MODELLING THE WATER BALANCE OF A SMALL CATCHMENT: A CASE STUDY OF MUHU CATCHMENT IN SOUTHERN HIGHLANDS OF TANZANIA

BY

SIPHO SIMEON S. T. SHIBA

A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE (AGRICULTURAL ENGINEERING) OF SOKOINE UNIVERSITY OF AGRICULTURE

2000

ABSTRACT

The water balance of Muhu catchment located in the Southern Highlands of Tanzania in Iringa region was modelled by establishing the empirical relations that exist between storage parameters, rainfall parameters and runoff components. Storage parameters included soil moisture storage and interception. Rainfall parameters included rainfall amount, intensity, duration, throughfall, stemflow and evaporation. Runoff components included total runoff, direct runoff and base flow. The catchment's physical and hydrological characteristics that affect these parameters were determined.

The assessment of hydrological and physical properties showed that the soils were predominantly sandy clay, having high organic matter content, with a moderately rapid hydraulic conductivity (Ks) of 4.2 cm/h and infiltration rate of 3.8 cm/ h. The bulk density was generally low with an average of 0.9 g/cm^3 for 0 - 15 cm depth; 1.11g/cm^3 for 15 - 30 cm depth and 1.30 g/cm^3 for 30 - 45 cm depth. The catchment had a slope steepness of 35 % and a varying vegetal percentage cover of about 56 %.

The 1997/98 water year was exceptional with high rainfall (1934 mm) mainly due to the El-niño phenomenon. Sixty-seven percent of the rainfall received in the catchment penetrated the canopy to reach the forest floor as throughfall. On average 3.3 % of the rainfall reached the forest floor as stem flow while 25.5% of the rainfall was intercepted by the canopy. Throughfall, stemflow and interception were linearly

related to rainfall. The regression coefficients of all the relationships were significantly different from zero at 1% level ($\beta \neq 0$). With increasing percentage surface cover, interception increased while throughfall decreased. The storage capacity of the forest cover was estimated to be 0.7 mm.

It has been found in this study that stream flow and runoff have gradually been increasing since the 1994/95 season. However the rainfall trend does not support this development. A consideration of runoff curve numbers showed that the observed trend was partly due to catchment degradation. Farming activities in the area have gradually been substituting the forest with arable land, thus reducing surface cover. Records indicated that the lowest recorded daily mean flow was 0.27 m^3/s, while the highest was 1.6 m^3/s.

The water balance was positive during the first five months of the wet season. The highest water balance was in April. During this period there was more recharge to the soil moisture and ground water storage. Water balance was negative in the remaining seven months of the water year, with the lowest in September. The developed direct runoff model and water balance model were found to be valid and useful in estimating the respective parameters in forested catchments of the southern highlands of Tanzania.

DECLARATION

I, Sipho Semakhwanazi Simeon Thokozane Shiba do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is my original work and has never been submitted for award of higher degree in any other University.

Signature:..

Date: ......18/05/2000......

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ACKNOWLEDGEMENTS

First and foremost, thanks to God the creator of the universe for granting me life, wisdom, intellect, and his tireless intervention to the several attacks of malaria I received while at SUA - Tanzania.

The author is deeply indebted to his supervisors. Dr. H. F. Mahoo and Dr. N. I. Kihupi for their guidance and valuable suggestions during the study.

Thanks are due to Iringa Hima Project and Ministry of Water for permission to conduct the study in one of the catchments where they have a water resource monitoring programme. Their support and co-operation during the data collection stage is appreciated. The appreciation is directed to the management and staff of Iringa Hima Project under the leadership of Dr Arif Qaraeen at regional level and Jane Mwalusanya at district level. Special appreciation to all the technicians and support staff of the hydrology section of the Ministry of Water under the leadership of Aloyce Mwitagila. Special thanks to Kavinde, Meshack and Winston for their hard work, commitment and company during field work.

Special thanks to the family of Mr and Mrs Nnko of Kibwabwa in Iringa for inviting me to stay with them in their house, and the support they gave me physically, domestically, spiritually, and financially.

Further I deeply acknowledge SACCAR/ GTZ for the financial support rendered to this study.

The contribution of my colleagues. Kapele. W.. Zisengwe. D.. Nnko. A.. Hammad. J.. Subira. S., Lauwo. L., Kongola. M., Sitali. M., Tembo. M.. Bakari, A., Kingamkhono. R. and all who contributed in one way or the other cannot go without due thanks. Also the contribution of the late Siapondolo Siatembo. the warrior that died of malaria while in the army of education cannot pass without notice. May your soul rest in peace.

Finally the author wishes to express his appreciation to the Queen. princess Nthati Moonyane of Matsieng. and friends: Botle. Futhi. Olivia. Ernest. Kgomotseo, Carol. Jasinta, Chibuye. Nthonyiwa, Munisi. Lugwenza. Mkabenga. Shadrack. Faith. Leonard. Lydia. Love-joy. Tumain-small one. Angel and all other foreign and local students who spiced my stay in Tanzania. May God bless all who contributed to the success of this study (*Mungu awabariki wote*).

DEDICATION

This work is dedicated to my parents Joyina Absalom Shiba (Mthunzi Wokuphumula Ematjitji nemanjongosi - Mkhwanazi, Nabonkhosi. Simemo Lesihle) and Lillian Sibolile Shiba (La-Shongwe Mtimandze Lobhambo).

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(a,b)	Regression coefficients
A	Size of the catchment in square metres
Ao	Gravitational infiltration rate
ANOVA	Analysis of Variance
BD	Bulk density
BF	Baseflow
C	Storage capacity
CN	Curve number of the catchment
D	Depth of the auger hole
DRO	Direct runoff
E	Evaporation
Ea	The rate of evapotranspiration
Eo	Open water evaporation
Eto	Evapotranspiration
f	Regression function
fi	Infiltration rate
fi*	Infiltration capacity
FAO	Food and Agriculture Organization
For	Forest vegetation
ho	surface retention capacity

h (ti)	Height of water in the auger hole measured from the bottom in the beginning of the experiment at time ti
h (tn)	Height of water in the auger hole measured from the bottom after commencing the experiment at time tn
i	Precipitation rate
I	Interception
Ks	Saturated hydraulic conductivity
LAI	Leaf area index
M	Total length of contours within the catchment
N	Contour interval in metres
Obs	Observed parameters
P	Precipitation
Pred	Predicted or simulated parameters
Q	runoff
r	Correlation coefficients
Rsj	Storm rainfall excess
Ri	Rainfall intensity
Rd	Rainfall duration
R2	Regression coefficient of determination
R	Runoff from a site following rainfall event
S	Stemflow

SWMRP	Soil and water management research project.
T	Throughfall
TR	Total runoff
ti	Initial time
tn	Any time interval from the initial time
to	Time at which surface reaches saturation
tr	Storm duration
URT	United Republic of Tanzania
W	Water balance or change in water storage
WMO	World Meteorological Organisation
WRM	Water resource monitoring program

1. INTRODUCTION

The profound impact of human activities on their environment through witting or unwitting manipulation of the hydrological cycle is demonstrated by the wide spread distribution of saline soils, breached water impoundment and devastated valleys. Less obvious, but more insidious, are the effects of changes in land use done deliberately (but in ignorance of the hydrological consequence) to produce crop yields of great immediate value. Most frequently the changes involve the cutting down of indigenous forest, often in uplands areas to facilitate agricultural expansion with little regard to the environment. Many new agricultural schemes being implemented in the evergreen tropical rain forest have fallen short of expectation and caused considerable damage to the environment. This is mainly so because of incomplete knowledge and understanding on how to manage the land and water resources of such fragile ecosystems.

In East Africa there are many examples of disastrous erosion brought about by the removal of forest in favour of over - enthusiastic cultivation on steep slopes and overgrazing by herds of cattle, sheep, and goats. Examples include Kericho in Kenya, where the forest was cleared in favour of tea plantation, Mbeya in Tanzania where the forest was cleared in favour of vegetable and crop production and Kimakia in Kenya where the indigenous bamboo forest was cleared in favour of pine plantation (Pereira, et al., 1962; Edwards and Blackie, 1975). The intensive cultivation of steep slopes under a subsistence economy relying predominantly on annual crops has led in turn to severe erosion and deterioration of water yields in terms of quality and quantity (Temple and Sundeborg, 1972).

In many parts of Kenya, Tanzania, and Uganda, perennial streams originate in the high - rainfall mountainous areas. The interference with the ecosystem of these mountainous areas poses a serious threat to future water supplies. It is therefore important to understand the ecosystem, together with the interaction of the human activities with the system.

Although it is established beyond doubt that the removal of the forest cover in virtually all environments leads to instability in the soil cover, changes in the hydrological regime, soil erosion and loss of productivity, there are still few studies of water, sediment, and nutrient redistribution following disturbance and recovery within tropical forests (Anderson and Spencer, 1989). It remains a challenge to narrow this gap in knowledge.

The challenge facing the governments of East Africa in these areas is therefore to develop methods of land use which will give a livelihood to the maximum number of people and yet will cause minor deterioration in the river regimes. The thrust should be to develop appropriate and socially acceptable management interventions for improving the soil water availability and use. In order to meet such challenges more studies should be embarked upon to assess the hydrological regime of the catchments.

According to Russel (1962), only 4 % of the East African land surfaces reliably receive a mean annual rainfall greater than the mean annual potential evapotranspiration. Such areas include the highlands of Tanzania, with altitude of 2000 m and above. Therefore most of the remaining parts in Tanzania receive unreliable rainfall of less than 1000 mm (Griffith, 1972). The nature of rainfall characteristics in Tanzania has necessitated efforts to capture, conserve and efficiently utilise the scarce rainwater. Such efforts include rainwater harvesting in both small and larger catchments, and encouraging practice of conservation tillage. Proper management of the catchments especially those found in the highland areas is crucial. This is due to the fact that these water catchments represent the major source of water for the surrounding areas of marginal rainfall where water may be extremely scarce during the dry season.

