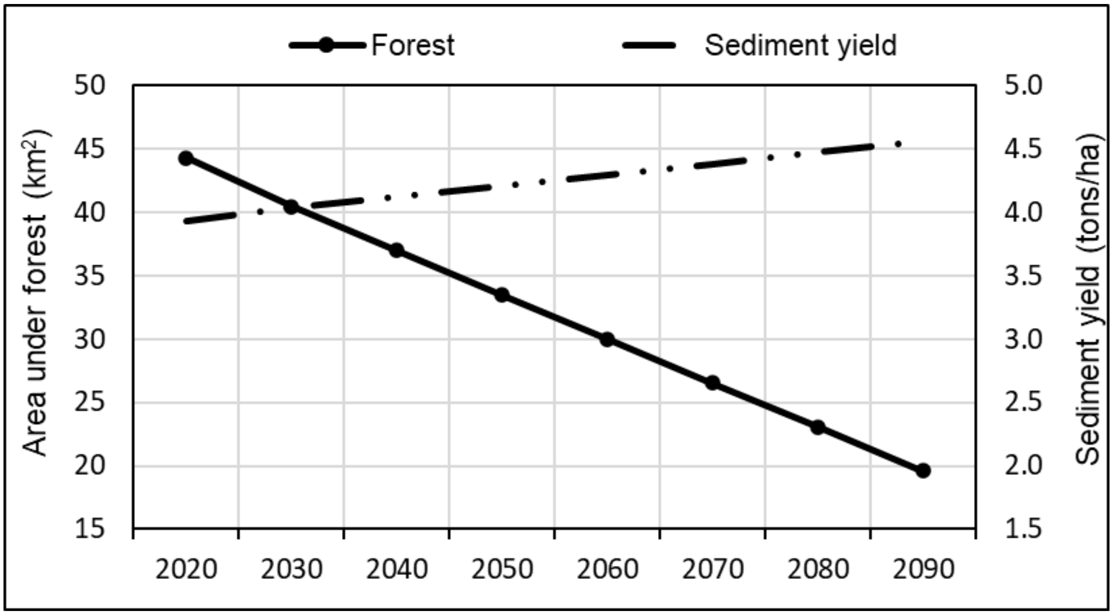


Figure 4.4.17: Projected sediment yields and forest in the Kiptiget sub basin (2020 – 2090)

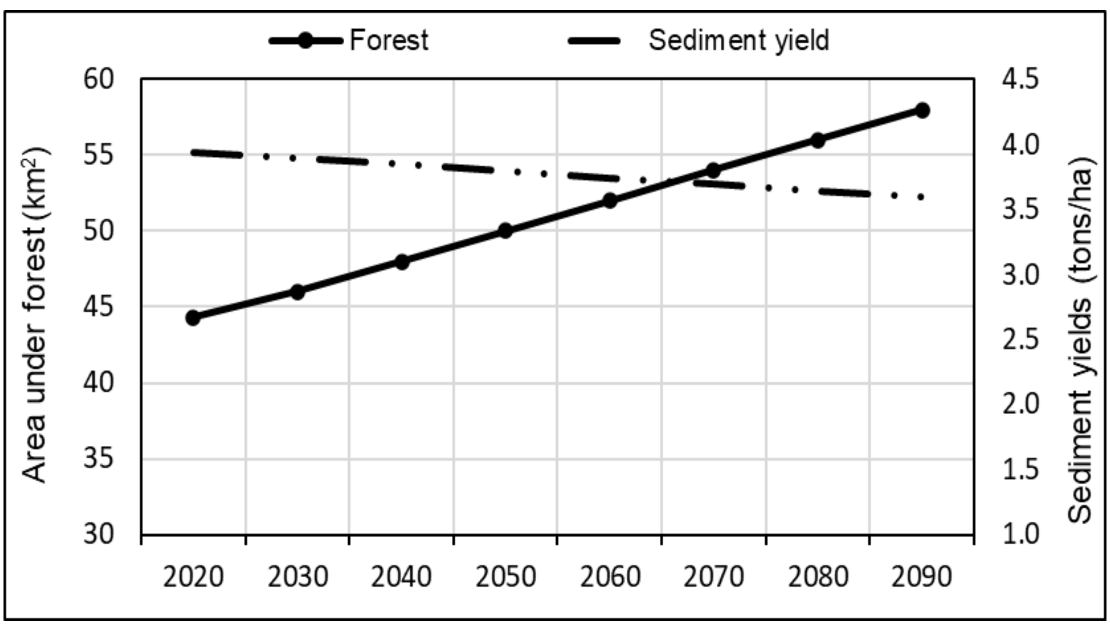


Figure 4.4.18: Predicted sediment yields and forest in the Kiptiget sub basin (2020 – 2090)

4.4.3.3 Simulation of sediment yields in the sub basin dominated by mixed farming land cover

The simulated sediment yields in the Kipsonoi sub basin dominated by mixed farming showed trends in the periods 1961 – 1999, 2000 – 2010 and 2011 – 2020 (Figure 4.4.19). In the period from 1961 to 1999, it showed oscillation trend pattern with sediment yields ranging from maximum of 132 tonnes/ha and minimum of 60 tonnes/ha. During this period the area of land under mixed farming declined by approximately 86 km^2. In the period between 2000 and 2010, the sediment yields increased by 193 tonnes/ha while the area of land under mixed farming increased by about 10 km^2. Further in the period between 2011 and 2020, the sediment yields increased from 24 tonnes/ha in 2011 to 169 tonnes/ha in 2020. During the same period, it was noted that the area under mixed farming increased from 1350 km^2 between 2011 and 2018 to 1386 km^2 in 2020.

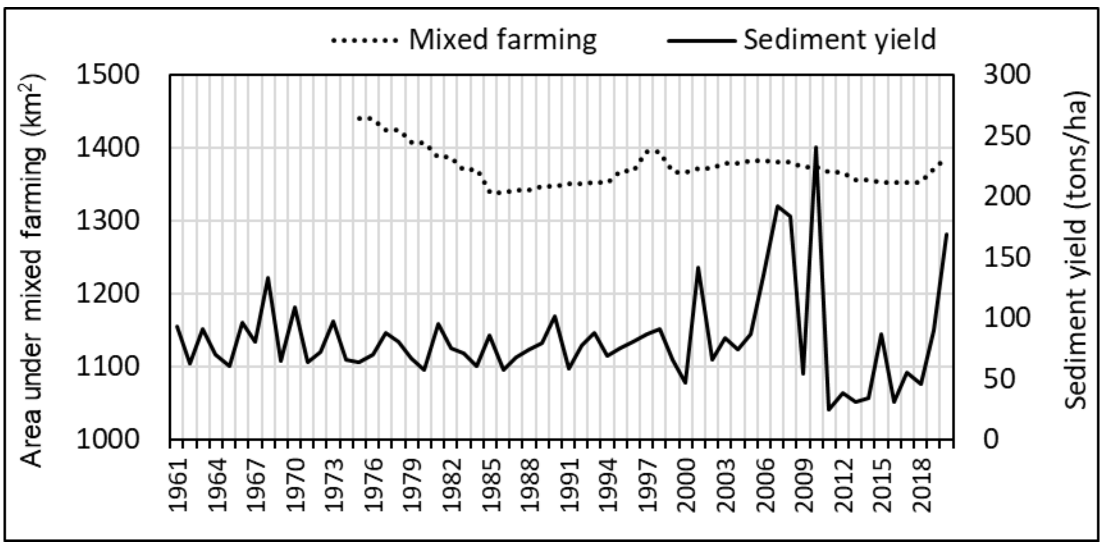


Figure 4.4.19: Sediment yields and mixed farming in Kipsonoi sub basin (1960 – 2020)

The predicted sediment yields in the sub basin dominated by mixed farming showed a reducing trend over time at interval of about 0.79 km^2 per annum (Figure 4.4.20). The results indicated that the area under mixed farming will be expected to reduce by almost 55 km^2 between the year 2020 and 2090. In this scenario the reduction in mixed farming will decrease sediment yields generated to about 6 tonnes/ha in 2090. On contrary if the area of land under mixed farming expands between the year 2020 and 2090 by 210 km^2, then the projected sediment yields generated will increase by about 55 tonnes/ha in 2090 (Figure 4.4.21).

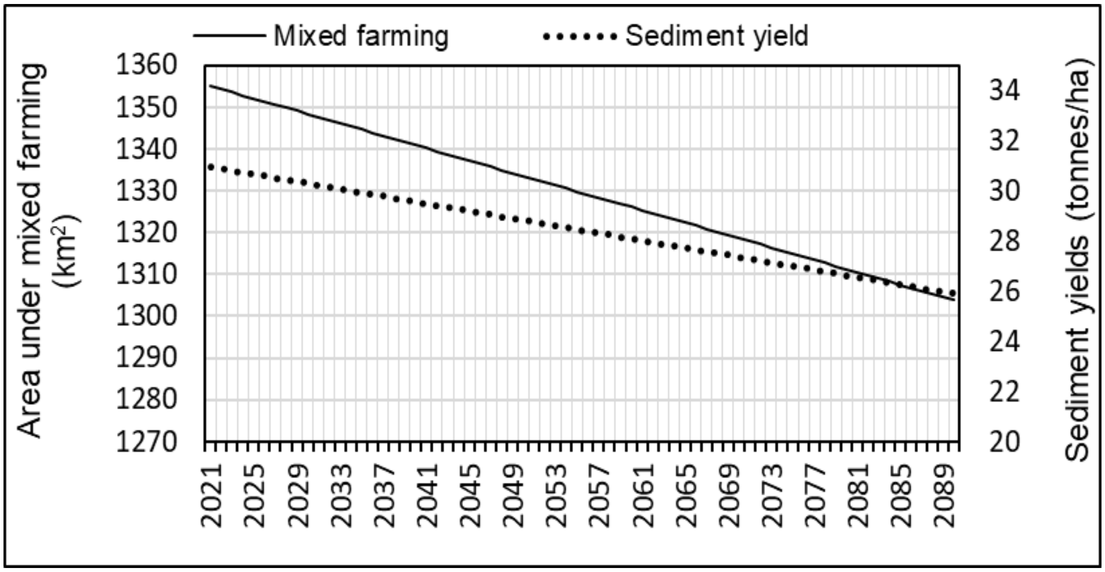


Figure 4.4.20: Forecasted sediment yields and mixed farming in the Kipsonoi sub basin (2020 to 2090)

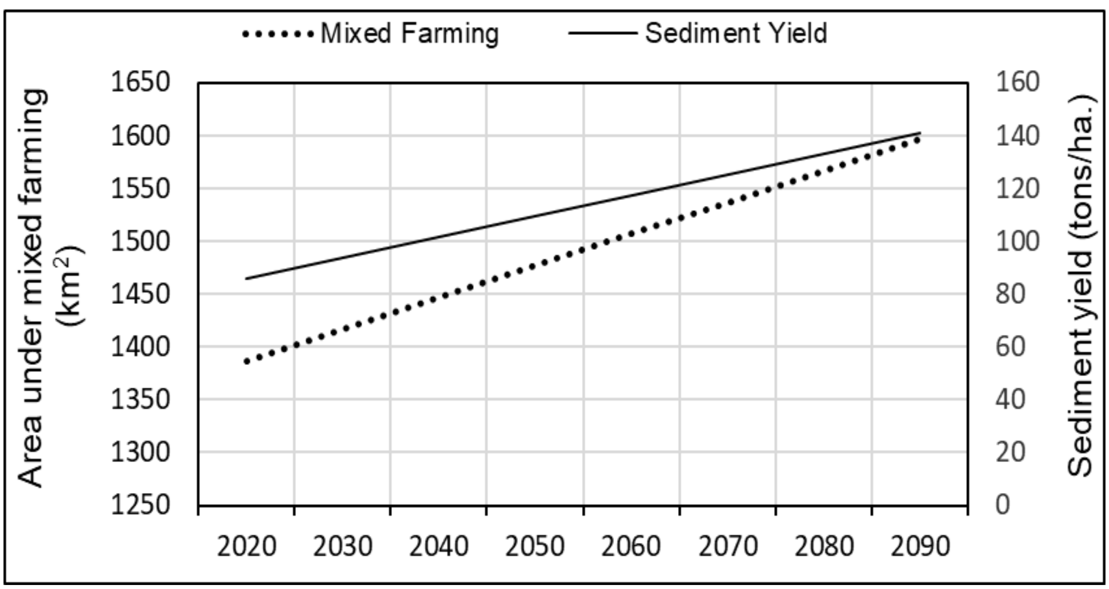


Figure 4.4.21: Predicted sediment yield and mixed farming in the Kipsonoi sub basin (2020 – 2090)

4.4.3.4 Simulation of sediment yields in the Sondu Miriu basin with combined/mixed land covers

The simulated sediment yields for the entire Sondu Miriu River Basin showed different trend in the period 1962 – 2011 and 2012 – 2018 (Figure 4.4.22). The sediment yields increased from 43 tonnes/ha in 1962 to 104 tonnes/ha in 1979. In the period between 1980 – 1989 sediment yields decreased with the declined in the area of the land under combined land cover. During this period the area under combined land cover where mixed farming dominates reduced by 66 km^2 while sediment yields reduced by about 60 tonnes/ha. Also, sediment yields increased in the period 1989 to 2009 due to increase in the area of the land under combined land cover by 20 km^2. In the period between 2012 and 2018, the sediment yields decreased from 36 tonnes/ha in 2012 to 17 tonnes/ha in 2018. The area of land under combined land cover in the same period declined from 1466 km^2 in 2012 to 1450 km^2 in 2018.

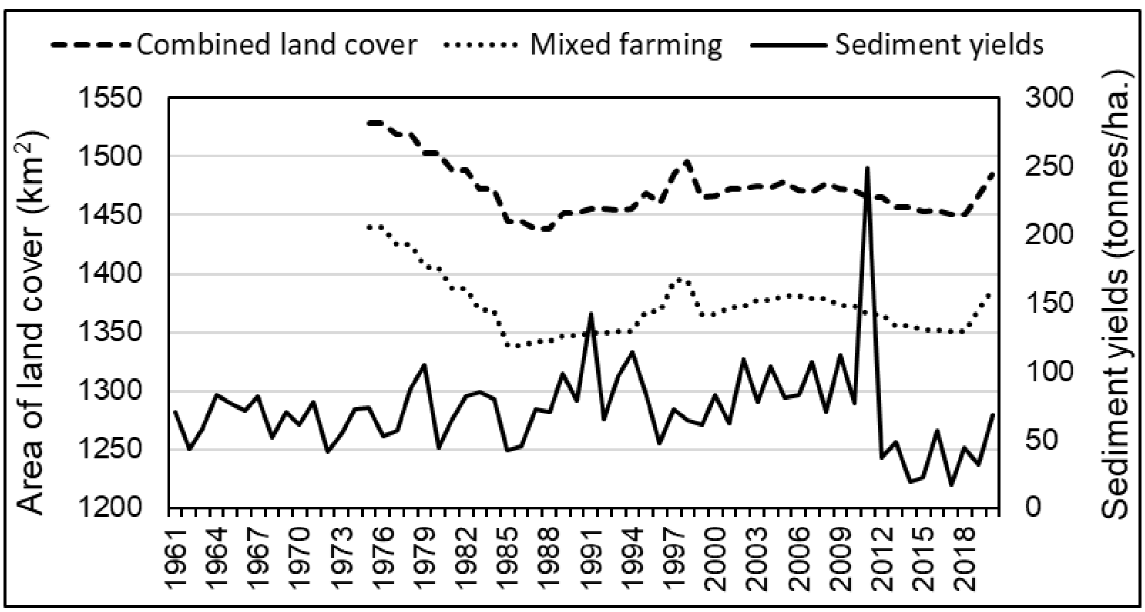


Figure 4.4.22: Sediment yields in the Sondu Miriu Basin with combined land covers (1960 – 2020)

The spatial analysis of the sediment generation in the Sondu Miriu Basin revealed three critical areas of high sediment discharge in which sediment yield ranged from 115 tonnes/ha/year to 180 tonnes/ha/year (Figure 4.4.23). The first area is situated in the upstream of the basin in the sub basin dominated by mixed farming in Nakuru County. The second area is located at the midstream of the sub basin dominated by mixed farming in areas of Bomet County. The third area is located in the downstream of the river basin dominated by mixed farming in Kericho County near Sondu. The results showed that areas under forest cover and tea plantations generated small quantities of sediment yields ranging between 2 tonnes/ha/year and 25 tonnes/ha/year. The areas bordering the tea plantations and forested land covers had sediment flux ranging approximately between 25 tonnes/ha/year and 44 tonnes/ha/year. The sediment yield in the mixed farming zones ranges from 25 tonnes/ha/year to 180 tonnes/ha/year. This showed that high sediment yields occurred in the zones of the basin characterised by combined land cover.

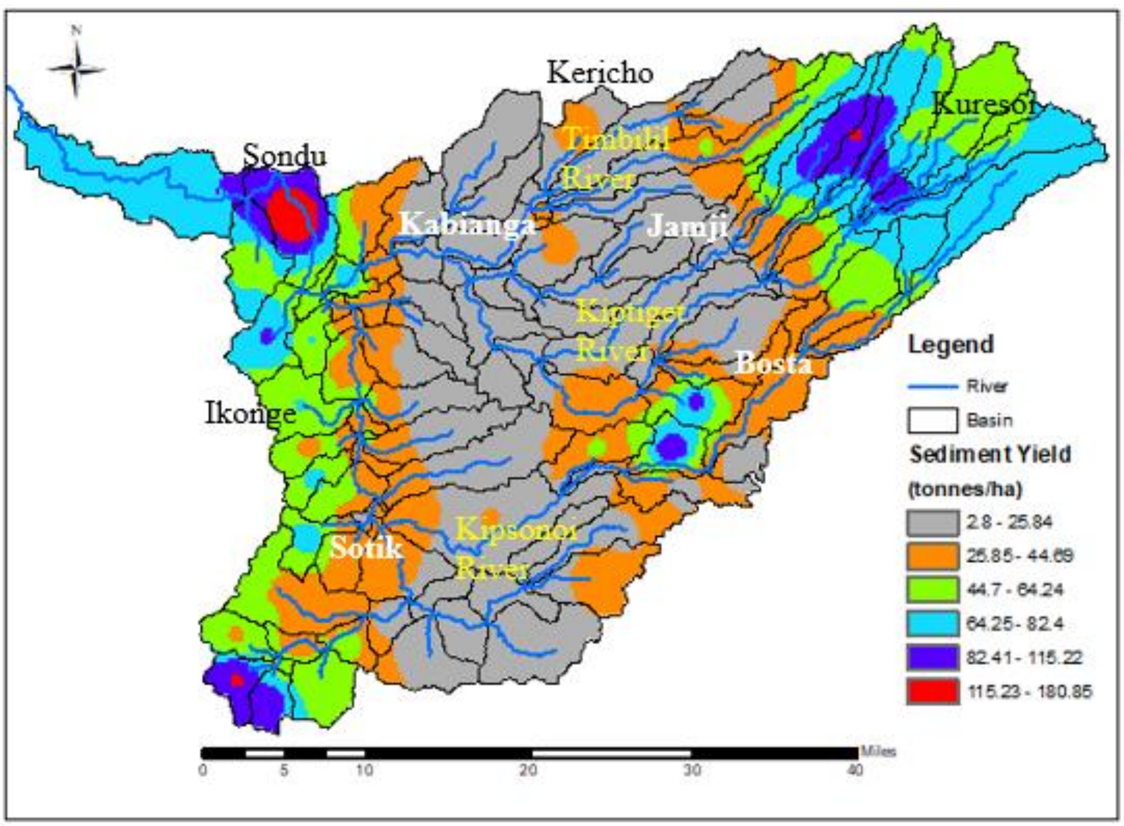


Figure 4.4.23: Mean spatial distribution of sediment flux in the Sondu Miriu River Basin (Koech,2021)

The null hypothesis stated that there was no major statistical difference in sediment discharge in the sub basins dominated by tea plantations, forest and mixed farming land covers. This hypothesis was tested using ANOVA at $p<0.01$). The calculated F was 232.4 while the F-critical value was 3.05. This showed that the F calculated was greater than F critical and the null hypothesis was rejected.

4.5 Water balance components in the sub basins dominated by land covers

The main water balance components considered in this study were rainfall, evapotranspiration, soil moisture and change in water storage. The rainfall was the main input into the sub basins dominated by tea plantation, forest and mixed farming land covers/land uses. Continuous changes in the land covers/land uses have significant impact on the water balance components in the sub basins with dominant land covers and land uses. The detailed results are presented in the following sections.

4.5.1 Water balance components in the sub basin dominated by tea plantations

4.5.1.1 Rainfall in the sub basin dominated by tea plantation land cover

The rainfall received in the sub basin dominated by tea plantation land cover showed an increasing trend in the period between 1960 and 2020. The highest observed rainfall of approximately 2500 mm/a was measured in 2006 and the lowest rainfall of 1260 mm/a was received in 1986.

The mean monthly rainfall (see Figure 4.5.1) indicates that the peak rainfall months are March, April and May. During these periods the rainfall ranged from 170 mm/month to 270 mm/month. Comparison of the land area under tea plantations land cover and annual rainfall received in the sub basin indicate that rainfall increases with expansion of tea plantations (Figure 4.5.2). Rainfall in the Timbilil sub basin showed a seasonal and inter annual variations. The mean annual rainfall in the sub basin was 1832.8 mm. The minimum rainfall was 1303 mm and maximum of 2504 mm. In the period between 1981 – 1995, the rainfall increased from 1150 mm to 1250 mm. In this period, land area under tea plantations increased by approximately 6 km^2. Also, in the period between 2006 and 2011, rainfall showed increasing trend from 1125 mm to 1252 mm. In the same period between 2006 and 2011, area under tea plantations expanded from 129 km^2 to 135 km^2. The relationship between rainfall and area under tea plantation was insignificant in the sub basin was a positive trend with coefficient of determination of $R^2 = 0.15$ and correlation r of 0.39 at p value > 0.05. This indicates that variations in the rainfall explains 15% of the variations in the area under tea plantations while the 95% could be attributed by external factors such ITCZ and climate change.

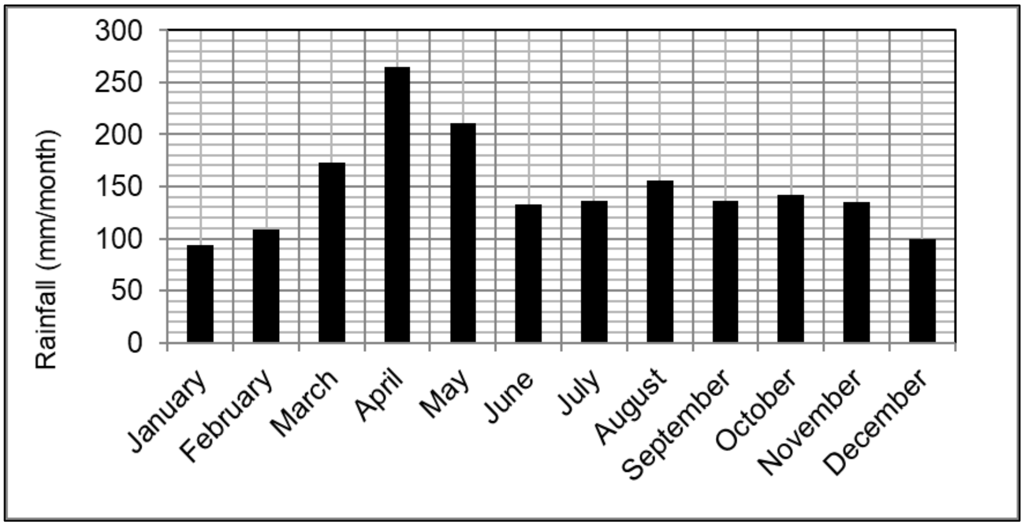


Figure 4.5.1: Mean rainfall in the sub basin dominated by tea plantation (January – December)

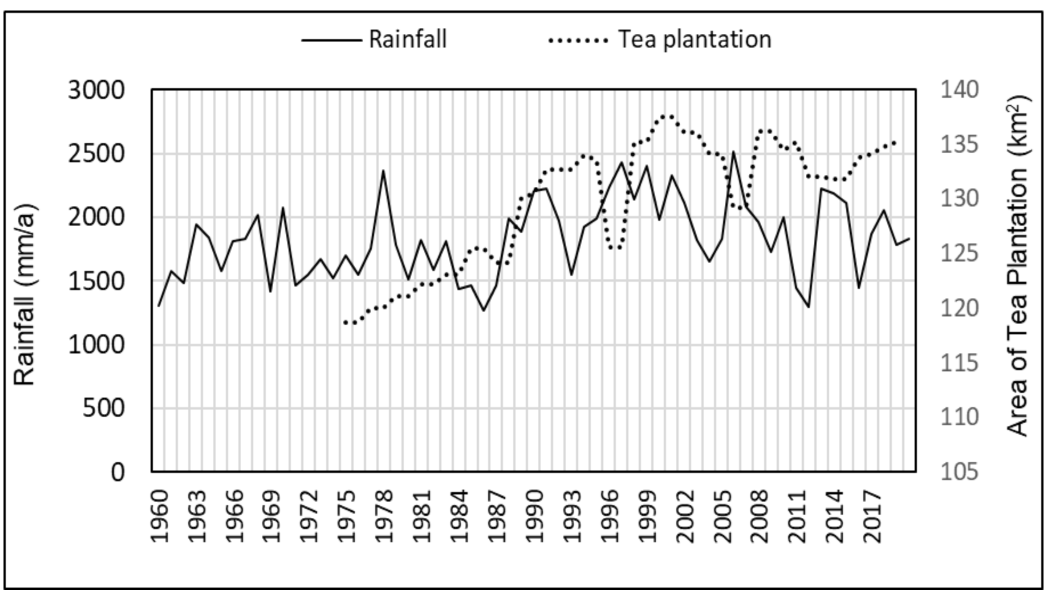


Figure 4.5.2: Rainfall and tea plantation land cover in the Timbilil sub basin (1975 – 2020)

4.5.1.2 Evapotranspiration in the sub basin dominated by tea plantations

In the sub basin dominated by tea plantation, data showed that evapotranspiration and the area under tea plantation has insignificant relation (Figure 4.5.3). The seasonal variations showed that the high evapotranspiration occurs in the period between March and August. During this period, evapotranspiration ranges from 40 mm/a to 110 mm/a. The lowest evapotranspiration occurs in the periods between October and February with evapotranspiration of about 20 mm/a (Figure 4.5.4). The mean evapotranspiration was 750 mm, minimum evapotranspiration was 500 mm and maximum of 830 mm. In the period between 1985 and 1995, the area under tea plantations expanded by 10 km^2 and the evapotranspiration increased from 674 mm to 820 mm. The decrease in the area under tea plantations between 1996 and 1997 by 8 km^2 and evapotranspiration reduced from 821 mm to 678 mm. In the period between 1998 and 2010, an increase in evapotranspiration from 655 mm to 815 mm and the expansion of the area under tea plantations was 6 km^2. However, the decrease in the area under tea plantations by 2.5 km^2 reduced evapotranspiration from 815 mm to 469 mm in the period 2010 – 2013. The relation between area under tea plantations and evapotranspiration was insignificant with coefficient of determination R^2 of 0.0063 and correlation r of -0.08 at $p > 0.05$. The results showed that changes in the area under tea plantations had little influence on the temporal variations of evapotranspiration. While the relationship between rainfall and evapotranspiration was positive with correlation r of 0.4 and R^2 of 0.16 indicating that rainfall contributes to changes in evapotranspiration in the sub basin.

