TWO-DECADE VARIATIONS IN HYDROLOGY OF TWO RIVER BASINS IN THE USAMBARAS OF NORTH-EASTERN TANZANIA

by

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ABSTRACT

Quantifying local, regional, and global climatic and hydrologic changes is relatively difficult due to high temporal and spatial variability, and to the length of time it takes for these changes to be monitored and detected. The study of precipitation and river flow patterns of two watersheds, Sigi and Soni Rivers, that drain the east and west Usambaras in northeastern Tanzania over a two decades period 1965 to 1989, show that there were varying patterns of precipitation and river flow on the Usambaras over the period. Though a non-significant trend, precipitation increased by 2.7% in the east Usambaras while it decreased by 7.7% in the west Usambaras during the period 1965-1990. The mean annual discharge increased by 2.6% in the east and 44% in the west Usambaras. During approximately two decades, discharge per unit of precipitation did not change significantly in the east Usambaras whereas it appeared to increase at a rate of 0.02 $m^3 s^{-1} yr^{-1}$ in the west Usambaras ($P = 0.06$). This is about 0.4 $m^3 s^{-1} yr^{-1}$ (1.2 $cm\ ha^{-1} yr^{-1}$) more water flowing into the river today compared to 1965.

There has been an increase in the proportion of precipitation reaching the rivers especially in the west Usambaras, which seems to have started about in the mid-1960's. Such watershed response to rainfall may be attributed to climatic and land use factors. In the Usambaras, changes in hydrologic response coincide with high rates of deforestation and changes in land use patterns. It is recommended that the remaining catchment areas on the Usambaras, and vegetation filter strips along river/stream banks should be protected. Appropriate reforestation work in degraded lands including agroforestry in farmlands should form the framework of conservation measures.

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the Usambaras in North-Eastern Tanzania

The Tanzanian government has been aware of the value of the Usambara forests (and other protective forests) in protecting the environment since 1930's (Hamilton and Mwasha, 1989). Therefore in 1976 most of the forests on the Usambaras and other mountain forests were placed in the special category of Catchment Forests in recognition of their environmental importance. The management of such forests aims primarily to protect these forests from destructive use, and to conserve their genetic resources. Timber production is entirely a secondary objective.

The outstanding biological values of many mountain forests in Tanzania have been known for many years. However, a wide awareness among biologists and the urgent need for forest conservation has only developed within the past twenty years. For example, the need to conserve the East Usambara forests for their biological value has been stressed by the Uppsala Association for the Taxonomic Study of the Flora of Tropical Africa (AETFAT) meeting in 1966. Large scale anti-erosion measures which included reforestation of degraded lands were established in the west Usambaras in 1950's in order to control severe erosion resulting from deforestation (Egger et al., 1980; Scheinman and Mchome, 1986). Recently, such measures have been established in the west Usambaras under the Soil Erosion Control and Agroforestry Project (SECAP). Several recommendations have therefore been given to conserve the Usambara forests in future forestry planning (Ahlback et al., 1984; Ahlback., 1986; Maata, 1988; Hamilton, 1989). Several interrelated climatic and hydrologic changes are suspected to have occurred on the Usambaras, calling for detailed investigation on their impact and interrelationship in order to enable appropriate scientific recommendations and justifications for conservation of the Usambaras . Such changes are presented in the following descriptions.

1.1.1 Climate and Climatic Changes

Deforestation and changes in land use on the Usambaras, have caused serious environmental degradation. This might in turn have affected the hydrologic patterns over different parts of the region. Although not well documented and analyzed, among many other negative impacts of deforestation on the Usambaras include changing patterns of climate (temperature and precipitation) and in stream-flow which includes diminishing water supply especially during the dry season to towns and other settlements that depend on the Usambara catchments as their sources of water (Hamilton, 1989; Bruen, 1989).

Past experience on climatic statistics from meteorological stations have indicated some climatic changes over the area. Moreau (1935a) and other authors following him have indicated the unusual biological climate of the east Usambara plateau, related to exceptional mistiness and general wetness. Accordingly, Moreau writes that, "relative humidity at Amani is high throughout the year and dews and mists were common. On the plateau especially where large areas of forests remain, the rainfall is supplemented by so called 'occult precipitation'. For example at Amani heavy dews form nearly every night in the year, and white fog envelope the ridges and permeate the forest especially above the lowland zone". Walter (1972), observes that the high humidity in the virgin forests that persisted even after a number of days without rain is attributed to the large quantities of dew condensing on the crown canopy. Dews measured at Amani, for example, during 40 nights without rain recorded a maximum amount of 0.26 mm per night (over 0.15 mm per night on 14 occasions, 12 times between 0.5 mm and 0.1 mm, and only 3 nights which were hardly measurable). A dew of 0.1 mm corresponds to 100 mm per m^2 of leaf surface and can quite possibly drip from the leaves which show no residue wetness.

Recent meteorological records from the east Usambaras show some evidence of temperature increase from the mid 1970's and also an increased number of years with extreme rainfall especially very dry years since 1960 (Hamilton and Macfadyen, 1989; Bruen 1989). According to Hamilton and Macfadyen (1989) and Hamilton (1989), long time residents of the East Usambaras have insisted on occurrence of major climatic changes during the late 1970's and 1980's, with less sustained rainfall, decreased mistiness, and increased warmth. Such expressions by long time residents on climatic changes have been documented elsewhere in Tanzania (Munishi and Temu, 1992). The studies by Hamilton and Macfadyen (1989), and Hamilton (1989) show that incidences of dew and mist seem to have decreased during recent years, and during 1986/87, they were not intense and were noticeable only between April and May. Recent exceptional number of large trees dying at Kwamkoro-East Usambara, and Mazumbai-West Usambara, have created a strong suspicion that drier conditions have stressed large number of trees to the point of dying (Hall, 1985; Biggelli, 1989). A decrease in the abundance of vascular epiphytes near Amani in the East Usambaras since 1970 has been associated with decreased atmospheric humidity (Poc's, 1989). It has also been argued that climatic changes are responsible for alterations in the types of crops which can be grown at higher altitudes on the East Usambaras. For example, mangoes, citrus trees, and coconuts today yield fruits in the Amani area but formerly did not, also malaria is spreading in the high altitude areas which has formally not been common. These changes have been attributed to increased warmth and decreased mist (Hamilton, 1989; Hamilton and Mwasha, 1989). It is widely speculated that climatic changes have been partly due to deforestation, although decreased reliability of rainfall is normally regional and can marginally have been caused by vegetation changes on the Usambaras. Widespread ecological degradation in East Africa might be a contributing factor in addition to the local effects (Hamilton, 1989).

Regardless of the possible contribution of other factors, reductions in vegetation cover with its effects on energy and water budgets on the earth's surface will certainly have adverse influences on climate. Probably the decline in mistiness which has occurred at the higher altitudes on the east Usambaras can be blamed with greater confidence on local forest clearance because it is precisely the type of climatic change that may be predicted (Dowsett et al., 1954). Normally forests release more water into the atmosphere than many other types of vegetation and help to maintain a high relative humidity. In the Usambaras, especially the east, the origin of moisture is mainly from the Indian Ocean. However, the forest microclimate is greatly influenced by presence of forests and may partly contribute to moisture circulation over the area.

1.1.2 Hydrology and Hydrologic Changes

Many types of hydrological experiments are long term. However, short term field studies are important in providing assessments of the magnitudes of some major variables such as precipitation, runoff, and stream flow. Such studies have been initiated in the Usambaras, the information of which is still inadequate or yet adequately analyzed. A theoretical analysis of the values of different parts of the East Usambaras for catchment purposes for example has resulted in the identification of areas regarded as critical (Bruen 1989), i.e. areas considered to provide a significant contribution to water flowing in a river/stream on a watershed/catchment area based on susceptibility to soil erosion and contribution to soil moisture storage. Maintenance of forest cover on such areas is essential as the best practical method of preserving their catchment properties.

It has been for example reported that the Sigi River may not be able to supply enough water to support the growing population of Tanga Town by 1995 (Hamilton, 1989). The Tanga Water Master Plan (1976) show that today the only permanent river on the East Usambaras is the Sigi on the southern part of the main range and all rivers flowing to the north are seasonal. However, the Kihuhwi River rising on the south-eastern part was also perennial as were various rivers coming from Mlinga (Dowsett et al., 1954, Hamilton, 1989). Drying up of springs following forest clearance has been observed and reported from the west Usambaras (Egger et al., 1980). Although the permanency of rivers is only a crude guide to changes in climatic patterns, it can at least be a good source of additional information on predicted climatic changes on the Usambaras.

1.1.3 Impacts on Forest Cover

Man has been exploiting forests on the Usambaras for at least 2000 years. According to Schmidt (1989), contrary to common opinions, there is evidence for Early Iron Age (EIA) activities in the forests zone of the Usambaras probably dating back to first millennium AD and perhaps earlier. The Late Iron Age is also represented in the records. In the West Usambaras, evidence show that Early Iron Age people were living in the areas above 1400 m in a former forested zone (Schmidt and Karoma, 1887; Schmidt, 19[illegible]). The exploitation of the forests by the groups could have been intense at least locally. Archaeological evidence show that the montane environment of the Usambaras have experienced periodic localized, but intense exploitation during three periods, 100-400 AD, 900-1100 AD, and probably 1600 or 1700 to present (Sopper, 1967; Schmidt,1989).

The severe pressure on the East Usambara mountains however is probably recent. Comparison of air photographs taken in 1976, 1982, and 1986, and maps based on air photos taken in 1957-58 shows that much forest clearance has occurred on the east Usambaras, and that the amount of clearance varies greatly from place to place (Kikula, 1989), where the extent of clearance and decreased forest cover varies from 46% to 100% in the period 1958 to 1986. Due to human impacts, forests on the East Usambara mountains today are restricted mainly to forest reserves (Hamilton, 1989; Author, this report).

Large areas of submontane forests were still present on the Usambaras at the beginning of the 20th century, but even at that time the lowland forests had probably been considerably reduced through small-scale agriculture activities (Hamilton, 1989). Large tracts of land at all altitudes for example were expropriated as estates and cleared to give way to different agricultural crops. This land continued to be owned under British rule until 1960's.

Since the 1960's, there has been a major pressure on submontane forests through the expansion of peasant agriculture and large-scale logging operations by sawmills and pit sawyers. Demand for fuelwood and construction material have been greatly intensified, and there are a few areas of the remaining forest from which building material have not been removed (Hamilton, 1989). This development have been accompanied by soil deterioration on land previously cleared for farming as well as climatic deterioration.

1.2 Objectives of the Study

The study's objective was to evaluate climatic and hydrologic changes in the Usambaras by studying precipitation and river flow patterns (trend) of two watersheds, the Sigi River and Soni River in the east and west Usambaras, respectively. The hydrologic changes were then related to climatic and land use changes around these catchments.

The specific objectives of the study were to:

i) determine whether there has occurred any changes in precipitation over the Usambaras in the past 15-20 years,

ii) predict any changes in the runoff characteristics/patterns of Sigi and Soni rivers on east and west Usambaras respectively associated with climate and land use changes,

iii) determine the magnitudes of these changes in precipitation and runoff patterns if any, the relationship between the two, as well as relating them to land use changes.

vi) consider and suggest management practices for improving or rectifying watershed problems specifically the flow of the rivers.

1.3 Literature Review of the Interrelationship Between Vegetation, Climate and Water Yield

Climatic changes are important to a variety of economic activities, but especially agriculture, hydrology, and water resource management. Hydrologic changes induced by climate and land use changes can be of particular importance in monitoring and assessing the extent of the changes in particular areas of interest. Recently, the interest in climatic and hydrologic changes have increased as there might be potential hydrologic changes due to the rapidly increasing atmospheric carbon dioxide levels. General circulation models that simulate a doubling of carbon dioxide levels observed an increase in global mean precipitation (Amanatidis et al., 1993). Some model simulation from southern Europe have shown that winter precipitation increased while summer precipitation decreased (Houghton et al., 1990).

Despite limitations in analyzing precipitation records, important decreasing precipitation trends have been observe at different stations in central and south Europe, and in Cypress since about the first quarter of this century (Cehak, 1977; Brazdil et al., 1985; Colacino and Purini, 1986; Rapapis et al., 1989), in the western U.S.A. and Japan since 1955 (Diaz and Quayle, 1980; Takahasi, 1989), in India since the beginning of this century (Soman et al., 1988) and in north-western and north-eastern Tanzania since early 1960's (Sene and Pliston, 1993; Kite, 1981; Piper et al., 1986; Hamilton, 1989; Ilari, 1992). Other studies have shown decreasing long term precipitation trends in Greece and south eastern Europe (Rapapis, 1989; Kandilis, 1991; Schonwiese and Birrong, 1990; Amanatidis et al., 1993). A number of studies which are based on available instrumental records (Bradley et al., 1987; Diaz et al., 1989; Vinikov et al., 1990) that deal with changing global precipitation have related this change to the increase in global temperature over the last century. Such studies by Pittock (1983) in Australia showed that annual rainfall had increased in the south east of Australia while it had decreased in the south west. According to Yu and Neil (1993) annual rainfall has decreased significantly in south west of western Australia during the period 1911-1990.

Climatic and subsequent hydrologic changes have often been linked to deforestation especially in the tropics (Hamilton and Macfadyen, 1989; Pereira, 1973; Salati and Vose, 1984; Sagan et al., 1979; Henderson-Seller and Gornitz, 1984). The process is however not unidirectional, and there are strong interrelationships between vegetation, climate, and water yield globally if not regionally. Climate influences vegetation as well as water yield. On the other hand vegetation influences both climate and water yield.

1.3.1 Influence of Vegetation on Climate

The effect of forests and vegetation generally on climate is controversial subject, and no incontrovertible evidence has ever been produced that clearing of forests has materially altered local or regional rainfall (Reynolds and Wood, 1977; Hamilton, 1989; Pao-Shin et al, 1990). The climatic effects of conversion of tropical rain forests to grasslands or agricultural land have been the subject of various numerical model experiments. The processes involved are complex. Pereira (1973) provided some evidence that the clearing of 800 km^2 of tall forest in southern Tanzania for subsistence agriculture halved the number of occasions on which slight rainfall was recorded. Anecdator information from certain areas of Tanzania (east Usambaras and southern Highlands) report a similar decline in the incidence of rainfall (rain days) and reduced mist following major deforestation (Hamilton, 1989, Munishi and Temu, 1992). Although many other factors might be contributing to climatic changes, reduction in vegetation cover with its various effects on energy and water balance at the earth's surface will certainly have some adverse influence on climate. Normally forests should increase local humidity more than most other types of vegetation, mainly because forests intercept more water above ground than other vegetation types (later to be evaporated) and because deep roots of forest trees can draw water from larger soil water reservoirs. It has been observed that more than 22% of rainfall is intercepted by the canopy of a submontane forest at Mazumbai, west Usambaras and does not reach the ground (Lundgren and Lundgren, 1979). In some cases in high altitudes, forests can capture atmospheric aerosols (Zadroga, 1981). This "occult" precipitation is added to the effective moisture received by the area, and where the necessary conditions are exceptionally persistant (e.g. persistent clouds), it may represent a substantial amount of total precipitation. Ekern (1964) showed that in Hawaii, occult precipitation on a single open grown tree represented an increase of 760 mm above a non forested 2600 mm of rainfall.

Conditions of watershed's vegetation can determine how much of the rain delivered in a particular storm is returned to the atmosphere (which may later form clouds and precipitation), how much enters the soil and how much is diverted into surface runoff. In several regions of the tropics for example, large amounts of precipitation come from local (land) evaporation (e.g. Moran, 1981). In these areas, vegetation plays a great role in the hydrologic cycle. If for example forests are cleared or replaced with other vegetation that transpires differently and more or less seasonally like grass, there will be a modified amount of input as precipitation. When a forest is replaced by a pasture, the absorption of solar radiation at the surface is reduced due to the higher albedo for grass as compared to forest. Reduced surface net radiation would leave less energy for evapotranspiration and smaller roughness length of grass may have consequences for surface temperature with further implications for the Bowen ratio. Dickinson and Henderson-Seller (1988) using the general circulation model and biosphere model have inferred reduced precipitation and evaporation and a lengthening of the dry season by converting an Amazon forest to grassland. Recent studies using similar model indicated a basin wide rainfall decrease of about 20% (~600 mm) in the Amazon due to deforestation (Nobre et al., 1991; Shukla et al., 1990).

There has been various observations on climatic changes with its effects such as decreased rainfall, mist, increased temperatures, increased number of natural tree deaths and reduced number of bryophytes in Tanzania and other parts of the world, all of which have been associated at least partly to deforestation (Hall, 1985; Hamilton, 1989; Bruen, 1989; Hamilton and Macfadyen, 1989; Binggeli, 1989; Poc's, 1989; World Water, 1981). Although forests are not themselves the cause of the rainfall, they have important local effects on the climate due to the high rates of evaporation from the foliage which cools the forest and the air above it, resulting into mist which is a characteristic feature of dense forests (Pereira 1989). Evaporation is increased by both the aerodynamic roughness of the canopy and the very large surface area of the foliage. Some Russian work summarized by Shpak (1968) showed 10% more rain in forest area as opposed to adjacent open areas. Early studies by Hursh (1948), following large scale deforestation by smelter fume injury in the Copper Basin of Tennessee (U.S.A.) showed a 14% greater precipitation in the forest compared to the denuded areas. Although further analysis of the experimental procedures showed lower differences when catch differences between the two are accounted for (Lee, 1978), the difference still exists showing that the forests have at least a recognizable effect on rainfall. Although it cannot be proved in retrospect that certain climatic changes are due to local deforestation, the coincidence in many cases suggests the possibility that it has at least in part contributed.

1.3.2 Influence of Vegetation on Water Yield

Vegetation, through the influence on the hydrologic processes, exerts a very large influence on water yield and stream flow (Colman, 1953; Dunne and Leopold, 1974; Waring and Schlezinger, 1974). There is a general agreement that forests in relation to other land uses consume large volumes of water and reduce water yield (Lull and Reinhart, 1967; Hubert, 1967; Bosch and Hewlett, 1982; Trimble and Weirich, 1987). Forests increase interception and transpiration losses so that net evapotranspiration is increased and stream flow is thereby reduced. Potential transpiration of trees is similar to evaporation rates from saturated bare soil, but trees can maintain a high transpiration rate by drawing moisture from a full depth of the soil profile even when the surface is relatively dry. On the other hand, according to Dowsett et al., (1954), Ekern (1964), Zadroga (1981), Walter (1972), montane and submontane forests (such as forests on the east Usambaras) can substantially augment the moisture of these areas as well as soil moisture by different ways including fog drip and occult precipitation. The effects of deforestation and reforestation on water yield have long been investigated using catchment experiments and reviews of the worldwide results published (Hibbert, 1967; Bosch and Hewlett, 1982). There is typically a decrease in stream flow with increasing reforestation under experimental conditions. On a river basin-wide scale, Trimble and Weirich (1987) showed that a 10-20% reforestation of degraded lands in the southern Piedmont region of the U.S.A. resulted in a statistically significant decrease in water yield (stream discharge) of 4%-21%, depending on watershed.

Vegetation acts to hold down the development of wastefully high stream flows by interposing barriers and interruptions to the rapid flow of water in streams, and diverting water received by watersheds into flow beneath the soil surface. Therefore, vegetation cover reduces the development of wasteful high peaks of stream flow and favors the yield of water at reduced amounts as slower, more prolonged, and more uniform ground water flow. This might mean that forest removal generally but not always increases stream flow. Vascular plants, and particularly trees exert a unique influence on the hydrologic properties of terrestrial ecosystems, by extracting water from the soil below the shallow depth that is usually affected by evaporation. This in turn affects/reduces the amount of water remaining for seepage and stream flow. Different vegetation types have different effects on stream flow due to their differing morphological structure above and below ground (Colman, 1953; Swank and Douglass, 1974; Waring and Schlesinger, 1985; Hough, 1986). Vegetation manipulation have been observed to regulate water yield/stream flow from watersheds. For example, methods used for increasing the water yield from watersheds include removal of vegetation, replacement of one tree species by another, and structural alteration of existing stands (Waring and Schlesinger, 1985; Dunne and Leopold; 1974).

1.3.3 Influence of Climate on Water Yield

Precipitation is the ultimate source of water yield. The quantity of water yield is influenced very strongly by three factors: volume of precipitation, which determines the gross supply, the seasonal distribution of precipitation, which determines when it is delivered, and the quantity of solar energy received annually by the land which controls to a large extent the amount of water returned to the atmosphere by evaporative loss (Colman, 1953). Other secondary factors that control water yield include soil depth, permeability, and geological characteristics of watersheds. In any rainfall event, the land releases water to streams and underground basins under either of two conditions: surface runoff, or subsurface flow after infiltration. Therefore, the quantity of water released is the surplus/portion of supply remaining after certain demands have been satisfied including storage by the soil, evaporation from vegetation and land (which is largely controlled by weather conditions).

CHAPTER TWO

2.0 MATERIALS AND METHODS

2.1 Study Site Location

The Usamabaras are a range of block (crystalline) mountains on the north eastern part of Tanzania. These ranges are divided by the Lweyengera valley into two; the eastern and the western. They are part of the crystalline mountains in Tanzania referred to as the Eastern Arc Mountains. The Usambaras lie roughly between latitudes 4° 30' and 5° 13' S and 38° 25' and 38° 48' E. The eastern Usambaras follow a main range running SSW-NNE in a fault-determined direction. The western Usambaras form a range adjacent to the east Usambaras running SSE-NNW direction. Administratively, the east Usambaras fall under Muheza and Korogwe districts while the west Usambaras fall under Lushoto and part of Handeni districts, both being part of Tanga region (Appendix 1a). This study was done on the Sigi river watershed in the east Usambaras and the Soni river watershed in the west Usambaras which cover areas of about 717 km^2 and 528 km^2, respectively (Appendix 1 b, c).

2.2 Topography

The east Usambaras rise abruptly from the lowlands at 150-300 m above sea level and are bounded on all sides by steep escarpments leveling off at 900-1050 m onto a deeply dissected plateau most extensive to the south. The southern plateau forms the most important water catchment of the eastern Usambaras drained by the Sigi river. The east Usambaras can be divided into four separate mountain blocks (Appendix 1a); the main range in the west and three blocks in the east from north to south named by their tallest peaks; Mtai (1061 m), Mhinduro (1034 m), Mlinga (1069 m) and Toungue (1025 m). The western Usambaras form a rather broken topography with altitude range between 1300 m to 2300 m. The ridges run and increase in altitude more or less from SE to NW (Pitt-Schenkel, 1938).