There are many processes taking place in water catchments that need understanding before developing any catchment management plan. The processes are part of the water balance, which consider both flow processes and storage parameters and hydrological cycle, a concept that considers the processes of motion, loss and recharge of earth's waters. Processes such as interception, stemflow, evaporation in catchment ecosystems act on the water input (rainfall) before any water output (for instance, surface runoff) is produced. This gives an indication of the effectiveness of a catchment system in controlling the water input and also, the amount of water that replenishes soil moisture.

Interception is a process in which rainfall is caught by the vegetation canopy and redistributed as absorption, stemflow and evaporation into the atmosphere (Zinke, 1967; Hamilton and Rowe, 1949). It is a function of biomass and spatial arrangement of the vegetal cover. Modification and/or removal of the vegetal cover influence the magnitude of the interception loss which plays a significant role in water balance. Interception losses should be distinguished from evapotranspiration losses. The latter is the loss of water that has been absorbed by plants in the soil, and the former is the loss of water that has been intercepted during rain. Both processes take place at the leaf surface.

Stemflow is that part of rainfall that moves down the tree stem until it reaches the ground. It plays a significant role in replenishing the soil moisture around the root zone. There has been controversy concerning the contribution of stemflow to the water balance. Some have claimed that its contribution is not significant while others have claimed that it is significant (Leonard, 1961; Jackson, 1971; Lull, 1964). There are few studies in the tropics that have been done to justify its contribution.

Evaporation is a process by which water received in the form of rainfall by the canopy, earth's surface , soil and water bodies is taken back to the atmosphere. It is considered as water loss from hydrological point of view and as an input to the atmosphere from the meteorological point of view .

Surface runoff is the portion of rainfall that moves on top of the earth, part of which infiltrates the soil while the other part joins streams as stream flow. From a consideration of the water balance equation runoff is shown to be a residual which is dependent upon the magnitude of losses. Removal of vegetation increases surface runoff although the resulting yield varies from one ecosystem to another. The study of surface runoff is of great practical significance for various estimates of water economy, and its relation with rainfall is one of the important indices for expressing the hydrological behaviour of a watershed (Malchanov, 1963).

The quantity of water available from a stream at a given point over a specified duration of time is referred to as basin yield. It is a consequence of all hydrologic events resulting in flow, including storms of all duration and intensities, and the climatic, geologic and land use factors in a given environment. Other factors such as terrain configuration, size of the watershed, vegetation cover and erosion processes also affect basin yield. Any human activity which impinges on these factors will affect the watershed storage and stream flow.

Careful measurement of the parameters related to the components of the water balance is crucial in developing a catchment model. Models are useful tools in future planning. Most of the catchment models developed originated in advanced countries of temperate regions. The models have been transferred to developing countries especially in the tropics and equatorial regions. However problems have been encountered in the applicability of such models (WMO, 1979). According to the WMO (1979) report, problems were encountered due to the following :

(i.) Little had been done in investigating the applicability of such models

(ii.) Temperate conditions where most models were developed differed from the conditions in the tropics.

(iii.) Wrong assumptions that provision and supply of technical instruments to developing countries will solve all potential problems.

It is therefore important to investigate the applicability of the catchment models in the tropics. It is also crucial to develop models that will have tropical origin. The present study is part of the ongoing endeavour on this subject.

The Iringa Soil and Water Conservation Project or Hima has a long-term objective of helping farmers to practise and benefit from improved sustainable agricultural and natural resources management (HIMA, 1997). The project encompasses four catchments, namely Mgera, Gendavaki, Muhu and Ihaka. The project incorporates a water resources monitoring (WRM) programme which has been going on since 1993. The major aims of the WRM are:

(i.) To develop a better understanding of the influence of land use practices in the project area, including afforestation and soil water conservation measures, on hydrological regime.

(ii.) To facilitate quantification and assessment of soil erosion, sedimentation, runoff collection, water resources and soil water balances.

(iii.) To promote soil and water conservation.

However, to date, a detailed study has not been undertaken to assess the effect of the changes in land use on the hydrological regime of the catchment. It is envisaged that the present study, employing the water balance approach will characterise the catchment and provide information on the trends of all the important components over time. Such information will be useful in providing a base for future planning and management of the catchment. It is against this background that this study was initiated with the general objective of developing an empirical water balance model for the Muhu catchment in Iringa region. The specific objectives were as follows:

(i.) To identify and take inventory of the major catchment characteristics.

(ii.) To take inventory of climatic and meteorological data.

(iii.) To assess throughfall, stemflow and runoff in the catchment

2. LITERATURE REVIEW

2.1 Water balance studies

Various studies have been conducted in catchment areas in the temperate regions to quantify the effects of changes in land use and cultural practices in the water balance (Edwards, 1977). Human activity processes causing forest clearing has been reported to increase annual stream flow by many researchers (Wilcock, 1979; Clarke and McCulloch, 1979). Reasons for increased stream flow as a result of clearing has been attributed to reduced transpiration from vegetation (Hibbert, 1967) and the increased aerodynamic resistance from the clear felled surface compared to the forest (Calder, 1979). Afforestation, on the other hand, has resulted in decreases in stream flow due to increased water use (Eschner, 1965; Wicht, 1967). However in some instances these activities failed to yield expected results due to other interactive processes in the catchment ecosystem responsible for the generation of stream flow (Dagg and Blackie, 1965; Edwards and Blackie, 1975).

So far water yield augmentation through vegetation manipulation by altering the ratio of vegetation types has been a popular, though somewhat controversial subject. Part of the controversy is a result of little knowledge backed up by empirical research (Harr, 1976; Edwards and Blackie, 1975). Increase of knowledge in this subject will increase the effectiveness of planning in protecting the soil and water resources (Ursic, 1986).

Wilcock (1979) studied the effect of channel basin clearance on water balance over a period of five years in Northern Ireland. He found that the variations in water balance were more obvious immediately following the clearance with more depletion.

Clarke and McCulloch (1979) found that in United Kingdom water losses from forested catchments was greater than in catchments with herbaceous vegetation. In the study of Severn forested catchment and Wye upland pasture. Clarke and McCulloch (1979) found that Severn had losses of 717mm while Wye had losses of 431mm. The explanation was that the additional losses from the forest were a result of evaporation of raindrops intercepted by the tree canopies.

Research conducted in Tanzania and Kenya has shown that replacing indigenous forest by alternative forms of land use produces increases in stream flow depending on the type of vegetation chosen (Dagg and Blackie. 1965: Edwards and Blackie. 1975). Pereira et al. (1962) found that clearing indigenous bamboo forest at Kimakia in Kenya resulted in an increase of 16 percent in annual stream flow compared with the one not cleared. In a study conducted in Mbeya by Edwards (1977). annual stream flow from cultivated catchment was 652mm while stream flow from forested catchment was 522 mm. The studies in East Africa were an effort to assess the effects of changes in land use in the tropical region. It was anticipated that experience from these experiments would have provided useful reference for other similar experiments (Pereira et al., 1962).

2.2 The hydrological water balance

Scotter et al. (1979) suggested a simple water balance equation :

$$W = P - E - Q \tag{2.1}$$

where:

P	=	precipitation
E	=	evapotranspiration
Q	=	runoff
W	=	change in the water storage

According to Merlet (1973), water balance in practice is computed from two factors, (P-E) and W, which are sufficient to give an approximate description of hydrological cycle. Merlet (1973) separated the water balance into four stages as follows:

(i.) Ground water storage build up stage: (P - E > 0)

(ii.) Runoff stage: the soil is saturated or at the saturation limit; (P - E > 0)

(iii.) Restitution stage: return of water to the atmosphere from the reserve in the ground (P - E < 0).

(iv.) Deficit stage: insufficient water for vegetation (P - E < 0).

2.3 Forest hydrological cycle

The distribution and transport of rain water obey a fundamental law of equilibrium, the hydrologic cycle (Forbes and Meyer, 1965).

$$RO = P - (T + E) \pm S \tag{2.2}$$

where:

RO = runoff

P = precipitation

T = transpiration

E = evaporation

S = soil moisture and ground water storage

The rain falling on a forest is subjected to interception by vegetation canopy. Some of the intercepted water evaporates, while the remainder falls to the forest floor. The latter may reach the ground by falling as throughfall, or by running down the stems as stem flow. Together these make up the net rainfall.

On the forest floor water may be subjected to a number of processes such as infiltration, evaporation from the soil surfaces and from the upper most soil layers, and surface runoff. All these are controlled by vegetation and dependent on its density. The vegetation cover on a given piece of land will also influence the soil through the processes of interception, transpiration, shading, and wind modification (Herring, 1970). Once in the soil, water is subject to gravitational and capillary forces that causes it to restrict its movement. Because of the slope on most forest lands and because soil conductivity generally decreases with depth, water entering the soil begins to move down slope as it moves deeper into the soil.

2.4 The interception process

Interception represents the part of precipitation that is caught temporarily by forest canopies, which include foliage, twigs, branches of trees and lesser vegetation or by surface debris. It is then redistributed either to the atmosphere by evaporation from the exposed surfaces or is absorbed by the foliage, twigs and branches of trees or channeled to the forest floor. The result is a reduction in the precipitation reaching the ground (Forbes and Meyer, 1965; Brown et al., 1972; Szabo, 1975).

In the past, interception was considered as part of evapotranspiration, and therefore little attention was given to this subject. There is a general consensus today that interception should be treated as a separate part and this makes interception studies important (Haldin, 1988). A study by Singh and Szeics (1978) showed that exclusion of interception resulted in an error of 100 mm in the water balance. More studies are needed to justify its role in the forest water balance especially in the tropics.