4.5.1.3 Soil moisture in the sub basin dominated by tea plantations

The soil moisture in the sub basin was determined from top soil and the sub soil at the depth from ranging from 0-100cm. The mean annual soil moisture in the sub basin was 22.9 mm. The minimum soil moisture in the sub basin was 13.8 mm and maximum of 37.6 mm. There was inter annual variations in soil moisture in the sub basin dominated by tea plantations (Figure 4.5.5). In the period between 1989 and 1993 the area under tea plantations increased by 3 km^2 and the soil moisture decreased from 24.3 mm to 16 mm. Also, in the period between 1997 and 2004, the area under tea plantations increased by 8.5

km^2 while the soil moisture decreased from 32.1 mm to 17.2 mm. This indicates that there exists negative insignificant relationship between area under tea plantations and soil moisture with coefficient of determination R^2 of 0.00001 and correlation r of -0.003 at $p > 0.05$. The relationship between soil moisture and rainfall was positive with R^2 of 0.42 and correlation r of 0.65 at $p < 0.05$. Hence rainfall has strong influence on the quantity of soil moisture than tea plantation land cover.

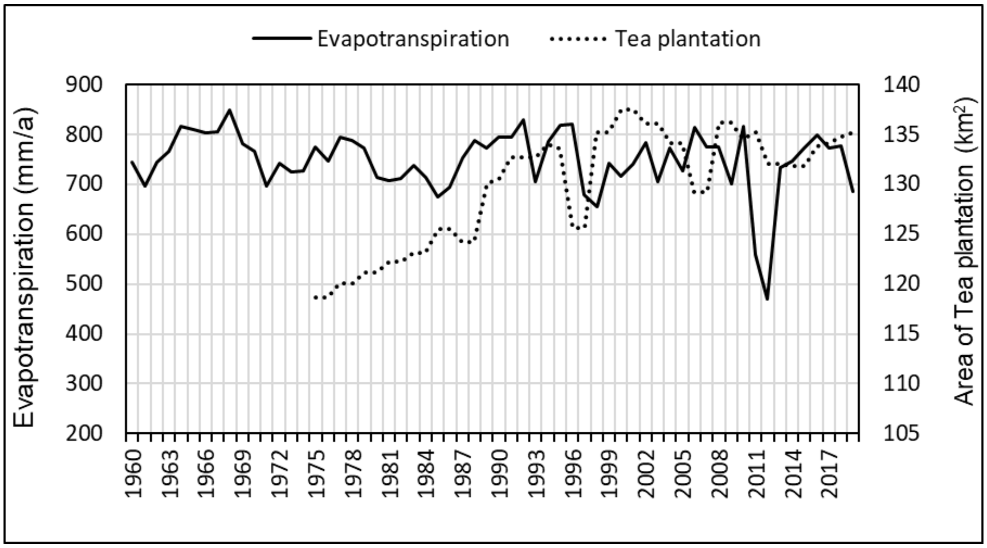


Figure 4.5.3: Evapotranspiration in the sub basin dominated by tea plantation

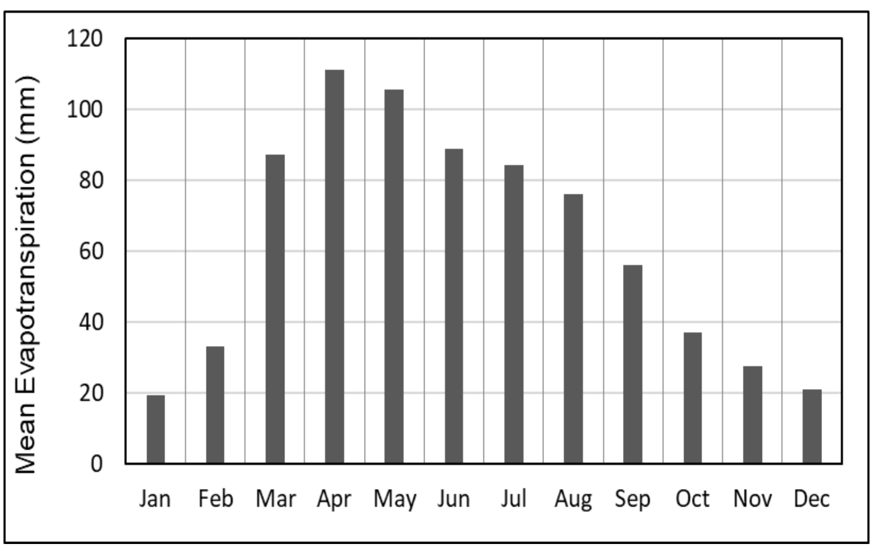


Figure 4.5.4: Mean evapotranspiration in the sub basin dominated by tea plantation (January – December)

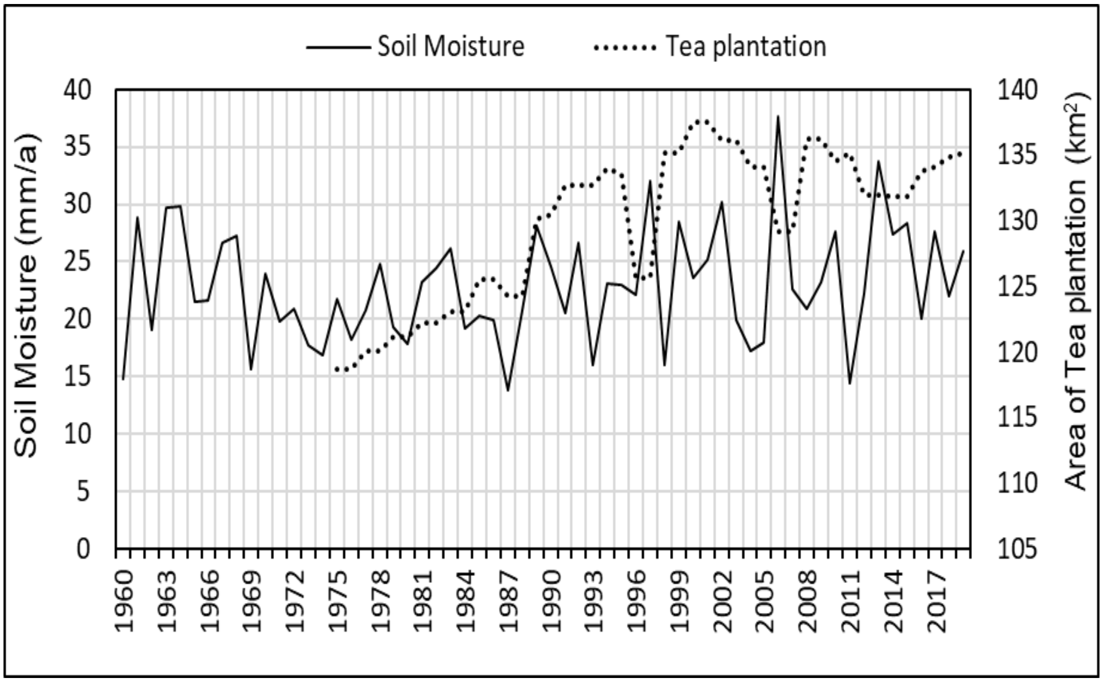


Figure 4.5.5: Soil moisture in the sub basin dominated by the tea plantation (1960-2020)

4.5.1.4 Change in water storage in the sub basin dominated by tea plantation land cover

These results showed that there has been changes in the water storage in the sub basin as a result of an increase or decrease in the sub basin under tea plantation. But an increasing trend in the change of water storage occurred during periods 1975-2020 (Figure 4.5.6). The insignificant relationship between change in water storage and area under tea plantations was R^2 of 0.0079 and correlation of 0.089 at $p > 0.05$. The mean annual change in water storage was 26.8 mm. The maximum change in water storage in the sub basin was 64.7 mm, the minimum was 2.68 mm and mean of 26.8 mm. In the period 1961-1970, the change in water storage decreased from 47 mm/a in 1960 to 2.9 mm/a in 1970. In the period 1971 – 1992, the change in water storage in this period had insignificant change hence oscillating between 38 mm/a and 33.5 mm/a. In the period 1993 – 2020, the change in water storage increased in magnitude ranging between 5 mm/a and 30 mm/a. This was attributed to the increase in tea plantations by 3 km^2 during the same period.

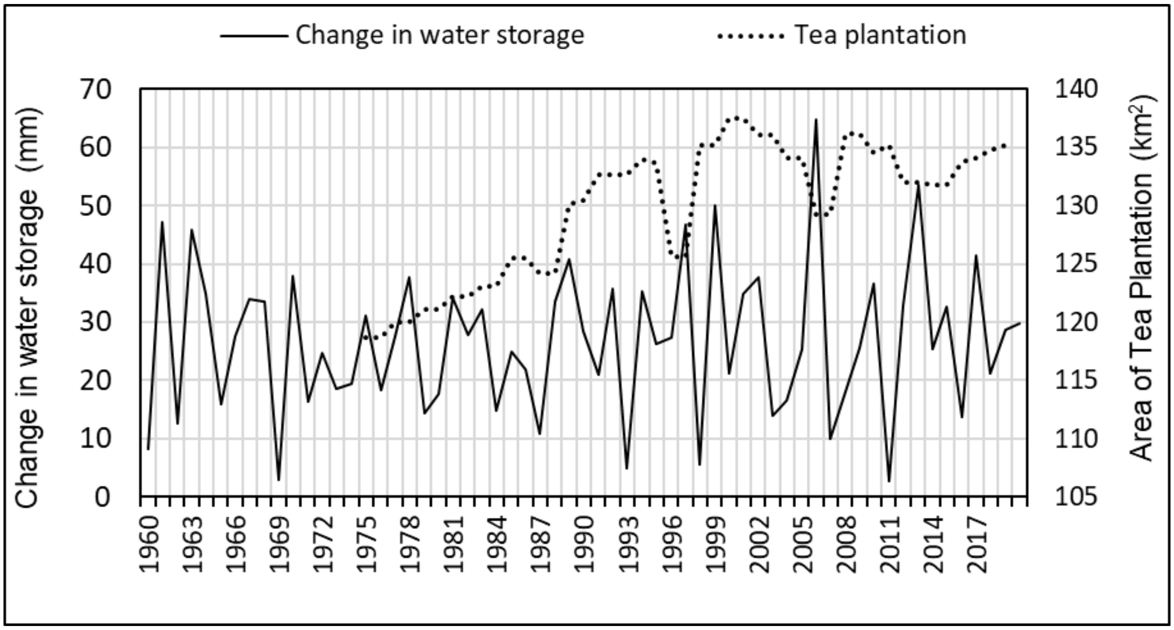


Figure 4.5.6: Change in water storage and tea plantation in Timbilil sub basin (1960-2020)

4.5.2 Water balance components in the sub basin dominated by forest land cover

4.5.2.1 Rainfall in the sub basin dominated by forest land cover

The rainfall in the sub basin dominated by forest land cover was observed at Chebang'ang weather station and it showed different trends in three periods. The mean rainfall in the sub basin was approximately 1830 mm per annum. The minimum rainfall was 1265 mm and maximum rainfall was 2516 mm. In the period from 1960 to 1970, rainfall increased from 1305 mm/a to 2075 mm/a. In the period between 1975 and 1986, forest cover increased by 10 km^2 while rainfall decreased from 1699 mm to 1265 mm showing reduction by 434 mm/a. On the other hand, rainfall increased in the period between 1987 and 2004 by 391 mm/a while area under forest cover declined by 20 km^2. This shows that the increase in rainfall during the period 1986 - 2006 was not related to changes in the forest land cover. The period between 2007 and 2017 annual rainfall showed a decreasing trend from 2081 mm/a in 2007 to 1450 mm/a in 2017 (Figure 4.5.7). Increasing in the forest land cover between 1973 to 1984 had no significant influence in the rainfall received in that period. Further declining trend in the forest land cover in the period 2007 to 2017 showed that there is no significant relationship between forest land cover and rainfall in the sub basin. The mean monthly high rainfall occurred in March, April and May and their observed rainfall ranges from 170 mm/month to 270 mm/month. The negative relationship was observed between rainfall and forest cover with R^2 of 0.14 and correlation r of -0.37 at the p value > 0.05.

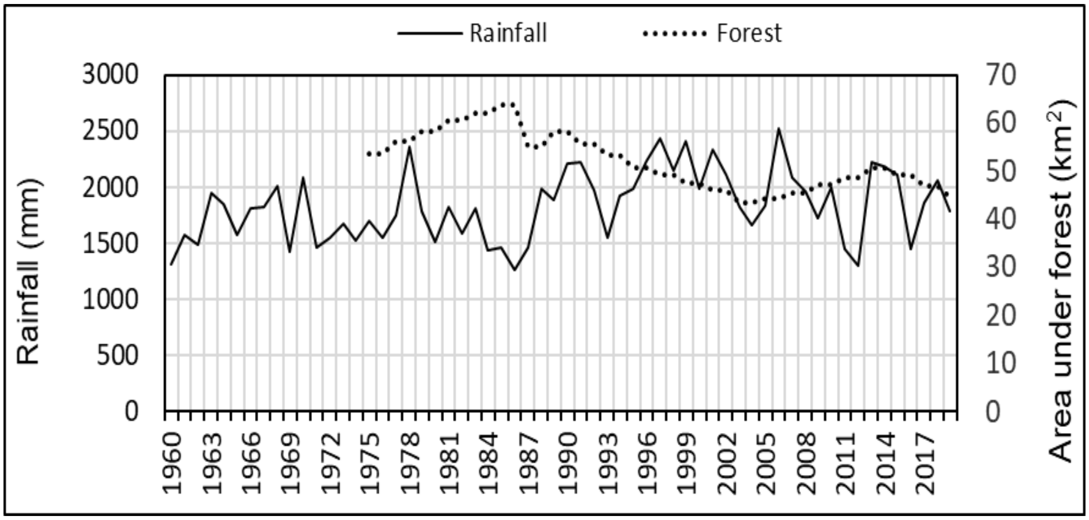


Figure 4.5.7: Rainfall and forest in the Kiptiget sub basin in the period 1960 - 2020

4.5.2.2 Evapotranspiration in the sub basin dominated by forest land cover

Seasonal variations of evapotranspiration in Kiptiget sub basin occurred in the period between March and October ranging from 38 mm/month to 118 mm/month. The evapotranspiration that occurred in the period between November and February ranged from 20 mm/month to 63 mm/month. There was a small change in annual trends with positive relationship between evapotranspiration and area under forest cover R^2 of 0.0021 and correlation r of 0.045. The mean evapotranspiration in the sub basin was 905 mm, minimum evapotranspiration was 560 mm and maximum evapotranspiration was 1006 mm. For instance, in the period between 1991 and 1999, there was a decrease in the area under forest cover from 55 km^2 to 47 km^2 while the evapotranspiration decreased from 988.6 mm to 807.5 mm (Figure 4.5.8). Similar relationship was observed in the period between 2004 and 2010 where increase in the area under forest cover by 4 km^2 led to increase in evapotranspiration from 869 mm to 989 mm. This similar observation was made in the Timbilil sub basin dominated by tea plantations.

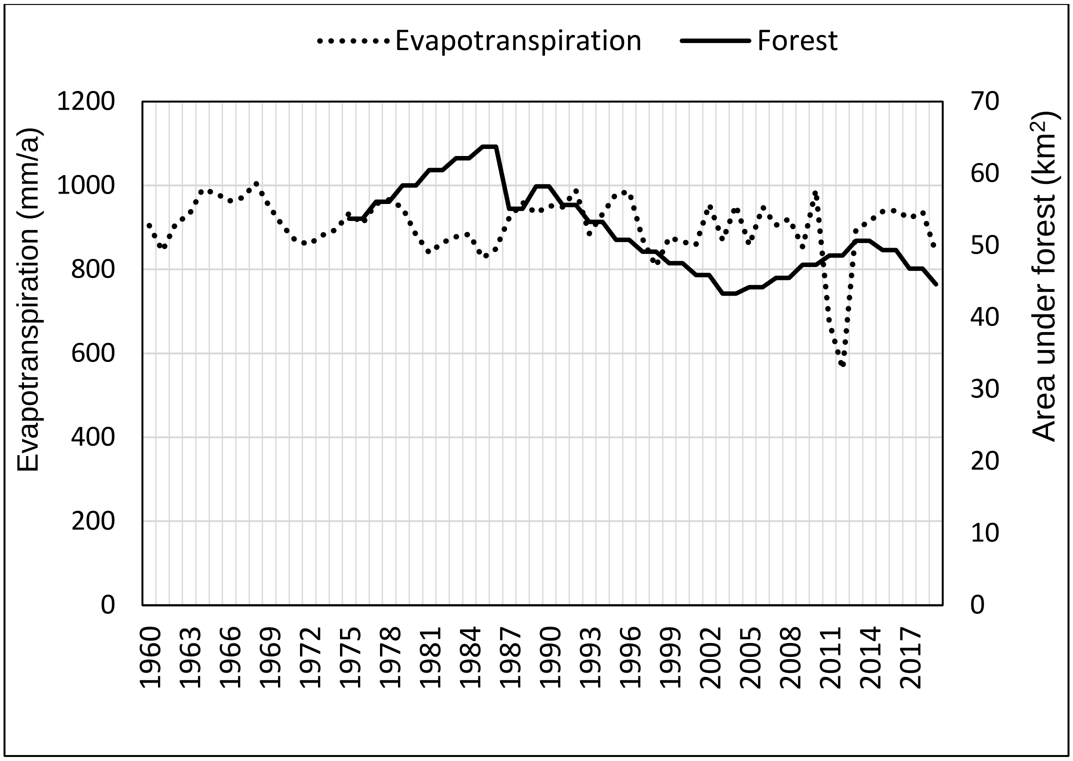


Figure 4.5.8: Evapotranspiration and forest in Kiptiget the sub basin (1960-2020)

4.5.2.3 Soil moisture in the sub basin dominated by forest land cover

The trend in soil moisture at the top soils and sub soils and area under forests in the sub basin showed that decrease in the forest cover increases soil moisture in the sub basin. The mean soil moisture in the sub basin was 26.3 mm. The minimum soil moisture in the sub basin was 14.1 mm and maximum soil moisture was 40.2 mm. In the period between 1986 and 2002, the area under the forest cover declined from 63.7 km^2 to 45.9 km^2 while the soil moisture increased from 15.9 mm to 35.6 mm. Also, in the period between 2004 and 2011, the area under forest cover increased from 43.3 km^2 to 48.6 km^2 and soil moisture decreased from 40.2 mm to 20.3 mm (Figure 4.5.9). This showed that there was negative relationship between soil moisture and area under forest cover with coefficient of determination, R^2 of 0.07 and correlation r of -0.26 at p of 0.05. The significant variations observed in the temporal soil moisture were due to rainfall. This was confirmed by the significant relationship between rainfall and soil moisture R^2 of 0.49 and correlation r of 0.7 at p of 0.05.

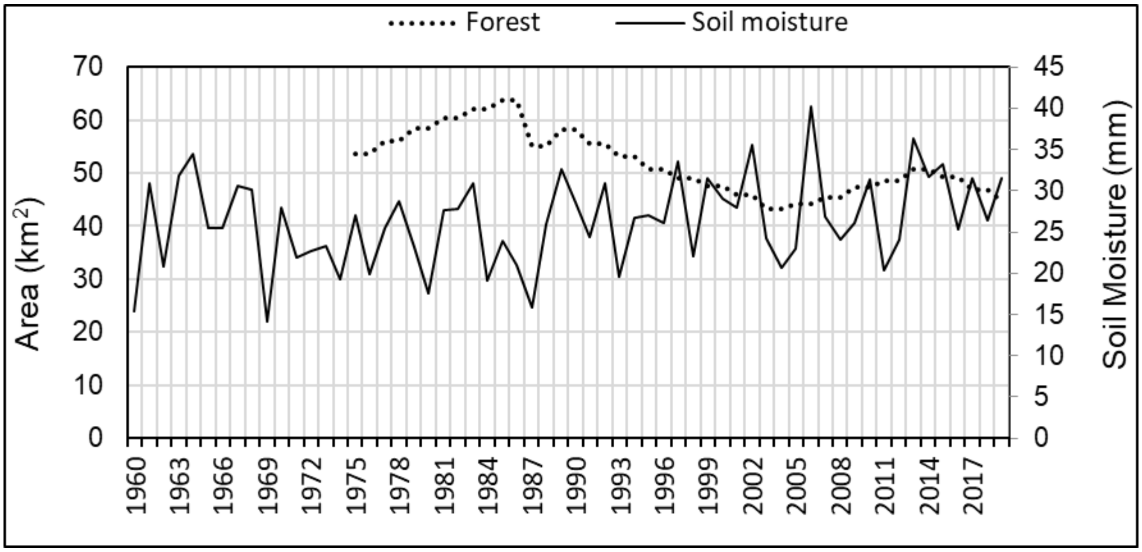


Figure 4.5.9: Soil moisture and forest in the Kiptiget sub basin in the period 1960-2020

4.5.2.4 Change in water storage in the sub basin dominated by forests

In the Kiptiget sub basin dominated by the forest land cover, it was discovered that most of the study period from 1960 to 2020 experienced positive water balance ranging between 0.6 mm to 63 mm/a. While in 1969 negative water balance of -5.7 mm was observed as depicted in Figure 4.5.10. The mean annual change in water storage was 28.6 mm. The minimum change in water storage was -5.8 mm and maximum change in water storage was 63.8 mm. In 2006, the change in water storage was high compared with other years with 64 mm. This high peak in 2006 was attributed to high rainfall received in the sub basin. The mean annual change of water storage in the sub basin was 28 mm/a. In relation to the forest land cover, the change in water storage decreased with increase in the area under forest land cover as depicted in the period between 1986 and 2006. In this period the area under forest cover decreased from 63.7 km^2 to 44.2 km^2 while the water storage increased from 19.4 mm to 63.8 mm. Further, in the period between 2007 and 2011, the area under forest cover increased from 45.4 km^2 to 48.6 km^2 but the water storage decreased from 13.7 mm to 8.96 mm. These showed that there was insignificant relationship between change in water storage and area under forest land cover with R^2 of 0.0048 and correlation r of -0.07 at $p > 0.05$.