2.3 General Climate

The climate of the Usambaras is monsoonal with two rainy seasons and high relative humidity (Hamilton 1989). The long rain season on both the east and west Usambaras is between March and May, and the short rain season is between October and December. There is also occasional rain during the dry season. In the east Usambaras the mean annual rainfall varies between 1000 and 1300 mm in the lowlands to the south to less than 600 mm in the south. On the plateau it declines from over 2000 mm in the south to about 1500 mm in the north. On the west Usambaras, the mean annual rainfall varies from 1250 mm to 1620 mm. There are generally major variations in rainfall associated with elevation and aspect, although there is a high temporal correlation in precipitation over the watersheds. Precipitation is higher on higher altitudes and on the south east facing slopes.

Despite the marked seasonality, rainfall is reasonably well distributed over the year (Hamilton, 1989). However, no year is an average year, and severe dry periods may occur. The elevation-temperature relationship is very steep (Hamilton, 1989; Moreau, 1934; 1935a, b). The east Usambaras are close to the coast, and their proximity to the coast contribute greatly to the higher rainfall and also to exceptionally low temperatures experienced on their upper slopes compared with similar elevations at inland parts of the country (Moreau, 1934; 1935a, b; Hamilton, 1989). On the east Usambaras there is a 5^{o} C difference in mean temperature between the hottest and the coldest months. Maximum and minimum temperatures are abnormally below normal compared to other similar parts in Tanzania (Hamilton 1989, Moreau, 1934; 1935a, b).

2.4 Potential Evapotranspiration

On an annual basis, the potential evapotranspiration in most of the Usambaras is less than precipitation resulting in excess precipitation. For example, the potential evapotranspiration for Amani on the east Usambaras has been estimated to be 1505 mm with an annual excess precipitation of 1910 mm (Hamilton 1989). At higher elevations of the west Usambaras, the potential evapotranspiration is likely to be less due to decreasing temperatures with altitude and increased cloud cover.

2.5 Geology and Soils

The Usambaras rocks are Precambian and are assigned to the Usagaran basement system. They consist mostly of gneisses with some granulites and amphibolites after many years of folding, metamorphism, and migmatization. The soils are generally deep to very deep (1-5m). On the east Usambaras, the soils are of two types corresponding approximately to the occurrence of lowland and sub-montane forests. They are clays, or clay-loams, red or otherwise yellowish red, usually deep and very freely draining (Hamilton, 1989; Ilari, 1992). These forest soils are Ferrasols as classified by FAO/UNESCO classification. The submontane forest soils above about 850 m are acidic (pH 5.5) leached with low inherent fertility. The lowland soils are less acidic (pH 6-7), richer in cations, with high potential for agriculture than soils at above 850m (Hamilton 1989). On west Usambaras the soils are mainly gray brown, yellow-brown, or dark-brown loams, sometimes sandy loams. Sub-soils are highly leached and are more reddish.

2.6 Data Collection

Precipitation data was obtained from the directorate of meteorology in Dar-es-Salaam, Tanzania. This is an institution which keeps records of precipitation data from meteorological stations throughout the country and from the Department of Water and Energy, Tanga regional directorate. Most of the data records are of monthly precipitation.

The rain gauges used in Tanzania are the non-recording types. They are 12.5-cm diameter, and 30 cm in height. They consist of a conical collector, and a measuring tube (cylinder) which can be measured to the nearest 0.2 mm. Except for the type of rain gauges, there is no information available about measuring instruments, changes in measuring instruments and gauging methods. However, a major change which could have taken place is the change from imperial to SI units of measurement. Changes and their effects are assumed to be minimal and marginal, although changes on gauging sites, and precipitation gauging methods that might influence observations or measurements cannot be included in these evaluations. Precipitation data for nine stations on the east Usambaras (Sigi River watershed) and eight stations on the west Usambaras (Soni River watershed) for the past 26 years were used in this study. The gauging stations selected were the ones in areas observed to contribute water to the respective rivers (Table 1, Appendix 1 b, c).

The discharge data were obtained from the Ministry of Water and Energy in Dar-es-Salaam. The data represented the daily discharge for Sigi river at Lanzoni gauging station (Sigi watershed) and Soni river at Mombo gauging station (Soni watershed). The Sigi river data were from 1957-1989 (33 years) period, while the Soni river data were from 1965-1983 (19 years) period. Part of these data may also be available from the Hydrologic Yearbooks 1965-1970, and 1971-1980, which are publications prepared periodically by the Ministry of Water and Energy containing discharge data for different watersheds in Tanzania. Discharge data are normally obtained as the average of water levels/stage heights recorded from a set of stuff gauges read several times a day. For each river sample data for discharge and water height from each gauging station collected over different periods are used to prepare rating curves/tables. These rating curves and tables are then used to determine the flow at each stage height. Extensions to rating curves outside the range of observed discharge are sometimes made based on values computed by the Department of Hydrology of the Ministry of Water and Energy from hydraulic measurements, comparison with other stations and the logarithmic plotting of the stage discharge observations (Hydrologic Year-Book, 1971-1980; Ilari, 1992).

2.7 Data Analysis

The time series for annual precipitation (mm), and mean, minimum, and maximum annual discharge rates ($m^3 s^{-1}$) were developed for the periods of available data. These data sets included both watersheds and each rainfall gauging station. Bivariate time series graphs were then developed from these data (plot of observed values against time) to evaluate trends in the data over time. The graphs included linear regression predictions of trend lines based on simple least square regressions of precipitation and discharge over time, assuming low month to month autocorrelation. Despite that it does not take into account the presence of seasonality, the method is unquestionably the single best way to examine a relationship between pairs of variables, and can fairly be used to indicate linear trends in a data set (Hirsh et al., 1991; Reckhow et al., 1992). Other methods used to test for any trend were Kendall test for non parametric trend analysis (Kendall, 1938; Hollander and Wolfe 1973), and running means/moving averages.

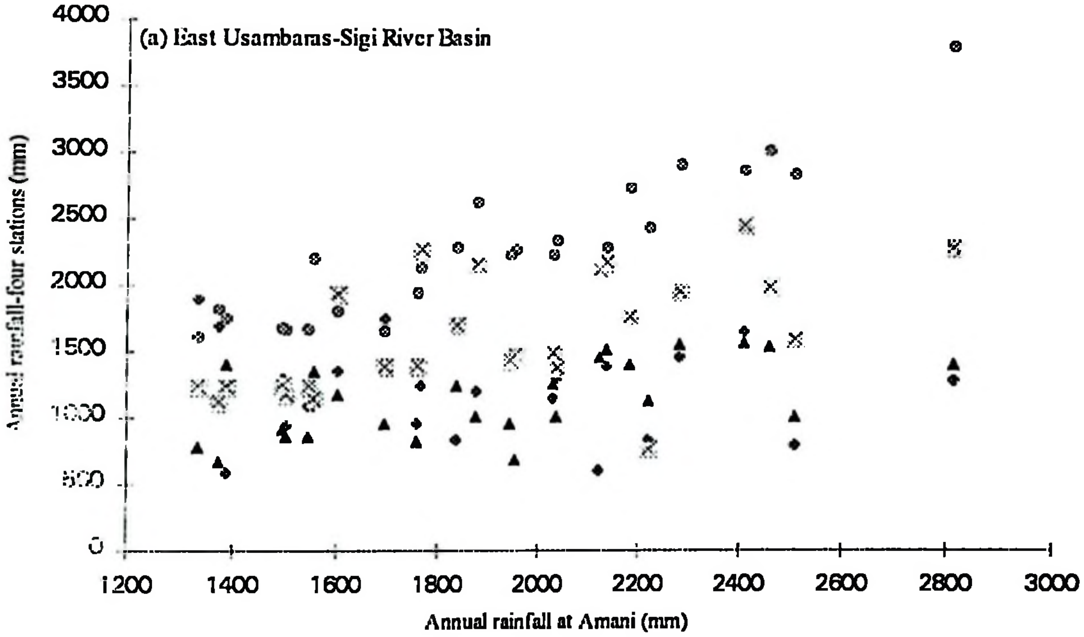
In order to examine the constancy of the relationship between precipitation and flow volumes, double mass curve analysis was used. These curves related flow volumes in each river with both the mean watershed precipitation and individual station precipitation on each watershed. This was done by plotting the cumulative flow volume (m) against cumulative precipitation (m). To make the data in similar units each data set for total annual flow volume ($m^3 s^{-1}$) was divided by the respective watershed area (m^2) and precipitation data was converted into meters of rainfall. An estimated straight line was then drawn based on the initial portion of the curve taking the starting point as zero and the first year of the data set as initial year. This analysis enabled the prediction of points/periods of change in the rainfall-runoff relationship. This estimated straight line, though subjectively drawn, can give an approximation of the deviation in the relationship, it probably works better where the starting period of the data on different stations is the same especially when comparing two or more stations/watersheds.

For each watershed, a regression based trend analysis was estimated by computing the regression between the daily discharge (m^3 s^{-1}) and mean watershed precipitation (m). Residual analysis was then performed by regressing the residuals against time to determine the discharge trend and whether runoff has changed over time. The significance of the slope for the trend line was also tested.

2.8 Data Reliability

Precipitation data have relatively few missing dates (0.3% - 9.6%). The missing information on the data set is low enough to assume negligible effect on the annual mean precipitation (Table 1). Therefore the annual mean precipitation was calculated as the arithmetic mean of the months in which data were available. A high correlation in annual precipitation between different stations on the Usambaras has been observed by Hamilton and Macfadyen (1989). This is also shown by a correlation in precipitation between different stations on the two basins for the data used in this study (Fig. 1).

Discharge data show a missing information of about 359 days out of 33 years (12045 days) on the east Usambaras and 91 days out of 19 years (6935 days) on the west Usambaras. This is roughly about 0.03% and 0.013% on the east and west Usambaras respectively. The duration of missing information varied from 8 to 46 days per year. The mean discharge was therefore calculated from the number of days of available data.



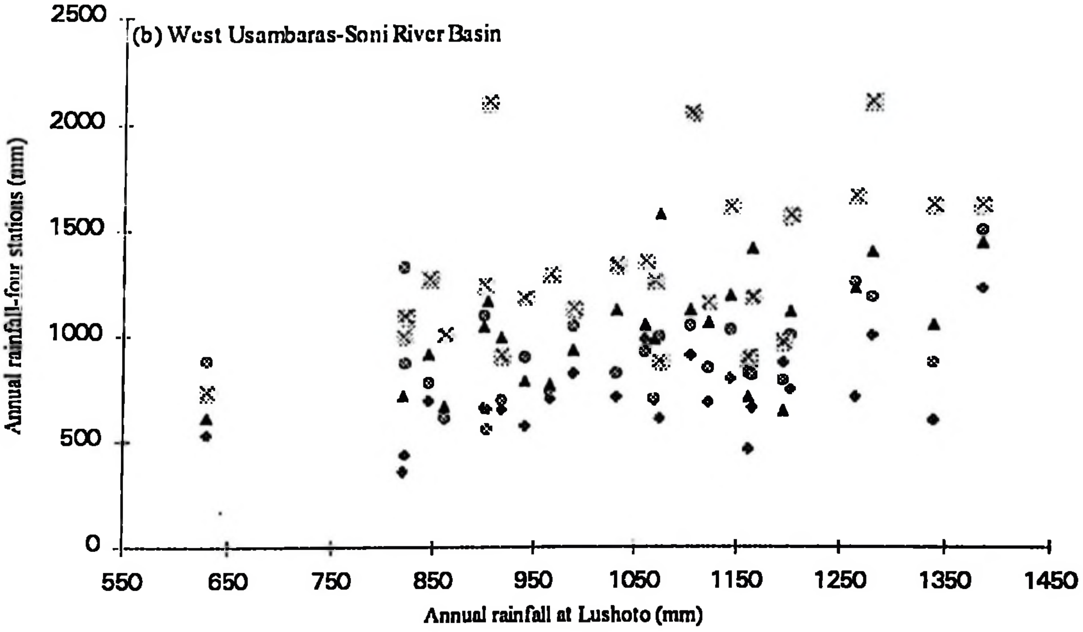


Fig 1. The Relationship between precipitation at different satations on the Usambaras. (a) East Usambaras-Sigi River Basin; Amani and four other stations-Bombwera (♦), Kwamkoro (•), Ngombezi (Δ), and Longuza (⊗). (b) West Usambaras-Soni River Basin; Lushoto and four other stations-Shume (♦), Shagayu (•), Magamba (Δ), and Herikulu (⊗). There is fairly good correlation in rainfall between the different stations on the two basins.

CHAPTER THREE

3.0 RESULTS AND DISCUSSION

Large scale forest clearance on the Usambaras started in the early 1960's. Further clearing of land for farms on the abandoned tea estates started on large scale in 1967-1968 (Hamilton and Mwasha, 1989). For example, on the west Usambaras about 13,400 hectares of Shume-Magamba forest reserve was degazetted in 1963 and given to small holder farmers as a response to a popular cry for land (TRDP, 1975; Egger et al., 1980). Large parts of Shume-Magamba are until now barren (Hamilton and Mwasha, 1989; Author, this report). Forest clearance has therefore triggered several hydrologic changes on the watersheds which may have resulted in increased direct run-off in these basins due to vegetation removal, and a change in the relationship between precipitation and discharge and the behavior of the double mass curve relating the two parameters. Such changes in the relationship between precipitation and discharge (behavior of the double mass curve) has also been observed at Mavera, Kwamkoro, and Magunga on the east Usambaras (Bruen, 1989; Ilari, 1992).

The results from analysis of precipitation and discharge data from the two watersheds give varying trends over the analysis period. Both significant and non significant increasing and decreasing trends are observed with individual rainfall stations though a decreasing trend seems to be more pronounced. The double mass curve analysis show two periods of deviation in the relationship between precipitation and discharge, suggesting a change in the relationship between the two parameters at different time periods. This shift reflects changes in the watershed response to rainfall that may be attributed to climatic and land use factors. Table 1 contains a list of stations used in this study from the two watersheds. Table 2 summarizes the observed climatic and hydrologic changes on the two watersheds.

Table 1. Precipitation gauging stations within the Sigi and Soni River basins in the eastern and western Usambaras, NE Tanzania.

Watershed	Station	Information Period		Missing	
		Year	# Months	# Months	%
Sigi River, East Usambaras	Amani	1965-1990	312	-	-
	Kihuhwi	1965-1990	312	-	-
	Bombwera	1965-1987	276	-	-
	Marikitanda	1969-1990	264	1	0.4
	Ngombezi	1965-1990	312	5	1.6
	Kwamkoro	1965-1990	312	-	-
	Longuza	1965-1990	312	-	-
	Mgambo	1966-1990	311	6	1.9
	Kigongoi	1971-1990	240	23	9.6
Soni River, West Usambaras	Lushoto (a)	1965-1990	312	-	-
	Shume	1965-1990	312	-	-
	Magamba	1965-1990	312	1	0.3
	Herikulu	1965-1990	312	1	0.3
	Shagayu	1965-1990	312	-	-
	Mlomboza	1965-1990	312	2	0.6
	Gologolo	1965-1990	312	1	0.3
	Lushoto (s)	1969-1989	252	-	-

Table 2. **Precipitation and runoff patterns in the Sigi and Soni River basins in the Usambaras NE Tanzania, 1965-1989.**

Parameter	Basin		Remarks
	East	West	
Annual Rainfall (mm)	Increase	Decrease	NS
Annual Discharge (m^3s^{-1})	Increase	Increase	NS
Max. Discharge (m^3s^{-1})	Increase	Increase (P=0.1)	NS
Min. Discharge (m^3s^{-1})	Decrease	Increase	NS
Residual Discharge (m^3s^{-1})	Decrease	Increase (0.02m3s-1yr-1, P=0.06)	NS (0.4m3s-1yr-1 more water today)
Prop. r'fall reaching rivers	Increase	Increase	Approximation

Note: NS = Non significant change * = Significant change

3.1 Precipitation Patterns

The station precipitation time series and linear regression model prediction against time on the east Usambaras for the period 1965-1990 have pronounced trends for three of nine stations. A significant decrease is observed at Bombwera (P=0.02), while increasing trends are observed at Ngombezi (P=0.049), and Kigongoi (P=0.051). The trends on the remaining stations are slightly increasing or decreasing and are not statistically significant. The change at Marikitanda, Longuza, and Mgambo show an increase while that at Amani, Kihuhwi, and Kwamkoro show a decrease (Appendix 2).

The analysis on west Usambara stations over the same period show a significant change on two of the eight stations. The increasing trend is observed on Mlomboza ($P<0.05$) while decreasing trends are observed on Gologolo ($P<0.05$). The other stations show slight but non significant changes. Slight decreasing patterns are observed at Herikulu, Lushoto agricultural station, Shume, Magamba, and Lushoto silvicultural station, while a slight increase is observed on Shagayu (Appendix 3).

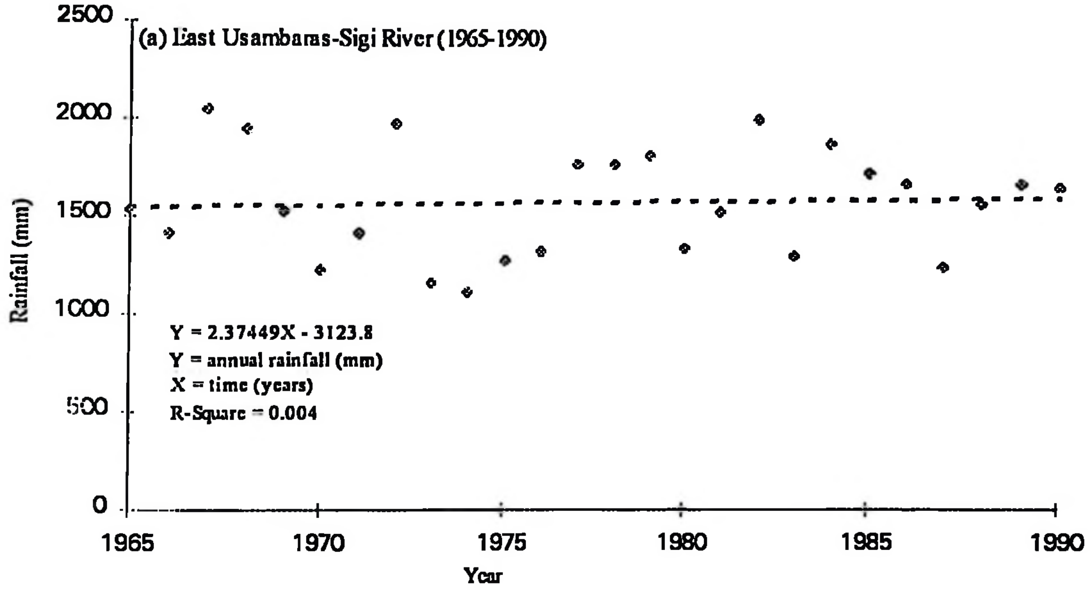
The trends and patterns observed on precipitation records on the watersheds in this study may be attributed to atmospheric circulation variations and oceanic influences especially in the east Usambaras. Though no clear meteorological explanations can be given, we cannot deny the existence of decreasing trends in precipitation at least for some stations on the basins. Ilari (1992) observed decreasing precipitation trends over longer periods of time at Amani (>88 years), Magunga (>51 years), Kwamkoro (>58 years), and suggested effects on the precipitation caused by local deforestation. The same analysis of precipitation records from Amani, Marikitanda and Kwamkoro indicated evidence of decreasing rainfall reliability since 1960's on a regional scale (Hamilton and Macfadyen, 1989). Their analysis indicated an existence of more very dry years with occasional very wet years but a clear trend was not suggested.

Individual stations may not give adequate information on the watershed, and therefore, the mean watershed precipitation is considered to give a better representation of the precipitation conditions on the watershed. Compared to 1965, the mean watershed precipitation time series computed as the arithmetic mean of the precipitation from individual stations on the respective watersheds show a general slight increasing precipitation pattern (an increase of about 2.7% or 2.4 mm yr.$^{-1}$) on the east Usambaras for the period 1965-1990 (Fig 2 a). On the other hand, west Usambaras show a decreasing pattern of precipitation (a decrease of about 7.7% or 2.9 mm yr.$^{-1}$) over the same period (Fig 2 b). Both trends are however statistically non significant (R-Square = 0.04, 0.016, and $P = 0.7, 0.5$ for east and west Usambaras respectively). The change on the two basins are in opposing direction. Such opposing trends in precipitation over two different parts of the same region has been observed in Australia by Pittock (1983). An analysis using Kendall non- parametric trend test show no significant trend in precipitation (Table 3). A five and nine- year moving average show no clear trend in precipitation (Fig 3). However, periods of low and high precipitation with more pronounced decreasing pattern in the west Usambaras can be observed.