2.4.1 Interception loss and storage capacity

The amount of rainfall reaching the ground surface is largely dependent upon the nature and density of the vegetation cover (Wigham, 1970). This cover intercepts part of the falling rainfall and temporarily stores it on its surface from where the water is either evaporated back into the atmosphere or falls to the ground. The factors affecting interception include, canopy storage capacity, leaf area index, stand characteristics, climatic conditions, and leafy and leafless periods.

Interception loss is conveniently calculated as the difference between gross and net rainfall (Reynolds and Henderson, 1967). Bringfelt and Harsmar (1974) calculated the amount of interception (I) for each forest stand from measurements of rainfall (P) , stemflow (S) and throughfall (T) using the following equation.:

$$I = P - (T + S) \tag{2.3}$$

He argued that the threshold value of P above which T commences is nearly always less than that at which S commences. Therefore, the storage capacity (C) can be derived from slope and intercept of a linear regression of T on P (equations 2.4 and 2.5 below) using data of individual storms or data of individual days of precipitation (Bringfelt and Harsmar, 1974).

$$T = b * P - a \tag{2.4}$$

$$C = a / b \tag{2.5}$$

where:

a = y-intercept

b = slope of the regression line

T = throughfall

P = precipitation

C = storage capacity

In most forest regions tree cover intercepts ten to about thirty per cent of annual precipitation before it reaches the ground (Eschner, 1967). Bringfelt and Harsmar (1974) found that the amount of intercepted water by forest in Velen was 74mm (26%) compared to a total rainfall of 288 mm.

2.4.2 Role of interception to water input

Wavering opinions exists as to the role of interception in the hydrologic cycle (Zinke, 1967). Some investigators have treated interception as total loss of water in terms of yields from the catchments (Leyton et al. . 1967). However, an opinion of this kind makes little or no allowance for the interaction between evaporation of the intercepted water and transpiration.

Interception losses in forests are of considerable quantitative significance in the water balance. The rate of evaporation of intercepted water can be of the order of 5 to 10 times that of transpiration with unrestricted water supply. Although wetting of the foliage certainly results in appreciable reductions both in water uptake and transpiration, the net interception loss is usually 90% of the amount of water intercepted (Leyton et al., 1967).

2.5 Gross and net rainfall

2.5.1 Gross rainfall

Precipitation in terms of rainfall is one of the most variable meteorological elements that an approximate idea of its large scale distribution can only be obtained by a network of gauges in a given region (Todorov, 1977). There are generally two ways of measuring gross rainfall in forested catchment areas. It can be determined by the use of a rain gauge positioned either a couple of meters directly above the canopy or near the ground in an open area close to the catchment area under investigation. For either case, problems in measuring gross rainfall abound and care is required in the installation of rain gauges (Jackson, 1971,1975). One of the major problems is the variation caused by the effect of wind especially when the collector is above the ground (Corbett, 1967).

2.5.2 Net rainfall

Essentially, net rainfall is the quantity of precipitation that actually reaches the ground. It is the sum of throughfall and stemflow. Most of the studies done on the net rainfall have tended to ignore the stemflow component on the pretext that it is usually negligible and, hence of insignificant contribution to net rainfall (Jackson, 1971; Reynolods and Leyton, 1963). These two parameters are further discussed in the following subsections.

2.5.2.1 Throughfall

The quantity of throughfall as a function of incident rainfall is mainly influenced by the canopy closure of different types of forest, and the canopy pattern of species and their values of canopy storage capacity (Szabo,1975). For a given gross rainfall, throughfall values are much higher or more in open woodland than for forest. Canopy storage capacity values are smaller in the former (open woodland) than in the latter vegetation type (Leyton et al., 1967; Thompson, 1972; Jackson, 1971,1975).

The value of precipitation corresponding to a zero throughfall value is regarded as an estimate of the depth of water needed to saturate the canopy, that is, the canopy storage capacity (Rutter, 1963). However, Reynolds and Leyton (1963) argued that this result is likely to be a biased estimate since the data will almost certainly have contained an inflection. For most forest stands allowance should be made for even the lowest measurable precipitation to fall unhindered to the ground.

In a study by Willis et al. (1975) in Alberta, Canada, it was shown that low intensity storms produced less throughfall than high intensity storms. Storm duration was also found to have a pronounced effect on throughfall. Storms of high intensity but with short to moderate duration resulted in the greatest throughfall.

A study by Pathak et al. (1985) at Kamaun Himalaya indicated throughfall of 74 - 91.5 percent. Nalon and Vellardi (1993) reported throughfall of 89.6% in Sao Paulo. Sood et al. (1993) reported throghfall of 70.6%, 69.8% and 78.1% respectively for *Quercus leucotriphora, Rhododerdron arboreum and Azadirachta indica.* Throughfall under beech forest at Donak Creek , New Zealand, averaged 69% (Rowe, 1963). A study by Jackson (1971) in Tanzania yielded average throughfall of 84%, while a study by Kayambazithu (1990) in Morogoro yielded a throughfall of 78%. The variation in throughfall with vegetation necessitates more studies in the tropics especially because of the great diversification in tree species in this region.

2.5.2.2 Stemflow

Stemflow is that part of net rainfall that reaches the ground by running down the stem. The water flowing down the stems concentrates at their bases. where the soil is apt to be most highly receptive to the water (Lull.1964).

Several investigators have reported stemflow from large diameter trees to be less than that from smaller stemmed trees (Bruijnzeel. 1990). This may be ascribed to differences in branching patterns. The amount of stemflow in forested areas depends largely upon the roughness of the bark (Lull. 1964). Rowe (1941) found that in the case of some smooth barked trees. like beech. stemflow could amount to 15 percent of the net rainfall. The stemflow component of net rainfall has been determined in some of the early and most recent studies on precipitation reaching the forest floor (Douglas. 1967: Reynolds and Leyton. 1963: Horton. 1919). In some cases it has been shown to be a negligible amount. Working under the tropical forest of Tanzania. Jackson (1971) reported that stemflow was unimportant as it comprised only about 1.5 % of the annual rainfall. However. in some instances. the contribution of stemflow to net rainfall has been significant. if not too large to be ignored (Lull. 1964. Rowe (1941). Moreover there is still little information on the contribution by stemfow in the tropics to support its negligence (Hamilton and Rowe, 1949: Leonard. 1961). Therefore, Rowe (1941) and Bruinzell (1990) have cautioned that when carrying out measurements of net rainfall in unfamiliar areas, the examination of stemflow must be done and difficulties concerning its measurement be overcome.

The results of Willis et al. (1975) on stemflow indicated that there was little stemflow during storms of 7.6 mm and less for all study trees. They explained that this could be due to absorption of the water by the bark. However stemflow increased geometrically during rainfall of more than 7.6mm. Small trees demonstrated the most rapid increase. They attributed this to the relatively smooth bark and ascending branches of small trees as opposed to the scaly bark and wide spreading branches of large trees.

2.6 Evapotranspiration

Evapotranspiration is a process by which water is transferred back to the atmosphere as vapour. It contributes to major losses in the water balance. It is affected by a number of factors which include meteorological conditions, availability of water to meet the atmospheric demand, and vegetation (Kijne, 1974). The water losses from a large area in which soil moisture is not a limiting factor is at potential rate. The actual evapotranspiration is the actual amount of vapour transferred to the atmosphere under any prevailing moisture conditions, and it is also affected by the same factors as above (Penman, 1963).

2.6.1 Factors affecting evapotranspiration

2.6.1.1 Vegetation type

The differences between vegetation types in relation to absorptivity, albedo, rooting depth and leaf area index cause the variability in evapotranspiration. It has been observed that deep rooted plants have high evapotranspiration than shallow rooted plants under the same conditions. Forests have low reflectivity for short wave radiation, hence making more energy available for evapotranspiration to take place. (Angstrom, 1925; Monteith and Szeicz, 1961, Stanhill, 1966). The magnitude of transmitted short wave radiation depends upon forest structure, composition and density. These factors imply that cover changes have large effects on energy budgets, which limit evaporation and transpiration (Rutter, 1972; Penman, 1963; Sharma, 1984).

The type of vegetal cover affects soil moisture depletion and influences soil moisture storage. Apart from the absorptivity and albedo differences, the major variables influencing differential evapotranspiration losses resulting from vegetation cover, are the rooting depth of the cover crop and the depth of the soil mantle (Douglas, 1967).

2.6.1.2 Land use

Land use modification results in a different hydrological equilibrium of a catchment. The new equilibrium is achieved by altering the proportions of the water balance components, which give rise to water management problems (Hibbert, 1967; Calder, 1979). According to FAO (1976), land use utilisation types include arable land, pasture land, range land, forest land, urban land, water bodies, irrigated land, recreation and game reserves and land for roads. The changes in land use have significant impact on our environment. The clearing of the natural forest to accommodate expansion of agriculture has disturbed the hydrological equilibrium. The level of technology changes with changes in land use has resulted in maximised soil tillage, construction of dams and ponds to facilitate irrigation and supply of water to urban areas. Evapotranspiration and other parameters such as streamflow, soil moisture storage have been affected by such land use changes (Borman and Likens, 1979). The alteration of evaporation has resulted to water management problems. Quantitative knowledge of evapotranspiration is therefore basic to most water management problems (Pereira, et al., 1962; Dagg and Blackie,1965).

2.6.1.3 Soil moisture

Soil moisture supports vegetation to meet its water requirements. Depletion of soil moisture with little or no recharge, reduces the amount of water available for evapotranspiration, creating a soil moisture deficit. Thus at high soil moisture tension, evapotranspiration rate will drop below the potential rate even if other conditions are favourable. The relationship between evapotranspiration rate and the soil moisture tension depends upon a number of factors such as soil texture, moisture tension characteristics, hydraulic conductivity of the soil, rooting depth, crop density and atmospheric conditions (Shaw, 1988).