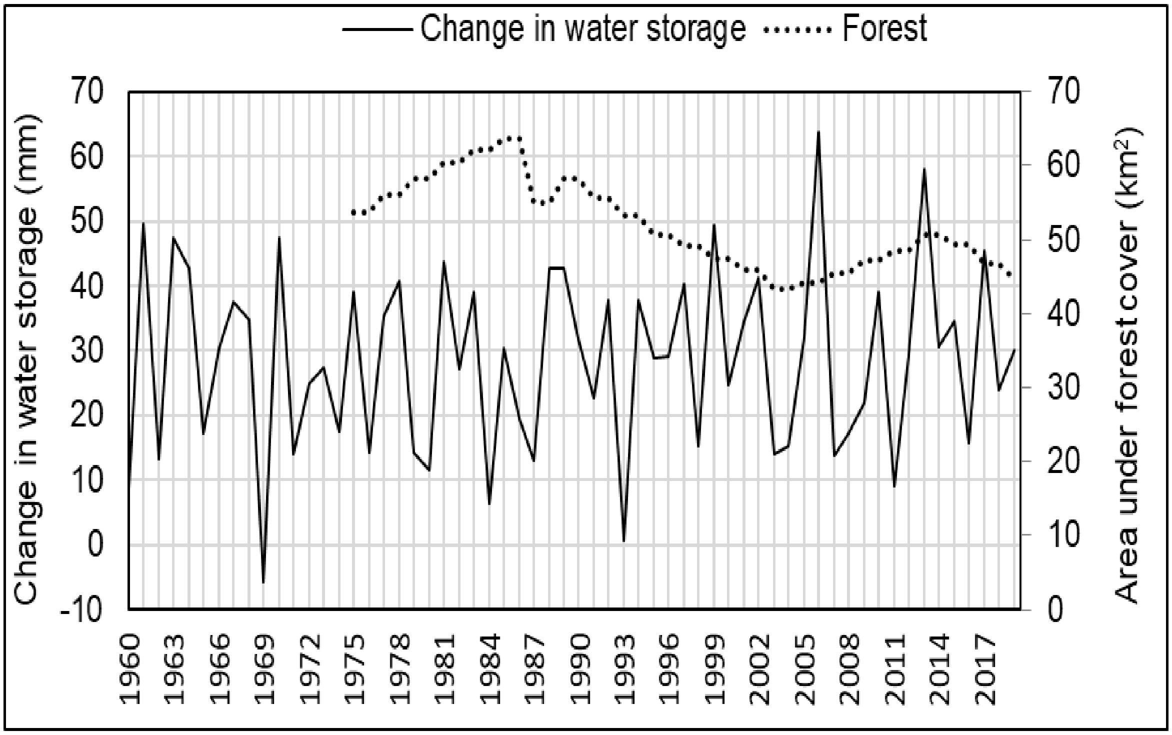


Figure 4.5.10: Change in water storage and forest in Kiptiget sub basin (1960 – 2020)

4.5.3 Water balance components in the sub basin dominated by mixed farming land use

4.5.3.1 Rainfall in the sub basin dominated by mixed farming land use

The rainfall time series showed seasonal and inter annual significant changes in the sub basin. The mean monthly time step (Figure 4.5.11) portrayed that the rainfall received have three distinct peaks in the months of April, August and November. In April the mean monthly rainfall received was approximately 200 mm/month while in August and November mean monthly rainfall estimated were 132 mm/month and 129 mm/month respectively. The mean annual rainfall received in the sub basin was about 1409 mm/a. The minimum and maximum rainfall in the sub basin was 750 mm and 2030 mm respectively. The relationship between rainfall and area under mixed farming was observed using trends of time series in the periods 1960-1977, 1978-1987, 1988-1998 and 2001-2013 (Figure 4.5.12). In the period between 1960 and 1977, the rainfall showed an increasing trend from 1344 mm to 1752 mm. During this period the rainfall had the highest peak in 1968 with the rainfall of 2030 mm. The period between 1978 and 1987, the relationship between rainfall and farming observed was positive. The rainfall showed a decreasing trend from 1732 mm in 1978 to 1174 mm in 1987. In this period the area of land under mixed farming decreased from 1424 km^2 in 1978 to 1338km^2 in 1987. In the period between 1988 and 1998, the area of land under mixed farming increased from 1341 km^2 to 1394 km^2 and the rainfall increased from 1216 mm to 1624 mm. While in the period between 2001 and 2013, the rainfall decreased from 1913 mm to 746 mm. The area under mixed farming declined in this period from 1377 km^2 to 1355 km^2. There was insignificant relationship between area under mixed farming and rainfall with coefficient of determination R^2 of 0.03 and correlation r of 0.17 at $p > 0.05$.

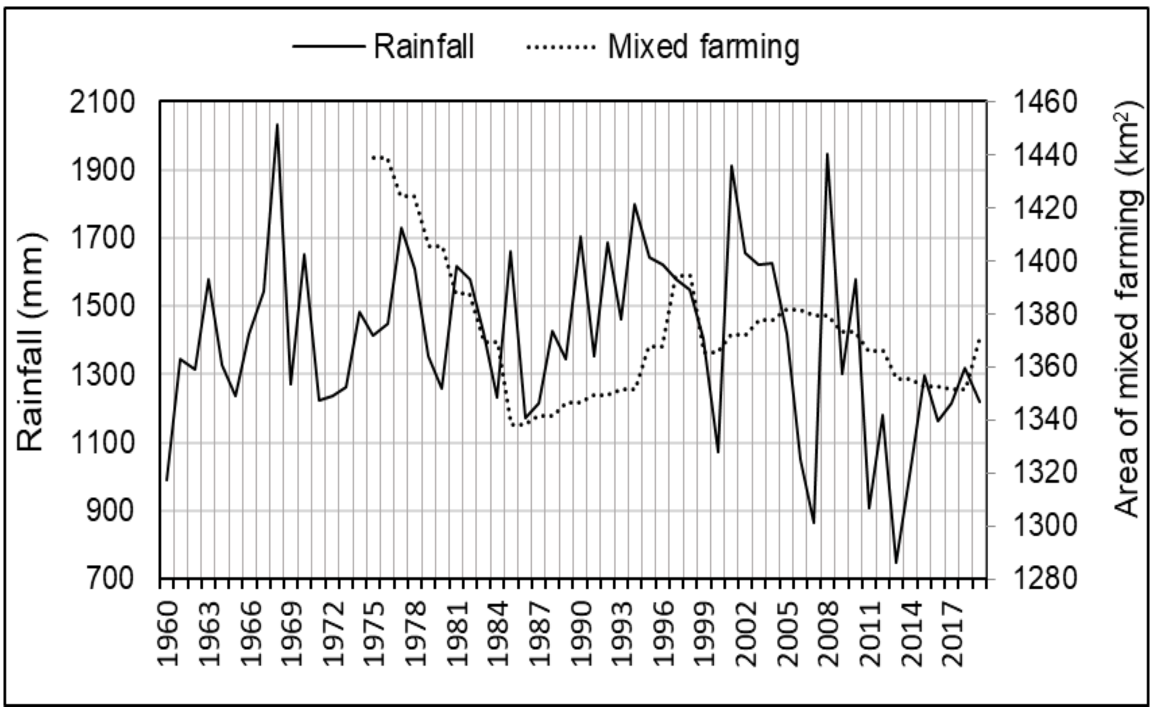


Figure 4.5.11: Rainfall and mixed farming in the Kipsonoi sub basin (1960-2020)

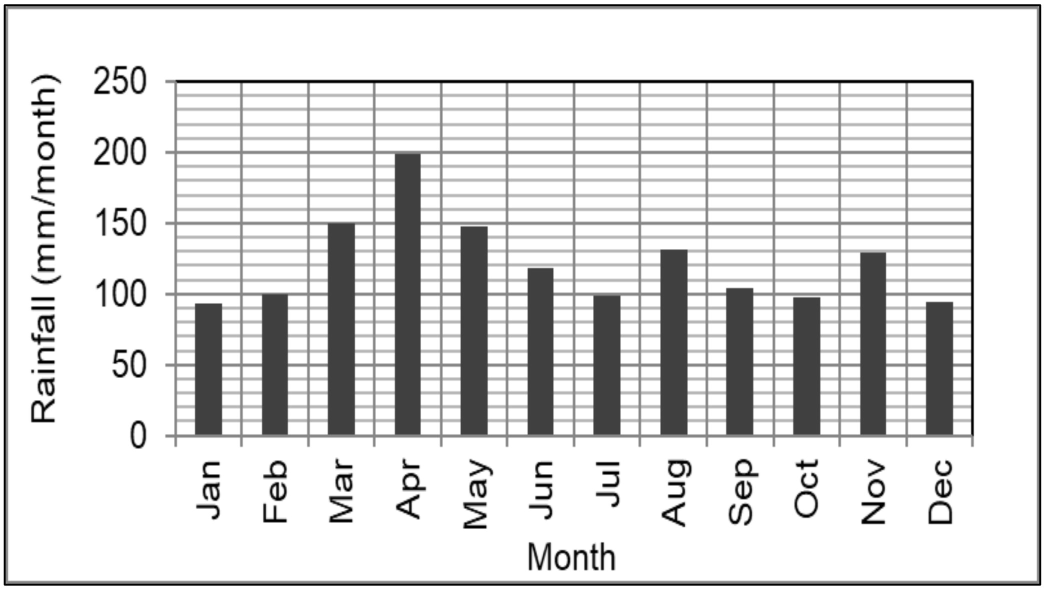


Figure 4.5.12: Mean rainfall in the sub basin dominated by mixed farming (1960-2020)

4.5.3.2 Evapotranspiration in the sub basin dominated by mixed farming land cover

The evapotranspiration in the sub basin dominated by mixed farming land cover and land uses shown insignificant relationship with correlation coefficient r of 0.14 and coefficient of determination R^2 of 0.0189 at $p > 0.05$ due to seasonality of mixed crops. The relationship between rainfall and evapotranspiration was positive with R^2 of 0.39 and correlation r of 0.62 at $p > 0.05$. This indicating that rainfall plays important role in evapotranspiration of the sub bain. The mean evapotranspiration in the sub basin was 760 mm. The minimum evapotranspiration was 400 mm and maximum evapotranspiration was 920 mm. In the period between 1977 and 1986, the evapotranspiration showed a declining trend from 878 mm in 1977 to 734 mm in 1986. During this period the area under mixed farming land showed declining trend from 1425 km^2 in 1977 to 1338 km^2 in 1986. In the period 1987 to 1996, the evapotranspiration showed an increasing trend from 734 mm in 1987 to 919 mm in 1996. While the area under mixed farming during this period increased by 52 km^2 from 1342 km^2 to 1390 km^2 (Figure 4.5.13).

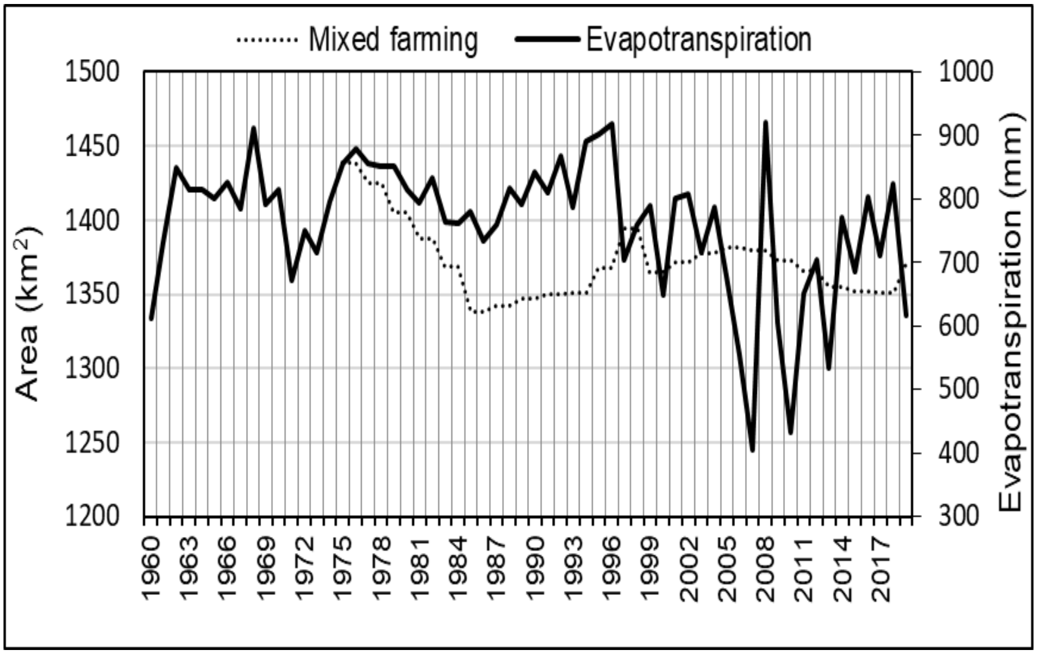


Figure 4.5.13: Evapotranspiration and mixed farming in the Kipsonoi sub basin (1960 – 2020)

4.5.3.3 Soil moisture in the sub basin dominated by mixed farming land uses

The mean annual soil moisture in the sub basin dominated by mixed farming was 19.8 mm. The minimum soil moisture was 6.4 mm while maximum soil moisture was 30 mm. In the period between 1987 and 2002, the soil moisture showed an increasing trend from 12.8 mm to 29.5 mm. While the area under mixed farming during this period showed an increasing trend from 1338 km^2 to 1378 km^2. In the period 2003 -2018, the soil moisture decreased by 17.2 mm while the area under mixed farming decline by 26 km^2 (Figure 4.5.14). The relationship between soil moisture and area under mixed farming was insignificant with coefficient of determination R^2 was 0.0063 and correlation, r of 0.06 at $p > 0.05$. Similar to the sub basins dominated by tea plantations and forest cover, the relationship between rainfall and soil moisture in this sub basin was positive with R^2 of 0.3 and correlation coefficient r of 0.55 at $p > 0.05$.

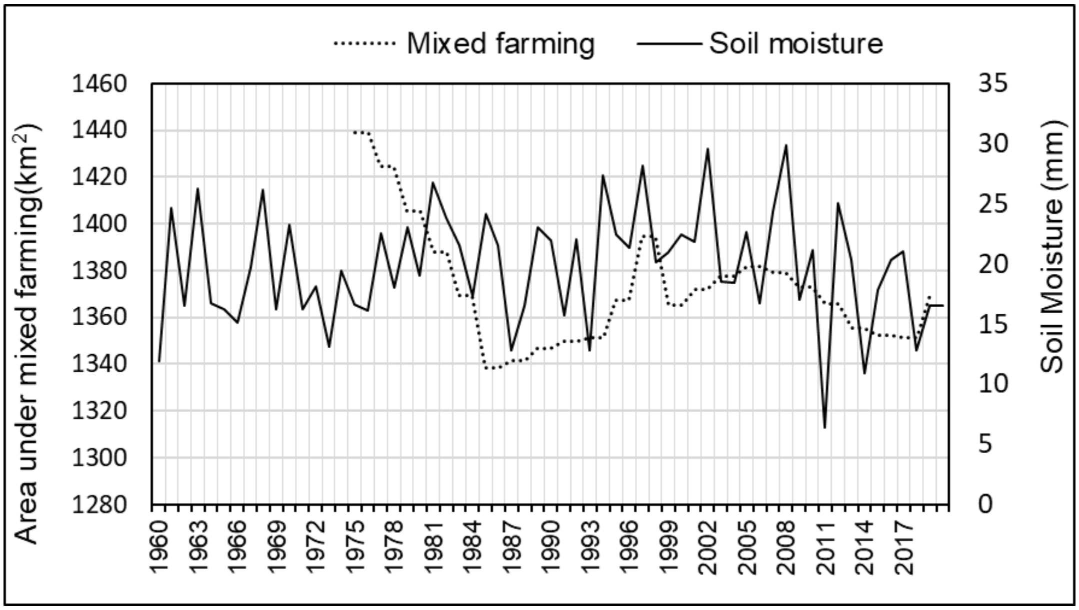


Figure 4.5.14: Soil Moisture and mixed farming in the Kipsonoi sub basin (1960 – 2020)

4.5.3.4 Change in water storage in the sub basin dominated by mixed farming land use

The annual change in water storages in the sub basin under mixed farming land cover showed that 23 years composing 35% of the study period had negative change in water storage. The 65% of the study period showed the positive change in water storages (Figure 4.5.15). The mean annual change in water storage was 2.69 mm. The minimum change in water storage was -14 mm and maximum change in water storage was 20.7 mm. The relationship between change in water storage and area under mixed farming was insignificant with R^2 of 0.00002 and correlation r of 0.004 at p of 0.05. This showed that mixed farming has no major influence on change in water storge of the river basin. In the period between 1975 and 1987, the change in water storage decreased from 10.24 mm to 6.49 mm while the area under mixed farming declined from 1439 km^2 to 1342 km^2. On the other hand, the change in water storage and area under mixed farming increased in the period between 1988 and 1998. In this period the change in water storage increased from 6.5 mm to 10.4 mm while area under mixed farming increased from 1342 km^2 to 1394 km^2. In the period between 2008 and 2018, the change in water storage declined from 11.8 mm to - 6 mm while the area under mixed farming decreased from 1379 km^2 to 1351 km^2.

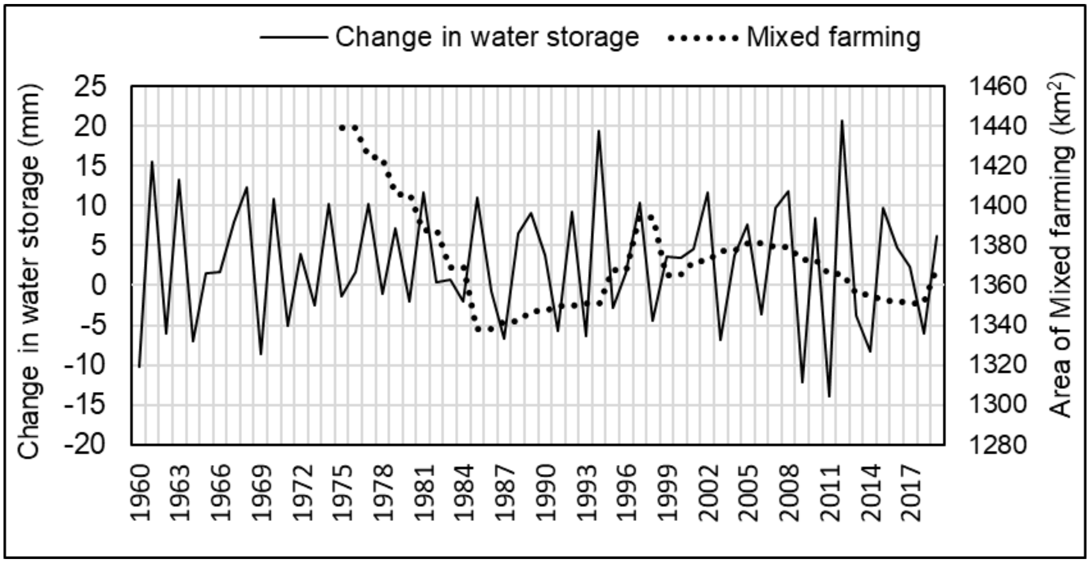


Figure 4.5.15: Change in water storage in the sub basin dominated by mixed farming (1960 – 2020)

4.5.4 Water balance components in mixed land covers in Sondu Miriu basin

4.5.4.1 Rainfall in the river basin with mixed land covers

The rainfall in the Sondu Miriu River Basin with mixed land cover (tea plantation, forest and mixed farming) showed that there was an inter annual variations in the sub basin dominated by mixed land cover and land uses. The periods showing rainfall increasing trends were 1970-1978, 1985-1990 and 2014-2020. Periods of declining rainfall trends are 1960-1969, 1978-1984 and 1990-2014 (see Figure 4.5.16). The highest rainfall received was 2087 mm/a in 1990 and the mean rainfall in the river basin was of 1350 mm/a. The minimum rainfall was 500 mm and maximum rainfall was 2087 mm (see Table 4.6). In the period between 1960 and 1969 the rainfall pattern showed a decreasing trend from 1280 mm/a in 1960 to 516 mm/a in 1969. Also, in the period between the 1970 and 1978, the rainfall showed an increasing trend from 516 mm/a in 1970 to 1878 mm/a in 1978. Further the period between 1979 and 1984 rainfall showed a decreasing trend from 1878 mm/a to 853 mm/a. In this period the area under mixed land cover declined from 1502 km^2 to 1439 km^2. In the period between 1985 and 1990, the rainfall increased from 1047 mm/a in 1985 to 2088 mm/a in 1990. At the same time the area under combined land cover increased in this period by 34 km^2 (from 1439 km^2 to 1455 km^2). In the period between 1990 and 2014, the rainfall declined from 2087 mm/a in 1990 to 733 mm/a in 2014. While the area under mixed land cover during this period showed insignificant increase of about 17 km^2. In the period between 2014 and 2020, the rainfall increased from 1011 mm/a in 2014 to 1362 mm/a in 2020 and the area under mixed land cover from 1450 km^2 to 1484 km^2.

The relationship between rainfall and area of mixed land cover land use in the river basin was insignificant with correlation r of 0.3 and coefficient of determination R^2 of 0.066 at $p > 0.05$. The spatial distribution of rainfall indicates that sub basins dominated by forest and tea plantation land covers receive high amounts of rainfall compared to sub basins with mixed farming land cover and land uses (Figure 4.5.17). The annual rainfall in the Timbilil and Kiptiget sub basins dominated by tea plantations and forest land cover respectively ranged between 1600 mm/a and 2000 mm/a. In the Kipsonoi and other downstream sub basins dominated by mixed farming land cover and land use showed that annual rainfall ranged between 1200 mm/a and 1460 mm/a.

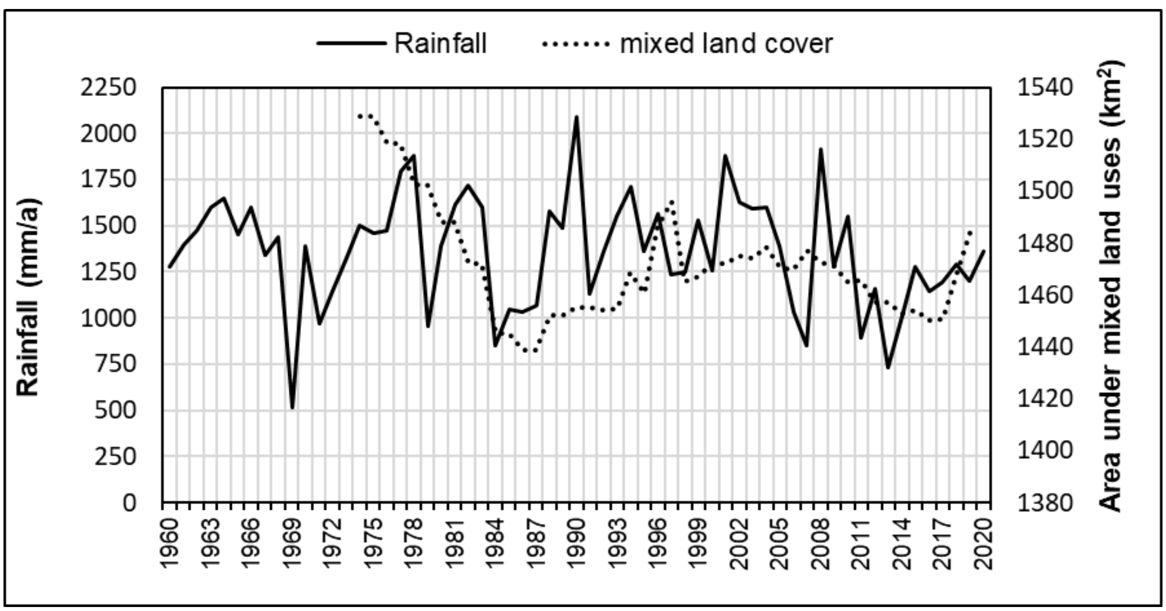


Figure 4.5.16: Rainfall and mixed land uses in the Sondu Miriu river basin (1960-2020)

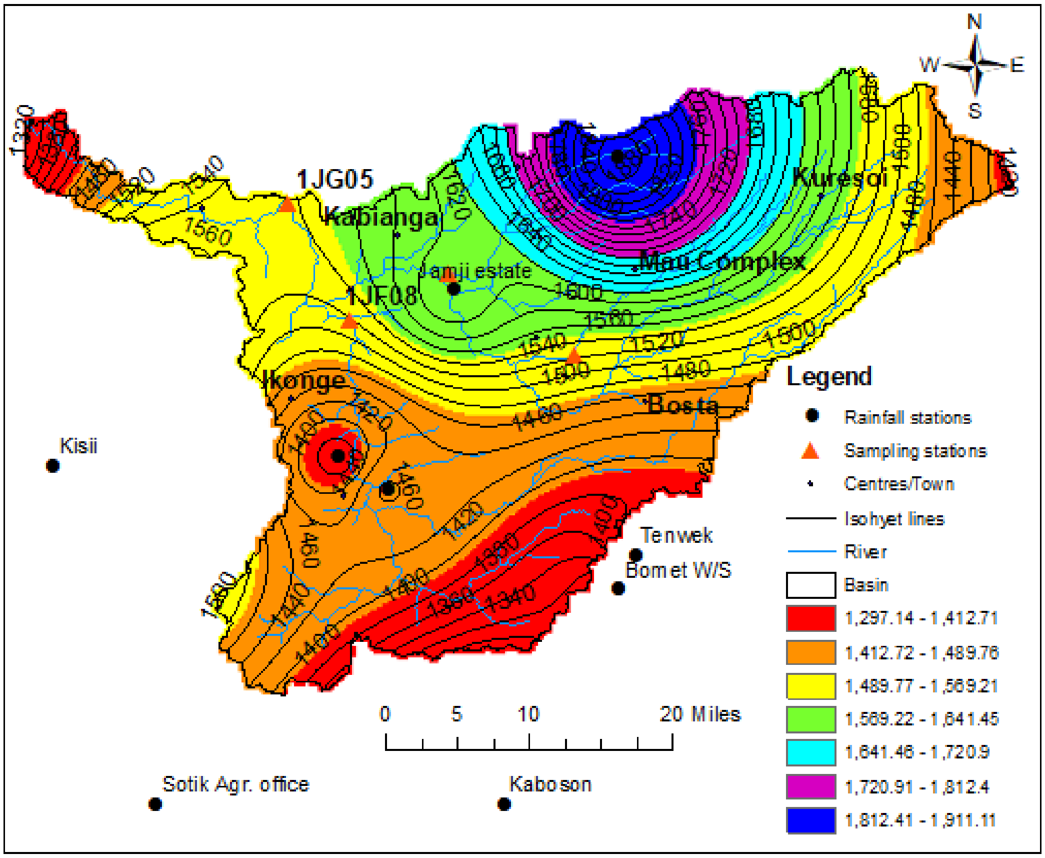


Figure 4.5.17: Spatial distribution of mean annual rainfall in the Sondu Miriu River Basin (Koech, 2021)

4.5.4.2 Evapotranspiration in the river basin with mixed land covers

The inter annual relationship between evapotranspiration and mixed land cover/land use (tea plantation, forest and mixed farming) in the Sondu Miriu River Basin was portrayed by similar trends (Figure 4.5.18). The trends for mixed land use/land cover and evapotranspiration showed similar patterns in the periods 1970-1978, 1979-1984, 1985-1995, 1995-2010 and 2011-2018. The mean annual evapotranspiration in the river basin was 630 mm (see Table 4.6). In the period between 1960 and 1969 the evapotranspiration declined from 750 mm to 247 mm. But in the period between 1970 and 1978, the evapotranspiration increased from 650 mm to 804 mm. During this period the mixed land use/land cover showed declining trend. Further in the period between 1979 and 1984, the evapotranspiration reduced from 535 mm to 438 mm while the mixed land use/land cover declined from 1529 km^2 to 1445 km^2. In the period 1985-1995, the evapotranspiration increased from 582 mm to 730 mm and the mixed land use/land cover increased by 1439 km^2 to 1495 km^2. In the period 1996 – 2010, the evapotranspiration decreased from 729 mm to 347 mm and mixed land use/land cover declined from 1529 km^2 to 1445 km^2. In the period between 2011 and 2018, the evapotranspiration increased from 549 mm to 742 mm.