Table 3. **Kendall Trend Test (non-parametric) for Precipitation and Discharge in the Usambaras NE Tanzania (Sigi River -East and Soni River Basin-West Usambaras).**

Parameter	Basin	P-value	Remarks
Annual Precipitation (mm)	East	0.93	Increase (K = 5)
	West	0.54	Decrease (K = -29)
Mean annual Discharge (m^3/sec)	East	0.36	Decrease (K = -24)
	West	0.20	Increase (K = 33)

Note: There is no evidence for significant trend in precipitation in either basin. (high P-values). However an increasing trend is suggested for discharge in the west Usambaras (P-value=0.2)



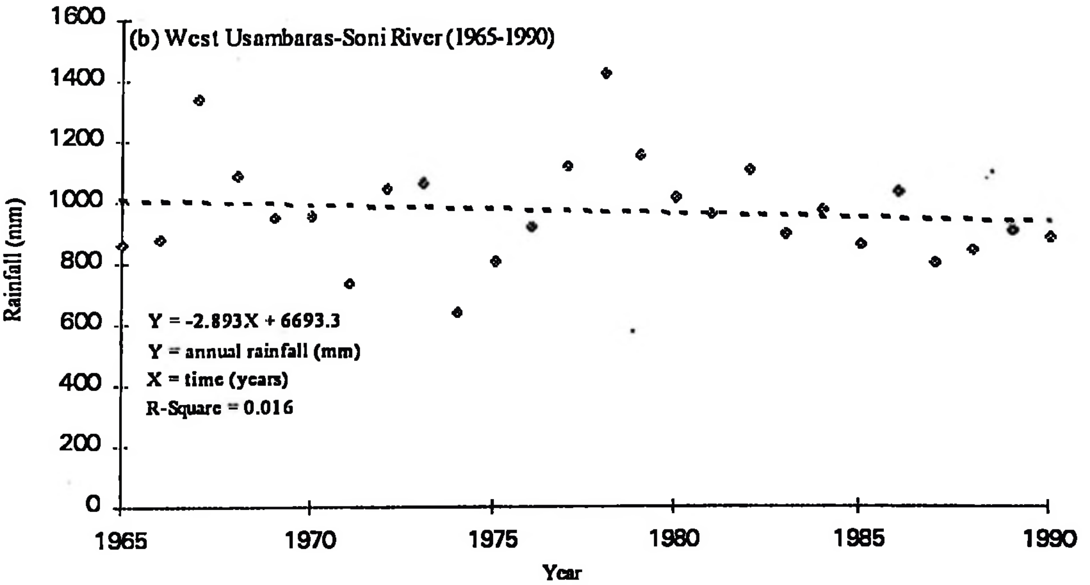


Fig 2. Watershed precipitation plot of observed and linear regression model prediction against time -Usambaras, NE Tanzania. (a) East Usambaras-Sigi River Basin (b) West Usambaras-Soni River Basin

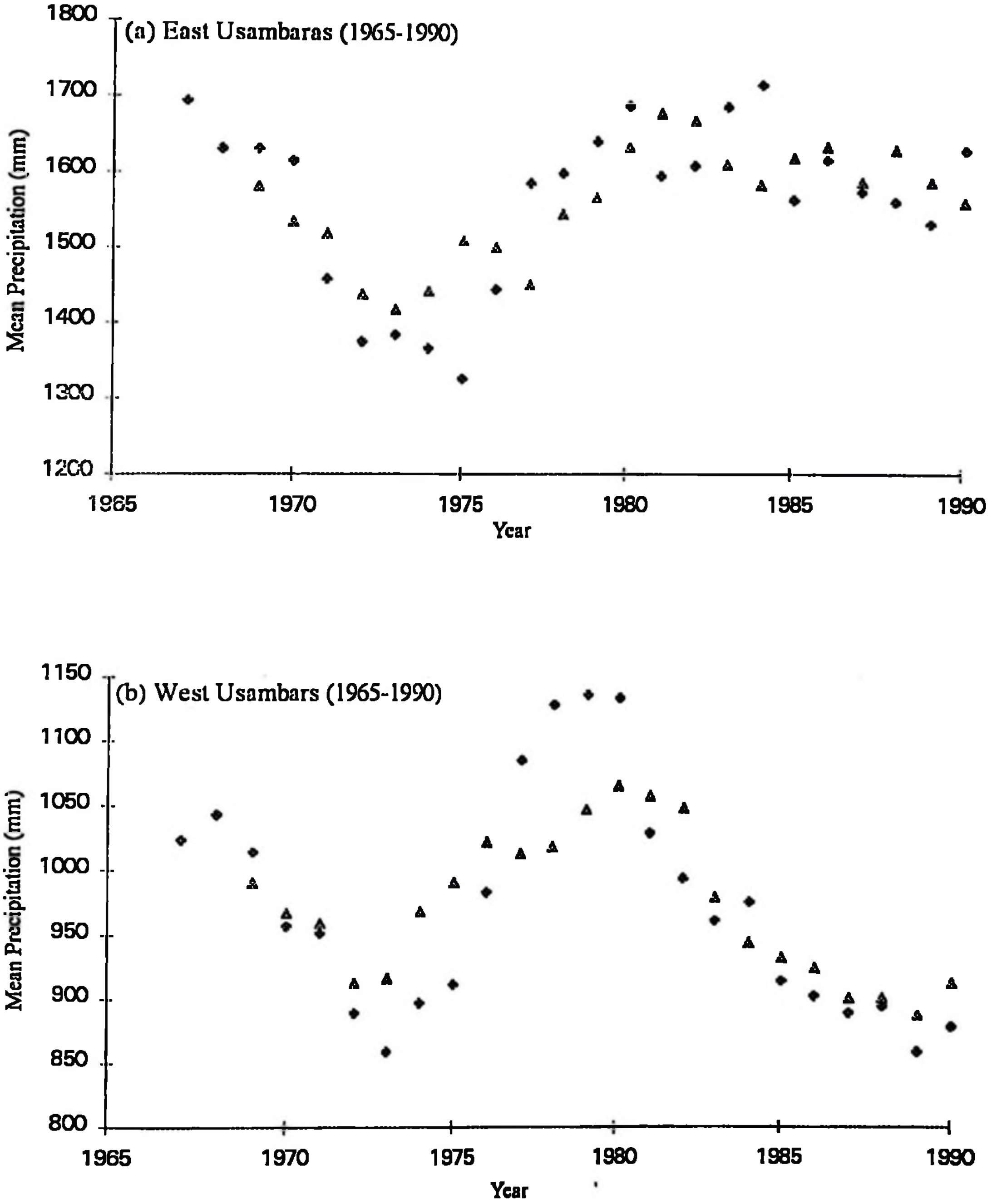


Fig 3. Analysis of mean precipitation in the Usambaras NE Tanzania. Five-year running mean (◆) and nine-year running mean(Δ). (a) East Usambaras (b) West Usambaras. No clear trend can be predicted than periods of high and low precipitation. The period between 1970 and 1975 seem to be drier years for both watersheds. A more visible decreasing pattern is observed in the west Usambaras after 1980.

The increasing precipitation trend on the east Usambaras would be expected based on physical explanation of increasing temperatures which result into increased capacity of the air to hold water. Bruen (1989) examining monthly extremes of temperature at Kwamkoro concluded that temperatures over the east Usambaras have increased from the late 1970's. Coupled with anecdotal information suggesting temperature increases (Hamilton 1989), we would expect precipitation to increase as increase in temperature would increase the capability of the atmosphere to hold a greater amount of water vapor resulting in an increase in the precipitable water.

There is no evidence of temperature patterns on the west Usambaras as no such studies have been done in this part. Therefore no precise explanation can be given in relation to effects of atmospheric circulation on the observed precipitation pattern. No much oceanic influences can be suggested as the area is far from the ocean. At the same time west Usambaras are at higher altitude and in that sense temperature changes will be more or less suppressed, thus less effect on the atmospheric conditions in terms of water holding capacity.

Since the results are non-significant, there is no conclusive evidence for significant trends. However patterns of increase or decrease and normal precipitation fluctuations with occasional drier and wetter years in precipitation on the two basins for the period 1965-1989 are detectable. Probably, other analyses that follows may enable more concrete conclusion. Similar observations were made by Hamilton and Macfadyen (1989) on some stations in the east Usambaras.

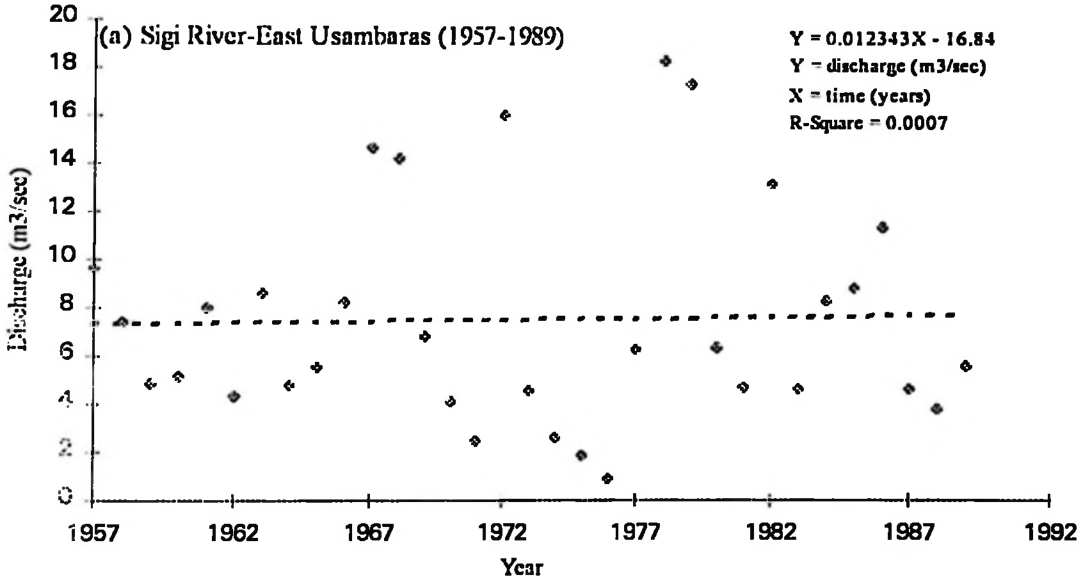
3.2 Discharge Patterns

The analysis of stream flow (discharge) data in relation to precipitation over time is assumed in this study to give a better indicator of climatic changes than precipitation alone. As stream discharge is highly related to precipitation, a change in precipitation pattern is easily reflected in the discharge pattern. On the other hand, at times stream flow may change pattern without measurable changes in the precipitation patterns (Pereira 1989). If this occurs it will indicate other changes on the watershed such as impacts related to human activities like deforestation which affects infiltration and evapotranspiration patterns.

The regression analysis of discharge through the Sigi River at Lanzoni show a slightly increasing non-significant trend with an increase of 2.6% or 0.01 m^3 s^{-1} $yr.^{-1}$ based on the slope of the regression line for the period 1957-1989 (Fig 4a). Kendall-trend test shows an increase but non significant (Table 3). A five and nine year running mean show no pronounced pattern in discharge, and periods of high and low flows are observed (Fig 5a). The changes in discharge may be related to the changing patterns in precipitation though the rate of change in discharge is less than the rate of change in precipitation . Despite these differences in change rates, we can infer that discharge has increased over the watershed and is related to the precipitation pattern (the correlation between precipitation and discharge is positive, high, and statistically significant ($R=0.63$, $P<0.05$) (Fig 6a). The differences between the increase in discharge and precipitation rates may therefore be related to physical characteristics on the watershed such as land use, geology, soil type, land configuration (slope), and vegetation composition.

The discharge into the Soni river at Mombo in the west Usambaras show an increasing pattern (R-Square = 0.06, P=0.21). The Kendall trend test gives a P-value of 0.2 (Fig 5b, Table 3). A five and nine year running mean show periods of high and low discharge into the Soni River, with a relatively drier period between 1972 and 1974 (Fig 5b). Compared to flow in 1965, discharge in 1983 had increased by 44% (or 0.04 m^3 s^{-1}

yr^{-1} based on slope). Compared to the east Usambaras, the discharge in the west Usambara increased at a higher rate. On the west Usambaras the discharge and precipitation trend are opposite to each other (one is decreasing while the other is increasing). Since the correlation between precipitation and discharge on the west Usambaras is positive and statistically significant (R-square = 0.75, $P < 0.05$) (Fig 6b), we would expect a positive trend in both precipitation and discharge (Fig 2b, 4b). However, this is not the case (they have opposite patterns). This implies that effects of changes of land use on the watershed can be predicted. Land use changes which cause reduction in vegetation cover for example or deforestation are expected to cause a relatively high proportion of the precipitation on the watershed to reach the river even perhaps in years with relatively low precipitation. The analysis shows an increase in discharge into the river of about 0.0356 m^3/sec/year. For the 19 years analysis period would mean there is about 0.6765 m^3 s^{-1} more water in the river at present. As far as this increase in discharge is related to changes in land use patterns, we can expect the discharge to be modified by any change in land use. Conservation measures such as tree planting and maintenance of vegetation filter strips along river/stream banks will certainly reduce excessive surface runoff and subsequent wasteful discharge rate.



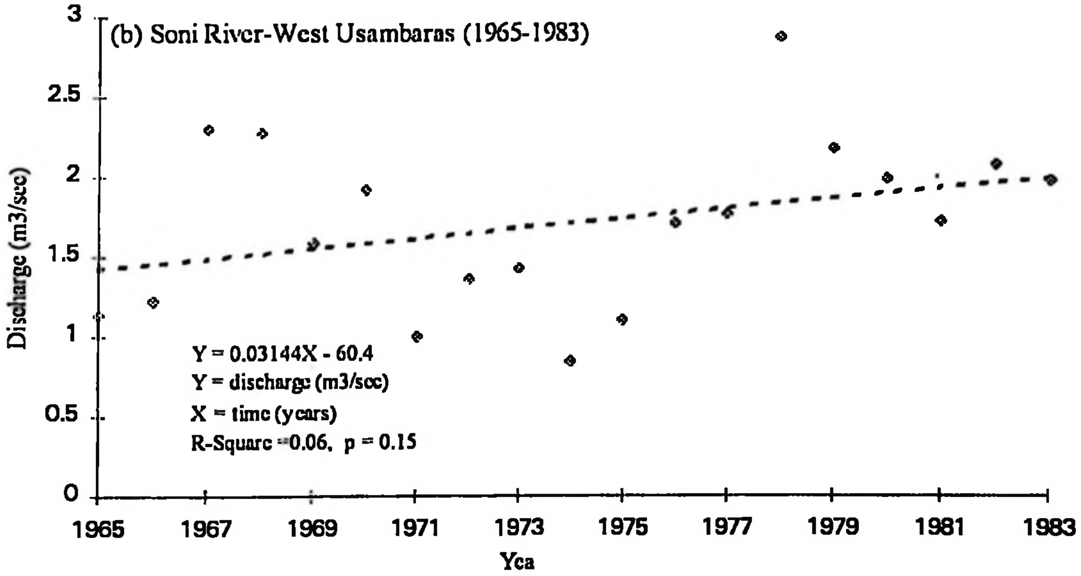
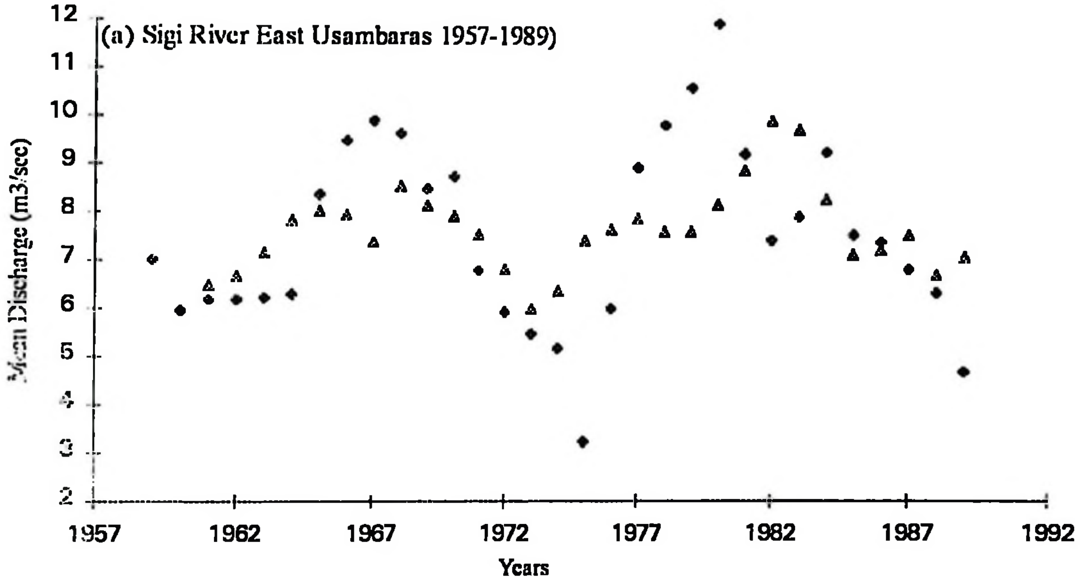


Fig 4. Discharge plot of observed and linear regression model prediction against time (a) Sigi River, east Usambaras (b) Soni River west Usambaras. No evidence of a significant trend in dicharge is detectable (P>0.05), though a slight increase can be noted. Wide variations in discharge can be noted in Sigi River between 1967 and 1979.



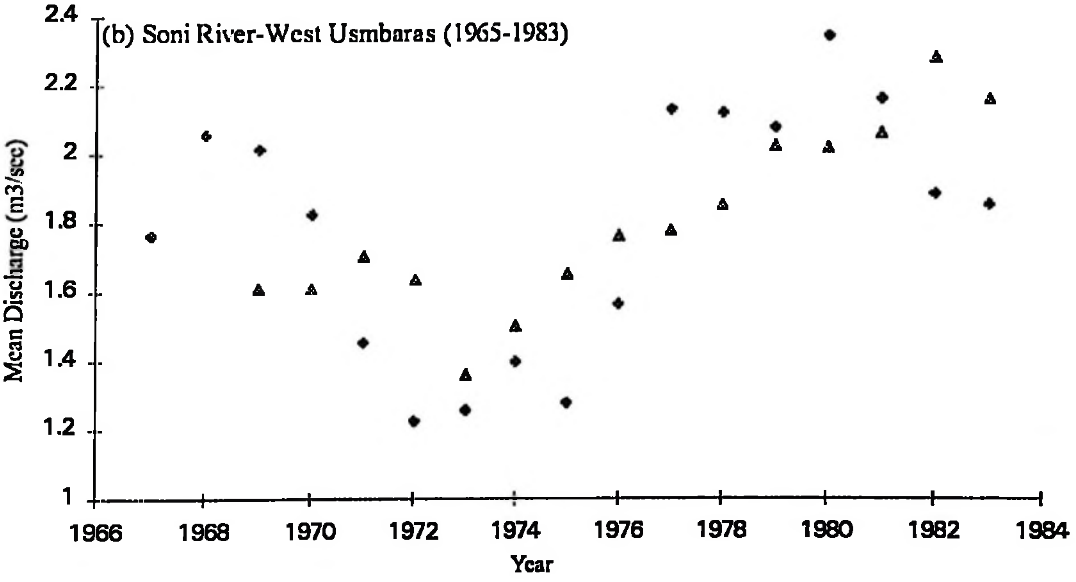


Fig 5. Discharge analysis in the Usambaras, NE Tanzania. Five-year running mean (◆) and nine-year running mean (Δ). (a) Sigi River (b) Soni River. Both rivers show periods of high and low flows. The period between 1972 and 1974 seem to have been the driest period (with relatively low discharge)

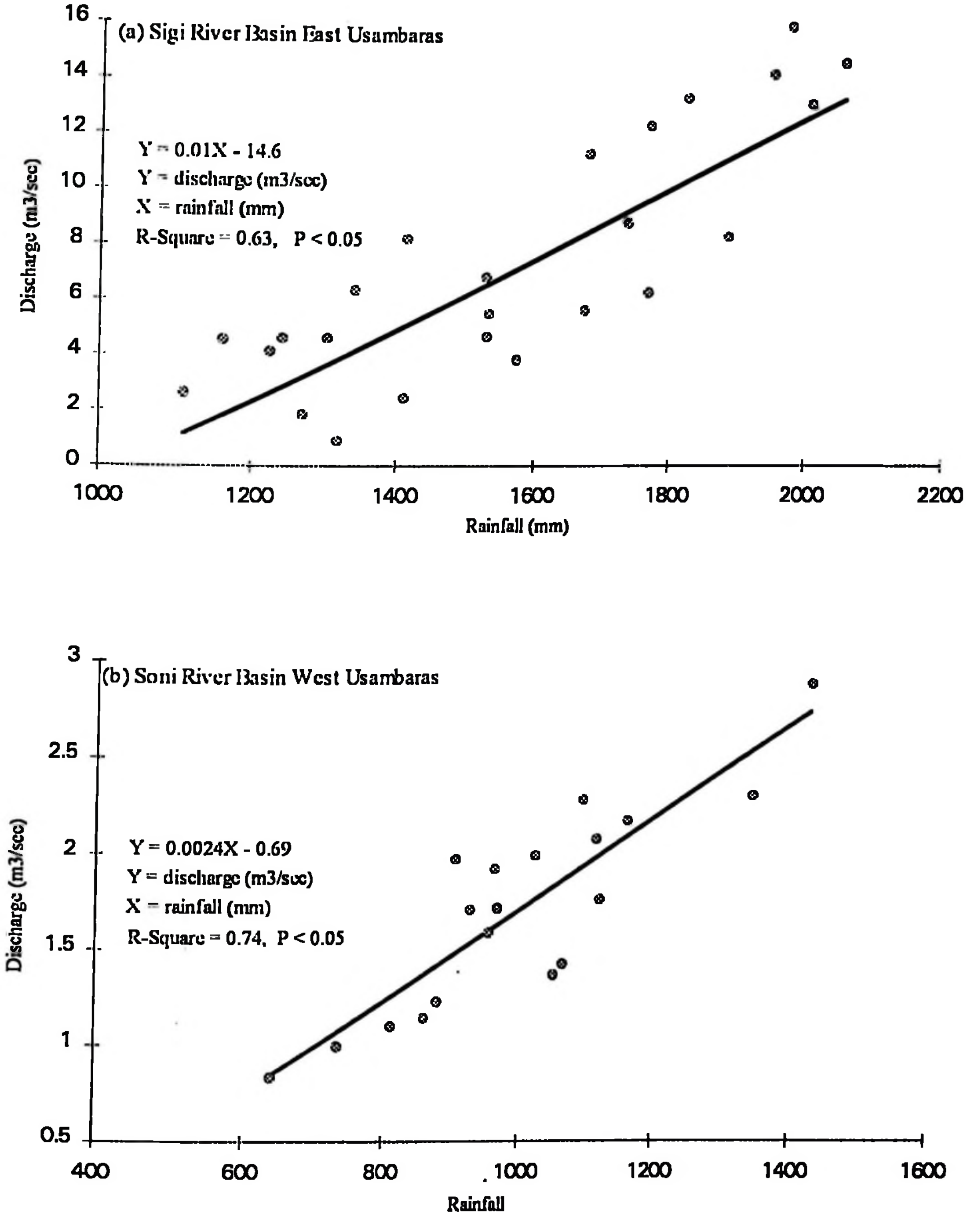


Fig 6. The relationship between precipitation and discharge in the Usambaras. (a) Sigi river basin east Usambaras (b) Soni river basin west Usambaras. The plot shows the predicted discharge (—) and observed discharge (⊗). The correlation between the two parameters is fairly good for both basins.