2.6.2 Evapotranspiration from tropical forests

A study conducted by Sharma (1984) on evapotranspiration from different plant communities (i.e. Eucalyptus, Pine, indigenous trees, etc) in Australia showed that overall evapotranspiration was more than 70 percent of the annual precipitation. Canopy interception played a significant role in the evapotranspiration process.

Dunin and Aston (1984) using weighing lysimeter supporting eucalyptus re-growth, reported higher annual evapotranspiration rates compared to pine. The leaf area index played a major role in these differences which affected the transpiration and evapotranspiration regimes of the eucalyptus re-growth.

In tropical Africa, studies on forest evapotranspiration have been carried out in the Congo basin (Bernard, 1945; Sengele, 1981) and in East and Central Africa (Pereira et al., 1962). Sengele (1981) measured evapotranspiration of the Loweo catchment and found that it amounted to 79 percent of the rainfall received. In catchment studies conducted in Kenya at Kericho and Kimakia, it was observed that mean annual evapotranspiration of forested control and of tea plantation was relatively the same. However initial clearing gave 11% reduction in water use which was accounted for by evaporation from bare soil and was estimated to be about 45% of the open water evaporation (0.45 Eo) (Edwards, 1977).

There are efforts to develop new methods and models for predicting forest evapotranspiration in the tropics. Rose (1984) has developed a new theory for predicting transpiration from an isolated tree. This allows the estimation of ratio of the transpiration rate from such a tree to that of a tree with the relevant characteristics exposed to similar environment. Such techniques provide understanding of the process. However the tropical rain forests are characterised by a wide range of diversified tree species, canopies, and under storey which makes evapotranspiration to be quite variable.

2.7 Runoff

Rainfall - runoff relationship is a process that reflects the release and retention of water from and in the soil of any given catchment (Jackson, 1987). Linsely et al. (1988) stated that runoff is generated where and when rainfall intensity exceeds the infiltration rate at which water enters the soil. Runoff is a component of rainfall which appears in surface streams of either perennial or intermittent form (Gupta, 1979). There are three main mechanisms that have been suggested for the way in which the major part of total runoff from a catchment is produced. These are subsurface, ground water and surface runoff (Pilgrim and Klaassen, 1975). The generation of surface runoff during a typical storm is illustrated in Figure.2.1. and equation 2.6.

Runoff can be affected by catchment characteristics and rainfall characteristics (Linsely et al., 1988). Rainfall characteristics that affect runoff include rainfall amount, intensity and duration while catchment characteristics include surface slope, vegetation cover, soil infiltration and water holding capacity (Linsely et al., 1988 and Klemer, 1982). The infiltration rate is influenced by a number of factors that include soil texture, porosity, hydraulic conductivity and soil moisture retention characteristics. These factors have an indirect effect on runoff. Since these factors vary from catchment to catchment, it would appear that the variation in surface runoff can be accounted for when a satisfactory statistical analysis is made on surface runoff and forest type data. According to Lundgren (1980), available information demonstrate the need for more research work for greater understanding of the rainfall - runoff relationships with respect to forest type on a regional scale and more so, at a local scale.

2.7.1 Effects of rainfall characteristics on runoff yield

Studies have shown that rains of big amount, high intensity and longer duration yield more surface runoff compared to rains of small amount, low intensity and shorter duration (Shanan and Tadmor, 1979; Pacey and Cullis, 1986). A study by Pandey et al. (1983) showed a positive relationship between overland flow and rainfall quantity and intensity. However, Hewlett and Fortson (1977) showed that hourly and minutely rainfall intensities during storms had no significant effect on runoff volume delivered by the basin. Such an observation indicated the effect of the interactive factors such as vegetation, soil and topography.

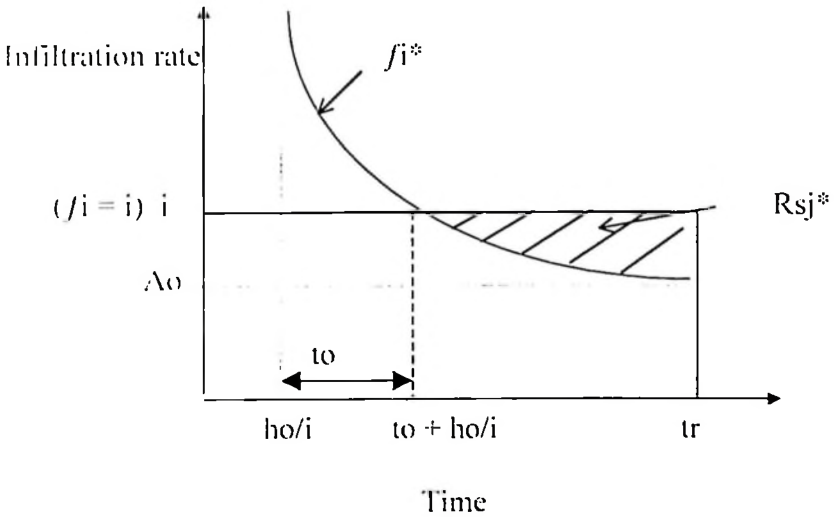

Figure 2.1: Generation of surface runoff (After Dunne, 1978).

$$Rsj^* = (i - fi^*)(t - to), \; t > to \tag{2.6}$$

where: fi = infiltration rate(mm/hr)

fi^* = infiltration capacity(mm/hr)

i = precipitation rate(mm/hr)

Rsj^* = storm rainfall excess(mm)

tr = storm duration(hr)

to = time at which surface reaches saturation during precipitation(hr)

t = time(hr)

Ao = gravitational infiltration rate as modified by capillary rise from water table

ho = surface retention capacity(mm)

2.7.2 Effects of catchment characteristics on runoff yield

Catchment characteristics that affect runoff yield from a catchment include the following: ground cover, size, slope and management practices. These are discussed in the following sub-sections.

2.7.2.1 Surface ground cover

The removal of vegetation and conversion to a farmland increases runoff although the resulting yield varies from one ecosystem to another. (Gupta, 1979; Shanan and Tadmor, 1979). Jones et al. (1991) observed that in areas where adequate amount of ground cover were produced either by natural vegetation or crops, the effect had been an increase in the infiltration rate and reduced runoff. A study by Kayambazithu (1990) indicated that surface runoff in Miombo woodland in Morogoro, Tanzania was significantly ($p<0.05$) higher than at dry semi- evergreen forest. This was attributed partly to the differences in thickness of vegetation cover. The more thickly the vegetation cover is the less the runoff yield.

2.7.2.2 Catchments size

Generally, large catchments generate higher runoff than small catchments (Shanan and Tadmor, 1979; Lal,1992; Reij et al., 1988). However, a study by Shanan and Tadmor (1979) showed that the runoff yield generated per unit area of catchment for relatively small catchments was higher than the runoff yield generated from relatively big catchments. Lal (1992) reported that forests areas of 44.3 ha and 10.6 ha on a slope of 2.8% discharged runoff of 3.5 mm and 0.9 mm from 199.2 mm of rainfall, respectively. A study by Ojesi (1997) in Kisangara indicated that the total mean runoff yield from a 6 m length water harvesting plot was 9% more than a 12 m plot. In Morogoro, Mahoo et al. (1994) observed a 10% increase in total runoff yield generated from a 5 m length plot compared to 10 m length plot.

2.7.2.3 Catchment Slope

Catchments which are steep have high velocity of flow and runoff takes less time to reach the lower end of the catchments resulting in higher runoff yields than gentle slope catchments . In Morogoro it was observed that there was significantly ($p<0.05$) higher runoff yields generated from catchments whose slope was 6-8 % than those whose slope was 3-4% (SWMRP, 1993; Mahoo et al., 1994). In a study conducted at Kisangara, Ojesi (1997), observed that catchments with 18% slope generated significantly higher mean runoff yields than the catchments with 6% slope. However the runoff from 18% slope and 15% slope were not significantly different from each other ($P<0.05$).

2.7.2.4 Management practices

Management systems or practices done on the land have an important influence on the runoff generated. SWMRP (1993) reported that bare and bare compacted catchments at Kisangara generated up to 26% runoff higher than natural vegetated catchments during the first short rainy season or Vuli in October/November, 1993. SWMRP(1995) further reported that in Hombolo, catchments under tied ridges produced the least runoff yield on average than all the other tillage treatments in all the rainfall events. Compacted soils have higher runoff yield than loose soils due to decreased water holding capacity as a result of decreased total porosity in the compacted soils.

2.8 Modelling

In hydrology and other related disciplines, various models have been developed ranging from stochastic models, deterministic models, conceptual models to empirical models. Such efforts have been expended to facilitate understanding, prediction and proper decision making (Walkman and Skaggs, 1941; Sheridian, 1994; Parkes et al., 1989). Some of the models developed include the Cream model (Kinsel, 1980), SWIM model (Ross, 1990), RUNOFF models (Sheredian, 1994; Boers et al., 1986; Lundren, 1980; Haldin, et al., 1979), SWATRER model (Dierchx et al., 1986), INTECEP model (Leonard, 1967), CANOPY model (Parkes et al., 1989), and Infiltration Model (Birtles, 1978).

Empirical models primarily based upon relationships derived from regression analysis have been useful in many hydrological related fields. Application of the models take into account assumptions that are governed by these models. These models apply only in the regions where they are developed or areas of similar conditions (Walkman and Skaggs, 1994; Erikson and Grip, 1978). Some examples of empirical models include:

(i.) Intecep model

$$I = (C)\,(1\text{-}Exp[-P/C]) + (LAI)\,(Ea)\,(t) \quad (2.7)$$

where:

I = interception

C = storage capacity

LAI = leaf area index

Ea = rate of evapotranspiration

t = rainfall duration

P = precipitation

(ii) Runoff model

$$R = \frac{(P - 0.2S)^2}{P} + 0.8S \quad (2.8)$$

where:

R = runoff from a site following rainfall event

P = rainfall amount

S = relation parameter.