In similar period the mixed land cover increased from 1457 km^2 to 1484 km^2. The relationship between evapotranspiration and mixed land cover/land use was insignificant with coefficient of determination R^2 of 0.109 and correlation r of 0.3 at $p > 0.05$. The annual spatial distribution of evapotranspiration in the river basin showed that areas covered by mixed farming had evapotranspiration rates ranging from approximately 600 mm to 720 mm. The evapotranspiration for the forested areas ranged between 700 mm and 800 mm. While in the areas covered by the tea plantation in the river basin had evapotranspiration rates ranging from 800 mm to 1000 mm (Figure 4.5.19).

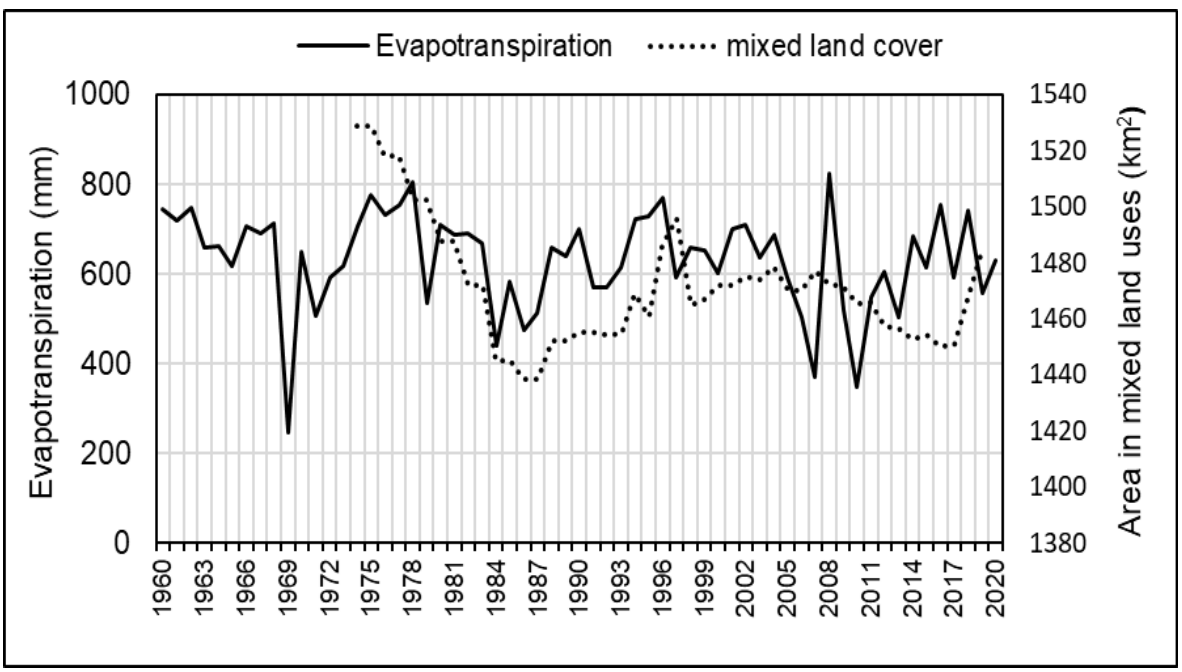


Figure 4.5.18: Actual evapotranspiration in the river basin with mixed land covers (1960-2020)

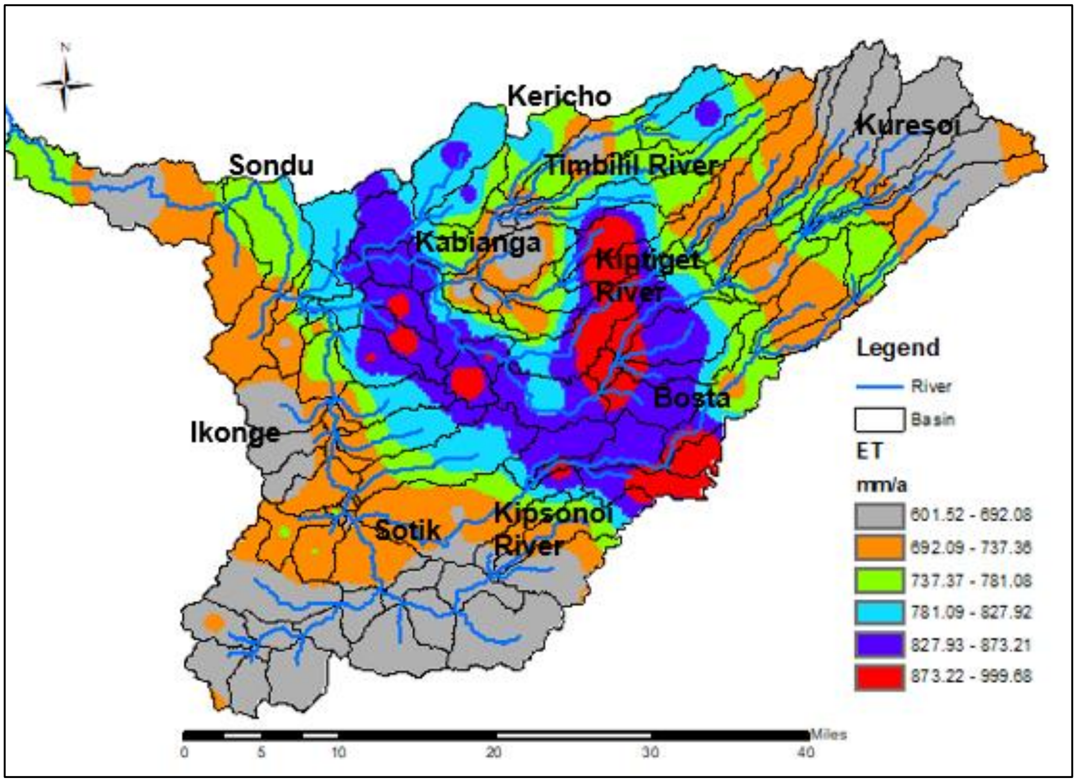


Figure 4.5.19: Distribution of evapotranspiration in the river basin with mixed land covers (Source: Koech, 2021)

4.5.4.3 Soil moisture in the river basin with mixed land covers

The inter annual relationship between soil moisture and mixed land cover (tea plantation, forest and mixed farming) was insignificant. The coefficient of determination R^2 was 0.08 and correlation r was 0.28 at $p > 0.05$. The inter annual assessment revealed two periods with increasing soil moisture 1974-1981 and 1992-2002. On the other hand, the periods with decreasing soil moisture were 1961 -1973, 1982-1991 and 2003 – 2011 (Figure 4.5.20). In the period between 1961 and 1973, the soil moisture decreased from 26 mm to 15 mm. In the period 1974-1981, the soil moisture increased from 17.8 mm to 26 mm. During this period the mixed land cover declined from 1529 km^2 to 1445 km^2. In the period between 1982 and 1991, the soil moisture decreased from 25 mm to 11.3 mm. In this period the mixed land cover further declined from 1471 km^2 to 1455 km^2. In the period between 1992 to 2002, the soil moisture increased from 12.5 mm to 32.5 mm. This high difference was attributed to increase in mixed land cover/land use from 1455 km^2 to 1475 km^2. In the period between 2003 and 2011, the soil moisture decreased from 20.5 mm to 7.2 mm. This change was attributed to decline in the mixed land cover/land use from 1472 km^2 to 1451 km^2.

The average soil moisture content for the study period was approximately 19 mm. The minimum soil water moisture was 26.5 mm and maximum soil moisture was 32.5 mm (see Table 4.6). Comparing soil moisture in three land covers of this study. It was revealed the highest volume occurred in 1978 with estimated volume of 5600 m^3/a (140 mm/a) and the second highest recurred in 2008 with volume of about 7140 m^3/a (178 mm/a). This showed that the peak in the soil water content occurs in approximately 30 years return period. The average annual net soil water content obtained in this study was approximately 3660 m^3/a (92 mm/a).

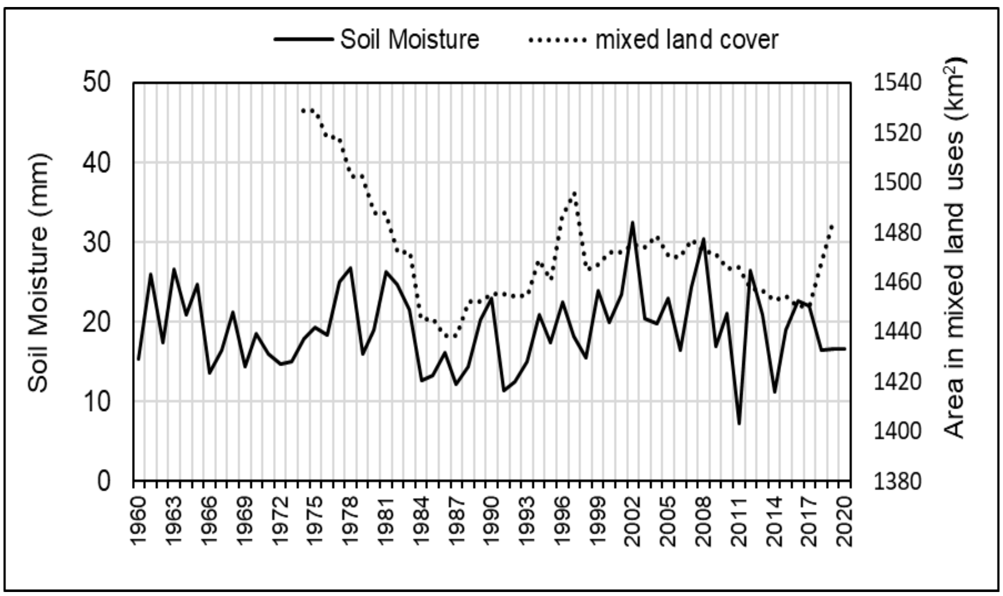


Figure 4.5.20: Soil moisture in the Sondu Miriu River Basin with mixed land covers and land uses (1960-2020)

4.5.4.5 Change in water storage in the Sondu Miriu River Basin with mixed land covers

The inter annual change in water storage in mixed land covers (tea plantation, forest and mixed farming) showed negative values especially in the period between 1960 and 2011.

This was about 90% of the entire period covered in this study. The change in water storage during this period ranged between -3.0 mm to -25 mm. However, in the period 1961, 2007 and 2012 the change in water storage showed positive values of 1.182 mm/a, 1.37 mm/a and 11.5 mm/a respectively (Figure 4.5.21). The mean annual change in water storage over time step obtained was about – 10.3 mm/a (see Table 4.6). In the period between 1962 and 1967, the change in water storage decreased from 1.2 mm to -23.4 mm. In the period between 1986 and 2008, the change in water storage increased from -6.02 mm to 1.37 mm while the area under mixed land cover increased from 1445 km^2 to 1472 km^2. Further, in the period between 2004 and 2013, the change in water storage showed increasing trend from -25.4 mm to 11.49 mm. At the same period the area under land cover decreased from 1474 km^2 to 1457 km^2. The relationship between area of land under mixed land cover and change in water storage was negative and insignificant with coefficient of determination R^2 of 0.0088 and correlation r of -0.09 at $p > 0.05$.

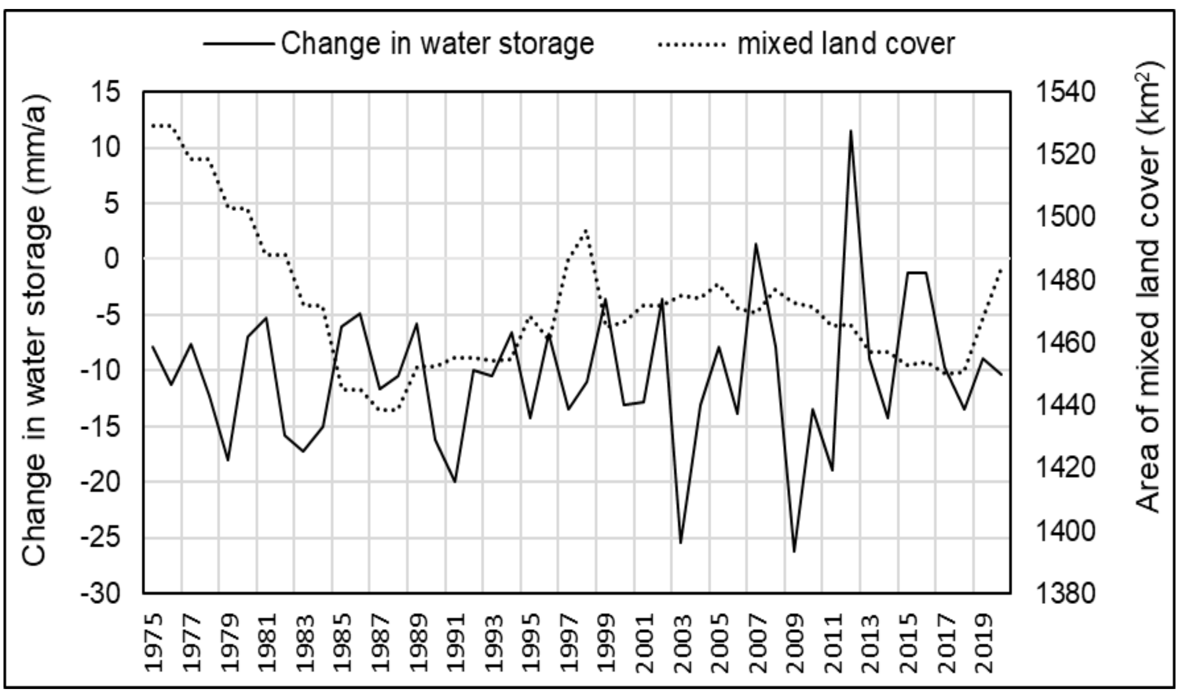


Figure 4.5.21: Change in water storage in the Sondu Miriu River Basin with mixed land covers (1960-2020)

Table 4.6: Mean, maximum and minimum values of water balance components in the period 1960-2020 in dominant land covers and uses

Components	**Land use/cover**	Tea Plantation	Forest	Mixed farming	Mixed land cover
Rainfall (mm)	Mean	1832	1830	1409	1350
	Max	2504	2516	2030	2087
	Min	1303	1265	750	500
Evapotranspiration (mm)	Mean	750	905	760	630
	Max	830	1006	920	800
	Min	500	560	400	250
Soil Moisture (mm)	Mean	22.9	26.3	19.8	19.2
	Max	37.6	40.2	30	32.5
	Min	13.8	14.1	6.4	26.5
Change in water storage (mm)	Mean	26.8	28.6	2.69	-10.3
	Max	64.7	63.8	20.7	12
	Min	2.68	-5.8	-14	-25
Mean Stream flow (m^3/s)	Discharge	10.8	4.5	32.4	4.5
	Surface runoff	3.2	1.8	28.2	1.8
	Base flow	7.6	2.7	4	2.7

The null hypothesis stated that there were no significant differences in the hydrological components of the sub basins dominated by tea plantations, forest and mixed farming land covers. The hydrological components (rainfall, evapotranspiration, soil moisture and change in water storage) of the sub basins were tested using the ANOVA one factor as follows;

1. The hypothesis testing significant different in rainfall component in the sub basins dominated by tea plantations, forest and mixed farming land covers. This was done at $p<0.01$ and it showed that F calculated was 42.7 while F critical was 3.05. The F calculated was greater the F critical hence the null hypothesis that there is no significant difference in rainfall in the sub basins dominated by tea plantations, forest and mixed farming land cover was rejected. Hence rainfall differ in the sub basins dominated by forest, tea and mixed farming land covers.

2. The evapotranspiration in the sub basins dominated by tea plantations, forest and mixed farming was tested using ANOVA with $p<0.01$ and found that F calculated was 66.6 and F critical was 3.05. The F calculated was greater than F critical and the null hypothesis was rejected.

3. The soil water moisture was tested using ANOVA with $p<0.01$ in the sub basins dominated by tea plantations, forest and mixed farming land covers. The results showed that the F calculated was 26.3 while F critical was 3.05. This indicated that the F calculated was greater than F critical hence the null hypothesis that there is no significant different in the soil moisture in the sub basin dominated by tea plantations, forest and mixed farming land cover was rejected.

4. The significant difference of the change in water storage in the sub basins dominated by tea plantations, forest and mixed farming land covers was tested using ANOVA with $p<0.01$. The results showed that the F calculated was 85.7 and greater than F critical 3.05 and hypothesis was rejected.

4.6 Relationship between stream flow and sediment yield in the land cover dominated sub basins

The assessments of relationship between stream flow and sediment yield on the stream networks in the sub basins dominated by tea plantations, forest and mixed farming land cover and land use were conducted and established that there was a significant relationship between stream flows and sediment yields in the sub basins with different land uses. The sections below describe the relationship between stream discharges and sediment yields in different land covers of the river basin.

4.6.1 Relationship between stream flow and sediment yield in the sub basin dominated by tea plantations

The inter annual trends showed that there was a decreasing trend in stream discharge in the period between 1962 and 1985 from 19.62 m^3/s to 7.82 m^3/s. Also, in the period between

1997 and 2014, the stream discharge decreased from 22.5 m^3/s to 9.02 m^3/s. The increasing trend was observed in the period between 1986 and 1995 from 9.8 m^3/s to 23.8 m^3/s (Figure 4.6.1). The sediment yields showed insignificant trend between 1962 and 1985. While an increasing trend occurred in the period between 1986 and 1998 with sediment yields from 0.91 tonnes/ha to 4.85 tonnes/ha. The decreasing trends occurred in the period between 2006 and 2016 with sediment yields from 2.4 tonnes/ha to 0.76 tonnes/ha. The insignificant relationship between stream discharge and sediment yields in the Timbilil Sub basin was positive with coefficient of determination R^2 of 0.23, correlation coefficient r of 0.5 at $p > 0.05$.

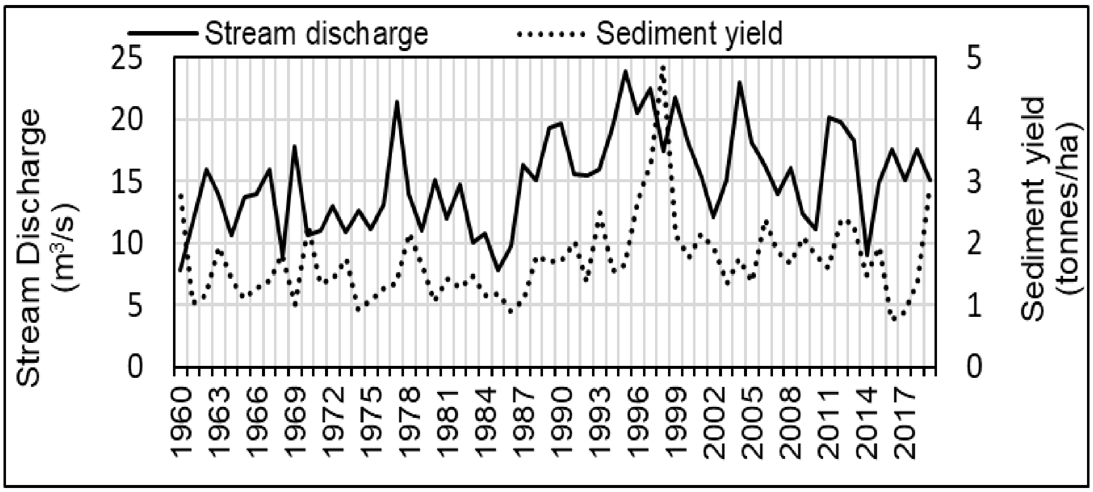


Figure 4.6.1: Stream discharges and sediment yields in the sub basin dominated by tea plantation land cover (1960-2020)

4.6.2 Relationship between stream flow and sediment yield in the sub basin dominated by forest land cover

The stream flows and sediment yields showed increasing and decreasing trends in almost similar periods while in the period between 1960 and 1969 there was no significant change. The stream discharges increased in the periods between 1970 and 1980 from 1.4 m^3/s to 3.8 m^3/s. Also, the stream discharges increased in the period between 1995 and 2006 from 3.2 m^3/s to 4.3 m^3/s. The decreasing trend occurred in the period between 1982 and 1994 from 3.67 m^3/s to 2.5 m^3/s. Similarly stream discharges also decreased in the period between 2007 and 2018 from 3.5 m^3/s to 2.28 m^3/s. The sediment yields increased in the periods between 1970 and 1982 from 0.49 tonnes/ha to 1.6 tonnes/ha. In the period between 1998 and 2006 the sediment yields increased from 1.2 tonnes/ha to 1.5 tonnes/ha. The decreasing trend occurred in the period between 1983 and 1995 from 1.3 tonnes/ha to 1.2 tonnes/ha. Also, decreasing trend in sediment yields occurred in the period between 2007 and 2018 from 1.2 tonnes/ha to 0.96 tonnes/ha (Figure 4.6.2). The insignificant relationship between stream flows and sediment yields were positive with coefficient of determination R^2 of 0.24, p >0.05 and correlation r of 0.48 (Figure 4.6.3).