3.3 Maximum and Minimum Discharge

The analysis of the maximum and minimum discharge into the two rivers is significant in determining the conditions of water availability during the rainy and dry seasons. Water availability during the dry season is critically important as decreasing discharge during this period will mean increasing water scarcity. Such analysis show that in the east Usambaras, the maximum discharge has increased (by as much as 40% or 0.3 m^3 s^{-1} yr^{-1}) while the minimum discharge has decreased (by as much as 5.9% or 0.01 m^3 s^{-1} yr^{-1}) in 1989 compared to flow in 1965 (Fig 7 a, b, Table 2). In the west Usambaras both the maximum and minimum discharge have increased over time (60% or 0.1 m^3 s^{-1} yr^{-1} and 10% or 0.006 m3 s^{-1} yr^{-1} respectively) during the period 1965-1983 (Fig 8a, b, Table 2). This suggests that less water has been available during the dry season in the east Usambaras with more water as floods during the rainy season. In the west Usambaras, the increase in maximum discharge has been significantly high which means that much more water has been discharging into the river during the rainy season. On the other hand, the minimum flow has been relatively stable. Ilari (1992) observed an increasing maximum flow into the Sigi river between 1960 and 1988. From this study, the trend in flow compared to precipitation trend show an increasing proportion of precipitation reaching the rivers on the two watersheds. There has been no much effect on low flow into the rivers and no alarm for decreasing water availability during the dry season for the analysis period. However, care should be taken as climatic patterns over short time might show negligible effect while small changes may mean a lot over time. Therefore a small change observed should not be discarded as ineffective in bringing larger changes on cumulative basis.

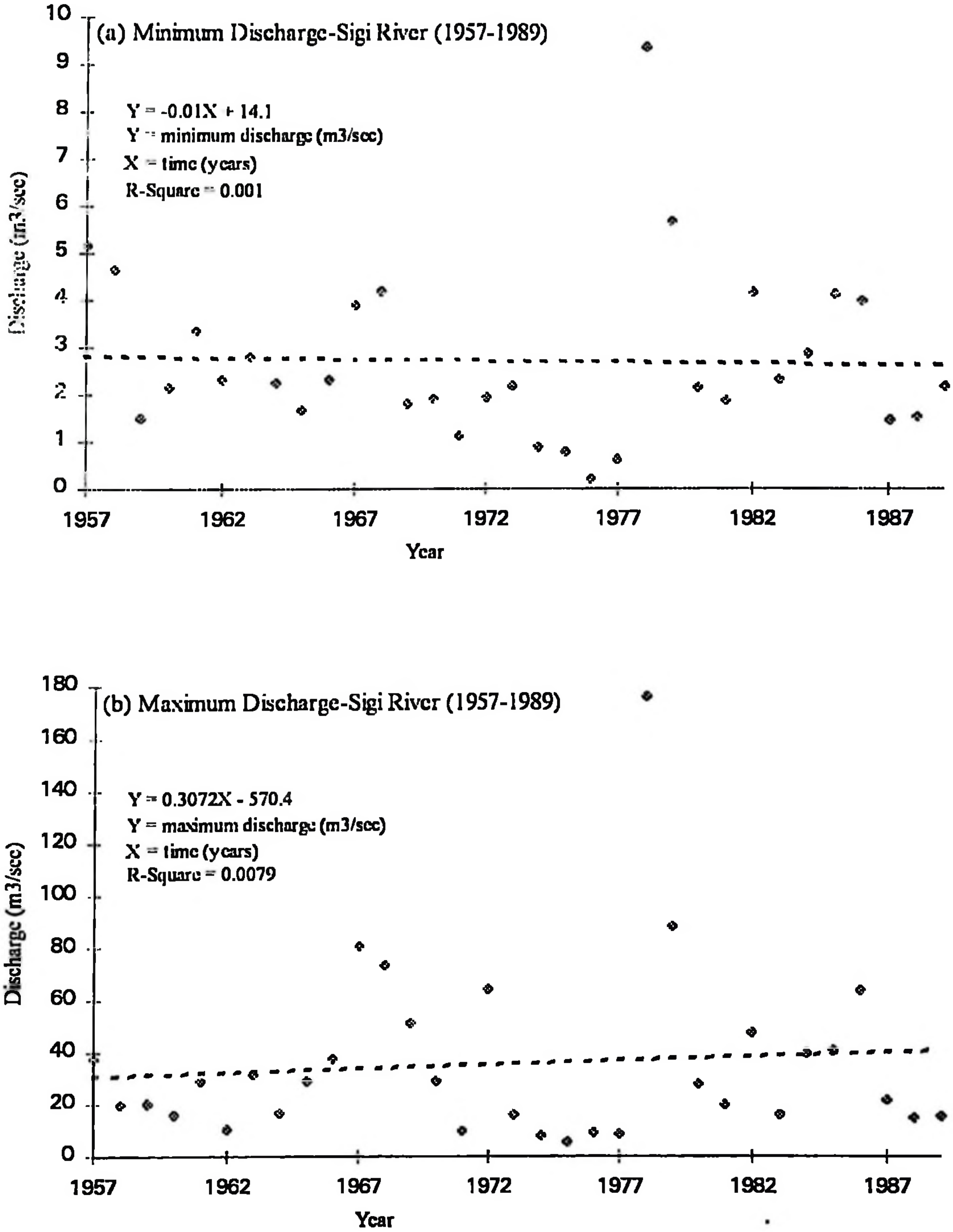


Fig 7. The highest (maximum) and lowest (minimum) discharge of the Sigi River at Lanzoni gauging station-east Usambaras. (a) minimum (b) maximum discharge. No evidence of trend in both maximum and minimum discharge ($P > 0.05$). However a slight decrease in minimum discharge and increase in maximum discharge is noted.

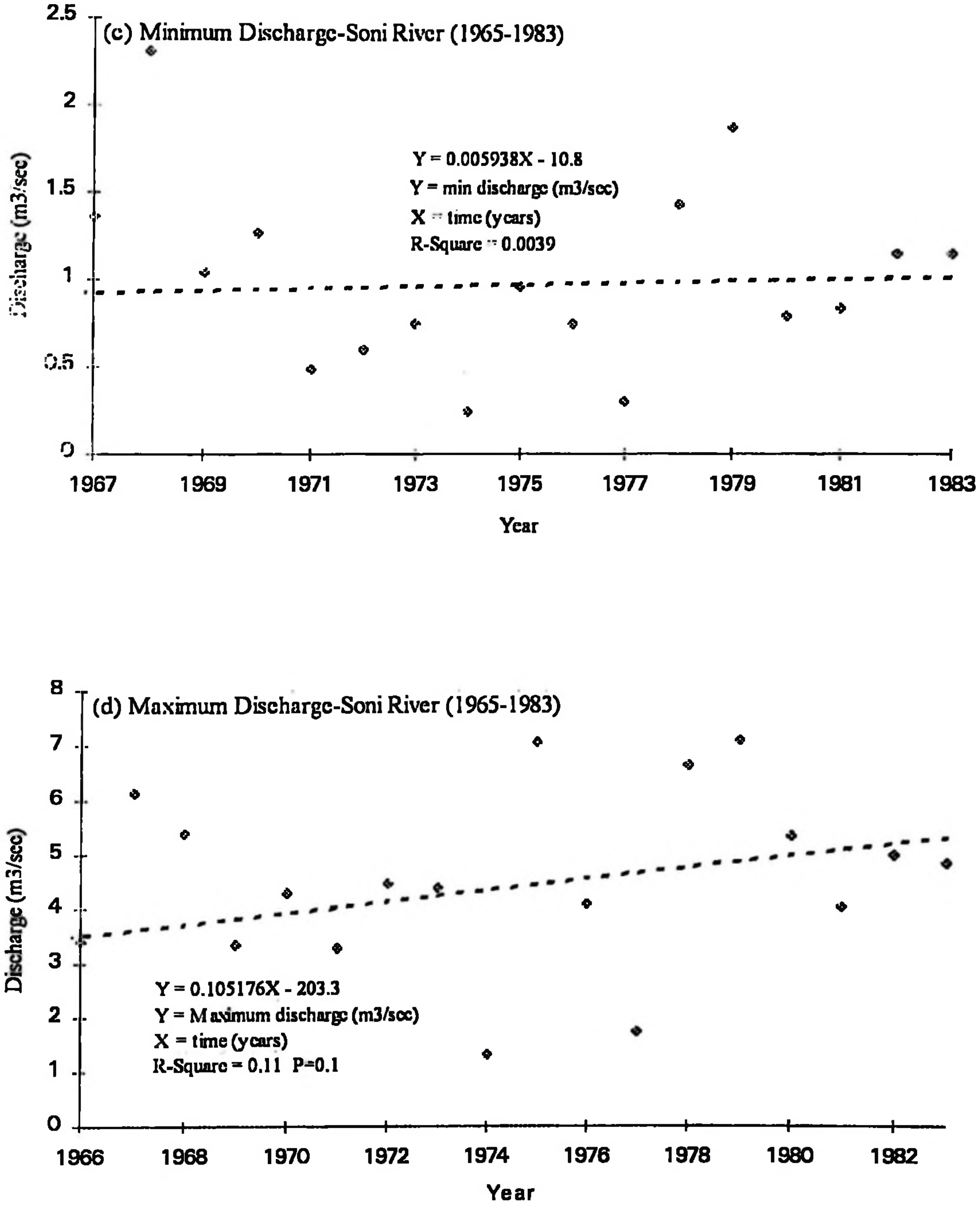


Fig 8. The highest (maximum) and lowest (minimum) discharge of Soni River at Mombo gauging station, west Usambaras NE Tanzania. (c) minimum (b) maximum discharge. Though slight increase, the minimum discharge did not significantly change whereas relatively maximum discharge increased (p = 0.1) in the period 1965-1983.

3.4 Residual Analysis of Discharge

In an attempt to evaluate temporal changes in discharge over time on the two watersheds, a regression based time series analysis of discharge against precipitation was conducted. In this analysis, a linear regression of runoff against precipitation was computed to generate residuals and therefore remove effects on runoff due to variations in precipitation. A residual plot and linear regression prediction against time was then computed to indicate how discharge has changed over time per unit of precipitation. This analysis show that in the east Usambaras discharge has decreased by about 0.08 m^3 s^{-1} $yr.^{-1}$ over time during the period 1965-1989 ($P = 0.30$, R-Square = 0.036) (Fig 9a). On the other hand the west Usambaras show that discharge has increased by about 0.02 m^3 s^{-1} yr^{-1} over the period 1965-1983, i.e. 0.4m^3 s^{-1} yr^{-1} (1.2 cm ha^{-1} yr^{-1}) more water today than 1965 ($P = 0.06$, R-Square = 0.14) (Fig 9b).

This analysis reflects the general trend observed in earlier analysis of discharge and gives more evidence of the discharge pattern. The east Usambaras show that the proportion of precipitation reaching the Sigi river has been decreasing over time though the trend is non-significant. The opposite is the case for west Usambaras where the discharge has increased over time. These observations have a great bearing on the land use changes over both watersheds. The increase in the proportion of precipitation reaching the Soni river may result from increased surface run-off and decreased evapotranspiration suggesting a decrease in vegetation cover on the watersheds during the period of analysis.

The most important observation in this study seems to be the increase in discharge per unit of precipitation in the Soni basin of west Usambaras while precipitation seems to have decreased over the same period. The maximum discharge into the Soni River appears to have increased over time ($P=0.10$) (Fig 8b). There appears to occur different responses in runoff on the two watersheds despite being close to each other and in the same general region. The explanation to such differences may be two-fold; first, a possible difference in the extent and intensity of changes in land use patterns, other watershed characteristics

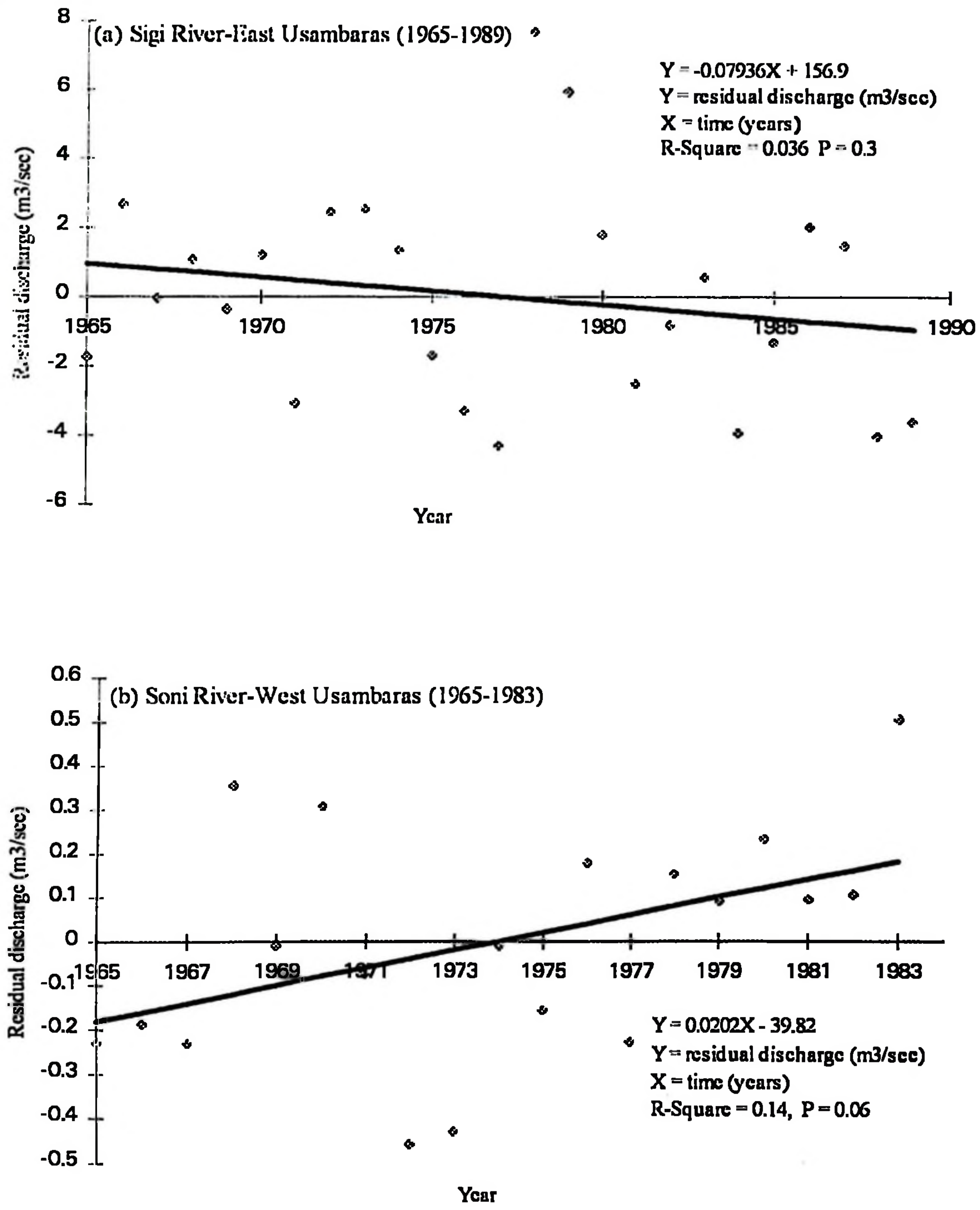


Fig 9. Discharge residual plot of observed and linear regression model prediction against time. (a) Sigi River east Usambaras (b) Soni River west Usambaras. A decrease in discharge into the Sigi river over time in the period 1965-1989 can be noted though there is no evidence of a significant trend (P > 0.05). A relatively low P-value (0.06) may suggest an increasing discharge trend in the Soni over time in the period 1965-1983.

such as soil type (structure, texture, permeability), and land configuration especially slope. Such differences are likely to cause differential impacts in runoff. Secondly, it may also be accounted for by differences in the hydrologic balances of the two basins (probably marginal) but also related to vegetation changes.

The history of the Usambaras show increasing deforestation trend since the 1960's by land transformation into agricultural lands. This evidence is also suggested by the present situation whereby most forests are confined to forest reserves (Hamilton, 1989; Kikula, 1989; Author, this report). There has been a major increase in small scale agriculture in the east Usambaras, often at the expense of forests (Hamilton and Mwasha, 1989). For example, there was a 50% reduction in forested area in a 30 km^2 area around Amani in the east Usambaras between 1954 and 1976 (Rodgers and Homewood, 1982). There has been a 40%-100% decrease in forest cover over different parts of the east Usambaras between 1958-1986 (Kikula, 1989). Farm expansion has affected both the lower and the higher altitude areas whereby in the lower altitudes the expansion has mostly been on the public forest lands and degazetted forest reserves, while in the higher altitudes it has mostly been in leased lands belonging to the tea estates. Degazettement of forest reserves has affected both watersheds but at differing intensity and rate. Although there has been degazettement of some forest reserves in the east Usambaras like the Bwiti, Magogo, and Msimbazi Forest Reserves, this has been relatively low and patchy compared with the west Usambaras. For example, in 1963, about 13,400 hectares (134 km^2) of Shume-Magamba Forest Reserve in the west Usambaras were degazetted and given to small holder farmers as a response to popular cry for land (Egger et al., 1989; TRDP, 1975; Rogers, 1993).

In most cases, productivity declines with time in cleared lands that are not well managed, and they are often abandoned in favor of fresh lands from the forest. Poor land management and increasing cultivation on steep slopes have since caused severe erosion of virgin forested lands and loss of land productivity in the west Usambaras in less than 20 years period (Rogers, 1993). Coupled with higher population density, abandonment of degraded lands in favor of fresh lands from the forest has intensified the rate of forest clearance in the west Usambaras (Scheinman and Mchome, 1986; Watson, 1972; Lundgren and Lundgren 1982). Though it may occur anywhere, depletion of soil resources is normally more serious on high altitudes such as in the west Usambaras (Hamilton, 1989), suggesting that the rate of land clearing has been higher in the west than in the east Usambaras which are at lower altitudes. Large parts of Shume-Magamba are now barren land and recent establishment of a soil conservation project - SECAP is an indication of the severity of land degradation in this part (Hamilton and Mwasha, 1989; Author, this report). These differences in the extent of land clearing in the west Usambaras may at least partially explain the differences in runoff between Sigi and Soni River basins. Forest clearing in the east Usambaras was accompanied by establishment of sisal and tea estates which are perennial crops while in the west Usambaras, most of the farms are planted with annual crops. Perennial crops in most cases ensure longer periods of ground cover compared to annual crops. When tea and sisal plantations are abandoned the crops remain to grow into bushes ensuring continued ground cover and reduced runoff. This may mean that the land remained under vegetation cover over relatively longer periods in the east Usambaras with perennial crops compared to the west Usambaras with mainly annual crops which are harvested yearly leaving the land bare over long periods during the year. The Soni river basin on the west Usambaras has mainly steep slopes on rocky terrain over most of the watershed, while the Sigi river passes over gently sloped land especially in the lowlands in the lower parts of the basin. These differences are likely to cause different rates of discharge into the rivers as surface runoff.

The difference in the water budgets of the two areas may also explain some differences in run-off. The west Usambaras are on higher altitudes and evapotranspiration can be expected to be less compared to the east Usambaras on low altitudes. If other factors remain constant, low evapotranspiration means relatively high run-off in the west Usambaras.

3.5 The Relationship Between Precipitation and Runoff

In this analysis, changes on the hydrologic regime of the rivers (watersheds) are examined by the double mass curve analysis to see whether there has occurred any significant changes in their relationships. For two parameters which are correlated and vary over time a suitable method of checking the constancy of their relationship is the double mass curve analysis (Bruen, 1989; Perrala, 1992).

This analysis assumes that if a relatively constant proportion of the rain falling on the basins eventually reaches the rivers (discharge gauging stations), then the double mass curve of discharge volume against precipitation should essentially be a straight line. Seasonal variations may be expected in the runoff and will appear as fluctuations of the curve about the general straight line trend. This analysis was performed both at the watershed scale and on individual stations on each watershed.

The analysis show that for both watersheds and individual stations on each watershed there is a change in behavior at two periods; about 1966/67 and 1976/77 through 1977/78 with some exceptions which might be expected under most physical phenomena (Fig 10a, b). The change in behavior of the watershed double mass curves suggest an increase in the amount (proportion) of precipitation on the watersheds reaching the gauging stations. On individual stations, the change in behavior of the double mass curve differs from station to station, showing that each station has a different impact, and is contributing differently in runoff into the rivers. This may mean different vegetation conditions in each area which expected under natural conditions. Most stations however show an increasing proportion of precipitation reaches the gauging station. (Appendix 4, 5). It is hereby noted that residual analysis indicate a decreasing discharge into the Sigi river over the study period. On the other hand double mass curve analysis indicate that there is a higher proportion of discharge reaching the river. This is possibly a cumulative effect since in the double mass curve analysis cumulative data are used while in the residual analysis individual year data sets are used. The effects of the two may be different and can lead to different conclusions. However because the double mass curve involves some sort of approximations which are relatively subjective a better conclusion can be drawn from residual analysis.

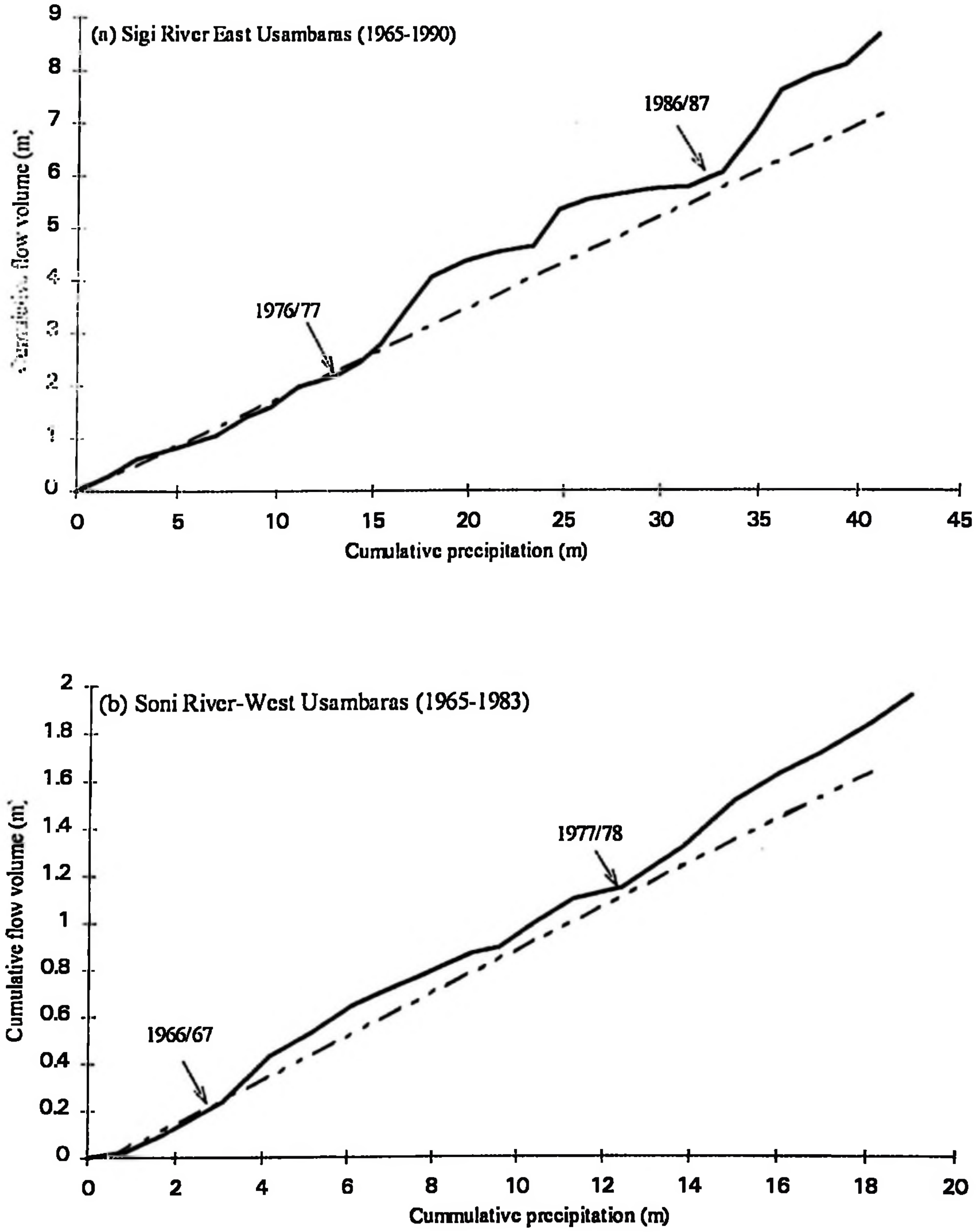


Fig 10. Double mass curve analysis relating flow volume of the two rivers with mean precipitation on the respective watersheds. (a) Sigi River (b) Soni River. A general deviation from the approximate straight line is observed in the years 1966/67 and 1976/77. An additional period on the Sigi River with longer period is observed in the year 1986/87. Both show an increasing proportion of precipitation reaching the gauging stations.