(iii.) Runoff model

$$Q = aP - c \tag{2.9}$$

where:

Q = annual runoff

P = mean basin precipitation

a and c are regression constants.

The tropical region has been dragging behind in developing models which has resulted into importing models from countries of the temperate regions. In trying to use these models, problems have emanated since conditions differ between the two regions (WMO, 1979). It remains a challenge to do more work on this subject in the tropics especially East Africa.

Modeling requires increased accuracy in the specification of the water balance elements. This inevitably leads to more reliable hydrological maps and improved hydrological forecasting. It enhances improvement in numerical prediction of the hydrological processes which facilitates better management and planning (Harr, 1776; WMO, 1979).

2.9 Synthesis of the literature review

The preceding literature review shows that land use changes have effects on the water balance of a catchment. All human activities that interfere with vegetation in catchments will disturb the hydrological equilibrium. Each of the individual components of the water balance would be affected differently by these changes. The direction, magnitude, and duration of probable changes will vary with catchments.

Vegetation clearance has led to increase of some of the water balance components. Some components of the water balance, on the other hand, have decreased. Increases have been recorded with stream flow, surface runoff, and throughfall. Infiltration, evapotranspiration, interception, recharge to ground and soil moisture have been reported to decrease with vegetation clearance. Afforestation and regeneration have been reported to have opposite effects compared to vegetation clearance. The magnitude of change in water balance depends on the interactive processes and factors within the catchment ecosystem. This includes: type, composition and density of vegetation; chemical, physical and hydrological properties of soil; soil conservation measures; topography of the catchment; interception process; runoff; evapotranspiration; and storage related parameters.

Altering the proportion of the water balance components has led to hydrological and management problems. It has been difficult to address this problem due to the agricultural oriented nature of economy and little knowledge backed up by empirical research in the tropics. It is apparent that more work is required to understand the processes and their interaction in these ecosystems in order to provide better management of the water resource. The present study is part of this endeavour.

3. MATERIALS AND METHODS

3.1 Description of the study area

3.1.1 Location

The study was carried out at Muhu catchment within Bomalang'ombe village in Iringa region. The catchment is 4.87square kilometres, located 80 km south of Iringa town. The location is at latitude 8°21' South and longitude 35°35' East (Figure 3.1) The altitude is about 2000 meters above sea level.

3.1.2 Rainfall

The area is within the southern highlands of Tanzania and receives an annual rainfall ranging from 1200 to 1400 mm (URT, 1976). The area has two distinct seasons. The wet season which begins in December and extends to May. The dry season extends from June to November.

3.1.3 Temperature

The temperature has been modified slightly compared to other tropical regions due to altitude. The area is cool with mean monthly temperatures ranging from 10.7°C to 17.5°C (HIMA, 1997). The area experience a maximum temperature in January and a minimum temperature in July. The rainy season months are warm compared to dry season months.

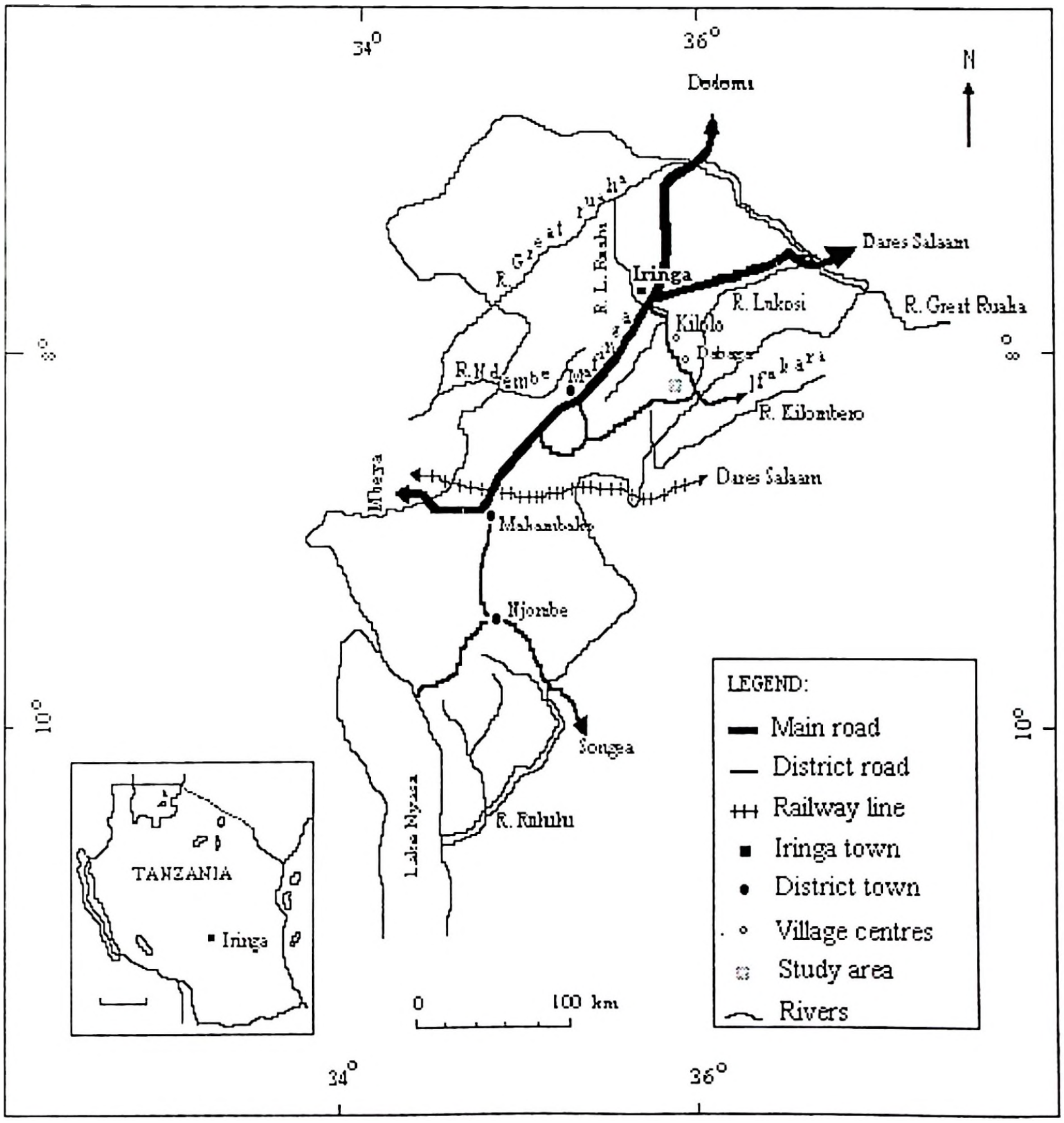

Figure 3.1: Map of Iringa region showing the study area

3.1.4 Evapotranspiration

The annual evapotranspiration ranges from 995 mm to 1138mm. Generally it exceeds rainfall only during the dry season months. Relative humidity, wind speed and radiation, factors known to have effect on evapotranspiration, are respectively 80%, 103km/day, and 1175 W/m^2 on average (HIMA, 1997).

3.1.5 Topography

The catchment has a steep rugged terrain (i.e. dissected steep convex slopes). The area has a range of small hills arranged in an undulating fashion. Such terrain makes the area to have a wide range of altitude, from 1880 m to 2040 above sea level. The escarpments are very steep and covered by vegetation.

3.1.6 Geology

The deep layers of this catchment consist of the pre-Cambrian metamorphic rocks. These rocks are mainly composed of gneiss, amphibolites, granulates, schists, quartzite and migmatites. They form the bed rock in the catchment (i.e. origin of the soils).

3.1.7 Soils

Soils in this area are weathered, leached, and are classified as sandy clay loam. Such soils are easy to work with and do not form very stable aggregates. Generally they are darkish in colour. They have high organic matter content which helps improve the aggregates. The soils are deep and well drained supporting a variety of crops and vegetation. The soil profile is well layered (i.e. mature soil) (URT. 1976).

3.1.8 Vegetation

The area is covered by various types of vegetation. The human activities such as cultivation. timber production and fuel (charcoal) have put pressure on the forest. This has resulted to a mixture of vegetation which consists of plantation forest. patches of natural forest with shrubs and grasses and cultivated crops. The predominant tree species include Eucalyptus. Pine and Black wattle. The main crops cultivated are maize. beans. Irish potatoes and sweet potatoes. There is more surface cover in the middle of the wet season as a result of growth from the crops.

3.1.9 Hydrology

The catchment has five tributaries contributing to the main stream - Muhu. Muhu is a small perennial stream supporting the Bomalang'ombe village and other small villages downstream. The catchment does not receive external runoff. The stream drains into a small river called Lukosi. The catchment is part of the source area for this river (i.e. part of Lukosi river basin). The Lukosi river drains into the Great Ruaha river.

3.2 Instrumentation and measurement

3.2.1 Determination of soil textural classes

The catchment was divided into square grids of 300m by 300m resulting in a total of 54 plots. A systematic composite sampling plan as outlined by Peterson and Calvin (1985) was adopted whereby a central position in each of the 54 plots was used as a site. A total of 54 soil samples were obtained for determination of particle size distribution and organic carbon. The pipette method and the sieve test method as outlined by Kemper and Chepil (1985) were used to determine particle size distribution. The Walkey - Black dichromate method (Peterson and Calvin, 1985) was used to determine organic carbon. The percentage of the various soil particles as obtained from the particle size distribution analyses, was used in the textural triangle to obtain the textural class of each sample. The data from organic carbon analyses were used to estimate the organic matter content in each sample. After compiling the data the modal soil profile was classified according to the FAO–UNESCO Legend (1989).