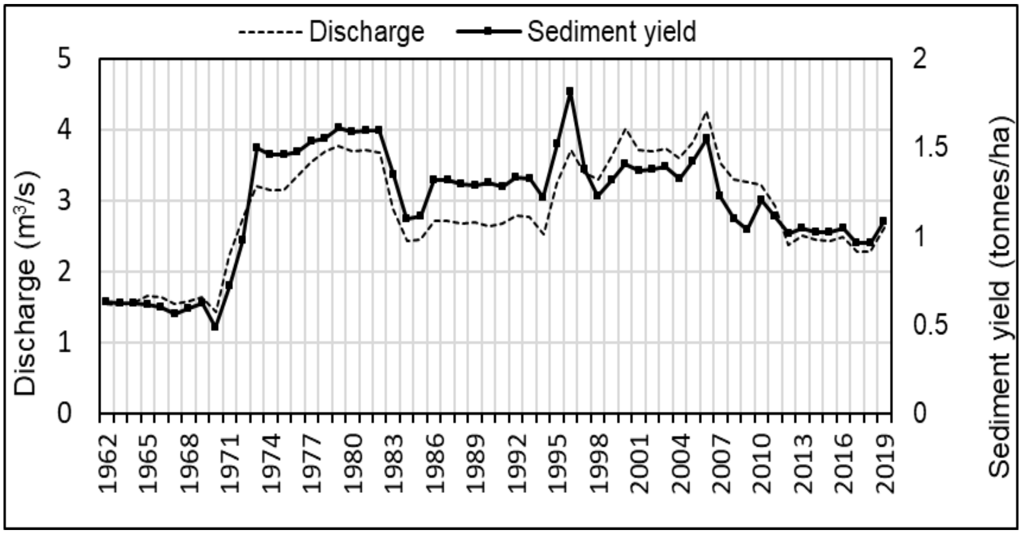


Figure 4.6.2: Stream discharges and sediment yields in the forest dominated sub basin (1960 – 2020)

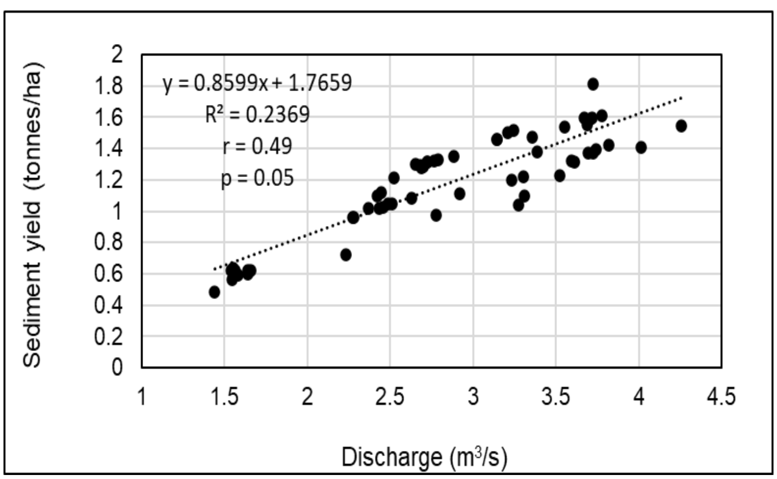


Figure 4.6.3: Relationship between stream flows and sediment yields in the forest dominated sub basin (1960-2020)

4.6.3 Relationship between stream flow and sediment yield in mixed farming dominated sub basin

The trends for stream discharges and sediment yields in the Kipsonoi Sub basin were insignificant in the period between 1972 and 1998. However, in the period between 1960 and 1968 the stream discharges increased from 17.9 m^3/s to 50.9 m^3/s. In the period between 2001 and 2013, the stream discharges decreased from 50.9 m^3/s to 9.98 m^3/s. In the period between 1960 and 1968 the sediment yields increased from 32.75 tonnes/ha to 109 tonnes/ha in 1968. In the period between 2001 and 2013, the sediment yield decreased from 118.5 tonnes/ha to 10.9 tonnes/ha (Figure 4.6.4).

There is significant relationship between stream discharge and sediment yield in the Kipsonoi Sub basin dominated by mixed farming land use. This was evident by the high coefficient of determination R^2 of 0.902, significance $p < 0.05$ and correlation r of 0.95 (Figure 4.6.5). The stream discharges ranged from the peak flow of 52.3 $m^3/$ in 2010 to minimum flow of 9.98 m^3/s in 2013. The mean stream discharge in the sub basin was 29.5 m^3/s. The maximum sediment yield in the sub basin was 120.8 tonnes/ha in 2010 while the minimum sediment yield was 10.9 tonnes/ha in 2013. The mean sediment yield was about 53.7 tonnes/ha (Table 4.7).

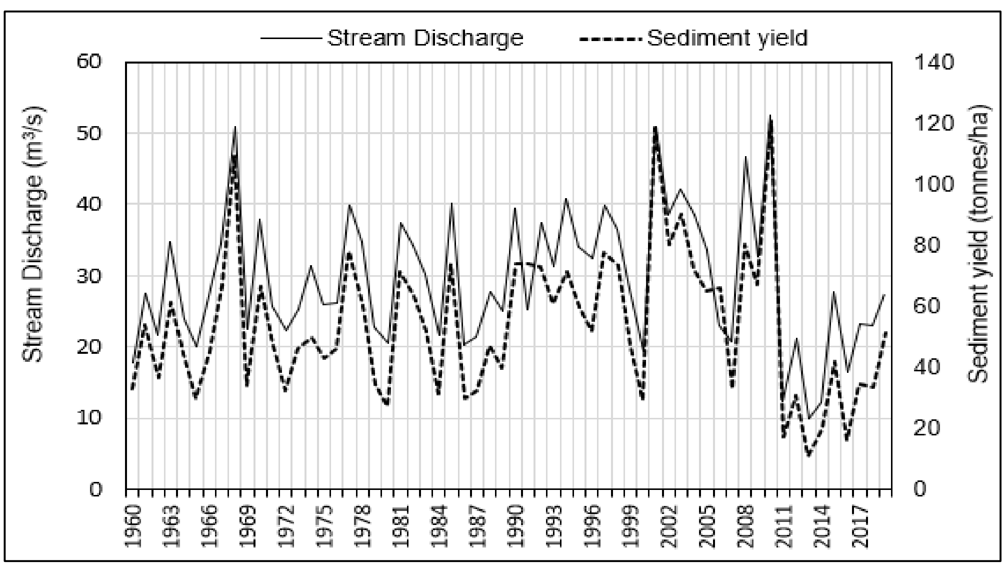


Figure 4.6.4: Sediment yields and stream discharges in the mixed farming dominated sub basin (1960-2020)

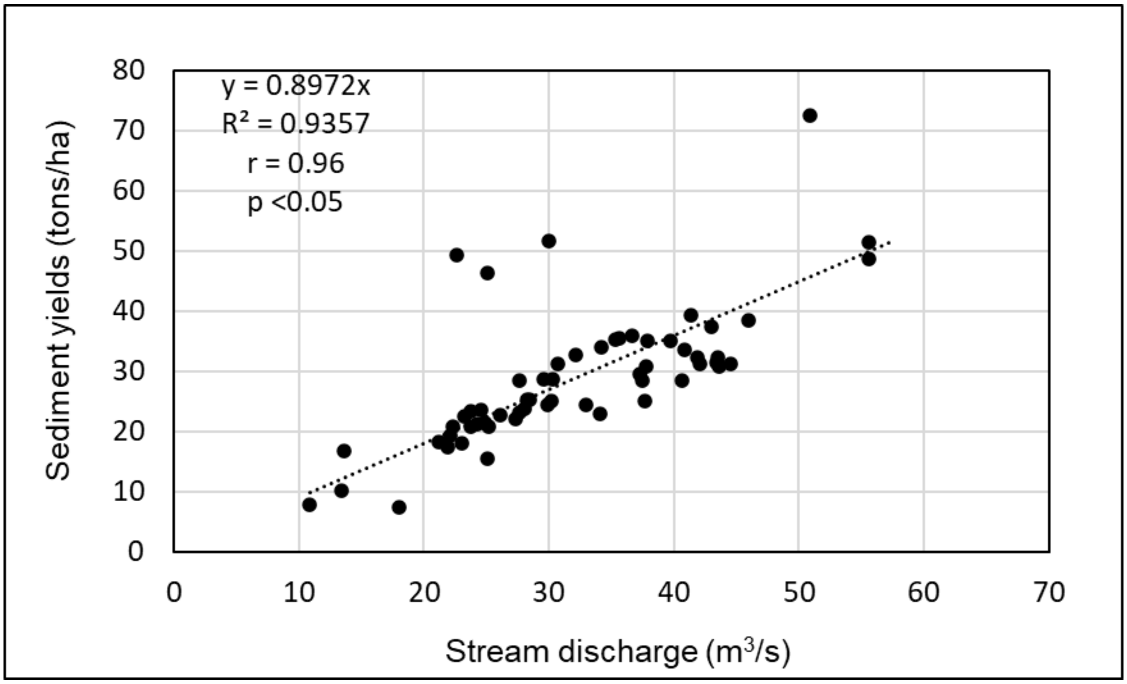


Figure 4.6.5: Relationship between stream discharges and sediment yields in the mixed farming dominated sub basin (1960-2020)

4.6.4 Relationship between stream flow and sediment yield in Sondu Miriu River Basin

There was insignificant trend in the stream discharges and sediment yields in the period between 1960 and 1986. The increasing trend for the stream discharge occurred in the period between 1987 and 1998 from 129.3 m^3/s to 335.1 m^3/s. However, in the period between 1999 and 2016 the stream discharge decreased from 278 m^3/s to 83.8 m^3/s. The sediment yields in the river basin increased in the period between 1985 and 1993 from 45.1 tonnes/ha to 113.9 tonnes/ha respectively. Also, in the period between 1995 and 2010 from 47.2 tonnes/ha to 248.4 tonnes/ha. In the period between 2010 and 2016 the sediment yields decreased from 248.4 tonnes/ha to 17.13 tonnes/ha (Figure 4.6.6).

The relationship between stream discharges and sediment yields was positive with coefficient of determination R^2 of 0.59, correlation r of 0.76 and significance $p < 0.05$ (Figure 4.6.7). The maximum stream discharge in the river basin was 335.1 m^3/s and it occurred in 1998. While the minimum stream discharge was 83.8 m^3/s and it occurred in

2016. The mean stream discharge was approximately 180 m^3/s. The sediment yields in the river basin ranged between maximum yield of 248.4 tonnes/ha in 2010 and minimum yield of 17.13 tonnes/ha in 2016. The mean sediment yield was 72.4 tonnes/ha (Table 4.7).

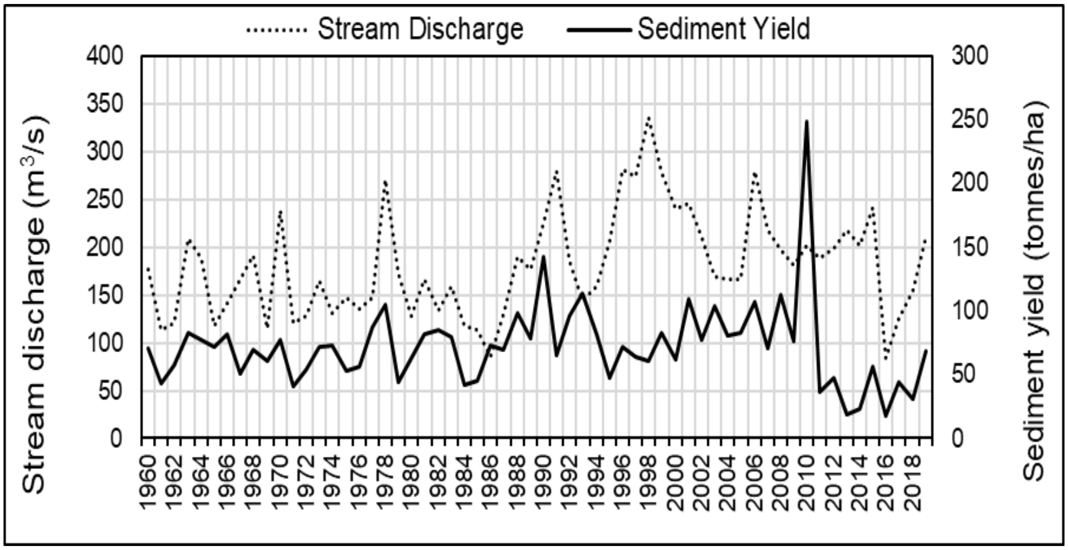


Figure 4.6.6: Sediment yields and stream discharges in the Sondu Miriu River Basin (1960-2020)

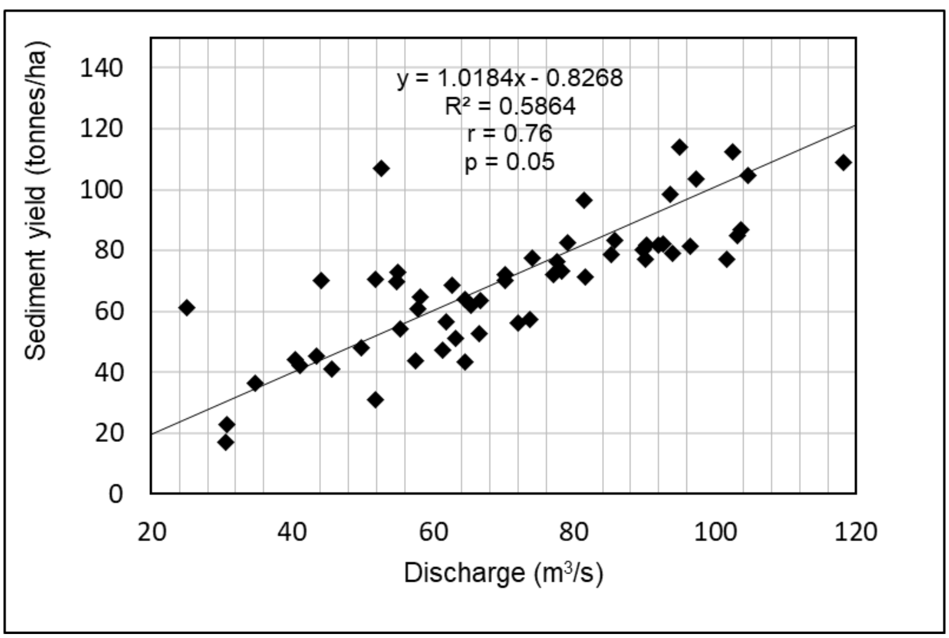


Figure 4.6.7: Relationship between sediment yields and stream discharges in the Sondu Miriu River Basin (1960-2020)

The null hypothesis that there was significant relationship between stream flows and sediment yields in the sub basins dominated by tea plantations, forest and mixed farming land covers. The null hypothesis was tested in each sub basin using t-test at $p<0.01$ as follows;

1. The null hypothesis tested in the sub basin dominated by tea plantations showed that the t stat calculated was 11.3 while t critical one tail and two tail were 1.7 and 1.99 respectively. Given that the t stat calculated was greater than t critical, then the null hypothesis was rejected in the sub basin dominated by tea plantations.

2. The results showed that the sub basin dominated by forest land cover, the t stat calculated was 3.2 while t critical one tail and two tail were 1.66 and 1.98 respectively. The t stat calculated was greater than t critical and hence the null hypothesis was rejected in the sub basin dominated by forest land cover.

Further the null hypothesis was tested in the sub basin dominated by mixed farming and the results showed that the t stat calculated was -9.6 while t critical one tail and two tail were 1.68 and 1.99 respectively. Hence the t stat calculated was less than t critical and the null hypothesis was accepted that in the sub basin dominated by mixed farming.

4.7 Suitable land use and land cover types and catchment management practices

4.7.1 Suitable land use/cover types for sustaining stream flows and reducing sediment transport

The sub basins dominated by tea plantations and forest land covers had higher base flows compared to surface runoffs. The mean base flow in the sub basin dominated by tea plantations was 7.56 m^3/s while the mean surface runoffs was 3.24 m^3/s. The mean soil moisture and the mean change water storage in the sub basins dominated by tea plantations were 22.9 mm and 26.8 mm respectively. Low sediment yields generated in the sub basin dominated by tea plantations with mean sediment yield of 7.69 tonnes/ha was observed.

The water loss through evapotranspiration was moderate with mean annual loss of 747.7 mm.

In the sub basin dominated by forest land cover the mean base flow was 3.15 m^3/s while the mean surface runoff was 1.35 m^3/s. This indicates that in the sub basin there was high infiltration rate that increases the soil moisture and water storage. The soil moisture and change in water storage were high in the sub basin with mean annual value of 26.4 mm and 28 mm respectively. The sediments generated in the sub basin was low with mean sediment yield of 3.8 tonnes/ha. The water loss through evapotranspiration was high with mean annual value of 903.9 mm (see Table 4.7).

In the sub basin dominated by the mixed farming, the base flows were low compared to surface runoffs. The mean base flow was 3.98 m^3/s and mean surface runoff was 28.38 m^3/s. The mean change in water storage and soil moisture were 2.7 mm and 19.8 mm respectively. The sediments generated in the sub basin was high with mean sediment yield of 82.3 tonnes/ha. The water loss through evapotranspiration was high with mean annual value of 762.5 mm. The hydrological components used in Table 4.7 indicated that forest land cover is the most suitable land cover. The results showed that mixed farming land use contribute high quantities of sediment yields about 25 times higher than forest cover. The forest cover and tea plantations reduce sediment generation by about 95%. Similar observations were made in the previous study (Njue *et al*., 2021).

4.7.2 Catchment management practices for sustaining stream flows and reducing sediment transport in sub basin dominated by mixed farming

The stripped cropping was applied in the sub basins discharging sediments as a catchment management operation. It was observed that stripped cropping can reduced the sediment generation by approximately 48%. The initial sediment yield had an average of about 140 tonnes/ha. while after use of strip cropping (Figure 4.7.1) the sediment yields generated had average of about 72 tonnes/ha. This indicates that farmers in the river basin should practice strip cropping in the catchment areas with steep slopes.

Table 4.7: Comparing hydrological components in the sub basins with dominant different land uses/land covers

Land cover/use type	**Parameter**	**Maximum**	**Minimum**	**Mean**	**Remark**
Tea plantations	Stream discharge **(m^3/s)**	17.35	5.7	10.8	High base flow, low surface runoffs, low sediment yield, high water storage, high soil moisture
	Sediment yield **(tons/ha)**	12.4	4.1	7.69	
	Surface Runoffs **(m^3/s)**	5.2	1.7	3.24	
	Soil Moisture **(mm)**	37.6	13.8	22.9	
	Evapotranspiration **(mm)**	849.2	469.1	747.7	
	Water storage **(mm)**	64.7	2.68	26.8	
	Base flow **(m^3/s)**	12.14	3.98	7.56	
Forest	Stream discharge **(m^3/s)**	7.5	2.02	4.5	High base flow, low surface runoffs, low sediment yield, high water storage, high soil moisture
	Sediment yield **(tons/ha)**	6.2	2.0	3.8	
	Surface Runoffs **(m^3/s)**	2.2	0.61	1.35	
	Soil Moisture **(mm)**	40.2	14.1	26.4	
	Evapotranspiration **(mm)**	1006.1	562	903.9	
	Water storage **(mm)**	63.8	-5.75	28	
	Base flow **(m^3/s)**	5.23	1.4	3.15	
Mixed Farming	Stream discharge **(m^3/s)**	57.2	10.9	32.4	Low base flow, high surface runoffs, high sediment yield, low water storage, low soil moisture
	Sediment yield **(tons/ha)**	239.7	30.4	82.3	
	Surface Runoffs **(m^3/s)**	52.5	7.98	28.38	
	Soil Moisture **(mm)**	29.5	6.4	19.8	
	Evapotranspiration **(mm)**	921.1	404.3	762.5	
	Water storage **(mm)**	20.6	-13.97	2.7	
	Base flow **(m^3/s)**	7.4	1.88	3.98	

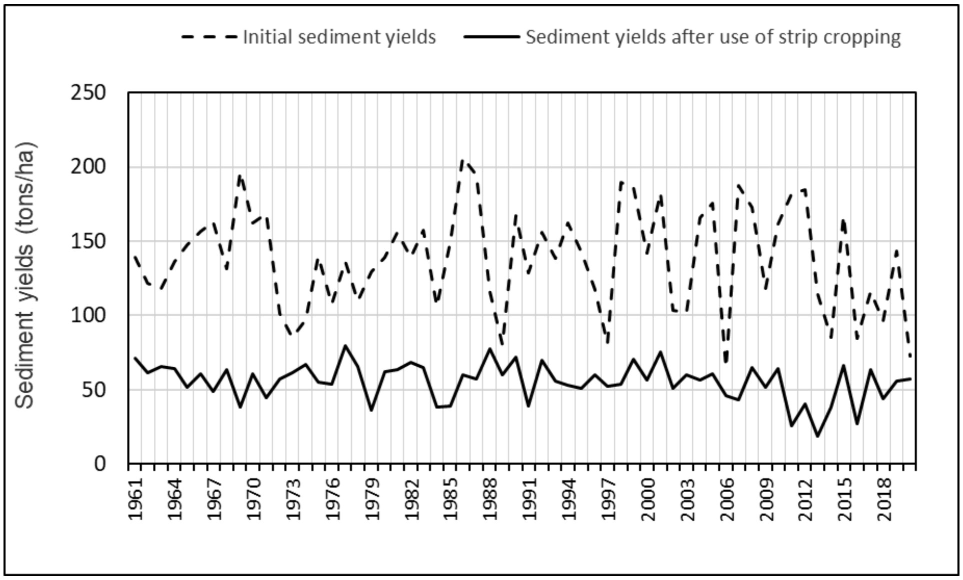


Figure 4.7.1: Sediment generation after use of strip cropping in the sub basin dominated by mixed farming land cover (1960-2020)

Terraces was applied as an operation to reduce sediment transport in steep terrain. The use of terrace operation in the river basin to conserve soils and reduced sediments by approximately 55%. It was noted that sediment yield peaks were reduced by the use of terraces from initial average of 140 tons/ha to about 63 tons/ha (see Figure 4.7.2).

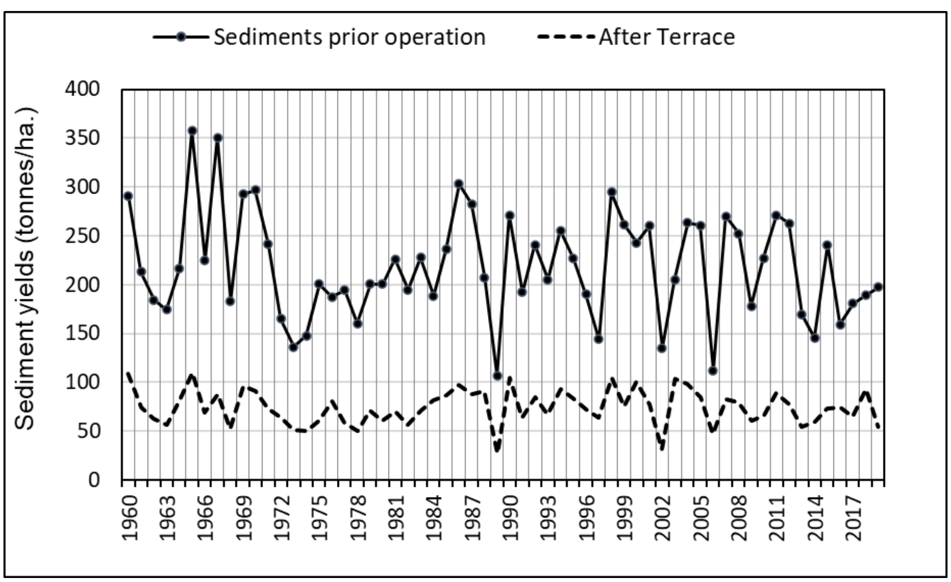


Figure 4.7.2: Sediment generation after use of terraces in the sub basin dominated by mixed farming land cover (1960-2020)

The application of vegetative filters in the river basin as buffers along the riparian lands as shown in Figure 4.7.3 reduced sediment yield by approximately 52%. This was evident by reduced average sediment yield from initial 140 tonnes/ha to 67 tonnes/ha. The high sediment yields observed in the river basin from 1965 to 1967 ranged from 100 tonnes/ha to 240 tonnes/ha. Application of vegetative filters reduced sediment yield in the same period between 50 tonnes/ha and 80 tonnes/ha. Also, in the period 1998 to 2012 high sediment fluxes ranging between 100 tonnes/ha and 189 tonnes/ha were reduced by half to a range between 40 tonnes/ha and 60 tonnes/ha.

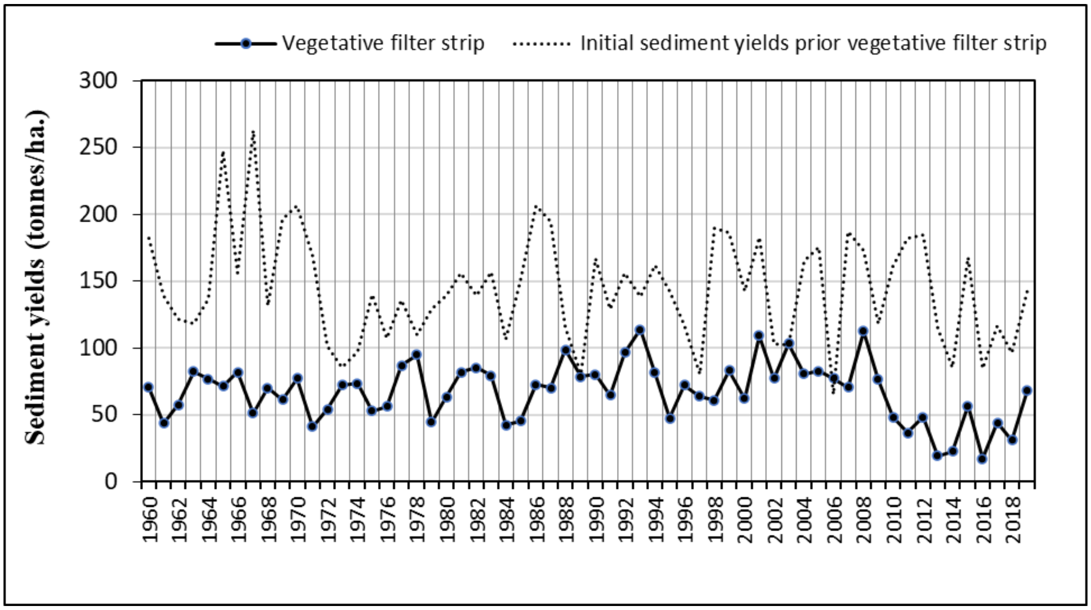


Figure 4.7.3: Effect of vegetative filter strips in the mixed farming dominated sub basin (1960-2020)

The null hypothesis stated that there was no significant difference in the catchment management structures used in reducing sediment yields generated in the sub basins. The ANOVA results showed that at $p<0.01$, the F calculated was 129.3 while the F critical in the table was 3.05. Hence the null hypothesis was rejected.