CHAPTER FOUR

4.0 CONCLUSION AND RECOMMENDATIONS

Precipitation and stream flow data from the east and west Usambaras north-eastern Tanzania show different trends in the past two decades. A slight increasing pattern is observed in the east Usambaras, while a decreasing pattern is observed in the west Usambaras. No evidence for trends in precipitation in the two basins as there was non significant trend. However a pattern of fluctuations with wetter and dryer periods was suggested. The increasing pattern of precipitation in the east Usambaras may be related to increase in temperature over the same period making the air able to hold more precipitable water.

Discharge in the Soni River (west Usambaras) increased over time while that in the Sigi River (east Usambaras) decreased though no significant trend was detected (P=0.06 and 0.3 respectively). This is related to higher rate of vegetation clearing (deforestation) in the west Usambaras compared to the east Usambaras, differences in watershed characteristics such as soil type, land configuration (slope) and type of farming especially the type crops grown. At the same time differences in the water balances of the two basins with higher evapotranspiration in the east Usambaras is suggested to contribute to low run-off in the Sigi river than in the Soni river.

The relationship between precipitation and discharge into the two rivers has been fairly inconsistent and periods of deviation in the relationship show to coincide with periods of recorded high rates of forest clearance and changing land use patterns. This study can conclude that local deforestation has greatly influenced at least run off patterns on the Usambaras and especially the west Usambaras. However, improvements in the climatic and hydrologic monitoring in the Usambaras will probably give more reliable information and better conclusion from such studies over the area.

From this study and other available knowledge and observations, a justification for caution concerning further forest clearing in the Usamabras can be made. Resource use in forested and fragile ecosystems like the Usambaras should aim at conserving the forest resources not only on local but for larger scales. Important catchment areas on the Usambaras should therefore be protected and appropriate aforestation work on degraded lands including agroforestry in farmlands should form the framework of conservation measures. Maintenance of vegetation filter strips along river/stream banks is of particular importance in reclaiming degraded lands.

Climatic and hydrologic monitoring stations in the Usambaras require strengthening in order to ensure proper future assessment and monitoring systems. An analysis of the extent of past land use changes on the Usambaras is of particular importance in order to enable stronger conclusions concerning land use patterns and hydrology over the area. From this perspective future studies in the area are suggested to include the analysis of land use changes on the two watersheds by use of aerial photographs to determine whether there has been any differences, analysis of the watershed characteristics including soil characteristics (structure, texture, and permeability). Such studies may enable the quantification of the differences observed in runoff patterns in the two basins.

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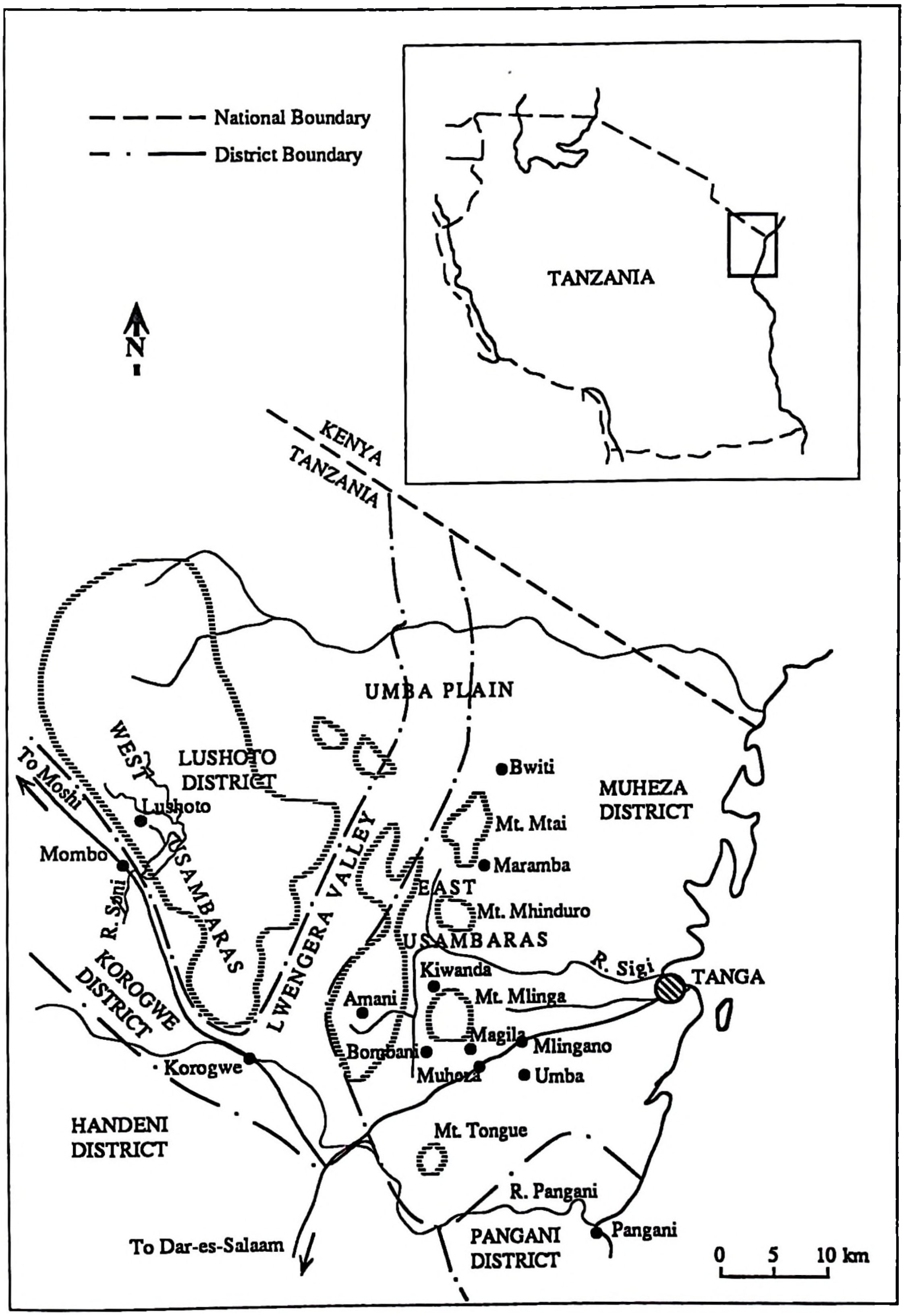
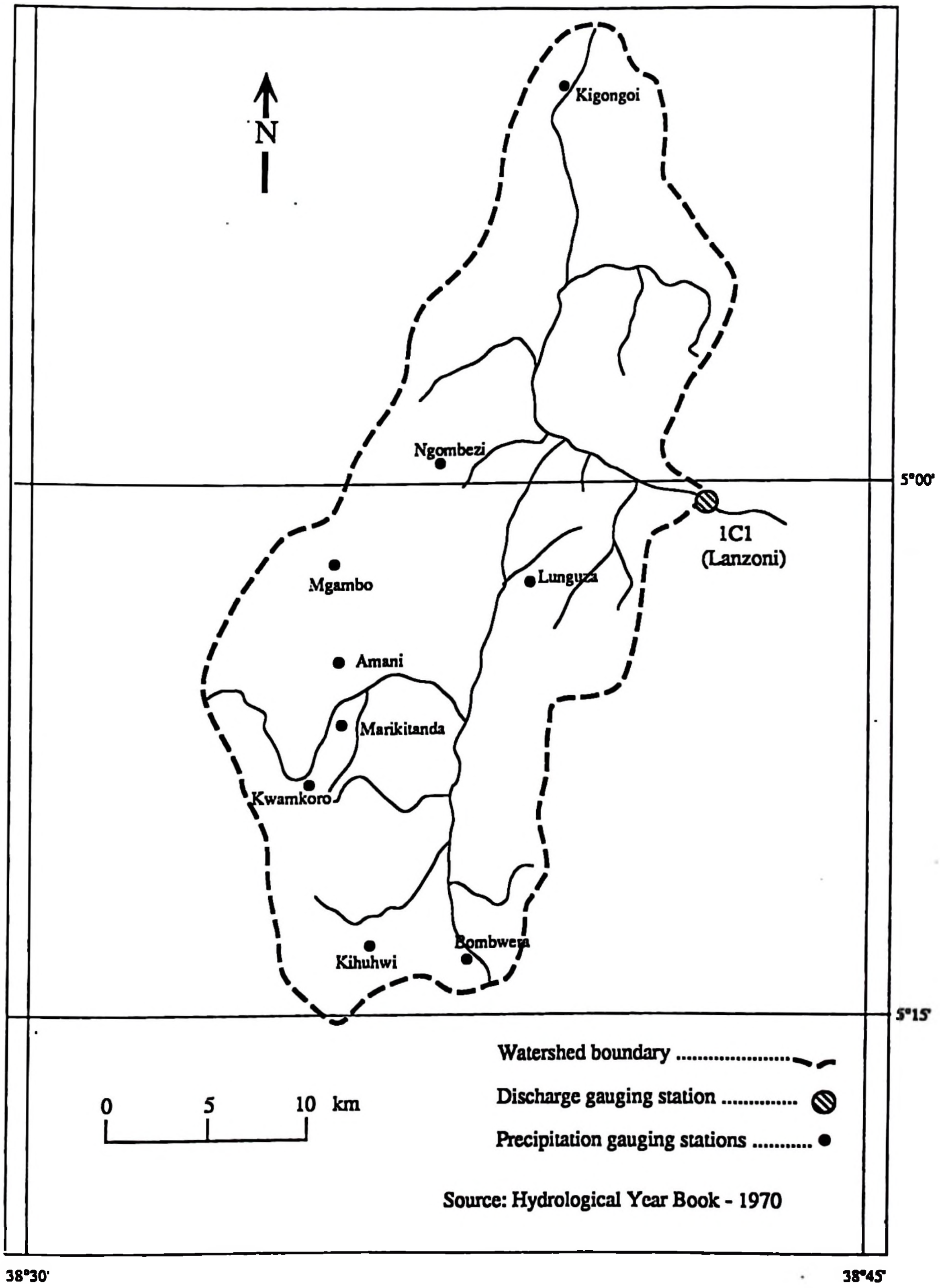
Appendix 1a. The Usambaras in Tanzania

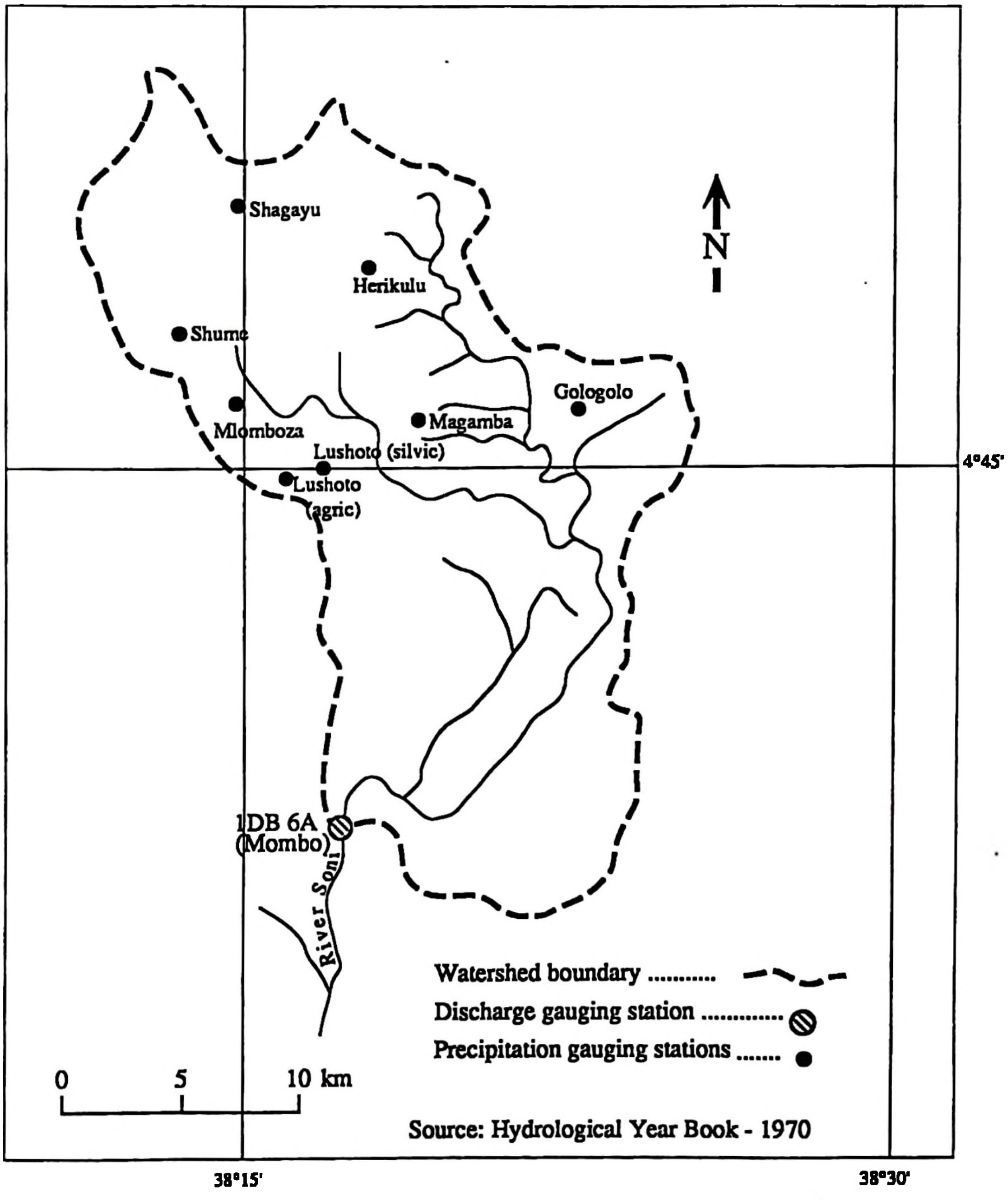


Appendix 1b. Sigi River Watershed-East Usambaras NE Tanzania (Area:717 km^2)



Source: Hydrological Year Book - 1970

Appendix 1c. Soni River Watershed-West Usambaras NE Tanzania (Area: 528 km^2)