3.2.2 Measurement of bulk density

Samples for bulk density determination were obtained in the 54 sites described in section 3.2.1. The core method as described by Blake (1985) was used to determine the bulk density. Core samples were taken at three different depths: 0-15cm, 15-

30cm and 15-45 cm. in each site. The cores were oven dried until a constant weight was reached, and bulk density was calculated using the following equation:

$$BD\ (g/cm^3) = \text{weight of oven dry soil} / \text{volume of core} \qquad (3.1)$$

3.2.3 Measurement of infiltration

Infiltration tests were conducted in 54 sites within the catchment. The catchment was divided into 54 plots as explained in section 3.2.1. A systematic sampling plan as outlined by Peterson and Calvin (1985) was adopted whereby a central position in each of the 54 plots was used as a site. The infiltration rate was determined using the method by Wigham (1970) whereby the double ring infiltrometer which consisted of an inner ring (27.8 cm diameter), and an outer ring (54.5 cm diameter) was used.

3.2.4 Determination of soil hydraulic conductivity

The same sites used for infiltration were used for hydraulic conductivity. The saturated hydraulic conductivity was determined using the inverted auger hole method as outlined by Landon (1991). An auger hole was dug to a depth (D) of 0.7 meters. The hole was filled with water till sufficient water had seeped into the surrounding soil to create a fairly saturated zone, and this took two to three hours on average depending on the soil type. The rate of the falling water in the hole was recorded (Figure 3.2). The data was used to calculate hydraulic conductivity (Ks) using the equation below:

$$Ks = 1.15r\left[\frac{\log(h(ti) + r/2) - \log(h(tn) + r/2)}{tn - ti}\right] \tag{3.2}$$

where:

h(ti) = height of water level in the auger hole at time ti measured from the bottom.

h(tn) = height of water level in the auger hole at time tn measured from the bottom.

r = radius of the auger hole.

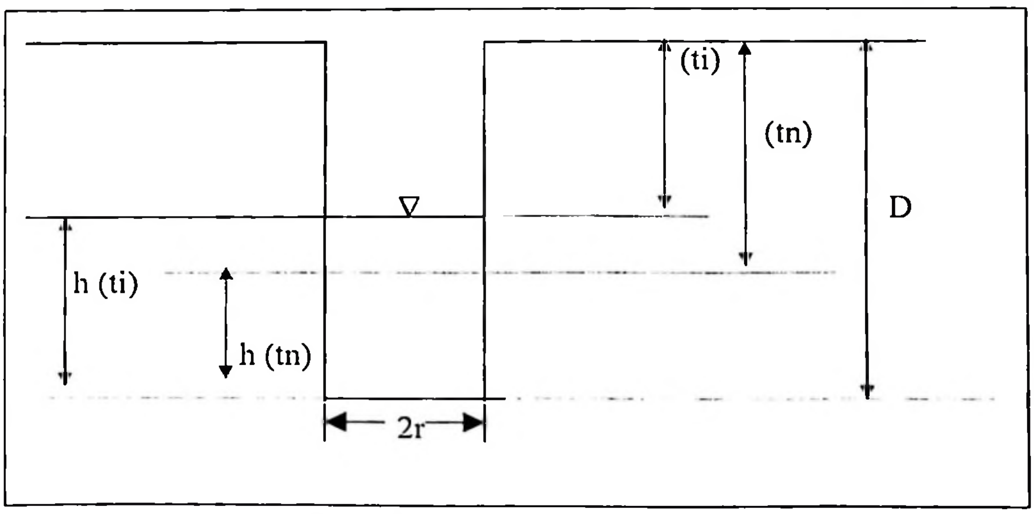

Figure 3.2: Inverse auger -hole method

3.2.5 Measurement of the surface cover

Two sighting frames were used for measuring surface cover for both tall and short vegetation as recommended by Elwell and Waandar (1977) (Plates 3.1 and 3.2). A 1.3 meter tall sighting frame (Plate 3.1) with a length of one meter was used to measure surface cover for short vegetation (i.e. less than 1.3 meters in height). Along the one meter length there were ten holes placed at equal distances which were used for sighting the vegetation. The legs were flexible to move and sharpened at the end, making it easy to level the frame using a sprit level. A 0.7 meter tall sighting frame with the same length as above (Plate 3.2) was used to measure surface cover for tall vegetation. It was having an additional arrangement of a mirror in the central position, with the upper section being flexible to be tilted to an angle of ten degrees in either direction. The mirror reflected the canopy of the tall vegetation, and measurements were taken at a tilted position of the upper section to avoid interference from the face of the observer. For both frames, if the hole was having half or more coverage, the surface was considered to be covered. If less than half, the surface was considered as not covered.

A total of forty stations were selected using a stratified random sampling procedure. The stratification was based on land use and vegetation type (i.e. forest, cultivated, grassland and shrubs). In each station there was a 1m x 1m plot, where measurements were taken (Elwell and Waandar, 1977).

Plate 3.1: Sighting frame for short vegetation

Plate 3.2: Sighting frame for tall vegetation

The sighting frame was moved at intervals of ten cm along the sides of the square plot, resulting in a total of 100 sightings. The measurements were done every 14 days.

3.2.6 Determination of the slope of the catchment

A contour map was used to calculate slopes for the catchment. An average slope for the catchment was calculated using the method by Chow (1964):

$$S = \frac{MN}{A} 100 \qquad (3.3)$$

where:

S = Slope (%)

M = Total length of contours within the catchment (m)

N = Contour interval (m)

A = Size of the catchment (m^2)

3.2.7 Climatic variables

3.2.7.1 Rainfall amount, duration and intensity.

The standard rain gauge with 12.7 cm (5 inch) diameter was used during the course of the catchment experiment to measure rainfall. Three standard rain gauges were placed within the catchment in an open area to measure the gross rainfall of the catchment. The gauges were placed using stratified random sampling procedure. The widest width across the main stream was divided into three strata, each being approximately one kilometre wide. One rain gauge was randomly placed in each of these strata and their location is shown in Figure 3.3. The measurements were taken at 9.00 a.m. every day using a standard rain gauge measuring cylinder. The rainfall data from the standard rain gauge was compared with that obtained automatically by the automatic recording rain gauge. The recording gauge was in the weather station. The data from the automatic rain gauge was used to calculate the rainfall intensity and duration for each storm.

3.2.7.2. Other climatic parameters

Other climatic parameters recorded from the catchment included temperature, relative humidity, wind speed and solar radiation. These were recorded automatically from the automatic weather station using sensors that detected changes of the respective parameters, and sent the data to a data logger. A computer was used to download the data from the logger for processing. Location of the weather station is shown in Figure 3.3.

3.2.7.3 Determination of evapotranspiration

The climatic data from the automatic weather station was used to determine evapotranspiration. The INSTAT (Stern et al., 1991) package was used to calculate potential evapotranspiration using the following climatic parameters: temperature, relative humidity, wind speed, solar radiation and rainfall.

3.2.8. Throughfall, stemflow and interception

3.2.8.1 Throughfall

The area was divided into square grids of 300m x 300m as shown in Figure 3.3, resulting in a total of 54 plots. A survey was done to make a quick notion of tree variation and density within each plot. This formed a basis for placing plots for measurement of throughfall and stemflow. Throughfall was measured by standard (12.7 cm diameter) rain gauges which were placed within the experimental area. The fixed area plot method as described by Kulow (1966) was used whereby 0.1 ha plots were located on the basis of tree variation and density. A total of four plots were used in the experiment (Figure 3.3). Each of these plots were divided into ten grids. A total of six rain gauges were randomly allocated per plot. The measurements were taken at 9.00 a.m. every day using a standard rain gauge measuring cylinder. It was not possible to take readings after every storm due to double storms at night.

3.2.8.2 Stemflow measurement

The method used by Bruijnzeel (1990) was employed in this study. In the same plots where throughfall measurements were taken, a total of six trees with varying stem size were randomly selected for stemflow measurements. An ordinary garden hose was slit into halves, wrapped spirally twice around the trunks, and secured to it with nails. The hose drained into a 20-liter container. An adhesive (putty) was used to close the gap between the hose pipe and the trunk to ensure that there was no leakage

(Plate 3.3). The volume of water collected in the container was converted to depth. in mm by dividing it with the crown area. The measurements were taken at the same time as throughfall. For each tree used for stemflow the following data were collected: diameter at breast height (m). spread of crown. and name of tree species.

3.2.8.3 Determination of interception

For each of the plots where throughfall and stemflow measurements were being conducted. a nearby site in an open area was used to place a standard rain gauge to measure gross rainfall. The amount of water intercepted was determined by getting the difference between gross rainfall and net rainfall (throughfall and stemflow) as described in section 2.3.1 and by equation (2.3). The intercepting capacity (C) was derived from the slope and y-intercept of a linear regression of throughfall (T) versus rainfall (P) using data of individual storms as described in section 2.3.1 and by equation (2.5).