CHAPTER FIVE

5.0 DISCUSSION

5.1 Introduction

The main goal of this study was to determine the extent to which sub basins dominated by tea plantations, forests and mixed farming land covers/land uses in the upper Sondu Miriu River Basin influence sediment fluxes and stream flows. The results of the study were presented in chapter four. The purpose of this chapter is to present the discussion of the results. This has been attempted by focusing on the specific objectives of the study as well as the results of other studies.

5.2 Patterns of land cover / use change in sub basins dominated by tea plantation, forest and mixed farming land covers

The findings of this study showed that in the period of four and half decades from 1960 to 2020 (Tables 4.1 – 4.4), the area of land under tea plantations had been increasing while forests and mixed farming land covers were reducing. But in 1986 the increment in the area under forest cover was attributed to catchment rehabilitation programmes that were implemented by the various stakeholders (UNEP, 2010). The expansion in tea plantations was the main cause of reduction of forest cover and mixed farming land use in the sub basins. However, increase in population was a driving factor in continuous expansion of tea plantations to meet demands for socio-economic development. This was confirmed with the positive relationship between area under tea plantations land cover and population growth with correlation coefficient r of 0.49. This also showed that tea plantations were an attractive land cover for the basin communities living in the highlands within the tropics. In a study conducted between 1958 and 1995 stated that introduction of tea plantations in the Kenya highlands had significant negative impact on the natural forest cover in the river basins (Imbernon, 1999). Sondu Miriu River Basin form part of Kenyan Highlands and it was observed that forest land cover decreased by approximately 17% that was comparable to the study done in Mau complex in the period between 1973 and 2010 (Ayuyo and Sweta, 2014). In Eastern Himalayan tropical river basin, it was reported that the tea plantations increased by 30% from 1874 to 2010 (Prokop, 2018).

In addition to the findings of this study, studies conducted in the Sub Sahara Africa identified increasing population growth, inadequate policies and lack of enforcement of the forest protection rules and regulations as the main causes of declining forests cover in the region (Semwal *et al*., 2004; Brink and Eva, 2008; Biervliet *et al*., 2009; Olang and Fűrst, 2011; Chrisphine *et al*. 2016; Hassan *et al*., 2016; Morara and Chebet, 2017; Kogo *et al*., 2019; Kibet *et al*., 2021; Masayi *et al*., 2021; Ndalilo *et al*., 2021).

5.3 Effects of sub basins dominated by the tea plantation, forest and mixed farming land covers and land uses on stream flows and sediment fluxes

The land cover and land use change in the sub basins dominated by tea plantation, forest and mixed farming was assessed in this study period in relation to the influence of land use change on stream flows and sediment yields. The land cover changes due to heterogeneous activities in the previous studies revealed that land cover and land use changes had triggered hydrological response on the local hydrological processes in the sub basins (Gathenya *et al*., 2011; Kundu and Olang, 2011; Masese *et al*., 2012; Kitheka *et al*., 2021).

5.3.1 Effects of sub basin dominated by tea plantation, forest and mixed farming on stream flows

In this study the influence of tea plantations on stream flows was observed through the positive relationship between area under tea plantations and stream flows. For example, in section 4.3.1, it was realized that expansion of area under tea plantations land cover results in the increase in the stream discharges. However significant changes on stream flows were also attributed to the rainfall variability in the sub basin dominated by tea plantations. For instance, a small decrease in area of land under tea plantations by 2 km^2 and significant decline of stream flows by 6 m^3/s was observed in similar period (Figure 4.3.1). This clearly indicates that despite tea plantations influence the stream flows, rainfall is key factor. This was further justified by strong relationship between rainfall and stream flows as presented in section 4.3.1.1. The observed stream flows in the sub basin dominated by tea plantations were perennial and it was suspected that tea plantations increased groundwater recharge. In a study conducted in East Africa montane areas, tea plantations were reported to reduce overland flows and increases vertical movement of water through soil profile into the ground (Kroese *et al*., 2020).

In a study conducted in the Ethiopian Highlands expansion of tropical forest led to positive response of stream flows (Woldesenbet *et al*., 2018). While in this study it was realized that decreased in the forest cover increased stream flows. These two studies showed that changes in the area under forest cover have positive responses in short and long term. For instance, expansion of the forest cover increases water infiltration into the sub surface increasing base flows and hence perennial stream flows. While reducing forest cover reduces infiltration and base flows but increases surface runoffs resulting in an increase of seasonal stream flows (Abera *et al*., 2019). It was also observed that surface runoffs and deforestation have a strong positive relationship (Ngeno *et al*., 2016; Cruz-Garcia *et al.*, 2020). This study like previous studies in the region showed that alterations of the forests cover have significant impact on the hydrologic response of the stream flows. This study noted that hydrologic response during the planting and growing stages of the forests are insignificant (Figure 4.3.2). But the significant hydrologic response on stream flows in afforested areas occurred after a decade (period 2007-2017) both in tropical and temperate climatic zones (Roberts, 2000; Brown *et al*., 2013).

The findings of this study further revealed that changes in mixed farming land cover had significant influence on stream flow. It was found that an expansion in the land under mixed farming caused an increase in the peak stream flows during wet season (Figure 4.3.3). This was due to the increase in the surface runoffs as a result of replacing forest cover with mixed farming. On the other hand, this study observed that reducing area under mixed farming and increase forest cover or tea plantations reduces surface runoffs and peak stream flows. This was in agreement with the findings of the study conducted in Gojeb and Upper Baro River Basins where the expansion of mixed farming by about 15% to 16% led to an increase in the stream flows by about 7 m^3/s to 8.6 m^3/s (Choto and Fetene, 2019; Mekuriaw, 2019).

Comparing influence of tea plantations, forests and mixed farming on stream flows portrayed different patterns. In the mixed farming land cover peak stream flows were higher than stream flows observed in tea plantations and forest land covers. This could be due to size of the sub basin and open fields with less surface runoff obstructions. While stream flows in sub basins dominated by tea plantations and forests land cover had similar patterns of high base flows compared to surface runoffs. Hence it was noted that dominant land covers play critical role in determining the response of stream flows. Previous studies mainly established the influence of the mixed farming land covers in the river basins. The previous findings agreed with the observations made in this study that mixed farming generates high surface runoffs and frequent peak flows raising annual average stream discharges (Lambin *et al*., 2003; Hartemink, 2010; Costantini, 2015; Kebede *et al*., 2020; Kroese *et al*., 2020). This study also found that despite land cover and land uses have effects on the response of the stream flows, the stream flows patterns variability is attributed to the rainfall received in the sub basin. This was a s a result of strong positive relationships between stream flows and rainfall in the sub basins dominated by tea plantations, forests and mixed farming with coefficient of determination $R^2 > 0.9$.

5.3.2 Effects of sub basin dominated by tea plantation, forest and mixed farming on sediment flux

The findings of this study showed that there is a significant relationship between TSSC and turbidity in the sub basin dominated by tea plantations. It was noted that in long rainy seasons an increase in TSSC did not respond positively with the turbidity. This was attributed to the fact that high TSSC during wet season was due to surface runoffs carrying humus from the base of the tea trees and other debris on the riparian lands into the stream channel. In this study it was also noted that the relationship between turbidity with sediment loads was poor with correlation coefficient r of 0.5. This indicated that 50% of the sediments transported in water in the sub basin was soluble. While 50% were debris which had low impact on water clarity. Further, this study revealed that an increased in the sub basin stream flows could not raise the quantities of TSSC, turbidity and sediment loads.

This indicated that tea plantations reduce velocity and quantity of surface runoffs resulting in less transport of sediment loads downstream.

This study showed that there was a strong positive relationship between turbidity and stream flow compared to relationship between TSSC and stream flows. In a study conducted in small section of forest in Kabianga, it was reported that forest cover generates low TSSC (Ouma *et al*., 2013). This indicates that forest land cover reduces transport of suspended sediments from the catchment areas to the stream networks. These observations were similar to the findings in the sub basin dominated by tea plantations. This study exposed that despite tea plantations are exotic plants, it has insignificant effects on the water quality. Comparing with the findings of Jamji tea estate by Masese et al. (2012), it showed that expansion of tea plantation reduces generation of TSSC. On the other hand, this study revealed that mixed farming had significant effects on the water quality of the river basin. This was demonstrated by strong relationship between turbidity and TSSC of more than 95%. These findings revealed that different land uses and land covers have negative or positive influences. Previous studies conducted in different river s reported that mixed farming land cover generates TSSC which increases turbidity (Hannouche *et al*., 2011; Tahiru *et al*., 2020; Njue *et al*., 2021). This study showed that mixed farming land cover generates high quantity of suspended sediments of about 600 mg/l compared to forests and tea plantations with less than 50 mg/l. The study conducted in Athi River Basin revealed the expansion of mixed farming land cover increases the quantities of TSSC to magnitude of more than 1000mg/l (Kitheka *et al*., 2022).

This study further established that seasonal variability in turbidity, TSSC and sediment generation in the Kipsonoi sub basin dominated by mixed farming occurred in three seasons. These were pre-planting, planting, growing and post-harvest seasons. In the pre planting season high sediment loads, TSSC and turbidity were observed than other seasons. This was due to field preparation process through ploughing exposing soils to erosion by surface run offs. During planting and crop growing seasons in the month of April to July (Figures 4.3.14 and 4.3.16). Comparing the three seasons, it was noted that crop growing seasons and post harvesting season had low impact on sediment transport. The high sediment discharge during pre-planting periods was also reported in the Gilgel Gibe tropical river basin (Woldeab *et al*., 2018). The difference between post-harvest periods and pre-planting is the ability of the farm residues after crop harvesting to protect the soils and reduces soil erosion. The findings of this study portrayed that Sondu Miriu River is undergoing land use and land cover transformations and experiencing transfer of sediment loads from upstream to downstream. Like other tropical river basins which have been investigated, it was realized that replacing of forested areas with mixed farming land covers had significant effects on water quality in the river basins. Also, rainfall was attributed to transfer of sediments through surface runoffs (Nyangaga, 2008; Ouma *et al*., 2013; Geeraert *et al*., 2015; Mello *et al*., 2018; Kroese *et al*., 2020).

5.4 Simulation of stream flows and sediment yield in sub basins dominated by different land covers and land uses

The long-term stream flows and sediment yields in the Sondu Miriu River Basin were simulated to determine past stream flows and sediment transport. The SWAT model was used to estimate stream flows and sediment flows in monthly and annual time steps. The outputs of the model after calibration and validation with coefficient of determination and Nash–Sutcliff model efficiency value above 0.6 revealed that the model performance was good. The SWAT model performance to predict the future hydrological scenarios of the river basin had been tested for a number of years. The suitability of the model to simulate well hydrological components of a river basin had been confirmed in various studies (Me *et al*., 2015; Das *et al*., 2019).

5.4.1 Simulation of stream flows in sub basins dominated by tea plantation, forest and mixed farming land uses

The findings of this study revealed that stream flows in sub basins the tea plantations and forests land covers comprised of about 60% base flows and 40% surface runoffs. While mixed farming land cover was dominated by high surface runoffs compared to base flows. The increase in surface runoffs was also confirmed in the Kiptiget sub basin faced with declining forest land cover. In a study conducted by Kiplagat *et al*. (2018), surface runoffs increased by 40% in sub basin with reduced forests cover. In a study conducted in East Africa it was noted that a decrease in the forest land cover increases stream flows by 16% while increase in the forest cover decreases stream flows (Guzha *et al*., 2018). This study further showed that high surface runoffs are generated from the sub basin dominated by mixed farming compared to surface runoffs generated from sub basins dominated by tea plantations and forest cover (Table 4.5). This indicated that in the mixed farming land cover infiltration is low compared to tea plantations and forest resulting in insignificant increase in the base flow. These findings were in consistent with observations made in the previous study in the Kimwarer River Basin that the mixed farming land cover and land use increases surface runoffs and reduces base flows (Kiplagat *et al*., 2018). In this study it was noted that different land cover stream flows both in seasonal and long-term temporal scale. But the strong relationship between rainfall and stream flows portrayed in the sub basins with dominant land uses and land covers of more than 90%, indicated that stream flow fluctuations in Sondu Miriu River Basin was attributed to both land cover changes and rainfall variability.

It was observed that 56% forest reduction in the projected period 2021-2090 might significantly affect the future sustainability of the base flow and high stream flows by about 43% due to increasing surface runoffs. However, maintaining a decadal increment in forest cover will increase infiltration by reducing surface runoffs by about 24%. Hence reforestation and afforestation will brighten future sustainable river discharges of the sub basin. The projections done in Blue Nile River Basin revealed that deforestation negative impacts on the stream flows while afforestation will enhance the long-term stream flow availability (Nadew, 2017). Future predictions in the neighbouring Mara River Basin agreed with the findings of this study and study done in Blue Nile River Basin. It was reported that mixed farming will reduce base flow volumes and instead upsurge the surface runoffs (Mango *et al*., 2011).

5.4.2 Simulation of sediment yields in sub basins dominated by tea plantation, forest and mixed farming land covers and land uses

The findings of this study showed that increase in area under tea plantations reduces sediment yields. The canopy in the tea plantations protects soils from direct impacts of rainfall. Also, close range between tree plants strengthens the power of the tea trunks and roots to holds soils firmly reducing the quantity of sediments being transferred into the stream networks. In Mau Complex, it was reported that tea plants reduced sediment fluxes and it was similar with the findings of the tea plantations zones (Kroese *et al*., 2020). Future projections done in this study revealed that expansion of tea plantations due to continuous population growth and demand for socio economic development will reduce sediment yields generated further to lower volumes which are insignificant to interfere with the water quality. Similarly increase in the forest land cover was noted to decrease generation of sediments in the sub basin dominated by the forest cover. This was observed in the period between 1978 and 1985 where an increase in forest cover decreases sediment yields. Tea plantations portray similar canopy characteristics with the forest cover, it was believed that sediment reduction power by the two land covers is almost the same. However, it was realized that forest cover reduces sediment transport better than tea plantations by 0.29 tonnes/ha per unit area increased. Conversion of the forest land cover to open fields compromises land surface stability and increases sediment generation which can be transferred into the stream networks (Zhu *et al*., 2018).

Comparing the sediment yields generated in the sub basins with dominant land covers in this study, it clearly indicated that tea plantations and forest cover are suitable in reducing sediment generation than mixed farming land cover. It was also noted that insignificant increase in the area under agricultural cover resulted in a significant generation of sediment yields especially in the period 2015-2020 (Figures 4.4.21 and 4.4.22). The increase in sediment yields in the five-year period was attributed rainfall and to exposure of soils in the open agricultural fields at the upper zone of the river basin which are easily eroded. Previous study stated that the high sediment discharge in the sub basin under crop farming was attributed to slopy terrain, encroachment of the land riparian and poor farming practices from upstream to downstream have caused increase in soil erosion into the river system (Memarian *et al*., 2014; Phuong *et al*., 2017). Future projection done in this study showed that an increase of sediment yields by 140 tonnes/ha in 2090. The outputs of the study conducted in Lake Victoria Basin agreed with this study that continuous increase in mixed farming land cover will reducing water quality due to sediment transport (Isabirye *et al*., 2010). Riparian encroachment and poor farming practices have contributed to the increase in sediment generation in most river basins. Therefore, riparian land protection and soil conservation measures should be practiced by basin communities to reduce sediment discharge. According to previous study hotspots areas of sediment flux can be reduced by use of riparian buffer with more than 0.5 efficiency (Vigiak *et al*., 2016).

5.5 Water balance components in the sub basins dominated by different land covers and land uses

This study found out that there was positive relationship between area under tea plantation and rainfall, a positive relationship between rainfall and area under mixed farming and a negative relationship was found between rainfall and the area under forest land cover. The positive relationship between area under tea plantation, area under mixed farming and rainfall was attributed to the expansion of tea plantations and mixed farming by the communities living in the Sondu Miriu River Basin due to increase in the rainfall availability. The negative relationship between area under forest cover and rainfall was attributed to reduction of forest cover to pave way for tea plantation and mixed farming due to high rainfall received. The spatial distribution of rainfall in the sub basins showed that sub basin dominated by tea plantations and forest cover received high rainfall almost of equal magnitude (Figures 4.5.2, 4.5.7 and 4.5.11). While sub basin dominated by mixed farming receives low quantity of rainfall (see Table 4.8). This agreed with the previous study conducted in Southwest Burkina Faso where the relationship between mixed farming and rainfall was reported to be strong and positive correlation (Zoungrana *et al*., 2015). Despite the fact that insignificant relation existed between rainfall and tea plantation and forest cover, it was believed in this study that cooling effect generated by tea plants and forests trees influence local weather conditions as it was reported in a study conducted in the Kara River Basin in West Africa where increasing forest cover was reported to increase the local rainfall (Badjana *et al*., 2017). Contrary to the findings of this study, reforestation in dry areas in West Africa showed positive relationship between forest cover and rainfall (Diasso and Abiodun, 2018). The difference between the observations made in this study and previous studies could be due to the small-scale size of the sub basin with dominant forest cover of 152 km^2 compared to large scale river basin. In addition, ITCZ has significant influence on rainfall within the tropics especially in equatorial region (Waliser and Jiang, 2015). Also, the Kiptiget sub basin is surrounded by sub basins with forest cover such as Timbilil, Kipsonoi and Itare-Chemosit sub basins and hence changes taking place in the sub basin had no influence on the rainfall.

This study found that there exists insignificant relationship of r of 0.1 between area under tea plantations and evapotranspiration in the sub basin dominated by tea plantation while the relationship between area under forest cover and evapotranspiration was positive. The poor relationship between tea plantation land cover and evapotranspiration could be due to close canopy cover that reduces evaporation from the soil surface. But insignificant relation between area under forest cover and evapotranspiration is because the changes in the area covered by forest cover was small (see Table 4.8). However, the forest cover has higher evapotranspiration rate compared to tea plantations land cover. This was attributed to thick canopy in the forests cover which intercept rainwater. The intercepted water increases evaporation in the forested land cover. Also, tall forest trees in the Kiptiget sub basin of approximately 50 m heigh has ability to abstract groundwater which increases transpiration. The tall heights and deep roots of forests trees increases groundwater uptake and their high stomatal conductance increases transpiration. While tea plants are short and has less canopy compared to forest cover. Hence expansion of tea plantations reduces forest cover and evapotranspiration. Albedo increases evaporation of intercepted water.

Rainfall also plays critical role in the evapotranspiration rates. The relationship between rainfall and evapotranspiration in the sub basins dominated by forest, tea plantations and mixed farming cover was high with more than 90%. Hence the variations in evaporations in sub basins over time was also attributed to rainfall patterns. The studies done in Ghaggar river basin, India and Brazil had similar findings to this study that increase in the forest land cover increases evapotranspiration (Setti *et al*., 2017; Jerszurki *et al*., 2018; Chauhan *et al*., 2020). The positive relationship between the area under mixed farming and evapotranspiration was attributed to poor farming practices which expose the soil surface and subsurface to direct solar radiation causing increase in evaporation. Also, during crop growing season high transpiration rates occurs than in post harvesting season. Hence expanding mixed farming resulted in increasing evapotranspiration. This was consistent with the findings obtained in the study conducted in Rift Valley Ethiopia. It was reported that the extension of mixed farming land covers and land uses increased evaporation and transpiration (Meaza *et al*., 2019).

The findings of this study also showed that there is insignificant negative relationship between soil moisture and the area under tea plantations. Increase in the area under tea plantations led to the decrease in the soil moisture. Similarly negative relationship existed between soil moisture and forest land cover. But there was positive relationship between soil moisture and area of mixed farming in the sub basin dominated by mixed farming. The different relationships exhibited in different land covers and land uses. Tea plantations and forest land cover withdraws water from the soil column through capillary rise and release through transpiration. Hence expansion of tea plantations and forest cover reduces soil moisture resulting in the negative relation. Alternatively, the negative insignificant relationship between soil moisture and forest cover showed that reduction of forest cover increases soil moisture. This was related to expansion of mixed farming that decreases area under forest cover. The tillage in the agricultural fields breaks the soils allowing water to infiltrate in the mixed farming hence increasing the soil moisture and this resulted in the positive relationship. Therefore, decrease of the forest cover results in the increase of mixed farming and soil moisture. In Table 4.8, the soil moisture was high in tea plantations and forest cover with ranging between 20 - 25 mm compared to mixed farming. But findings of the previous study conducted in Western Himalayan showed that the relationship between soil moisture and forest cover was positive (Tyagi *et al.*, 2013). The different observations between this study and previous was the land cover used in replacing forest cover. In the previous study it was stated that deforestation reduced soil moisture because of exposing soil moisture to evaporation and reduction of infiltration. While in this study forest cover was reduced and replaced by mixed farming that increases soil moisture hence resulting in increase in soil moisture while reducing forest cover.

The findings of this study showed that there was positive relationship between change in water storage and area under tea plantation. Similarly, insignificant positive relationship was observed between change in water storage and area under mixed farming land cover. But low negative relationship exists between change in water storage and area under forest cover. These indicated that tea plantation and mixed farming land covers and land uses in sub basins has insignificant influence on the change in water storage. But the negative relationship between the forest and change in water storage with r of -0.67 showed that decrease in forest cover increases water storage. This insignificant negative relationship was attributed to reduction of canopy cover with deforestation that led to reduced interception and evapotranspiration hence increasing water. The relationship between rainfall and change in water storage was strong. Hence changes in water storage was attributed to rainfall variability and water loss through evaporation.

5.6 Relationship between stream flow and sediment yield in the sub basins dominated by tea plantation, forest and mixed farming land cover

Stream discharge especially the surface runoffs is a good media of sediment transport into the rivers in the tropical region (Uwimana *et al*., 2018). This study showed that relationship existed between stream flows and sediment yields in the sub basin dominated by tea plantations, forests and mixed farming land covers. However, the relationship between stream flows and sediment yields was poor in sub basins dominated by tea plantations and forests land covers compared with sub basin dominated by mixed farming land cover. This revealed that low sediment yields were generated in the sub basins dominated by tea plantations and forests land covers. Further it was established that forests land cover generates sediments during wet season compared to tea plantations. This was suspected to be due to soils generated in the upstream of the forested area where deforestation has occurred. The poor relationship between stream flows and sediment yields in the sub basin under forest cover and tea plantations was attributed to high infiltration rates and low surface runoffs and soil surface protection by the land covers (Coynel *et al*., 2005; Wasis *et al*., 2020; Roy *et al*., 2021).

The relationship between stream flows and sediment yields in the sub basin dominated by mixed farming showed a strong positive relationship with correlation coefficient r of 0.94. This implies that surface runoffs generation was high in the sub basin and easily transports sediments from the agricultural fields into the stream networks. This indicated that catchment management and protection should be done to reduce sediment discharge and transport downstream. Similarly, river basins experiencing mixed farming land cover especially in the Kenyan highlands generates approximately 75% of the total sediment transported in the stream networks (Kroese *et al*., 2020). Comparing the previous study with this study revealed that mixed farming has significant effect on the water quality of a river basin. High surface runoffs on the tilled lands accelerated the transfer of sediments from the catchment areas in the streams (Ouma *et al*., 2013; Njogu *et al*., 2018).

5.7 Suitable land use and catchment management practices for sustaining stream flows and reducing sediment yields

The soil and water conservation in the river basin is critical in ensuring sustainable water quantity and appropriate water quality. Maintenance of the catchment areas enhance the ability of the ecosystem to be sustainable. The recent studies established that rising in the population increases the pressure on the river basin. The withdrawal of land natural resources to meet various social and economic demands in excess has resulted to adverse effects on hydrologic components of a river basin (Melland *et al*., 2014). This study has shown that different land covers and land uses influence the stream flows and sediment yields.

5.7.1 Suitable land use and land cover types for sustaining stream flows and reducing sediment yields

The findings of this study showed that tea plantations exhibit high base flows with a mean of 7.56 m^3/s, low surface runoffs of a mean of 3.24 m^3/s and generate low sediment yields with mean of 7.69 tonnes/ha. Similarly, the forest cover demonstrated high base flows compared with surface runoffs and low sediment yields generated with mean of 3.8 tonnes/ha. This clearly indicates that the tea plantations and forests land covers have comparable hydrologic responses. However, tea plantations have high base flows compared to forest cover and this indicates that tea plantations sustain stream flows more that forest cover. On the other hand, tea plantations generate more sediments twice the sediment yields generated by the forest cover. Hence forest cover was found to be effective in reducing sediment flux in the river basin. This study found that tea plantations and forests cover are suitable land covers to ensure sustainable stream flows and reduce sediment flux. A number studies including this study have demonstrated that forest cover is suitable land cover to reduce sediment yields in the river basins (Ayuyo and Sweta., 2014; Eckert *et al*., 2017; Njue *et al*., 2021). The mixed farming generates high surface runoffs with mean of 28.38 m^3/s, low base flows with mean of 3.98 $m^{3/}s$ and high sediment yield with of 82.3 tonnes/ha. This showed that mixed farming land cover was poor in sustaining stream flows and generates high sediments. Studies conducted at National and Regional scales reported that sub basins dominated by mixed farming are poor in sustaining stream flows and increases sediment production (Waswa *et al*., 2013; Gathagu *et al*., 2017).