Watershed boundary .... ‐ ‐ ‐

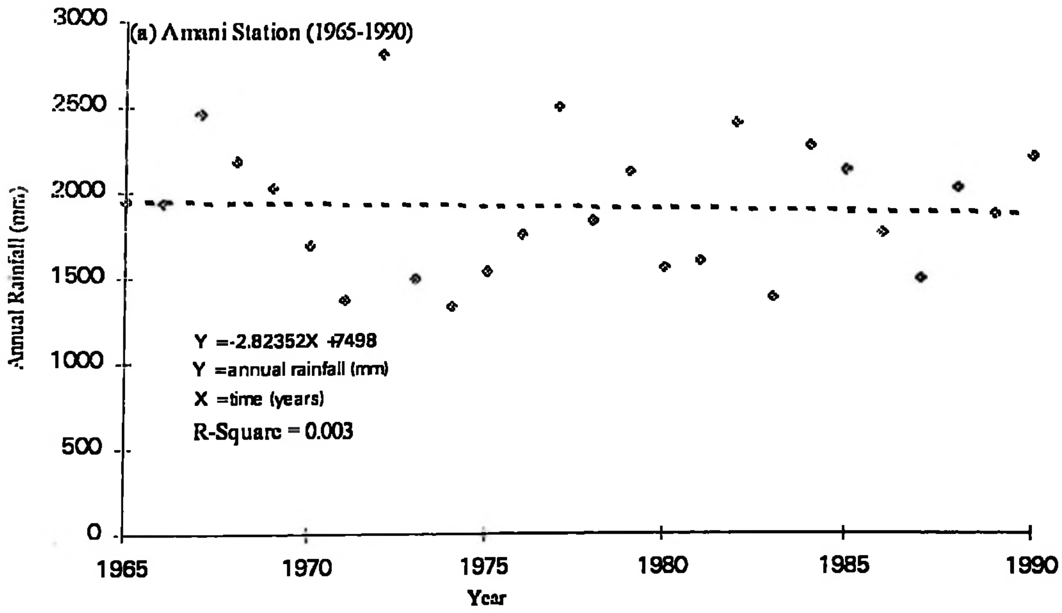
Discharge gauging station .... ⊘

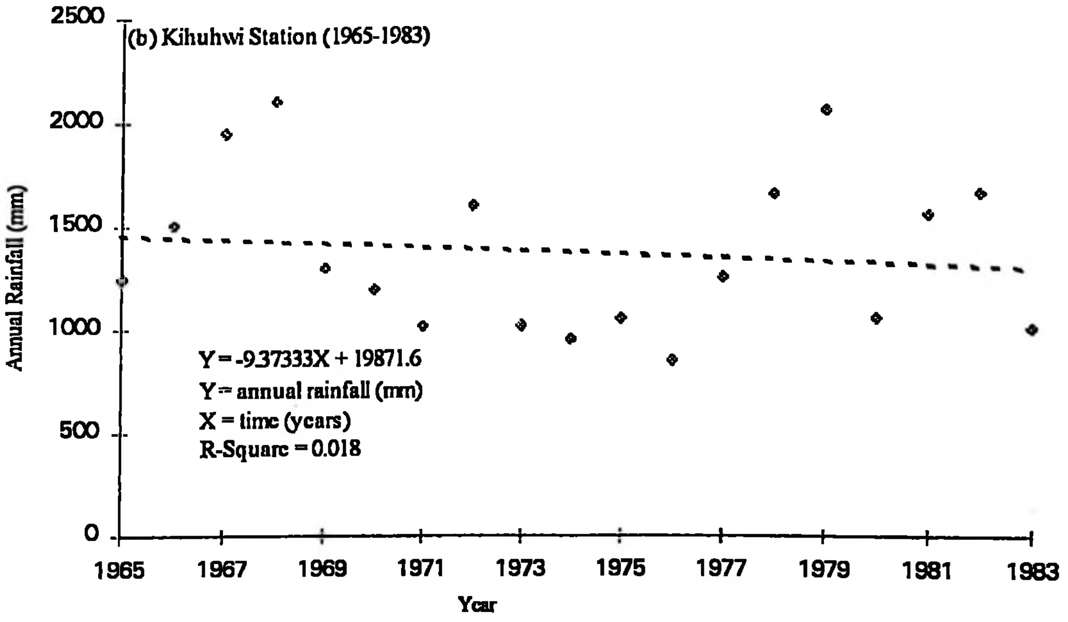
Precipitation gauging stations .... ●

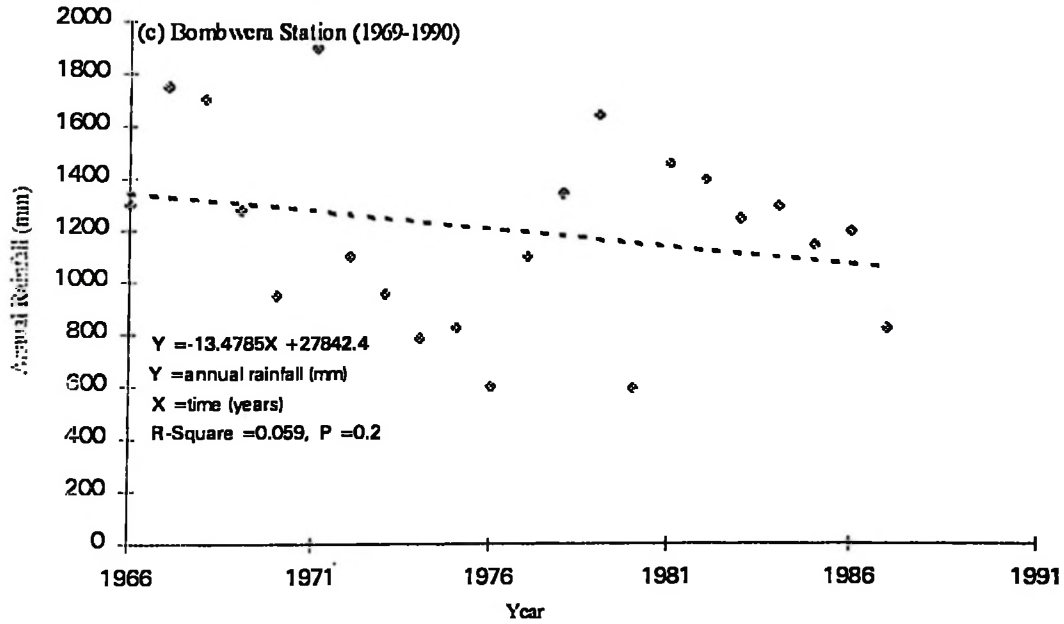
Source: Hydrological Year Book - 1970

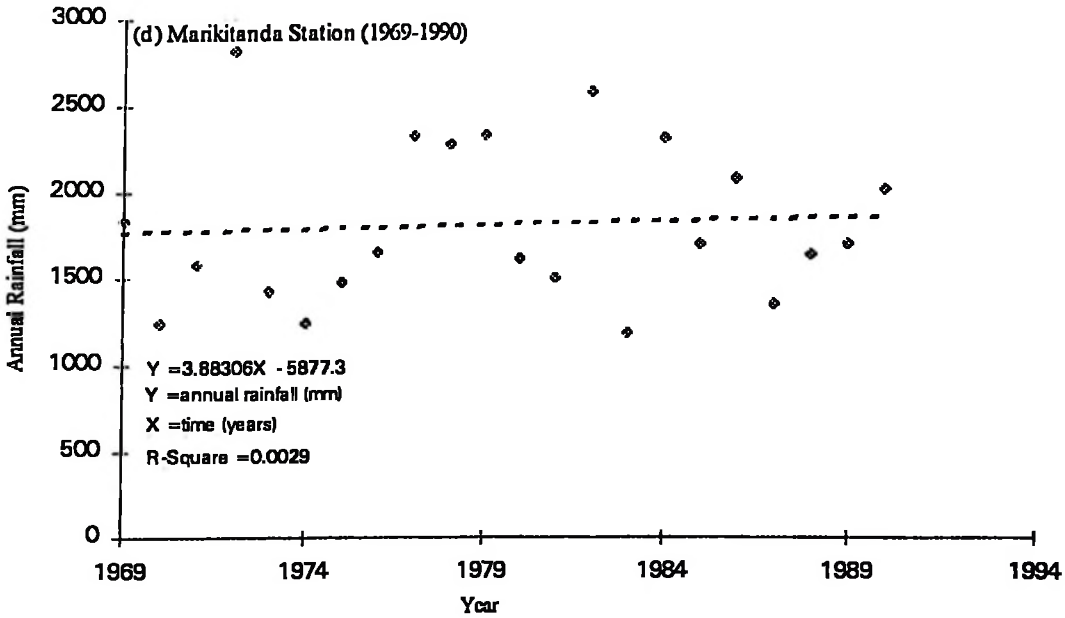
APPENDIX

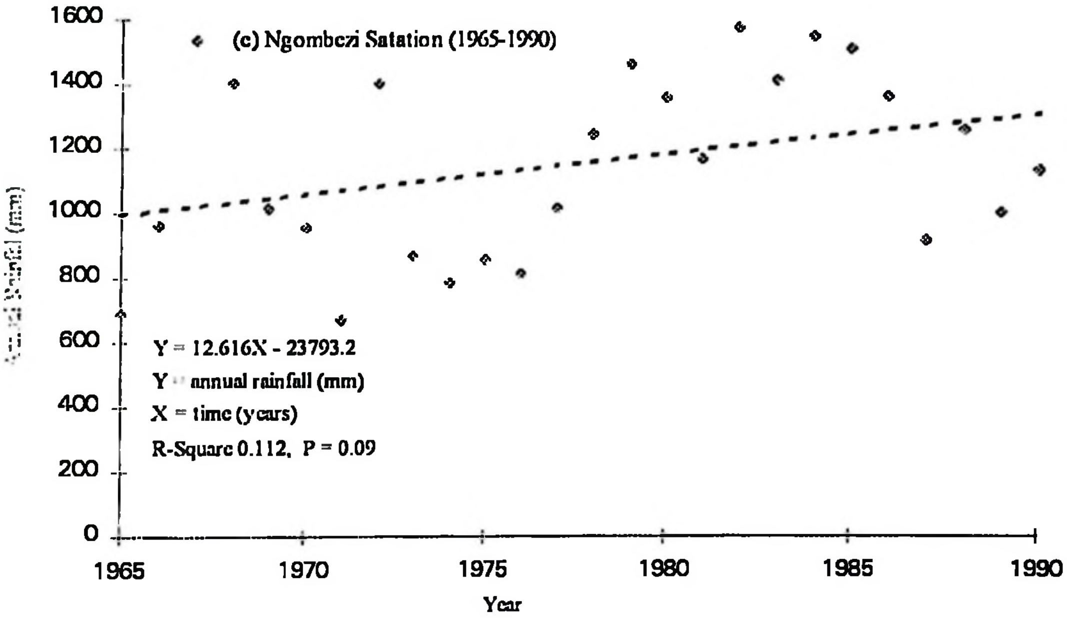
Appendix 2. Station precipitation plot of observed and linear regression model prediction against time - Sigi River Basin East Usambaras NE Tanzania

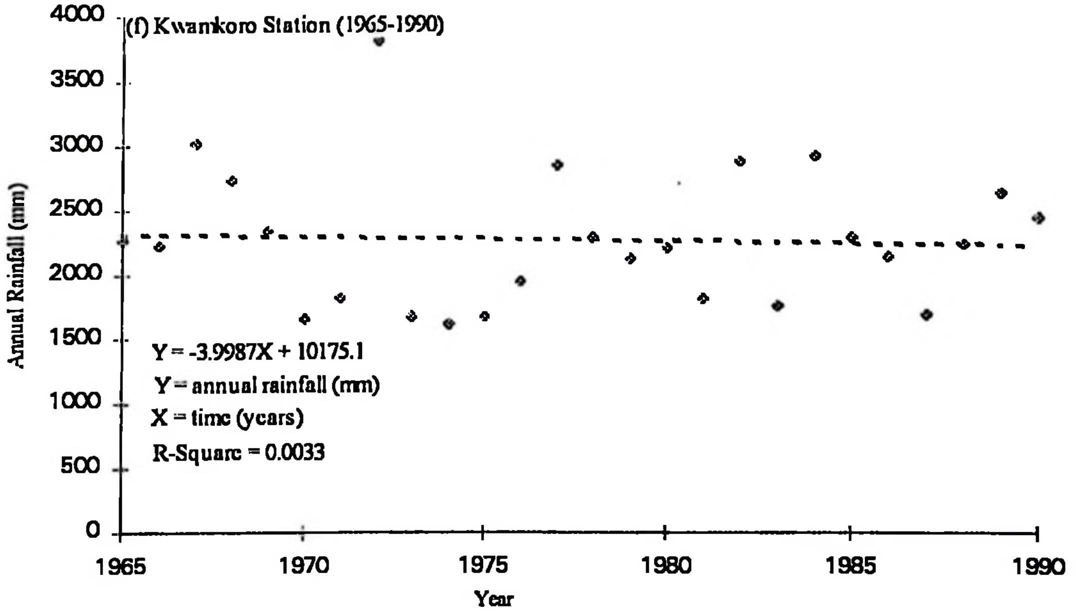


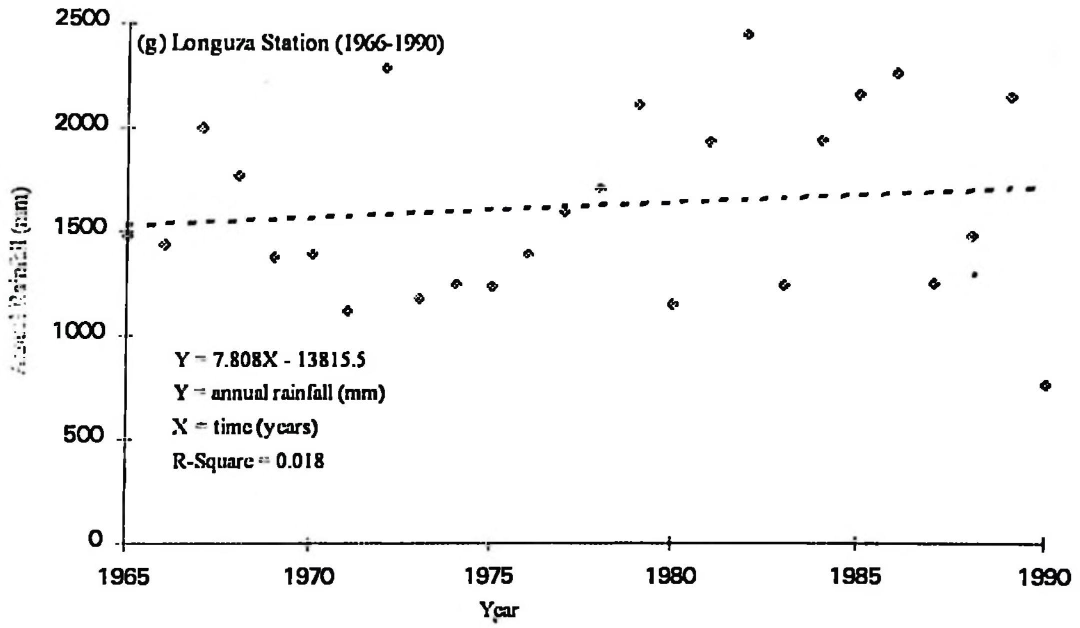


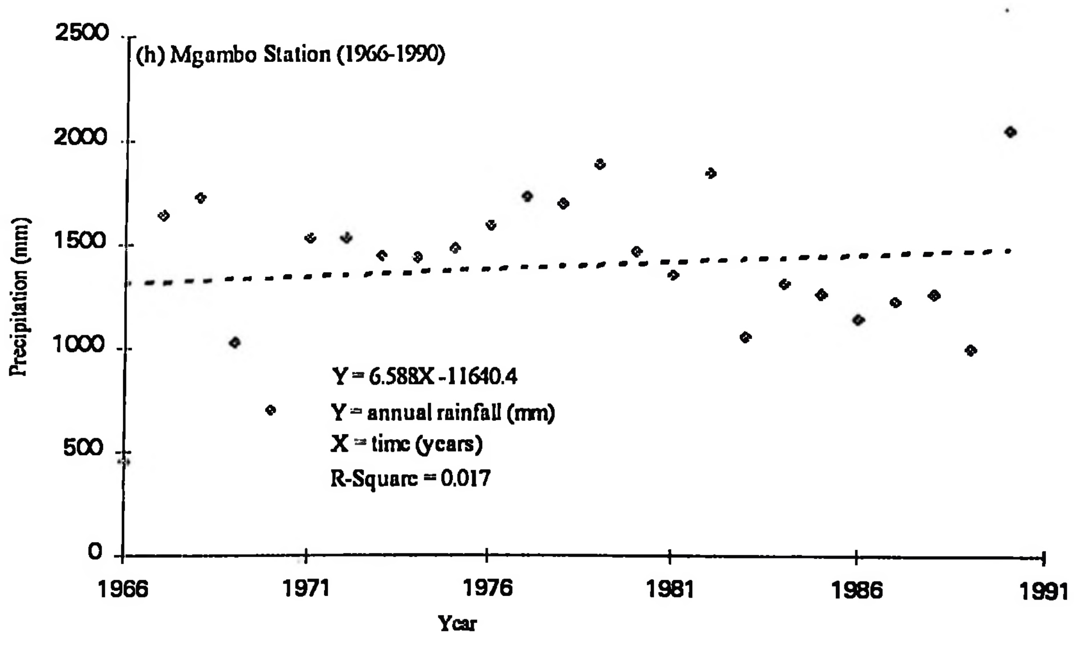

(c) Bombwera Station (1969-1990)
Y =-13.4785X +27842.4
Y =annual rainfall (mm)
X =time (years)
R-Square =0.059, P =0.2
Annual Rainfall (mm)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
1966
1971
1976
1981
1986
1991
Year

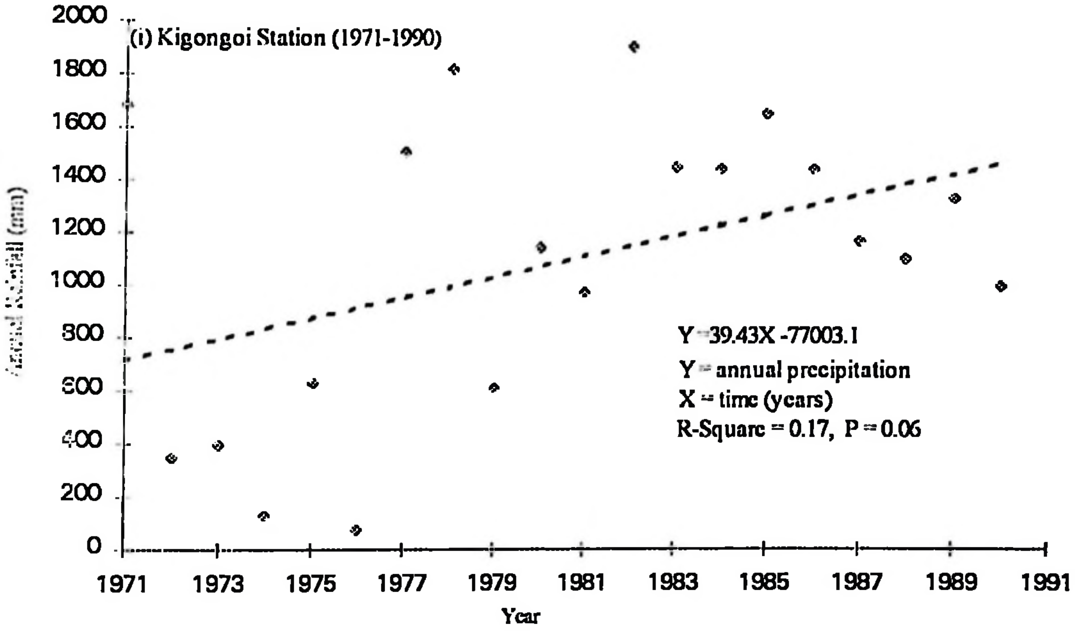

(d) Marikitanda Station (1969-1990)
Y =3.88306X - 5877.3
Y =annual rainfall (mm)
X =time (years)
R-Square =0.0029
Annual Rainfall (mm)
3000
2500
2000
1500
1000
500
0
1969
1974
1979
1984
1989
1994
Year


(c) Ngombezi Satation (1965-1990)
1600
1400
1200
1000
800
600
400
200
0
Annual Rainfall (mm)
Y = 12.616X - 23793.2
Y = annual rainfall (mm)
X = time (years)
R-Square 0.112, P = 0.09
1965
1970
1975
1980
1985
1990
Year

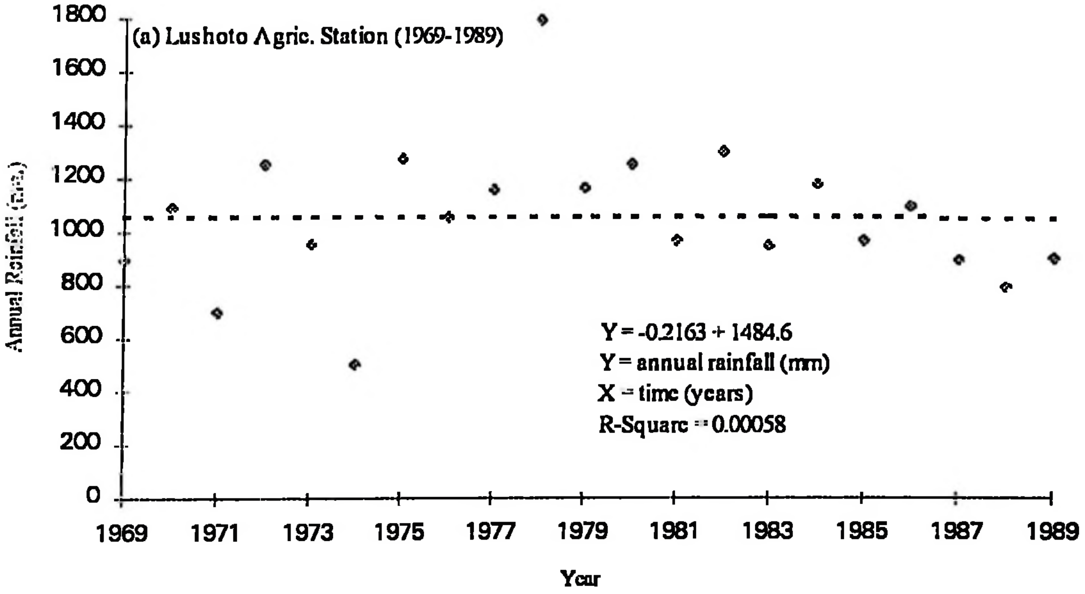

(f) Kwamkoro Station (1965-1990)
4000
3500
3000
2500
2000
1500
1000
500
0
Annual Rainfall (mm)
Y = -3.9987X + 10175.1
Y = annual rainfall (mm)
X = time (years)
R-Square = 0.0033
1965
1970
1975
1980
1985
1990
Year

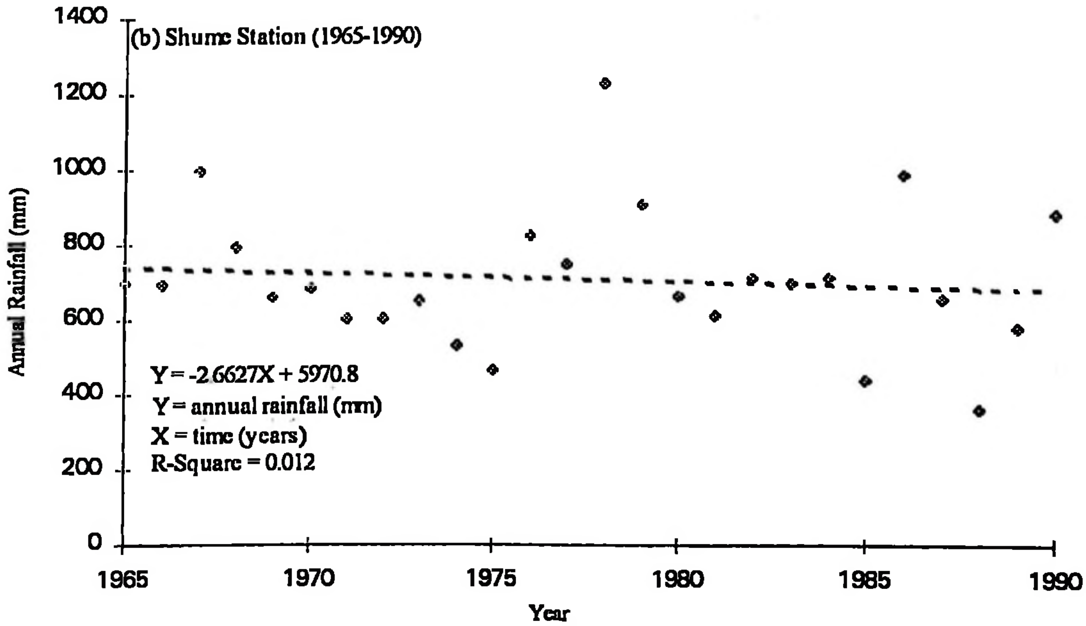

(g) Longuza Station (1966-1990)
2500
2000
1500
1000
500
0
Annual Rainfall (mm)
Y = 7.808X - 13815.5
Y = annual rainfall (mm)
X = time (years)
R-Square = 0.018
1965
1970
1975
1980
1985
1990
Year

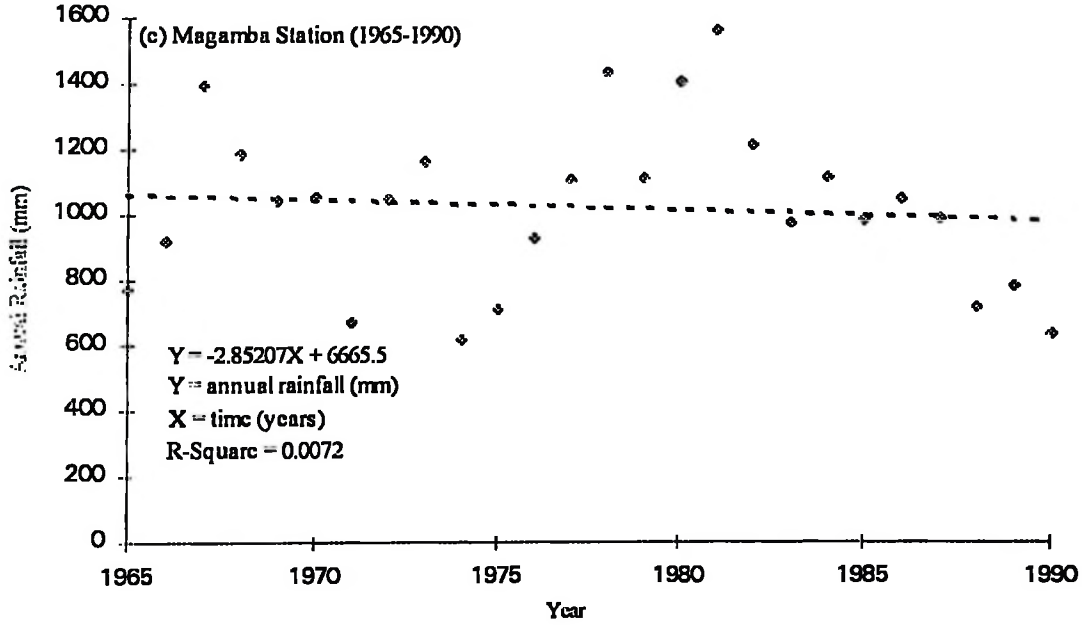

(h) Mgambo Station (1966-1990)
2500
2000
1500
1000
500
0
Precipitation (mm)
Y = 6.588X - 11640.4
Y = annual rainfall (mm)
X = time (years)
R-Square = 0.017
1966
1971
1976
1981
1986
1991
Year

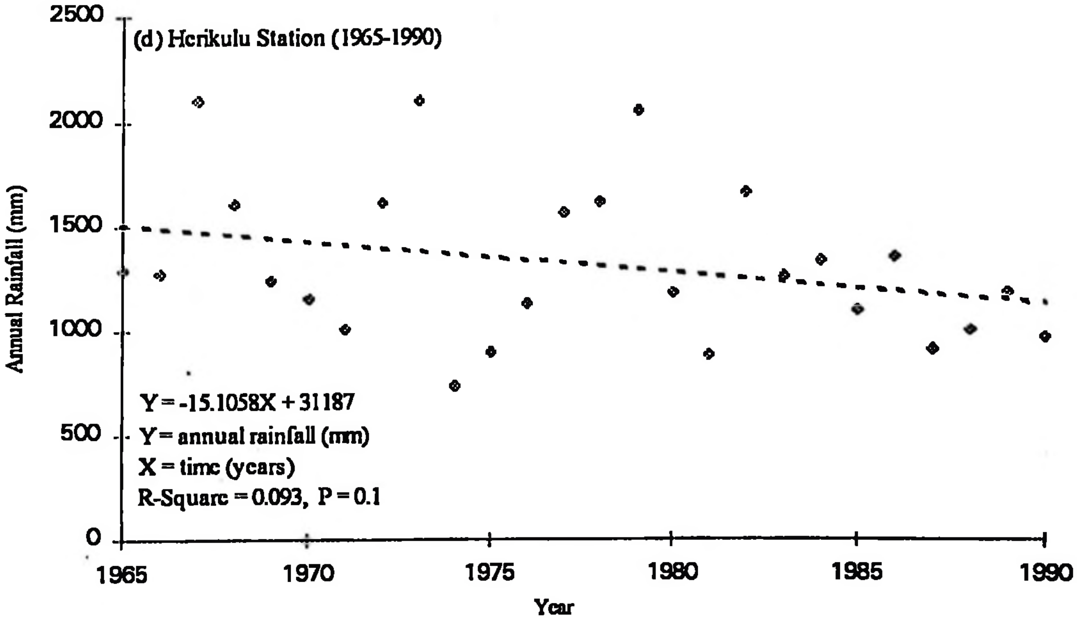

(i) Kigongoi Station (1971-1990)
Annual Rainfall (mm)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
Year
Y=39.43X -77003.1
Y= annual precipitation
X = time (years)
R-Square = 0.17, P = 0.06