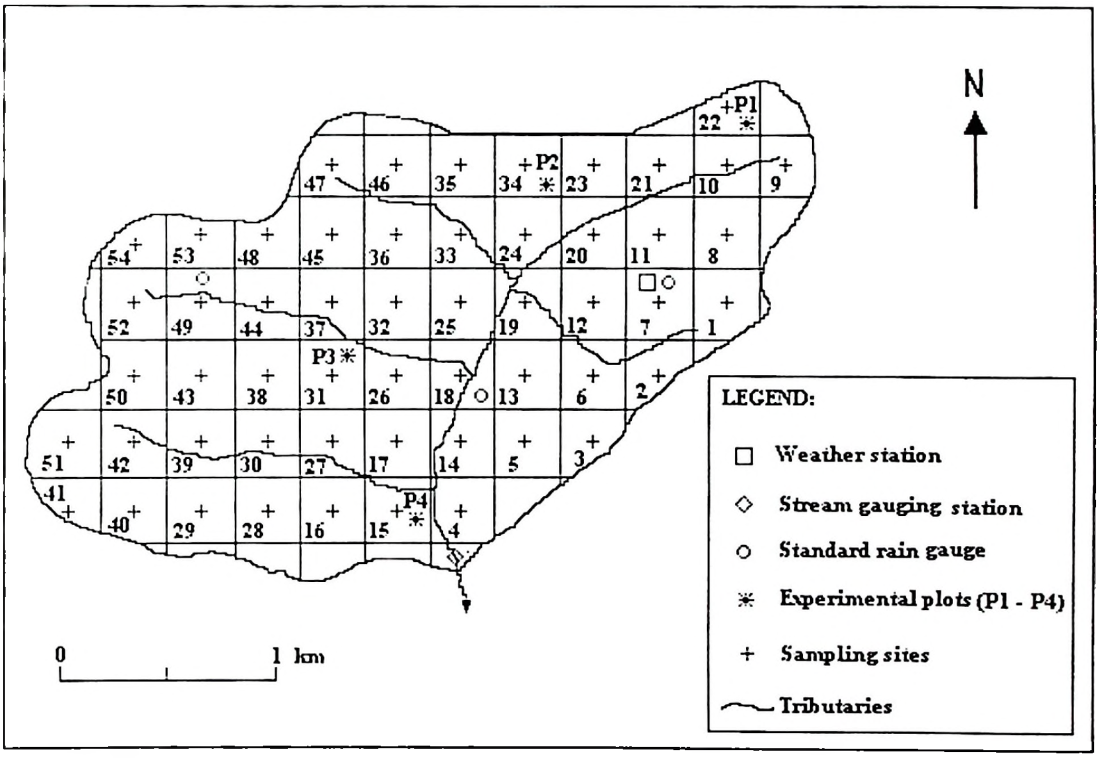

Figure 3.3: Muhu catchment (HIMA, 1997) with location of sampling sites, experimental plots, stream gauging station, weather station and standard rain gauges.

Plate 3.3: Stemflow measurement

3.2.9 Stream flow measurements

The stream flow from the catchment was gauged using an automatic water level recorder and staff gauges to generate stream flow data. The water level was converted to discharge using an established rating curve for the stream.

In order to obtain direct runoff, the mean daily discharge was plotted against time to get the monthly hydrographs. A technique by Linsely et al. (1988) was used to separate monthly base flow and direct runoff. The technique involved extending the recession that existed before the storm to a point under the peak of the hydrograph.

A straight line from this point was drawn to an arbitrary point on the lower portion of the recession segment of the hydrograph. In case of complex hydrographs. division between bursts of rain was usually accomplished by projecting the small segment of recession between peaks.

3.3 Model development

The runoff and water balance models were developed empirically using multiple linear regression. For each year the monthly runoff was regressed against throughfall. stemflow. infiltration rate. evaporation. rainfall intensity. rainfall duration. and precipitation as shown in equation (3.4). From this. regression coefficients for each parameter were obtained. Also the estimated water balance for each month was regressed against throughfall. stemflow. evaporation. runoff and precipitation as shown in equation (3.5). Change in water storage was estimated using equation (2.1) as outlined in section 2.1.1 above. Water balance empirical models for the catchments were developed based on multiple regression coefficients:

$$DRO = f(\,T, S, I, E, Ri, Rd\, P,\,) \qquad (3.4)$$

$$W = f(\,T, S, I, E, DRO\,, TR, Ri, Rd, P) \qquad (3.5)$$

where:

DRO = runoff

W = change in water storage

f = function

T = throughfall

S = stemflow

I = interception

E = evaporation

Ri = rainfall intensity

Rd = rainfall duration

P = precipitation

TR = total runoff

3.4 Model evaluation and validation

The nearby Gendavaki catchment was used to test and validate the models. The runoff and water balance model were used to predict the runoff and water balance respectively. The predicted parameters were compared with observed parameters using a t-test. This was done to assess whether the predicted and observed parameters were significantly different from each other or not. This indicated the capability of the model to predict the respective parameters.

4. RESULTS AND DICUSSION

4.1 Introduction

This chapter presents the results and discussion in relation to the four specific objectives: identification of the major catchment characteristics which include soil texture, bulk density, infiltration, hydraulic conductivity, surface cover, and slope; taking inventory of the climatic parameters which include temperature, relative humidity, wind speed, radiation, rainfall amount, rainfall intensity, rainfall duration, and evapotranspiration; assessment of throughfall, stemflow, interception, and runoff in the catchment; and development and validation of an empirical water balance model.

4.2 Catchment Characteristics

4.2.1 Texture

The soils generally have high proportion of sand and clay particles as shown in Table 4.1. The proportions varied across the locations as shown by the standard deviations from the same table, with a range of 7 to 56% clay, 3 to 19% silt, and 32 to 82% sand. Among the 54 soil sites studied, 24 are sandy clay, 22 are sandy clay loam, 5 are clay, 2 are sandy loam and one loam sand. The catchment, therefore is predominantly sandy clay and sandy clay loam. Such texture suggests moderate drainage, infiltration and hydraulic conductivity (Dieleman and Trafford, 1976).

Table 4.1: Soil physical and hydrological properties

Site	%Clay	%Silt	%Sand	%OC	%OM	Text. Class	Bulk Density 0-15 cm	Bulk Density 15-30 cm	Bulk Density 30-45 cm	Soil Moist %	Ks cm/hr	Inf. cm/hr	Cum Inf. cm
1	7	11	82	3.4	5.8	LS	1.3	1.3	1.5	18.2	18.7	17.8	169.3
2	40	13	47	5.9	10.2	SC	0.6	1.1	1.3	31.4	2.4	2.4	59.5
3	56	12	32	3.6	6.2	C	0.9	1.2	1.4	34.3	1.2	1.2	13.5
4	48	14	38	5.6	9.6	C	0.9	1.1	1.4	35.1	1.2	1.1	32.9
5	50	14	36	4.9	8.4	C	1.0	1.2	1.3	40.6	1.5	1.4	56.7
6	52	12	36	4.9	8.4	C	0.9	1.1	1.4	38.2	1.1	0.8	14.7
7	45	10	45	5.3	9.1	C	0.8	1.1	1.3	33.0	1.7	1.4	40.7
8	36	8	56	3.5	6.1	SC	1.0	1.1	1.3	22.1	3.7	3.2	32.1
9	43	12	45	4.9	8.5	SC	0.9	1.3	1.5	32.8	2.3	2.2	26.1
10	38	10	52	4.6	7.9	SC	0.9	1.3	1.5	22.6	3.1	2.8	20.0
11	43	10	47	5.1	8.7	SC	0.8	0.6	1.0	25.1	3.2	2.6	31.4
12	46	9	45	5.5	9.4	SC	1.0	1.1	1.3	34.9	2.1	2.2	50.1
13	31	11	58	5.3	9.2	SCL	0.7	0.9	1.1	29.3	4.8	4.2	31.1
14	34	14	53	5.2	9.0	SCL	0.9	1.2	1.4	29.8	3.9	3.3	50.8
15	43	10	47	5.2	9.0	SC	1.0	1.1	1.1	23.6	3.4	2.6	38.9
16	32	8	60	5.4	9.3	SCL	0.9	1.0	1.3	25.0	5.0	4.3	23.9
17	38	9	53	5.4	9.3	SC	0.8	1.0	1.1	22.5	3.2	3.0	28.5
18	34	10	56	5.3	9.1	SCL	0.9	1.2	1.4	29.5	4.1	3.8	56.7
19	23	12	65	5.5	9.4	SCL	0.8	1.2	1.4	24.6	4.5	4.4	33.3
20	36	10	54	5.3	9.0	SC	0.9	0.9	1.2	22.2	3.7	3.0	27.1
21	43	12	45	5.7	9.8	SC	0.7	1.1	1.3	33.6	2.4	2.4	31.7
22	40	8	52	5.2	8.9	SC	0.9	1.0	1.4	22.6	3.6	2.8	29.0
23	30	12	58	6.3	10.9	SCL	0.6	1.0	1.2	28.9	4.3	4.2	39.9
24	45	8	47	5.4	9.3	SC	0.8	1.0	1.3	25.4	3.1	2.6	52.4
25	36	6	58	5.3	9.1	SC	0.9	1.1	1.2	22.0	3.8	3.2	53.9
26	47	8	45	5.2	8.9	SC	0.9	1.2	1.2	33.3	2.4	2.4	58.0
27	38	10	52	5.2	8.9	SC	1.0	1.2	1.3	22.9	3.1	2.8	58.8
28	31	11	58	5.4	9.3	SCL	1.0	1.3	1.4	28.8	5.0	4.2	56.4
29	41	12	47	5.1	8.7	SC	1.0	1.1	1.3	25.0	3.0	2.6	17.7
30	11	9	80	3.6	6.2	SL	1.0	1.3	1.5	18.7	18.0	17.2	158.6
31	43	10	47	5.3	9.2	SC	1.0	1.2	1.3	24.1	3.3	2.6	88.3
32	34	12	54	5.7	9.8	SCL	1.1	1.2	1.3	29.7	4.0	3.4	46.5
33	32	12	56	4.7	8.1	SCL	0.9	1.1	1.3	29.1	4.1	3.8	55.7
34	38	11	51	4.2	7.2	SC	1.1	1.3	1.3	23.1	2.8	2.4	56.6
35	32	12	56	5.2	9.0	SCL	0.9	1.0	1.3	29.2	3.4	3.2	27.4
36	34	14	52	3.3	5.7	SCL	1.2	1.3	1.3	30.0	3.8	3.2	48.3
37	36	10	54	5.5	9.4	SC	0.9	1.1	1.2	22.3	3.7	3.0	34.0
38	34	12	54	5.7	9.8	SC	0.6	0.8	1.2	22.4	3.7	3.0	63.6
39	32	8	60	5.3	9.1	SCL	1.0	1.2	1.4	27.6	5.5	4.4	59.9
40	38	10	52	5.2	9.0	SC	0.9	1.2	1.4	23.2	2.8	2.8	20.2
41	43	10	47	5.2	9.0	SC	0.9	1.2	1.3	23.3	2.9	2.7	66.3
42	36	19	45	5.1	8.7	SC	1.1	1.2	1.3	31.8	2.4	2.2	17.0
43	30	19	51	5.8	10.0	SCL	0.8	1.2	1.3	30.1	3.7	3.2	54.1
44	27	12	61	5.1	8.7	SCL	1.1	1.2	1.5	24.8	4.4	4.4	71.4
45	38	8	54	5.3	9.2	SC	0.9	1.0	1.3	22.4	3.7	3.0	45.8
46	25	10	65	5.7	9.7	SCL	0.8	1.1	1.3	24.6	3.8	4.4	61.8
47	30	14	56	5.2	9.0	SCL	0.9	1.1	1.4	29.3	4.0	3.8	67.8
48	34	12	54	5.3	9.1	SCL	0.9	1.0	1.3	29.6	4.0	3.4	88.0
49	25	17	58	5.3	9.1	SCL	0.9	1.1	1.3	29.4	4.9	4.2	56.6
50	28	18	54	5.3	9.2	SCL	1.0	1.2	1.3	29.5	3.9	3.4	66.1
51	34	14	52	5.7	9.8	SCL	0.7	0.9	1.3	30.1	3.8	3.2	57.2
52	34	8	58	5.4	9.3	SCL	0.8	1.1	1.3	28.2	5.3	4.3	31.1
53	32	12	56	5.0	8.6	SCL	1.1	1.2	1.4	29.4	4.0	3.6	64.8
54	16	10	80	3.9	6.7	SL	1.1	1.2	1.3	25.0	17.9	17.0	183.5
Av.	35.6	11.3	53.3	5.1	8.8		0.9	1.1	1.3	27.5	4.2	3.8	51.2
SD	9.1	2.8	9.6	0.6	1.1		0.1	0.1	0.1	4.8	3.6	3.4	31.0