5.7.2 Suitable catchment management practices for sustaining stream flows and reducing sediment yields

This study showed that sub basins dominated by mixed farming generates high surface runoffs and sediment yields. Hence a number of management operations were tested using and established that strip cropping, terraces and vegetative filter strips buffer were effective in reducing surface runoffs and sediment yields. It was noted that vegetative filters reduced sediment yields by approximately 52% while terraces reduced by about 55%. These findings were close to those reported in Brazil that terraces reduce sediment transport by

40% (Strauch *et al*., 2013). Also, the findings of this study agreed with observations made in the previous studies that terraces are effective in increasing water infiltration and reducing sediment yields (Park *et al*., 2014; López-Ballesteros *et al*., 2019). Further, this study showed that strip farming reduces sediment transport by about 48%. This showed that terraces are more suitable catchment management practice and operation to reduce surface runoffs and sediment yields. This was similar to findings of study conducted in Santubong river basin and showed that terraces were effective in reduction of sediment yields into the river system and also causes decline in surface runoffs in the water bodies (Kuok *et al*., 2013). However, integrating terraces, vegetative filters and strip cropping showed reduction of sediment yields by 70%. This approach proved to be the best management practice for the sub basins dominated by mixed farming. Similar to the findings of this study, integration of filter strips, terraces and afforestation were better for rehabilitating affected sub basins in Gojeb river basin in Ethiopia. Although this integration yielded 30% success in reduction of sediment yields (Choto and Fetene, 2019). In addition, previous studies further promote the use of integrated catchment management measures for effective reduction of sediment yields and surface runoffs (Batchelor, 1999; Fenemor *et al*., 2011; Briak *et al*., 2019).

CHAPTER SIX

6.0 CONCLUSIONS AND RECOMMENDATIONS

This study assessed the hydrologic response of sub basins with dominant tea plantation, forest and mixed farming land covers and land uses. The stream flows, sediment yields and hydrologic water balance components depicted response variations based on the dominant land cover and land use types. In this chapter, the key findings of the study, conclusions and recommendations are provided. These are based on the specific results of the study. Attempt was made to relate the key findings to each of the main components of the study.

6.1 Summary of the key findings in this study

6.1.1 Patterns of land cover and land use change in sub basins dominated by different land covers

i. This study established that in the period between 1975 and 2021 the area under tea plantations increased by 44% while areas under forest and mixed farming covers decreased by 16.9% and 3.6% respectively in Sondu Miriu River Basin.

ii. This study showed that increase in the area under tea plantations was significant in the sub basin dominated by forest cover in the period 1975 and 2021. The area under tea plantations in this sub basin increased by 15.2% resulting in the decrease of the mixed farming cover by 15.2%.

6.1.2 Effects of sub basins dominated by different land covers and land uses on stream flows and sediment fluxes

i. This study showed that there was significant relationship between TSSC and turbidity in the sub basins dominated by mixed farming with coefficient of determination R^2 of 0.97 and correlation r of 0.98 at $p < 0.01$. While low relationship was observed at sub basin dominated by forest cover with coefficient of determination R^2 of 0.3 and correlation r of 0.5.

ii. This study also established that there is significant relationship between sediment loads and TSSC in the sub basin dominated by tea plantations, forest and mixed farming cover with coefficient of determination R^2 of 0.93, 0.73 and 0.87 respectively at $p < 0.05$. The correlation coefficients for this relationship were r of 0.96 in sub basin dominated by tea plantations, r of 0.85 in the sub dominated by forest cover and r of 0.93 in the sub basin dominated by mixed farming at $p <0.05$.

iii. There is insignificant relationship between turbidity and stream flows and between TSSC and stream flows in the sub basins dominated by tea plantations, forest and mixed farming land covers and land uses.

- ✓ The relationship between turbidity and stream flows and between TSSC and stream flows in the sub basin dominated by tea plantations were negative with coefficient of determination R^2 of 0.003 and 0.008 respectively.
- ✓ The relationship between turbidity and stream flows and between TSSC and stream flows in the sub basin dominated by forest cover were positive with coefficient of determination R^2 of 0.5 and 0.29 respectively.
- ✓ The relationship between turbidity and stream flows and between TSSC and stream flows in the sub basin dominated by mixed farming were positive with coefficient of determination R^2 of 0.08 and 0.07 respectively.

iv. The results of this study revealed that there is significant relationship between stream flows and sediment loads in the sub basins dominated by tea plantations, forest and mixed farming land cover and land uses.

- ✓ The relationship between sediment loads and stream flows in the sub basin dominated by tea plantations was positive with coefficients of determination R^2 of 0.42 and correlation r of 0.65 at p of 0.05.
- ✓ The relationship between sediment loads and stream flows in the sub basin dominated by forest cover was significant and positive with coefficients of determination R^2 of 0.74 and correlation r of 0.86 at $p<0.05$.
- ✓ The relationship between sediment loads and stream flows in the sub basin dominated by mixed farming cover was positive with coefficients of determination R^2 of 0.61 and correlation r of 0.78 at $p <0.05$.

- ✓ The relationship between sediment loads and stream flows in the mixed/combined land cover was positive with coefficients of determination R^2 of 0.41 and correlation r of 0.63 at p of 0.05.

v. The relationship between area under forest cover and stream discharges was negative with coefficients of determination R^2 of 0.17 and correlation r of -0.41 at $p > 0.05$. This showed that deforestation increases surface runoffs.

vi. The significant response between area under mixed farming and stream discharges was obtained. The expansion of area under mixed farming by 4.2% increases stream discharges by 18 m^3/s in the sub basin dominated by mixed farming. Similar response was observed between area under mixed farming and sediment loads. It was noted that sediment loads were high in pre planting season with sediment loads of 952 tonnes/day.

6.1.3 Simulation of stream flows and sediment yields in sub basins dominated by different land covers and land uses

i. The results of this study showed insignificant positive relationship between area under tea plantations and base flows with coefficient of determination R^2 of 0.17 and correlation r of 0.41 at $p>0.05$. This indicated that increase in the area under tea plantation increases base flows in the sub basin dominated by tea plantations. Despite the fact that positive relationship between areas under forest cover and tea plantations and base flows was shown, the mean base flows generated in sub basins dominated by tea plantations were 7.56 m^3/s than mean base flows generated in the sub basin dominated by forest cover of 3.16 m^3/s.

ii. The results of this study established that positive relationship exists between increase in the area under mixed farming and surface runoffs with coefficient of determination R^2 of 0.03 and correlation r of 0.17 at $p>0.05$. This showed that an increase in the area under mixed farming increases generation of surface runoffs.

iii. There is positive relationship between area under tea plantations and stream flows with coefficient of determination R^2 of 0.17 and correlation r of 0.41. This showed that expansion of the area under tea plantations increase stream flows through increased base flows.

iv. The negative relationship was noted between decreased area under forest cover and stream flows with coefficient of determination R^2 of 0.17 and correlation r of -0.41. This indicates that deforestation increases stream flows through increased surface runoffs.

v. The positive relationship was exhibited between area under mixed farming and stream flows with coefficient of determination R^2 of 0.02 and correlation r of 0.14. This showed that extension of the area under mixed farming increases stream flows through generation of surface runoffs. It was projected that expansion of mixed farming increases surface runoffs to about 40 m^3/s and discharges to 50 m^3/s by 2090.

vi. The negative relationship between area under tea plantations and sediment yields was observed with coefficient of determination R^2 of 0.01 and correlation r of -0.1. For example, the increase in tea plantation by 46% reduces sediment load generated by 0.79 tonnes/ha. These observations indicated that expansion of the area under tea plantations decreases sediment generation.

vii.The negative relationship was observed between area under forest cover and sediment yields with coefficient of determination R^2 of 0.03 and correlation r of -0.17. These observations indicated that reduction of the area under forest cover increases sediment yield.

viii. The positive relationship was established between the area under mixed farming and sediment yields with coefficient of determination R^2 of 0.02 and correlation r of 0.14. This showed that expansion of the area of land under mixed farming increases sediment yields. For example, the annual increase of 0.5% in the area under mixed farming for a decade will lead to an increase in the sediment yields by about 97 tonnes/ha.

6.1.4 Water balance components in the sub basins dominated by tea plantations, forest and mixed farming land covers

i. These results showed that there is insignificant positive relationship between area under tea plantation and the rainfall with coefficient of determination R^2 of 0.01 and correlation r of 0.21 at p>0.05. This showed increase in rainfall causes expansion of area under tea plantations.

ii. The positive relationship was observed between rainfall and area under mixed farming with coefficient of determination R^2 of 0.04 and correlation r of 0.19 at p>0.05. This showed that increase in rainfall result in expansion of area under mixed farming.

iii. The negative relationship between area under forest cover and rainfall was shown with coefficient of determination R^2 of 0.14 and correlation r of -0.37 at p>0.05. This indicated that changes in forest cover does not affect rainfall significantly.

iv. The positive and insignificant relationship between area under tea plantations and evapotranspiration was observed with coefficient of determination R^2 of 0.01 and correlation r of 0.1 at p>0.05. This indicated that increase in area under tea plantations increases evapotranspiration due to the reduction of the area under forest cover. The short tea plantations receive less albedo than tall forest cover hence reducing evapotranspiration.

v. These results showed positive relationship between area under forest cover and evapotranspiration with coefficient of determination R^2 of 0.0021 and correlation r of 0.045 with p>0.05. This indicated that decrease in the area under forest cover decreases evapotranspiration. Decreasing the area under forest cover reduces evaporation from intercepted water, low albedo and low water uptake from the groundwater aquifer decreasing transpiration.

vi. The positive relationship was observed between the area under mixed farming and evapotranspiration with coefficient of determination R^2 of 0.16 and correlation r of 0.4 at p>0.05. This indicated that increase in the area under mixed farming increases evapotranspiration. Reduction of the area under forest cover and increasing area under mixed farming increases soil surface evaporation and planting of crops in the fields increases water uptake from the soils resulting in the increase of transpiration.

vii. The negative relationship was established between area of forest cover and the soil moisture with coefficient of determination R^2 of 0.069 and correlation r of -0.26 at $p>0.05$. This indicated that decline in the area under forest cover reduces interception of rain water and increasing water reaching soil surface and sub surface. In addition, decrease in area under forest cover reduces water uptake from the soils increase soil water content.

viii. The positive relationship was noted between area under mixed farming and soil moisture with coefficient of determination R^2 of 0.0063 and correlation r of 0.079 at $p >0.05$. This showed that increase in the area under mixed farming increases soil moisture by breaking the soil surface during tilling allowing more water to infiltrate into the soil.

ix. The negative relationship between area under tea plantations and soil moisture with coefficient of determination R^2 of 5E-06. This indicated that increase in the area under tea plantations reduces soil moisture through interception of rain water and water uptake by the tea plants.

x. There was positive relationship between the area under tea plantations and mixed farming and change in water storage with correlation r of 0.089 and 0.004 respectively. This is because tea plants and crops in mixed farming have shallow roots which might not bring significant change in the water storage.

xi. The negative relationship was established between area under forest cover and change in water storage with coefficient of determination R^2 of 0.45 and correlation r of - 0.67. This indicated that decrease in the area under forest cover increases change in water storage. This is because forest trees have deep roots extracting water from the groundwater aquifers hence reduction of the forest cover increase groundwater storage. In addition, reduction in thick forest canopy increases water infiltration and percolation.

6.1.5 Determination of relationship between stream flow and sediment yield the sub basins dominated by different land cover and land use

i. The weak positive relationship between stream flows and sediment yields with the coefficient of determination R^2 was 0.0508 and correlation of r was 0.225 at $p>0.05$ in the sub basin dominated by tea plantations.

ii. The positive relationship between stream flows and sediment yields in the sub basin dominated by forest cover was positive with coefficient of determination R^2 was 0.24 and correlation of r was 0.49 at $p>0.05$.

iii. The relation between stream flows and sediment yields in the sub basin dominated by mixed farming showed a strong positive relationship with the coefficient of determination was R^2 was 0.90 and correlation of r was 0.94 at $p<0.05$.

6.1.6 Determination of suitable land use and land cover types and catchment management practices

i. This study showed that tea plantations was suitable land cover to sustained the stream discharges. The mean stream discharges were 10.8 m^3/s, base flow of 7.56 m^3/s and surface runoff of 3.24 m^3/s. The low surface runoffs and increased base flows showed that the stream discharges are being sustained by the base flows.

ii. The study established that forest cover reduces sediment generation and transport of sediment yields better than tea plantations and mixed farming. The mean sediment yields of 3.8 tonnes/ha was obtained in forest covers while 7.69 tonnes/ha was the mean sediment yield generated in the sub basin dominated by tea plantation. This showed that forest cover reduces sediment yields better than tea plantations and mixed farming.

iii. The study showed that mixed farming generates high sediment yields with mean value of 82.3 tonnes/ha. Also, the mixed farming cover generates high surface runoffs of mean value of 28.38 m^3/s, base flow with mean value of 3.98 m^3/s and mean stream discharges of 32.4 m^3/s. High surface runoffs increases seasonal stream discharges during wet periods.

This identified mixed farming land cover and land use as unsuitable for sustainable stream flows and sediment reduction.

iv. The study established that integration of tea plantations and forest cover is a suitable land cover and land use that ensure sustainable stream flows and low sediment yields are generated.

v. This study showed that terraces are most suitable catchment management practice in the sub basin dominated by mixed farming due to its ability to reduce sediment yields in the sub basin by 55%.

vi. This study established that integrating terraces, vegetative filters and strip cropping in the sub basin dominated by mixed farming were effective. This reduced sediment yields generated by 70%.

6.2 Key conclusions of this study

i. The area under tea plantations has been increasing at the annual rate of 1.1% decreasing area under forests cover and mixed farming in the Sondu Miriu River Basin.

ii. Increase of tea plantations annually is due to the annual population growth that demands socio-economic development. Hence tea plantations are the main cash crop for the communities living especially at the upper zone of the river basin.

iii. Suspended sediments increased turbidity in the sub basins dominated by tea plantations, forests and mixed farming covers. However, TSSC and turbidity had insignificant relationships with stream discharges.

iv. Deforestation and expansion in area under mixed farming increases surface runoffs and peak stream flows while reducing groundwater recharge and base flows.

v. Expansion of the area under tea plantations increases water infiltration and percolation hence causing rise in the base flows and stream flows.

vi. Forest covers and tea plantations are suitable for conservation of soils in the catchment areas. While mixed farming cover increases sediment generation in the catchment areas.

vii. Rainfall attracts crop farming in the river basin. Increase in the amounts of rainfall received raises the area of land under tea plantations and mixed farming. This led to the decline in the area covered by forests.

viii. Deforestation reduces evapotranspiration. While extension of area under mixed farming increases evapotranspiration.

ix. Increase in the area of land under mixed farming and deforestation increases soil moisture in the river basin. While increase in the area under tea plantations reduces soil moisture due to interception and capillary rise.

x. Deforestation increases water storage in the river basin while tea plantations and mixed farming land use have insignificant change in the water storage.

xi. Stream flows has weak relationship with sediment yields in the sub basin dominated by tea plantations.

xii. Strong relationship between stream flows and sediment yields exists in the sub basin dominated by mixed farming and deforested sub basins.

xiii. Tea plantations are suitable land cover/land use for sustaining stream flows through high base flows and low surface runoffs. While forest cover decreases sediment fluxes hence suitable for reducing sediment transport in the river basin.

xiv. Integration of tea plantations and forest cover is ideal land cover/land use for sustainable stream flows and low sediment yields.

xv. Terraces are appropriate catchment management practice that reduces sediment generation in the sub basin dominated by mixed farming in the river basin due to its terrain especially in the upper part.

xvi. Integration of terraces, vegetative filters and strip cropping is effective in reduction of sediment yields by 70%.

6.3 Recommendations of this study

This study established that changes in the land use and land cover affects the hydrologic response of the Sondu Miriu River Basin. Therefore, appropriate measures are required to guarantee sustainable water quantity and quality in the river basin. The following recommendations are being proposed for implementations by various stakeholders in Kenya;

Recommendations to the National Government

i. Forest land cover in the Sondu Miriu River Basin is under threat with declining trends due to its replacement by mixed farming and tea plantations. Therefore, the Ministry responsible for Environment and Forestry and the Ministry responsible for Water resources are recommended to review and enforce the implementation of policies, strategies and programmes to ensure maximum protection and conservation of the forested and catchment areas.

ii. Mixed farming was identified as the main cause of high turbidity and TSSC in the river system in the river basin. Therefore, it is recommended that the ministry responsible for Agriculture develop programmes which enable farmers to acquire best alternative approaches of conducting farming without generation of sediments.

iii. This study showed that high sediment yields are generated from the catchment areas due to deforestation. This study recommends that Water Resources Authority and Kenya Water Towers Agency conduct catchment rehabilitation programmes to restore the forests in the areas affected by deforestation, gazettement of forested lands and demarcate riparian lands.

iv. Mixed farming was shown to generate sediments in the river basin and are transported during wet periods into stream networks increasing water turbidity. Therefore, Water

Resources Authority is recommended to plant vegetation in the riparian lands that helps filter the sediments from reaching into the stream channel.

Recommendations to the County Governments

i. Forest cover is key in regulating hydrologic response of a river basin. In order to enhance sustainable stream flows and reduce suspended sediments in the river basin, it is recommended that County Governments of Kericho, Nakuru, Bomet and Nyamira Counties incorporate programmes and activities in their counties' development plans which promotes protection of water catchments and water resources from depletion and pollution.

ii. It was noted that communities in the river basin depends majorly on crop farming for food security and socio-economic development. In order to safeguard forests from depletion as population growth increases, the County Governments of Kericho, Nakuru, Bomet and Nyamira are encouraged to build capacity of communities in the river basin to adopt diverse methods of income generation such as small enterprises in the centres and towns.

Recommendations to the Communities

i. High surface runoffs result in peak stream flows downstream and may overspill to flood riparian lands. In order to avoid damages of crops and properties, communities are encouraged to settle outside riparian lands.

ii. High turbidity was showed in the sub basins dominated by mixed farming and this reduces the quality water for domestic use. Hence this study recommends that communities withdrawing water direct from the stream ensure water treatment is conducted to avoid diseases related to poor quality of water.

iii. Integration of tea plantations and forests cover was found to be effective in sustaining stream flows and reducing sediment yields. Tea farmers are encouraged to integrate forest trees and tea plants in their farms to enhance water quantity and quality.

iv. Mixed farming was identified as the main source of sediment fluxes in the river basin. Hence, it is recommended that farmers practice terracing and strip cropping to reduce soils erosion into stream networks.

v. Deforestation reduces evapotranspiration and hence reducing water vapour which condense and result in local precipitation. This reduces soil moisture and causes food insecurity. Therefore, it is recommended that communities embrace tree planting to increase forest coverage to increase precipitation in the river basin for food production and water supply.

Recommendations for further studies

i. Tea plantation has been recommended in this study as a suitable land cover to reduce sediment generation and enhance stream flows. However, further studies are recommended to understand the effects of tea plantations on groundwater resources.

ii. The three hotspots' areas of sediment flux in the Sondu Miriu River Basin were identified in this study. Further studies are recommended to determine activities which have led to high sediment generation in the hotspot areas.

iii. Forests land cover in this study was found to reduce soil moisture, it is therefore recommended that further study be conducted to determine effect of the forest cover on groundwater resources.

6.4 Conclusions

The land cover and land use change influence the hydrologic responses. The hydrologic responses differ in river basins based on their climatic zone variations. Hence this study established the effect of changing land use and land cover patterns on hydrological components and sediment fluxes in a tropical river basin. The land covers and land uses focussed mainly are tea plantations, forest cover and mixed farming. The area under tea plantations was noted to be increasing and has led to decline of the forest cover. The increasing population growth in the Sondu Miriu River Basin was identified as the key driving factor in the expansion of mixed farming and tea plantations land covers. Mixed farming and tea plantations satisfy the demands for food security and income generation especially for the communities living in the river basin. Nonetheless, the sustainability of water quantity and quality is paramount given that majority of the basin residents depend entirely on the stream water resources for their uses.

The total suspended solids are the main cause of high turbidity experienced in the river basin. In addition, increased surface runoffs have resulted in the increase of stream flows hence it is believed that continuous deforestation will result in siltation of the river bed reducing river capacity to contain excess flows during wet periods. This might jeopardise human lives and properties downstream through fluvial and flash flooding. At the same time, sediment yields shown an increasing trend as the area under forest cover was decreasing. The decline in the forest cover influences the basin's sediment generation, evapotranspiration, surface runoffs, base flows, water storage and soil moisture. This showed that forest cover is critical in the hydrologic cycle of the river basin. Hence there is need to focus on forest cover recovery process by all relevant stakeholders. The forest cover is suitable for reduction of sediment discharge and surface runoffs. In addition, expansion of forest cover increases evapotranspiration, base flows and indirectly precipitation. Integration of tea plantations and forest cover enhances accessibility of good quality water and sustainable stream flows. Catchment management measures such as terraces, strip cropping and vegetative filters are effective in the sub basins which are generating high sediment yields. The joint efforts by stakeholders are recommended for the development and implementation of policies, strategies, and programmes which reinstate the hydrological balance of the Sondu Miriu River Basin to meet the various demands of the future generation.