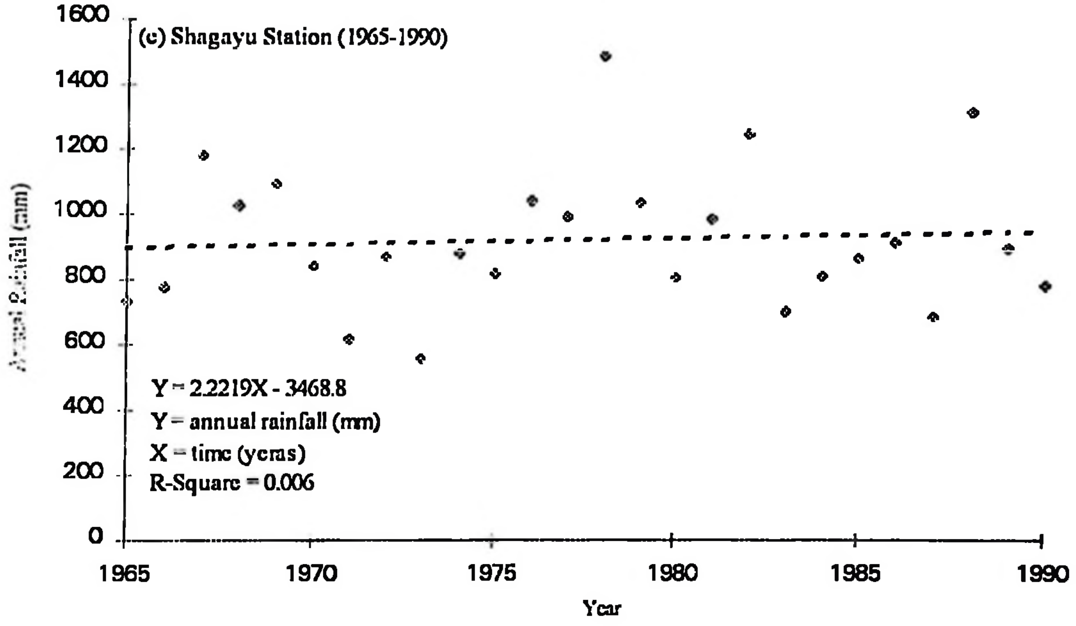
Appendix 3. Station precipitation plot of observed and linear regression model prediction against time-Soni River Basin West Usambaras NE Tanzania

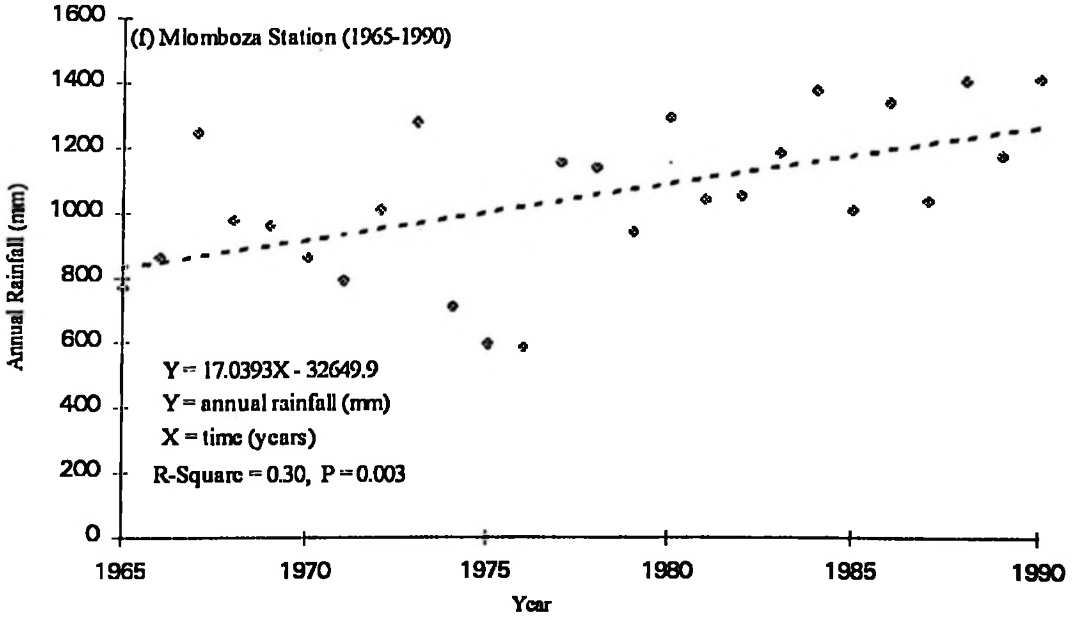


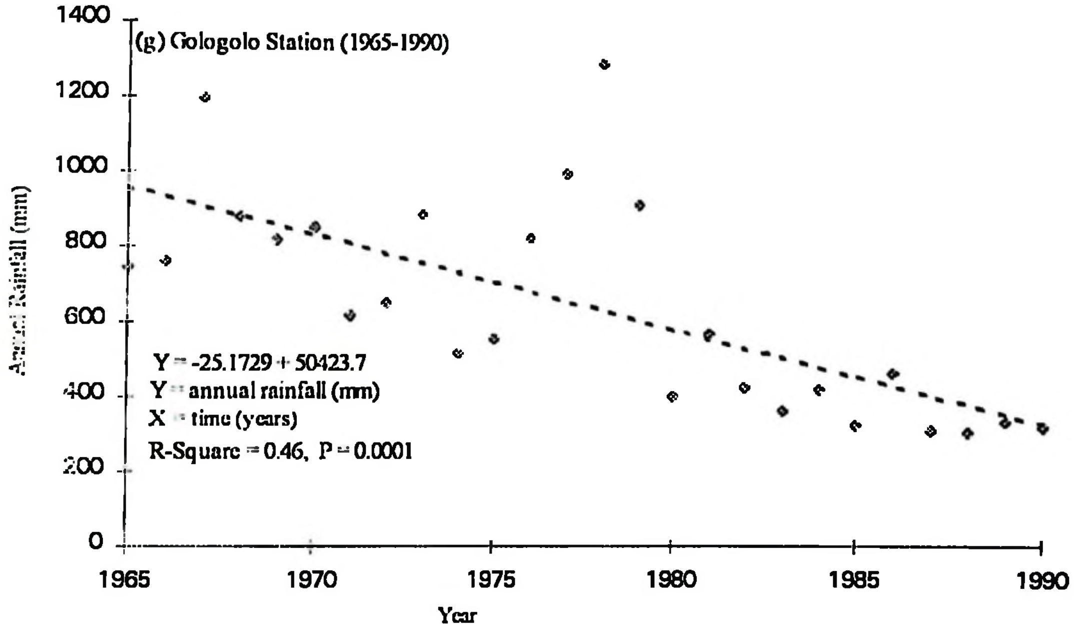


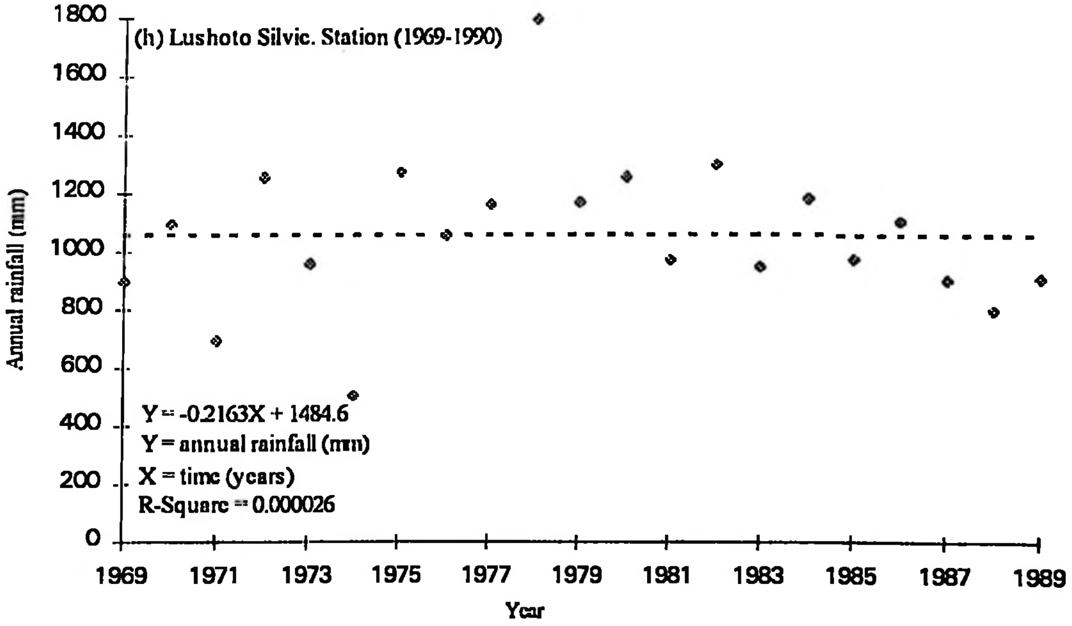

(c) Magamba Station (1965-1990)
Annual Rainfall (mm)
1600
1400
1200
1000
800
600
400
200
0
1965
1970
1975
1980
1985
1990
Year
Y = -2.85207X + 6665.5
Y = annual rainfall (mm)
X = time (years)
R-Square = 0.0072


(d) Herikulu Station (1965-1990)
Annual Rainfall (mm)
2500
2000
1500
1000
500
0
1965
1970
1975
1980
1985
1990
Year
Y = -15.1058X + 31187
Y = annual rainfall (mm)
X = time (years)
R-Square = 0.093, P = 0.1

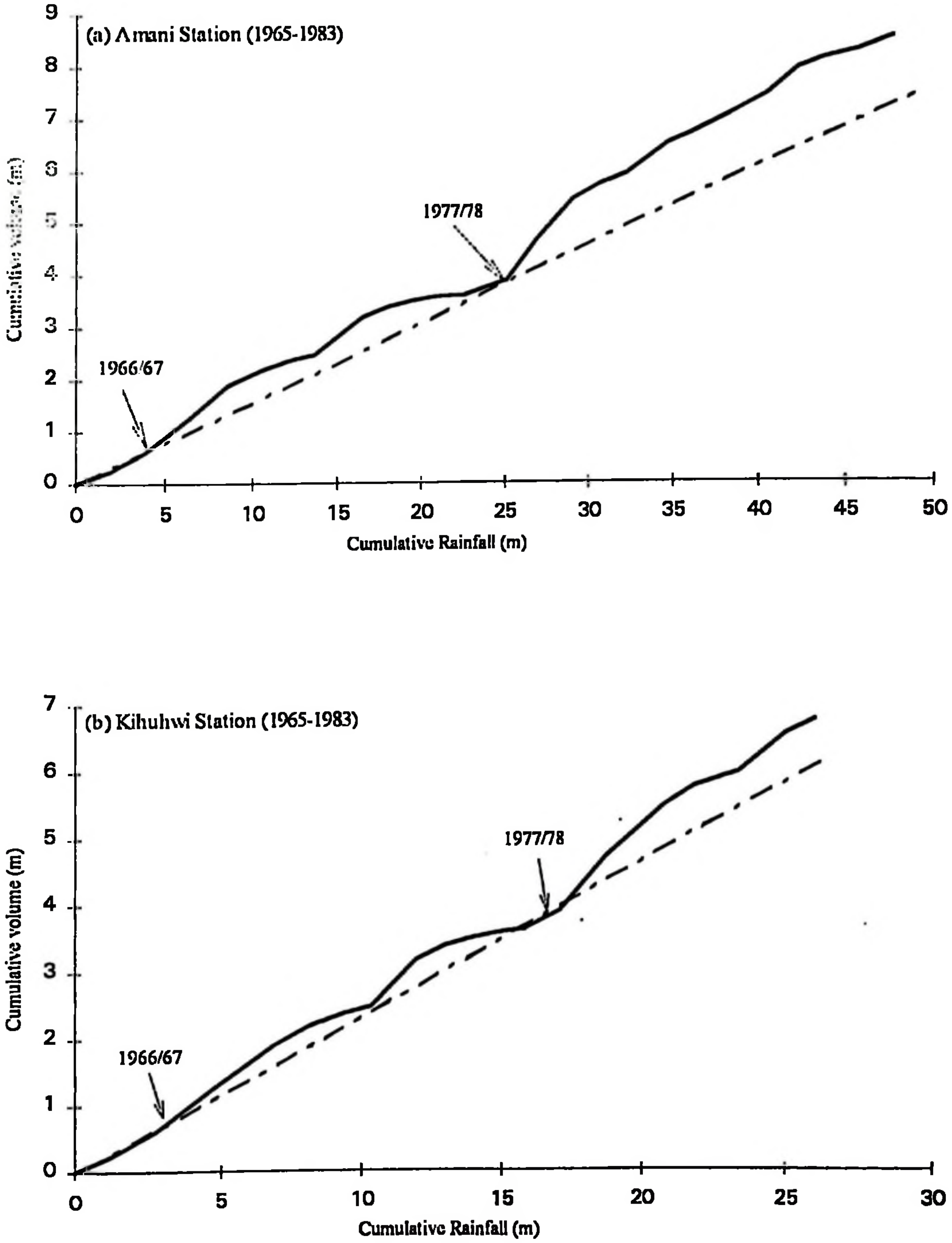

(e) Shagayu Station (1965-1990)
Y = 2.2219X - 3468.8
Y = annual rainfall (mm)
X = time (yeras)
R-Square = 0.006
Annual Rainfall (mm)
0
200
400
600
800
1000
1200
1400
1600
1965
1970
1975
1980
1985
1990
Year

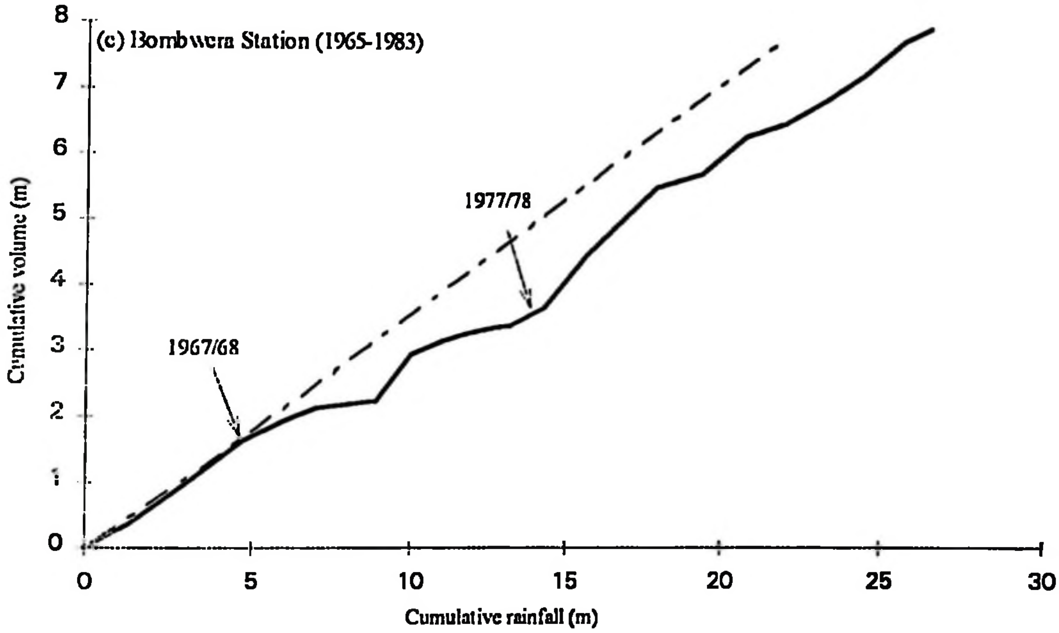

(f) Mlomboza Station (1965-1990)
Y = 17.0393X - 32649.9
Y = annual rainfall (mm)
X = time (years)
R-Square = 0.30, P = 0.003
Annual Rainfall (mm)
0
200
400
600
800
1000
1200
1400
1600
1965
1970
1975
1980
1985
1990
Year

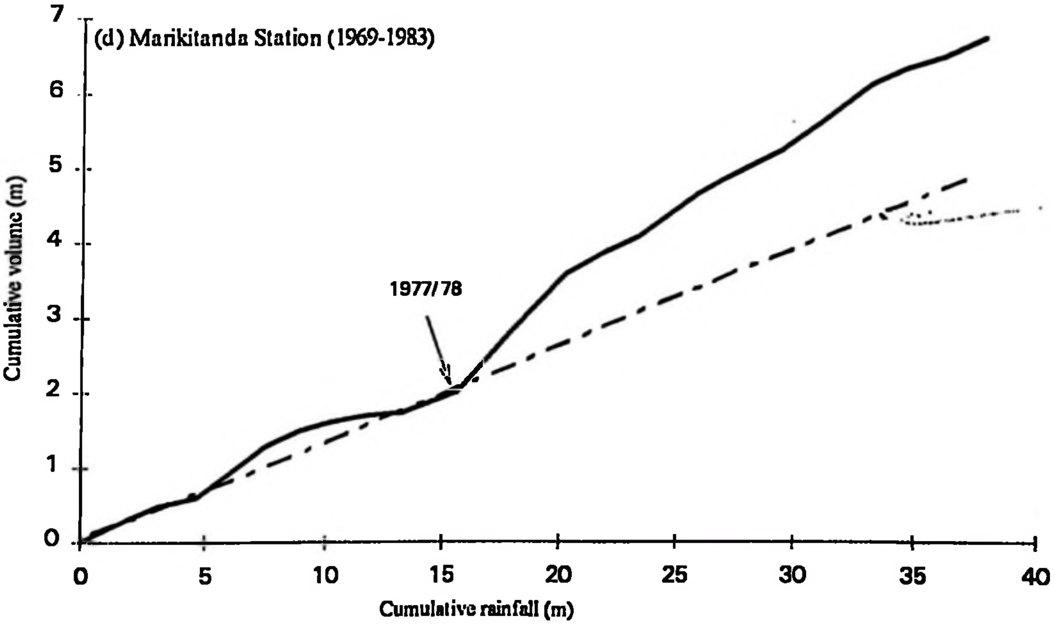

(g) Gologolo Station (1965-1990)
Y = -25.1729 + 50423.7
Y = annual rainfall (mm)
X = time (years)
R-Square = 0.46, P = 0.0001
Annual Rainfall (mm)
1400
1200
1000
800
600
400
200
0
1965
1970
1975
1980
1985
1990
Year

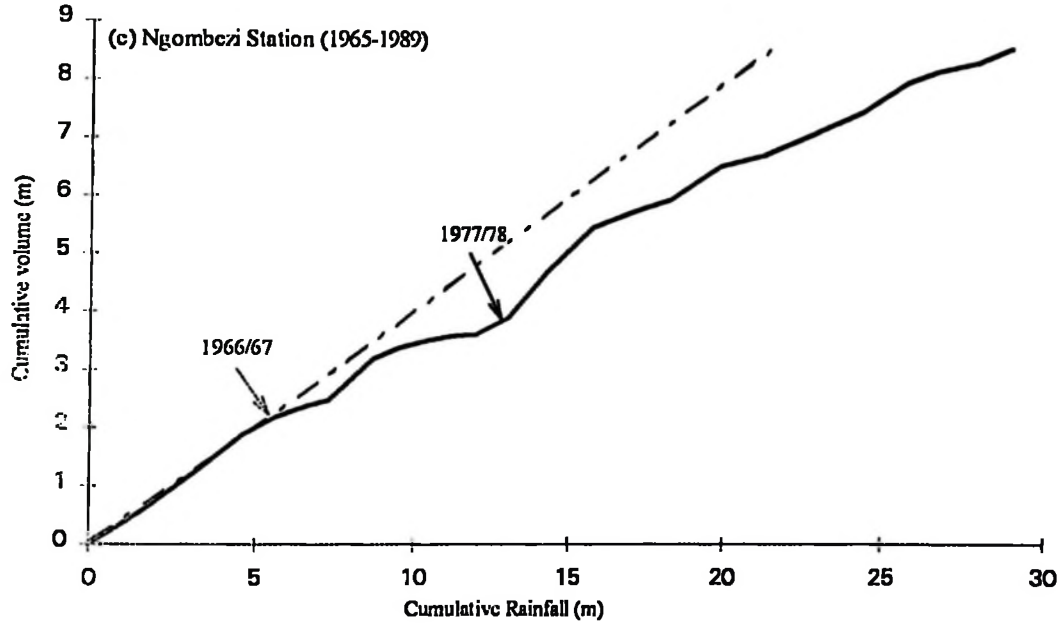

(h) Lushoto Silvic. Station (1969-1990)
Y = -0.2163X + 1484.6
Y = annual rainfall (mm)
X = time (years)
R-Square = 0.000026
Annual rainfall (mm)
1800
1600
1400
1200
1000
800
600
400
200
0
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
Year