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APPENDICES

a) Summary of Field Data

Appendix 1: River discharge data of the sub basins in the period July 2020 to June 2021 (m^3/s)

TIME	TIMBILIL SUB BASIN	KIPTIGET SUB BASIN	KIPSONOI SUB BASIN	SONDU MIRIU
Jul-20	7.20	3.75	5.05	34.77
Aug-20	4.53	2.85	5.12	24.60
Sep-20	5.82	3.83	8.85	20.50
Oct-20	4.87	1.64	7.89	20.60
Nov-20	5.13	2.17	9.12	31.53
Dec-20	3.33	1.09	8.29	28.18
Jan-21	3.71	3.30	17.77	45.68
Feb-21	1.18	0.83	7.01	11.29
Mar-21	1.24	0.47	5.28	5.83
Apr-21	5.10	0.74	27.17	40.78
May-21	4.05	2.61	12.81	39.32
Jun-21	5.14	3.05	10.10	36.08
Mean	4.27	2.20	10.37	28.26

Appendix 2: Sediment load data of the sub basins in the period July 2020 to June 2021 (tonnes/day)

TIME	TIMBILIL SUB BASIN	KIPTIGET SUB BASIN	KIPSONOI SUB BASIN	SONDU MIRIU
Jul-20	14.50	8.23	76.36	229.08
Aug-20	6.52	6.57	44.20	148.78
Sep-20	8.18	8.27	42.80	169.44
Oct-20	9.80	2.84	49.95	152.31
Nov-20	10.33	5.25	110.32	127.15
Dec-20	5.75	1.89	71.66	170.45

Jan-21	12.82	1.90	951.97	631.48
Feb-21	1.02	0.72	190.73	253.71
Mar-21	3.20	0.41	31.95	75.51
Apr-21	2.20	0.64	234.75	246.61
May-21	3.50	5.63	110.64	271.78
Jun-21	6.75	5.93	113.44	249.41
Mean	7.05	4.02	169.06	227.14

Appendix 3: TSSC data of the sub basins in the period July 2020 to June 2021 (mg/l)

TIME	**TIMBILIL SUB BASIN**	**KIPTIGET SUB BASIN**	**KIPSONOI SUB BASIN**	**SONDU MIRIU**
Jul-20	23.30	25.40	175.00	76.25
Aug-20	16.67	26.67	100.00	70.00
Sep-20	16.27	25.00	56.00	95.67
Oct-20	23.30	20.00	73.30	85.57
Nov-20	23.30	28.00	140.00	46.67
Dec-20	20.00	20.00	100.00	70.00
Jan-21	40.00	6.67	620.00	160.00
Feb-21	10.00	10.00	315.00	260.00
Mar-21	30.00	10.00	70.00	150.00
Apr-21	5.00	10.00	100.00	70.00
May-21	10.00	25.00	100.00	80.00
Jun-21	15.20	22.50	130.00	80.00
Mean	19.42	19.10	164.94	103.68

Appendix 4: Turbidity data of the sub basins in the period July 2020 to June 2021 (NTU)

TIME	TIMBILIL SUB BASIN	KIPTIGET SUB BASIN	KIPSONOI SUB BASIN	SONDU MIRIU
Jul-20	27.92	18.20	91.00	65.59
Aug-20	15.24	23.50	98.00	64.39
Sep-20	17.69	27.00	77.00	67.98
Oct-20	36.17	20.86	80.00	67.47
Nov-20	30.65	17.75	112.00	62.00
Dec-20	32.75	15.34	71.00	69.00
Jan-21	95.00	19.98	637.00	109.00
Feb-21	21.80	18.50	279.00	231.00
Mar-21	19.15	4.37	91.00	60.00
Apr-21	18.50	6.96	80.00	70.00
May-21	21.50	18.87	86.00	71.00
Jun-21	17.50	17.50	115.00	84.00
Mean	29.49	17.40	151.42	85.12

b) Land use /Land cover data

Appendix 5: Land Use/Land Cover data of the sub basins in the period 1975 - 2021 (km^2)

Time	Forest	Tea Plantations	Mixed Farming	**Time**	Forest	Tea Plantations	Mixed Farming
1975	53.7	36.3	1439.0	**1998**	49.1	52.2	1394.4
1976	53.7	36.3	1439.0	**1999**	47.5	52.2	1365.3
1977	56.1	37.6	1424.6	**2000**	47.5	54.1	1365.3
1978	56.1	37.6	1424.6	**2001**	45.9	54.1	1372.0
1979	58.3	38.7	1405.6	**2002**	45.9	54.0	1372.0
1980	58.3	38.7	1405.6	**2003**	43.3	54.0	1377.6

1981	60.5	39.8	1387.7	**2004**	43.3	53.1	1377.6
1982	60.5	39.8	1387.7	**2005**	44.2	53.1	1381.5
1983	62.1	40.7	1369.2	**2006**	44.2	45.0	1381.5
1984	62.1	40.7	1369.2	**2007**	45.5	45.0	1379.3
1985	63.7	43.0	1338.4	**2008**	45.5	52.2	1379.3
1986	63.7	43.0	1338.4	**2009**	47.3	52.2	1373.1
1987	55.1	41.9	1341.8	**2010**	47.3	50.9	1373.1
1988	55.1	41.9	1341.8	**2011**	48.6	50.9	1365.8
1989	58.2	47.3	1346.8	**2012**	48.6	51.3	1365.8
1990	58.2	47.3	1346.8	**2013**	50.7	51.3	1355.2
1991	55.6	49.8	1349.6	**2014**	50.7	51.1	1355.2
1992	55.6	49.8	1349.6	**2015**	49.4	51.1	1352.4
1993	53.2	49.8	1351.3	**2016**	49.4	52.2	1352.4
1994	53.2	50.4	1351.3	**2017**	46.8	52.2	1351.3
1995	50.8	50.4	1367.5	**2018**	46.8	52.7	1351.3
1996	50.8	42.6	1367.5	**2019**	44.6	52.7	1369.8
1997	49.1	42.6	1394.4				

c) Rainfall Data

Appendix 6a: Rainfall data in the sub basins in the period 1960 – 2001(mm/a)

Time	Kiptiget and Timbilil Sub basins	Kipsonoi Sub basin	Sondu Miriu	**Time**	Kiptiget and Timbilil Sub basins	Kipsonoi Sub basin	Sondu Miriu
1960	1305.3	991.2	1275.7	**1981**	1817.0	1619.2	1614.1
1961	1578.3	1343.6	1395.5	**1982**	1590.2	1580.2	1719.3
1962	1482.1	1315.0	1475.7	**1983**	1812.0	1423.4	1600.0
1963	1943.5	1580.0	1601.2	**1984**	1440.9	1233.5	853.2
1964	1842.0	1327.7	1650.0	**1985**	1464.6	1660.2	1047.1

1965	1578.2	1238.1	1450.3	**1986**	1265.9	1174.0	1031.4
1966	1809.0	1416.6	1602.3	**1987**	1463.0	1216.8	1068.5
1967	1828.4	1543.2	1338.7	**1988**	1989.2	1428.2	1580.4
1968	2015.3	2030.7	1435.2	**1989**	1884.6	1347.2	1487.3
1969	1417.3	1272.1	516.0	**1990**	2205.3	1704.2	2087.7
1970	2078.2	1651.2	1389.6	**1991**	2225.4	1354.6	1132.6
1971	1464.9	1225.9	970.2	**1992**	1973.7	1687.4	1360.6
1972	1546.1	1237.5	1147.7	**1993**	1547.2	1461.1	1552.2
1973	1673.6	1263.2	1328.6	**1994**	1926.3	1798.8	1712.1
1974	1525.7	1484.8	1504.5	**1995**	1985.7	1641.8	1361.6
1975	1699.8	1416.5	1461.4	**1996**	2229.3	1624.0	1565.3
1976	1552.6	1448.1	1472.8	**1997**	2429.5	1580.7	1235.8
1977	1753.4	1732.0	1792.1	**1998**	2140.9	1547.4	1246.9
1978	2361.0	1607.0	1877.4	**1999**	2404.1	1404.8	1528.1
1979	1780.5	1355.7	956.9	**2000**	1983.3	1074.8	1255.5
1980	1512.5	1256.8	1390.7	**2001**	2332.1	1913.7	1878.9

Appendix 6b: Rainfall data in the sub basins in the period 2002 – 2020 (mm/a)

Time	Kiptiget and Timbilil Sub basins	Kipsonoi Sub basin	Sondu Miriu
2002	2109.0	1657.2	1627.1
2003	1819.1	1623.6	1594.1
2004	1656.5	1626.8	1597.2
2005	1829.6	1418.1	1392.3
2006	2515.7	1051.9	1032.8
2007	2081.6	865.7	850.0
2008	1958.7	1947.5	1912.1
2009	1723.8	1301.9	1278.3
2010	1999.8	1579.4	1550.7

2011	1450.4	909.2	892.7
2012	1295.6	1182.9	1161.4
2013	2220.4	746.9	733.3
2014	2186.0	1029.8	1011.1
2015	2109.0	1297.9	1274.3
2016	1448.9	1165.6	1144.4
2017	1864.8	1216.7	1194.6
2018	2055.4	1317.3	1293.4
2019	1784.0	1220.5	1198.3
2020	1832.8	1406.2	1361.5

d) Sediment yield (tonnes/ha)

Appendix 7a: Sediment yield data in the sub basins in the period 1961-2002

Time	Kiptiget Sub basin	Timbilil Sub basin	Kipsonoi Sub basin	Sondu Miriu	**Time**	Kiptiget Sub basin	Timbilil Sub basin	Kipsonoi Sub basin	Sondu Miriu
1961	5.6	12.5	24.4	43.4	**1982**	3.2	15.3	28.5	85.0
1962	4.2	13.9	23.4	57.2	**1983**	3.8	17.6	24.5	79.1
1963	5.7	23.3	30.8	82.3	**1984**	2.8	13.8	20.8	42.2
1964	3.8	16.9	22.6	76.9	**1985**	3.0	14.2	30.9	45.1
1965	3	13.2	17.3	71.3	**1986**	2.4	10.9	19.3	72.7
1966	3.7	15.2	28.7	81.9	**1987**	2.9	12.8	22.4	69.8
1967	3.7	16.7	25.1	51.2	**1988**	4.8	21.5	28.7	98.5
1968	4.7	22.0	51.5	70.0	**1989**	4.3	20.3	22.2	78.5
1969	2.6	12.1	23.5	61.1	**1990**	4.3	20.7	37.4	142.5
1970	5.8	28.1	39.4	77.3	**1991**	4.2	24.3	23.1	64.6
1971	2.9	16.1	23.8	41.1	**1992**	3.1	16.6	28.5	96.6
1972	3.7	17.1	21.2	54.2	**1993**	4.2	29.8	33.9	113.9
1973	4.1	21.0	28.5	72.2	**1994**	3.1	18.5	31.2	81.5

1974	2.5	11.3	23.0	73.4	**1995**	3.6	19.7	29.6	47.2
1975	3.0	13.0	25.3	52.6	**1996**	4.9	32.3	35.3	72.0
1976	3.4	15.4	25.2	56.3	**1997**	5.2	39.6	32.4	63.8
1977	3.8	16.2	31.5	86.7	**1998**	5.4	58.2	35.0	60.7
1978	5.1	26.1	35.1	104.7	**1999**	3.7	25.5	31.2	83.2
1979	3.5	19.4	21.5	44.3	**2000**	3.2	21.2	18.2	62.1
1980	2.6	12.6	20.7	63.4	**2001**	4.4	25.7	48.7	108.9
1981	3.7	17.0	33.6	81.8	**2002**	3.5	22.9	31.3	77.0

Appendix 7b: Sediment yield data in the sub basins in the period 2003 -2020

Time	Kiptiget Sub basin	Timbilil Sub basin	Kipsonoi Sub basin	Sondu Miriu
2003	2.8	16.4	38.5	103.3
2004	3.3	21.0	32.4	80.3
2005	3.1	16.5	35.8	82.7
2006	4.6	28.8	46.3	107.0
2007	3.5	22.4	49.2	70.2
2008	3.3	19.9	72.6	112.4
2009	3.9	24.9	35.4	76.5
2010	3.3	21.7	181.1	248.4
2011	3.2	19.3	16.8	36.3
2012	6.0	28.8	18.0	48.0
2013	6.2	27.7	7.8	19.2
2014	3.1	17.7	10.2	22.6
2015	3.4	23.4	25.1	56.5
2016	2.0	9.1	7.5	17.1
2017	2.5	10.4	20.9	43.8
2018	3.8	16.4	15.4	31.1
2019	4.1	34.2	51.6	68.5

2020	5.1	20.5	32.6	72.4

e) Discharge/Stream flow (m^3/s)

Appendix 8a: River discharge data in the sub basins' outlets in the period 1960-2001

Time	Kiptiget Sub basin	Timbilil Sub basin	Kipsonoi Sub basin	Sondu Miriu	**Time**	Kiptiget Sub basin	Timbilil Sub basin	Kipsonoi Sub basin	Sondu Miriu
1960	2.0	5.7	19.5	59.8	**1981**	4.6	11.0	40.8	101.9
1961	3.4	8.6	29.9	74.0	**1982**	3.5	8.7	37.4	114.3
1962	2.8	7.4	23.7	81.6	**1983**	4.5	10.7	33.0	103.7
1963	4.8	11.6	37.8	103.5	**1984**	2.7	7.3	23.7	47.0
1964	4.1	10.2	26.1	110.3	**1985**	3.0	7.8	43.6	51.5
1965	2.9	7.7	21.9	91.9	**1986**	2.0	5.7	22.1	61.6
1966	4.1	10.0	29.6	100.6	**1987**	2.6	7.1	23.3	62.0
1967	4.1	10.1	37.6	71.5	**1988**	4.9	11.9	30.3	101.9
1968	4.8	11.6	55.6	79.5	**1989**	4.5	11.0	27.4	93.5
1969	2.3	6.5	24.6	30.5	**1990**	6.0	14.1	43.0	153.5
1970	5.6	13.0	41.4	81.6	**1991**	6.2	14.3	27.6	63.8
1971	2.9	7.7	28.0	51.9	**1992**	4.7	11.3	40.7	87.7
1972	3.3	8.0	24.3	61.8	**1993**	3.3	8.5	34.2	103.8
1973	3.8	9.5	27.6	78.7	**1994**	4.7	11.3	44.6	109.1
1974	3.1	7.9	34.1	88.2	**1995**	4.8	11.6	37.2	70.7
1975	3.6	9.1	28.2	75.7	**1996**	6.0	14.0	35.3	87.9
1976	3.1	8.1	28.5	82.4	**1997**	7.5	17.3	43.5	72.0
1977	3.8	9.5	43.4	114.4	**1998**	6.5	14.9	39.7	65.6
1978	6.7	15.6	37.9	118.7	**1999**	7.3	16.4	30.7	96.3
1979	4.1	10.1	24.9	48.1	**2000**	5.4	12.7	21.2	72.8
1980	3.1	8.0	22.3	75.2	**2001**	7.1	15.8	55.6	130.4

Appendix 8b: River discharge data in the sub basins' outlets in the period 2002-2020

Time	Kiptiget Sub basin	Timbilil Sub basin	Kipsonoi Sub basin	Sondu Miriu
2002	5.5	13.2	42.1	100.6
2003	4.6	11.2	45.9	107.6
2004	3.4	8.8	41.9	101.0
2005	4.6	10.9	36.7	88.5
2006	7.4	16.7	25.1	59.4
2007	5.7	13.2	22.7	52.5
2008	5.0	11.9	50.9	120.0
2009	4.2	10.2	35.6	85.9
2010	4.8	11.7	57.2	133.1
2011	3.8	9.0	13.6	39.7
2012	3.5	8.1	23.0	59.5
2013	6.3	14.7	10.9	26.3
2014	6.1	14.4	13.4	37.3
2015	5.6	13.3	30.2	72.3
2016	2.5	6.6	18.0	42.9
2017	4.5	10.8	25.2	67.1
2018	5.4	12.8	25.1	61.8
2019	4.6	11.0	30.0	71.1
2020	4.5	10.8	32.2	81.0

f) Evapotranspiration Data (mm/a)

Appendix 9a: Evapotranspiration data in the sub basins in the period 1960-2001

Time	Kiptiget Sub basin	Timbilil Sub basin	Kipsonoi Sub basin	Sondu Miriu	**Time**	Kiptiget Sub basin	Timbilil Sub basin	Kipsonoi Sub basin	Sondu Miriu

1960	904.1	744.8	612.9	714.4	**1981**	839.4	707.7	793.8	742.4
1961	843.9	696.8	731.2	720.7	**1982**	864.0	710.8	833.5	745.1
1962	909.4	744.6	848.2	794.8	**1983**	878.0	736.5	764.7	731.4
1963	930.9	766.4	813.7	795.2	**1984**	883.9	714.4	762.8	708.7
1964	990.4	814.8	815.1	818.1	**1985**	827.4	674.3	779.5	713.7
1965	981.6	809.6	800.0	817.6	**1986**	848.5	694.4	734.8	705.7
1966	962.8	803.7	825.8	803.2	**1987**	923.3	752.4	759.5	756.5
1967	970.8	804.9	784.9	789.9	**1988**	959.1	788.2	817.0	791.9
1968	1006.1	849.2	910.7	864.9	**1989**	934.3	771.3	792.1	788.3
1969	950.3	781.7	790.6	757.3	**1990**	951.6	793.5	843.2	819.6
1970	904.4	765.6	815.4	785.7	**1991**	948.7	793.8	809.5	791.9
1971	867.4	696.7	672.7	724.3	**1992**	988.7	828.3	867.4	805.1
1972	860.0	741.2	750.1	744.3	**1993**	885.6	705.5	786.5	714.1
1973	881.6	724.7	715.0	726.3	**1994**	933.0	786.3	891.2	815.3
1974	894.3	727.5	795.4	755.6	**1995**	979.4	817.2	902.3	839.5
1975	934.3	775.2	854.9	800.4	**1996**	985.5	820.9	919.1	866.4
1976	908.6	745.1	878.1	788.2	**1997**	871.4	678.2	703.3	704.5
1977	955.9	793.4	856.2	824.2	**1998**	807.5	655.2	759.6	698.3
1978	966.0	786.5	852.3	808.1	**1999**	876.5	742.8	789.7	764.5
1979	946.4	771.2	851.7	797.2	**2000**	865.3	716.1	648.3	727.1
1980	882.8	712.7	814.9	753.1	**2001**	858.8	739.9	800.7	766.4

Appendix 9b: Evapotranspiration data in the sub basins in the period 2002 - 2020

Time	Kiptiget Sub basin	Timbilil Sub basin	Kipsonoi Sub basin	Sondu Miriu
2002	955.0	784.1	806.6	805.9
2003	869.2	705.8	714.6	740.1
2004	952.1	771.5	787.3	781.9
2005	857.5	726.3	679.3	716.5

2006	948.6	814.6	555.3	761.9
2007	904.9	773.5	404.3	665.9
2008	920.2	774.9	921.1	783.4
2009	853.4	699.5	604.7	684.4
2010	989.1	815.5	431.6	667.7
2011	673.9	559.7	651.4	583.9
2012	562.6	469.1	703.7	511.3
2013	893.4	732.8	533.6	601.3
2014	915.0	746.6	771.1	664.2
2015	937.7	771.9	685.6	724.0
2016	940.4	798.1	802.3	702.7
2017	921.9	771.9	711.3	669.6
2018	936.8	776.2	823.1	802.8
2019	840.6	684.5	615.8	671.6
2020	903.9	747.7	762.5	748.6

g) Soil Moisture data

Time	Kiptiget Sub basin	Timbilil Sub basin	Kipsonoi Sub basin	Sondu Miriu	**Time**	Kiptiget Sub basin	Timbilil Sub basin	Kipsonoi Sub basin	Sondu Miriu
1960	15.4	8.3	11.9	15.4	**1981**	27.7	34.1	26.7	26.3
1961	30.9	47.1	24.7	25.9	**1982**	27.8	27.9	23.9	24.8
1962	20.8	12.6	16.5	17.4	**1983**	30.9	32.3	21.6	21.5
1963	31.8	45.9	26.2	26.6	**1984**	19.2	14.9	17.4	12.7
1964	34.5	34.9	16.8	20.9	**1985**	24.0	25.0	24.2	13.3
1965	25.5	15.9	16.2	24.6	**1986**	21.0	21.8	21.5	16.1
1966	25.5	27.6	15.2	13.6	**1987**	15.9	10.9	12.8	12.2
1967	30.6	34.0	19.7	16.5	**1988**	26.0	33.5	16.5	14.4

1968	30.1	33.5	26.2	21.3	**1989**	32.6	40.9	23.0	20.3
1969	14.1	2.9	16.2	14.5	**1990**	28.6	28.4	22.0	23.0
1970	27.9	37.9	23.3	18.5	**1991**	24.4	20.9	15.7	11.3
1971	21.9	16.4	16.2	15.9	**1992**	30.8	35.8	22.0	12.5
1972	22.7	24.7	18.1	14.7	**1993**	19.5	5.0	12.8	15.0
1973	23.3	18.6	13.1	15.0	**1994**	26.7	35.3	27.3	20.9
1974	19.3	19.5	19.4	17.8	**1995**	27.0	26.3	22.4	17.4
1975	27.0	31.1	16.6	19.2	**1996**	26.1	27.3	21.4	22.4
1976	19.9	18.3	16.1	18.3	**1997**	33.6	46.6	28.1	18.2
1977	25.4	27.7	22.6	25.1	**1998**	22.0	5.6	20.1	15.4
1978	28.7	37.8	18.0	26.8	**1999**	31.5	50.0	20.9	24.0
1979	23.2	14.3	23.0	16.0	**2000**	29.0	21.2	22.5	19.9
1980	17.6	17.7	19.0	19.0	**2001**	28.0	34.9	21.8	23.4

Appendix 10a: Soil Moisture data in the sub basins in the period 1960 - 2001(mm)

Time	Kiptiget Sub basin	Timbilil Sub basin	Kipsonoi Sub basin	Sondu Miriu	**Time**	Kiptiget Sub basin	Timbilil Sub basin	Kipsonoi Sub basin	Sondu Miriu
1960	15.4	8.3	11.9	15.4	**1981**	27.7	34.1	26.7	26.3
1961	30.9	47.1	24.7	25.9	**1982**	27.8	27.9	23.9	24.8
1962	20.8	12.6	16.5	17.4	**1983**	30.9	32.3	21.6	21.5
1963	31.8	45.9	26.2	26.6	**1984**	19.2	14.9	17.4	12.7
1964	34.5	34.9	16.8	20.9	**1985**	24.0	25.0	24.2	13.3
1965	25.5	15.9	16.2	24.6	**1986**	21.0	21.8	21.5	16.1
1966	25.5	27.6	15.2	13.6	**1987**	15.9	10.9	12.8	12.2
1967	30.6	34.0	19.7	16.5	**1988**	26.0	33.5	16.5	14.4
1968	30.1	33.5	26.2	21.3	**1989**	32.6	40.9	23.0	20.3
1969	14.1	2.9	16.2	14.5	**1990**	28.6	28.4	22.0	23.0
1970	27.9	37.9	23.3	18.5	**1991**	24.4	20.9	15.7	11.3
1971	21.9	16.4	16.2	15.9	**1992**	30.8	35.8	22.0	12.5
1972	22.7	24.7	18.1	14.7	**1993**	19.5	5.0	12.8	15.0
1973	23.3	18.6	13.1	15.0	**1994**	26.7	35.3	27.3	20.9
1974	19.3	19.5	19.4	17.8	**1995**	27.0	26.3	22.4	17.4
1975	27.0	31.1	16.6	19.2	**1996**	26.1	27.3	21.4	22.4
1976	19.9	18.3	16.1	18.3	**1997**	33.6	46.6	28.1	18.2
1977	25.4	27.7	22.6	25.1	**1998**	22.0	5.6	20.1	15.4

1978	28.7	37.8	18.0	26.8	**1999**	31.5	50.0	20.9	24.0
1979	23.2	14.3	23.0	16.0	**2000**	29.0	21.2	22.5	19.9
1980	17.6	17.7	19.0	19.0	**2001**	28.0	34.9	21.8	23.4

Appendix 10b: Soil Moisture data in the sub basins in the period 2002 – 2020 (mm)

Time	Kiptiget Sub basin	Timbilil Sub basin	Kipsonoi Sub basin	Sondu Miriu
2002	35.6	37.7	29.5	32.5
2003	24.3	14.0	18.5	20.4
2004	20.6	16.6	18.4	19.9
2005	23.1	25.4	22.6	23.0
2006	40.2	64.7	16.7	16.4
2007	26.9	9.9	24.3	24.4
2008	24.0	18.1	29.9	30.4
2009	26.0	25.5	17.0	17.0
2010	31.3	36.7	21.2	21.1
2011	20.3	2.7	6.4	7.2
2012	24.0	33.0	25.1	26.5
2013	36.4	53.6	20.3	20.9
2014	31.6	25.3	10.9	11.2
2015	33.2	32.6	17.8	19.0
2016	25.3	13.6	20.3	22.6
2017	31.5	41.4	21.0	22.0
2018	26.4	21.2	12.8	16.4
2019	31.5	28.6	16.5	16.7
2020	31.5	29.8	16.5	19.2

Appendix 11: Hypothesis testing

Hypothesis: There is no significance difference in the stream flows in the sub basins dominated by tea plantations, forest and mixed farming land covers

ANOVA: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Q $_{\text{Tea plantation}}$	60	647.99	10.80	8.35		
Q $_{\text{Forest}}$	60	270.48	4.51	1.85		
Q $_{\text{Mixed Farming}}$	60	1942.01	32.37	106.15		
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	25616.88	2.00	12808.44	330.25	0.00	3.05
Within Groups	6864.83	177.00	38.78			
Total	32481.71	179.00				

Hypothesis: There is no major statistical difference in the sediment discharge (Sy) in the sub basins dominated by tea plantations, forest and mixed farming land covers.

ANOVA: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Sy $_{\text{Tea plantation}}$	60	461.61	7.69	3.67		
Sy $_{\text{Forest}}$	60	228.48	3.81	0.95		
Sy $_{\text{Mixed Farming}}$	60	4939.12	82.32	1511.92		
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	234958.77	2	117479.38	232.40	0.00	3.05
Within Groups	89476.13	177	505.51			
Total	324434.89	179				

Hypothesis: There is no significant differences in the hydrological components of the sub basins dominated by tea plantations, forest and mixed farming land covers

ANOVA: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Water storage tea	60	1605.451	26.75752	168.87		
Water storage forest	60	1714.26	28.571	206.85		
Water storage mixed	60	161.339	2.688983	62.57		
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	25049.24	2	12524.62	85.73	9.23E-27	3.047
Within Groups	25858.76	177	146.09			
Total	50908	179				

Hypothesis: There is significant relationship between stream flows and sediment yields in the sub basins dominated by tea plantations, forest and mixed farming land covers.

Sub basin dominated by Tea Plantations		
t-Test: Two-Sample Assuming Unequal Variances	*Variable 1*	*Variable 2*
Mean	20.0495	7.693547
Variance	67.79492	3.674204
Observations	60	60
Hypothesized Mean Difference	0	
df	65	
t Stat	11.3212	
P(T<=t) one-tail	2.54E-17	
t Critical one-tail	1.668636	
P(T<=t) two-tail	5.09E-17	
t Critical two-tail	1.997138	

Sub basin dominated by Forest cover		
t-Test: Two-Sample Assuming Unequal Variances	*Variable 1*	*Variable 2*

Mean	4.507932	3.807954
Variance	1.846705	0.945544
Observations	60	60
Hypothesized Mean Difference	0	
df	107	
t Stat	3.24476	
P(T<=t) one-tail	0.000785	
t Critical one-tail	1.659219	
P(T<=t) two-tail	0.001569	
t Critical two-tail	1.982383	

Sub basin dominated by Mixed farming		
t-Test: Two-Sample Assuming Unequal Variances	*Variable 1*	*Variable 2*
Mean	32.36686	82.31867
Variance	106.1524	1511.925
Observations	60	60
Hypothesized Mean Difference	0	
df	67	
t Stat	-9.61894	
P(T<=t) one-tail	1.51E-14	
t Critical one-tail	1.667916	
P(T<=t) two-tail	3.02E-14	
t Critical two-tail	1.996008	