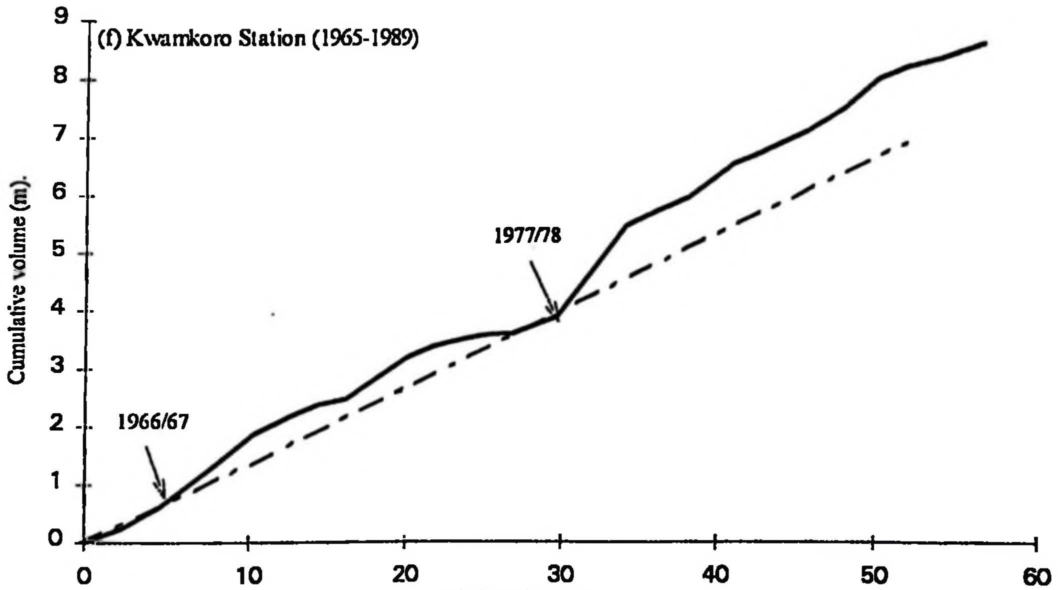
Appendix 4. Double mass curve analysis ralating flow volume with station precipitation on the Sigi River basin east Usambaras NE Tanazania

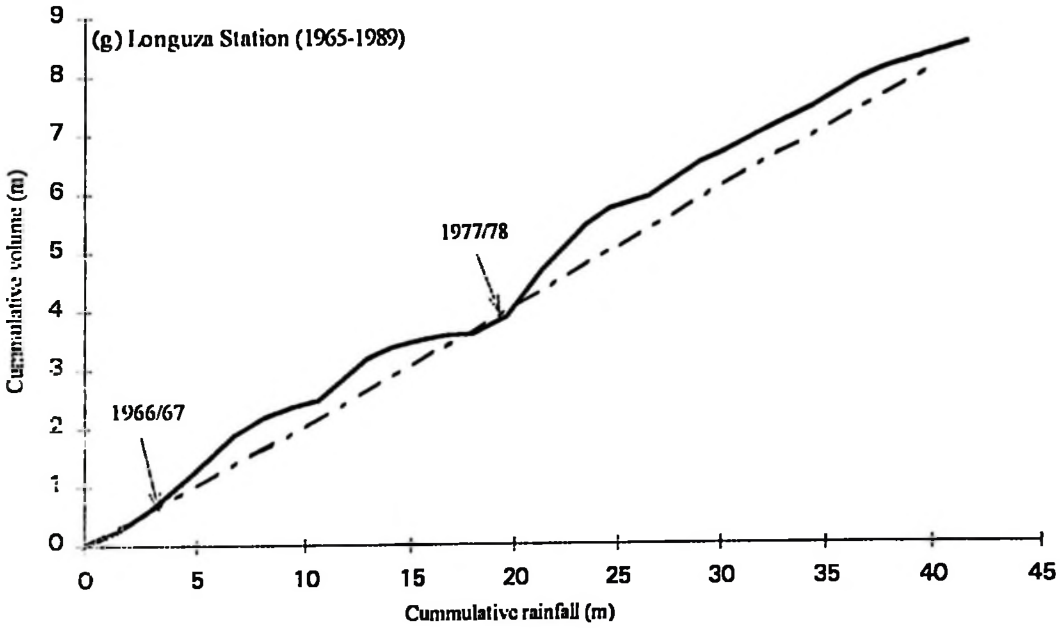


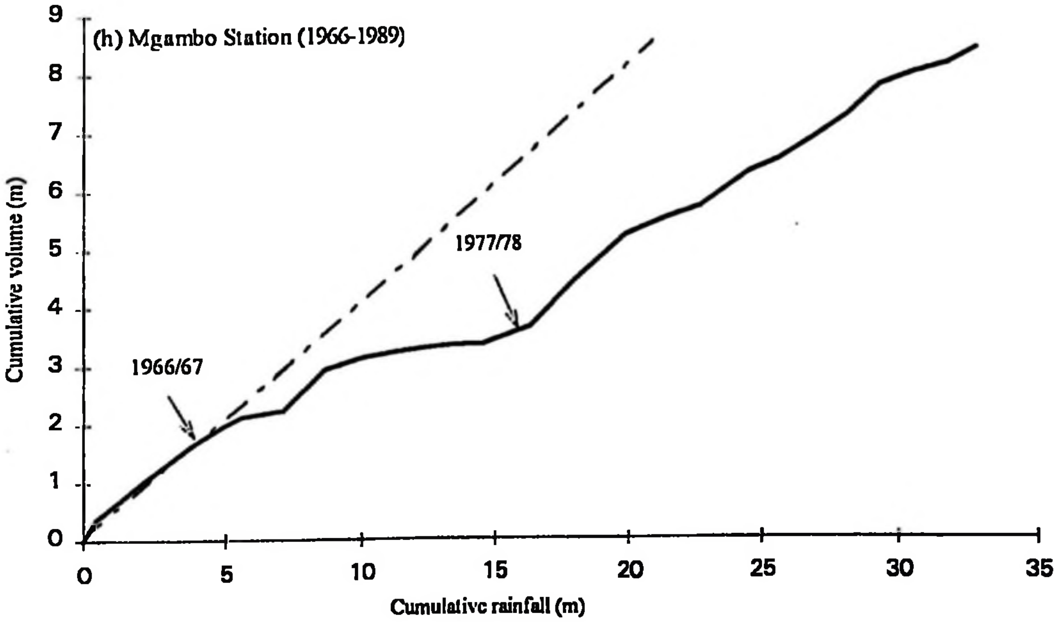

(c) Bombwera Station (1965-1983)
1977/78
1967/68
Cumulative volume (m)
Cumulative rainfall (m)
0
1
2
3
4
5
6
7
8
0
5
10
15
20
25
30


(d) Marikitanda Station (1969-1983)
1977/78
Cumulative volume (m)
Cumulative rainfall (m)
0
1
2
3
4
5
6
7
0
5
10
15
20
25
30
35
40

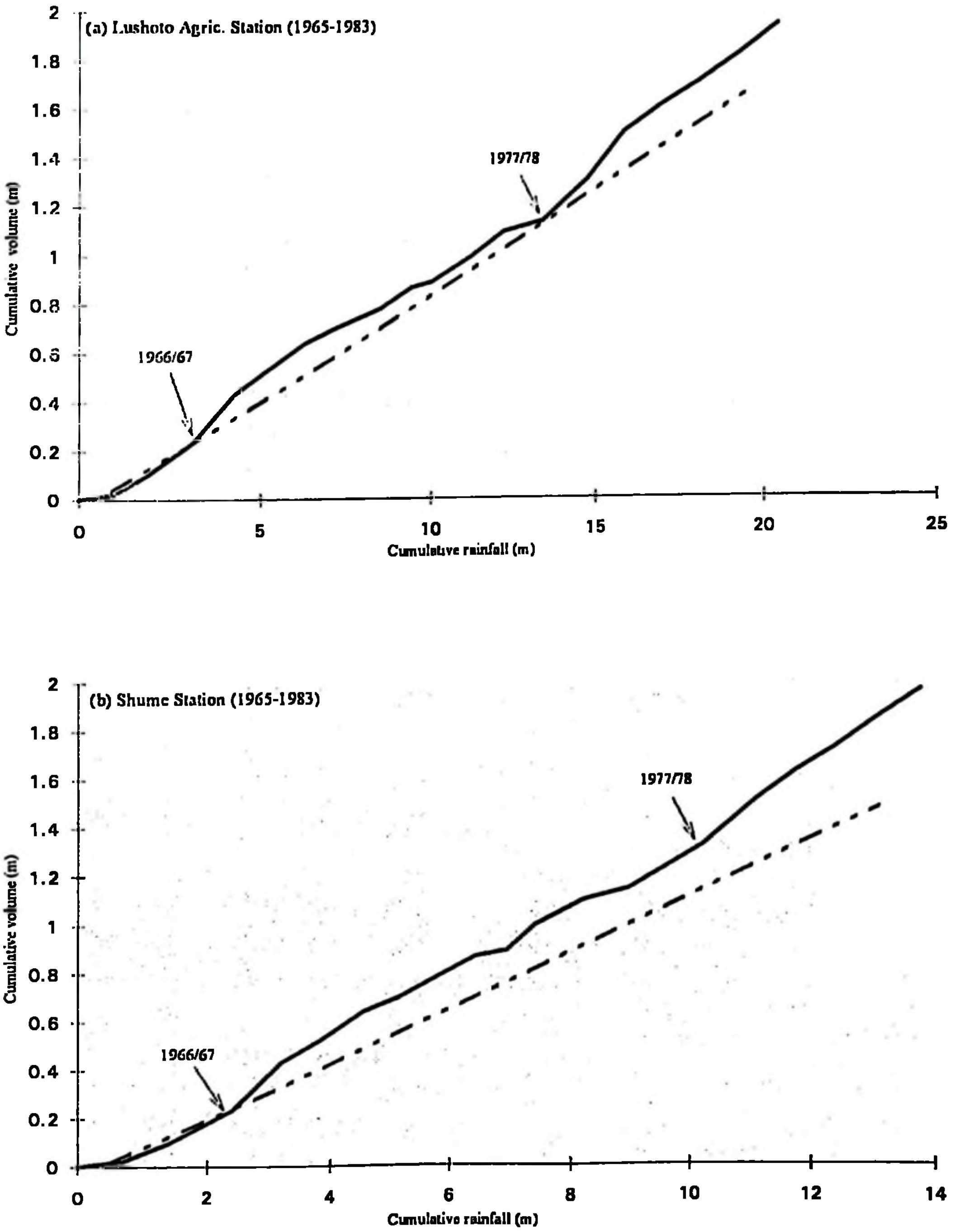

(c) Ngombezi Station (1965-1989)
1966/67
1977/78
Cumulative volume (m)
0
1
2
3
4
5
6
7
8
9
0
5
10
15
20
25
30
Cumulative Rainfall (m)

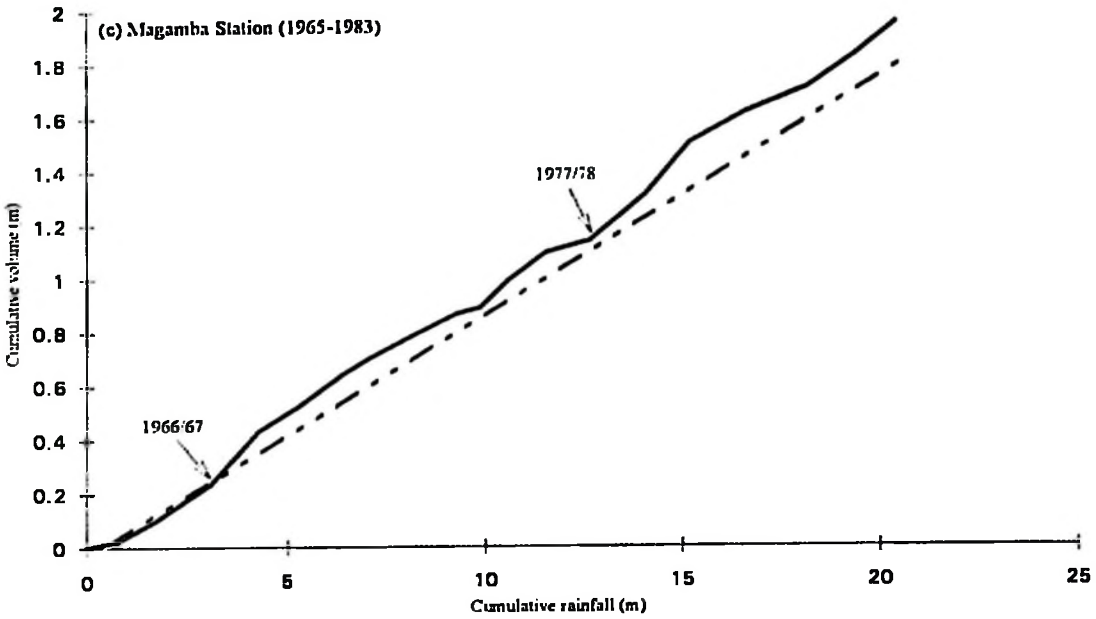

(f) Kwamkoro Station (1965-1989)
1966/67
1977/78
Cumulative volume (m)
0
1
2
3
4
5
6
7
8
9
0
10
20
30
40
50
60
Cumulative rainfall (m)

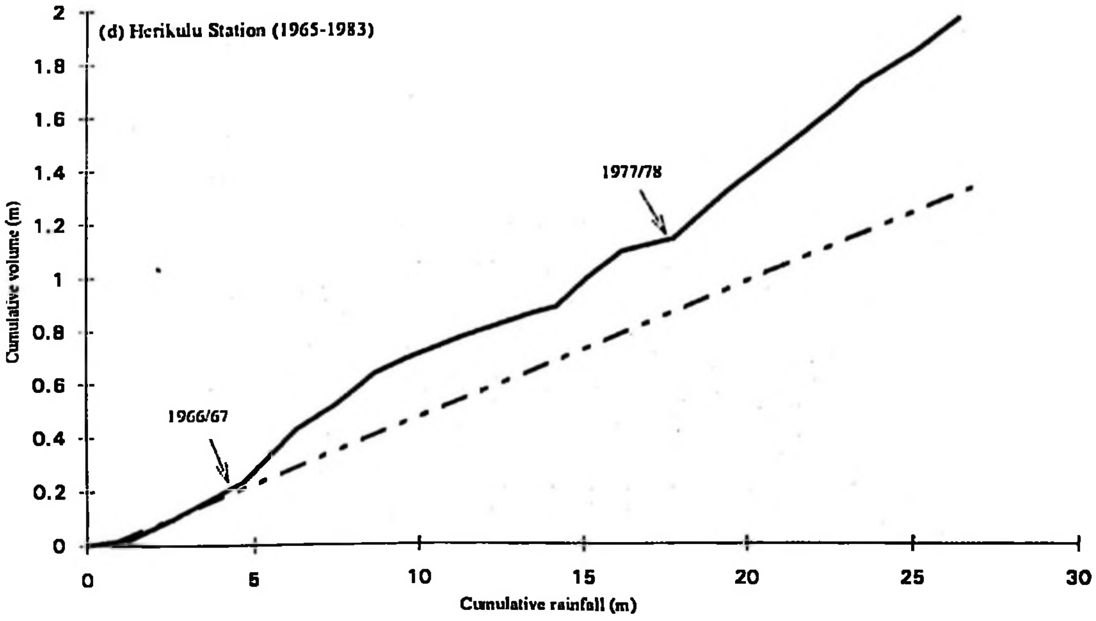

(g) Longuza Station (1965-1989)
1977/78
1966/67
Cummulative volume (m)
Cummulative rainfall (m)
0
1
2
3
4
5
6
7
8
9
0
5
10
15
20
25
30
35
40
45

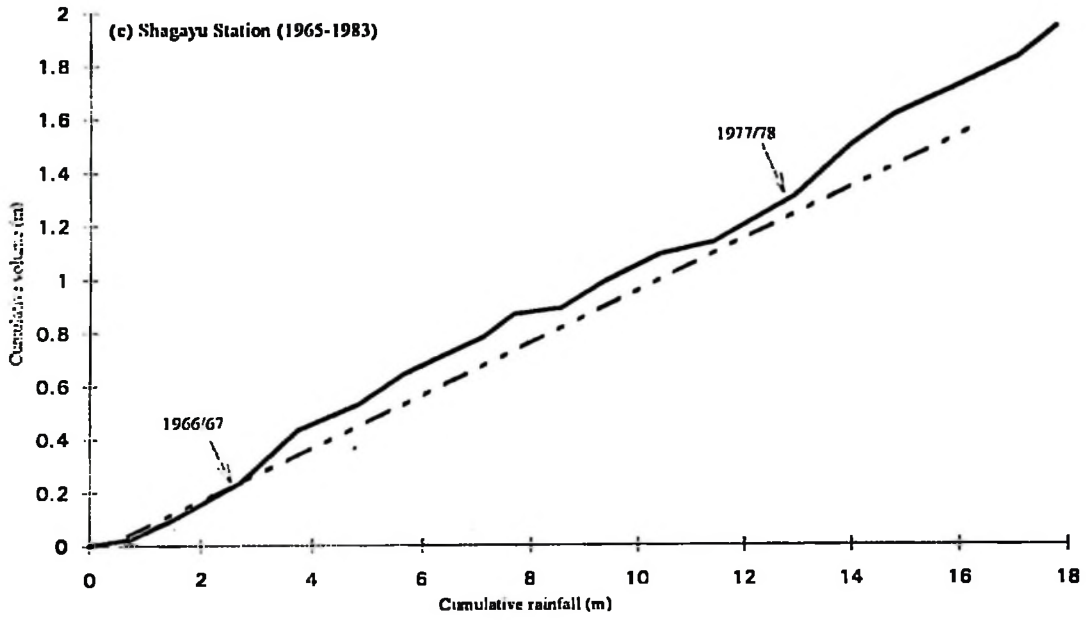

(h) Mgambo Station (1966-1989)
1977/78
1966/67
Cumulative volume (m)
Cumulative rainfall (m)
0
1
2
3
4
5
6
7
8
9
0
5
10
15
20
25
30
35

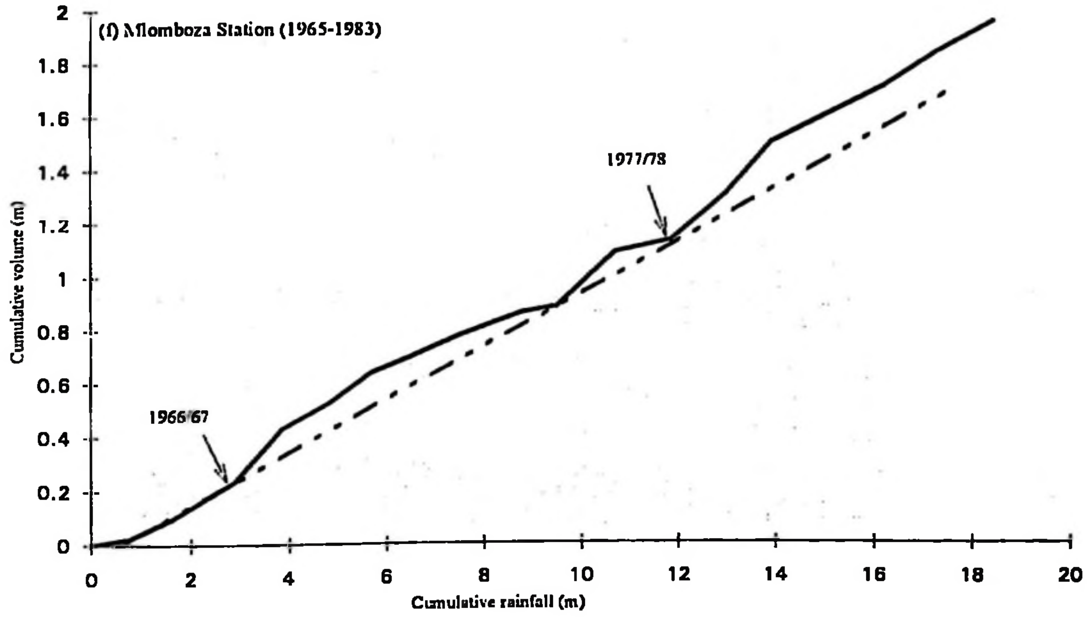
Appendix 5. Double mass curve analysis relating flow volume with station precipitation on the Soni River basin west Usambaras NE Tanzania.

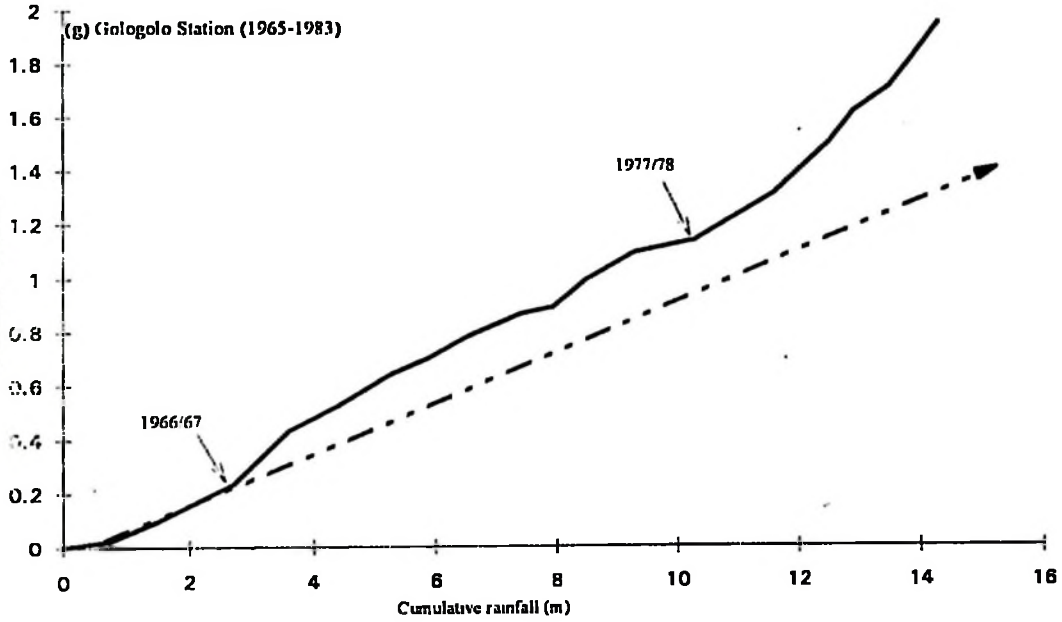



(c) Magamba Station (1965-1983)
1977/78
1966/67
Cumulative volume (m)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
Cumulative rainfall (m)


(d) Herikulu Station (1965-1983)
1977/78
1966/67
Cumulative volume (m)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
Cumulative rainfall (m)


(e) Shagayu Station (1965-1983)
1977/78
1966/67
Cumulative volume (m)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
2
4
6
8
10
12
14
16
18
Cumulative rainfall (m)


(f) Mlomboza Station (1965-1983)
1977/78
1966/67
Cumulative volume (m)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
2
4
6
8
10
12
14
16
18
20
Cumulative rainfall (m)


(g) Golologo Station (1965-1983)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1977/78
1966/67
0
2
4
6
8
10
12
14
16
Cumulative rainfall (m)