KEY:
C = CLAY = 5 sites
SCL = Sandy Clay Loam = 22 sites
SC = Sandy Clay = 24 sites
SL = Sandy Loam = 2 sites
LS = Loam Sand = 1site

NB: Soil moisture reported was taken at the time of sampling
OC = Organic carbon
OM = Organic matter = 1.72 * (%OC)

4.2.2 Bulk Density

The bulk density results are presented in Figure 4.1 and Table 4.1. It ranged from 0.59 - 1.26g/cm^3 for 0-15cm depth ; 0.63 - 1.26 g/cm^3 for 15-30 cm depth, and 1.18 - 1.46 g/cm^3 for 30 - 45 cm depth . There was little variation between sites within the respective depths. This is shown by the relatively small standard deviation of 0.14, 0.13 and 0.10 for the respective depths (Table 4.1). Generally, the bulk density increased with depth with an overall average of 0.9g/cm^3 for 0 - 15 cm depth, 1.11g/cm^3 for 15 to 30 cm depth, and 1.30g/cm^3 for 30 to 45 cm depth. Similar results have been observed by various researchers (Lal and Cumming, 1979; Mahoo, 1992). According to Taylor et. al (1966) the observed range of bulk density is suitable for root penetration. The low bulk densities are partly due to high organic matter content which is indicated in Table 4.1.

4.2.3 Infiltration

The steady state and cumulative infiltration were 3.8 cm/h and 51.2 cm respectively (Table 4.1). The equations for generating both infiltration curves for each site are presented in Appendix A.

Table 4.2 shows a comparison of the average steady state infiltration and cumulative infiltration between the different textural classes. The variation between sites was mainly due to the differences in soil texture. It can be seen from Table 4.2 that sites with sandy loamy and loamy sand texture had extremely high steady state infiltration rate (17.8 cm/h, 17.2 cm/h, 17 cm/h) and cumulative infiltration (183.5 cm, 158.6cm, 109.3cm.) compared to the rest. This is attributed to the high sand fraction of 80% and above. The lowest steady state infiltration (0.8 cm/h) was from sites with clay soils. According to suggested infiltration categories by BAI (1979) the sites had a moderate to rapid infiltration rate. The trend of increasing infiltration with respect to texture (i.e. from clay to loamy sand) depicted in Table 4.2 is in accordance with the guide by Israelsen and Hansen (1962) and FAO (1979). Many studies have shown that infiltration rates from forest soils or soils of areas that were previously forests is generally high. Dunne (1978) reported infiltration rates of 8.0 cm/hr and above in a pasture that was previously pine woodland. The high infiltration rates are associated with the high organic matter content and surface cover.

4.2.4 Modal soil profile

The modal soil profile was classified as Humic acrisols according to FAO – UNESCO Legend (1989). It was generally having weathered leached soil containing large amounts clay minerals, high organic carbon, rich in organic matter content and fairly fertile.

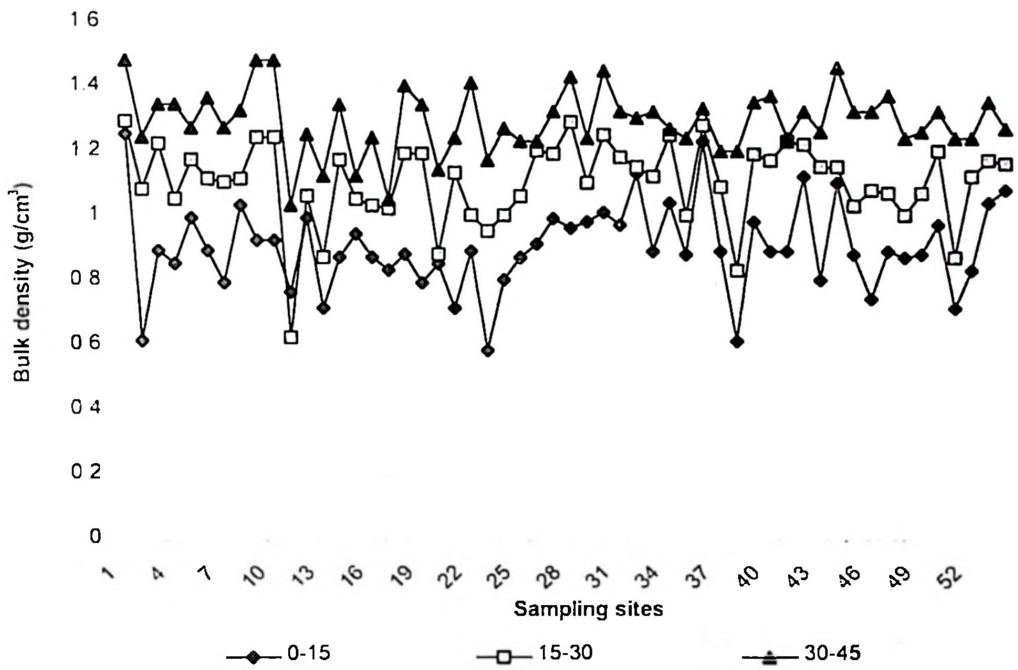

Figure 4.1: Soil bulk density measured at 54 different sites at Muhu

Table 4.2: A comparison of the hydrological properties between sites of different texture

Textural class	No. of sites	Av. Ks (cm/hr)	Av. Inf. (cm/hr)	Av. Cum. Inf. (cm)
Clay	5	1.31	1.17	31.70
Sandy Clay Loam	22	4.30	3.80	52.20
Sandy Clay	24	3.08	2.69	41.76
Sandy Loam	2	18.00	17.1	171.6
Loamy Sand	1	18.70	17.8	109.3
Total / Av.	54	4.2	3.8	51.2

4.2.5 Hydraulic conductivity

Table 4.1 shows the values of hydraulic conductivity as measured from 54 sampling sites. The overall hydraulic conductivity of the catchment was 4.2 cm h. It varied from one location to another as shown by the standard deviation of 3.6 (Table 4.1). The range was from 18.7 cm/h to 1.1cm/h. Table 4.2 shows that the soils with high clay content were generally having low saturated hydraulic conductivity, yet in those with high sand fraction it was moderately rapid. These results are in agreement with the general guide by Smedema and Rycroft (1983) shown in Table 4.3. However, the catchment can be generally classified to have moderately rapid hydraulic conductivity according to the classification by FAO (1963).

Table 4.3: Saturated hydraulic conductivity related to soil texture

Texture	Ks cm/h	Ks m/day
Coarse gravel sand	42 - 208	10 - 50
Medium sand	4.2 - 20.8	1 - 5
Sandy loam / fine sand	4.2 - 12.5	1 – 3
Loam / Clay loam / - well structured	2.1 - 8.3	0.5 - 2.0
Very fine sand	0.8 - 2.1	0.2 - 0.5
Clay loam / clay / - poorly structured	0.08 - 0.8	0.02 - 0.2
Dense clay, not cracked and no bio-pores	<0.008	<0.002

Source: Smedema and Rycroft, 1983.

4.2.6 Surface cover

The percent surface cover increased as the season progressed (Figure 4.2). At the beginning of the rainy season, surface cover was 48%, and increased to 84% after 126 days from the beginning of the season. The gradual increase of the surface cover was attributed to plant growth. The increase in foliage resulted in higher proportions of the surface being covered. The forested vegetation has high percent cover compared to Field crops (Figure 4.3). Among the types of vegetation at Muhu catchment, grasses had the highest overall percent cover followed by trees, shrubs, potatoes, beans, maize and sweet potatoes respectively (Figure 4.4). It can be shown from the results that among other things surface cover is influenced by climate and type of vegetation. During the dry season, surface cover reduced due to senescence and reduced growth as a result of little soil moisture.

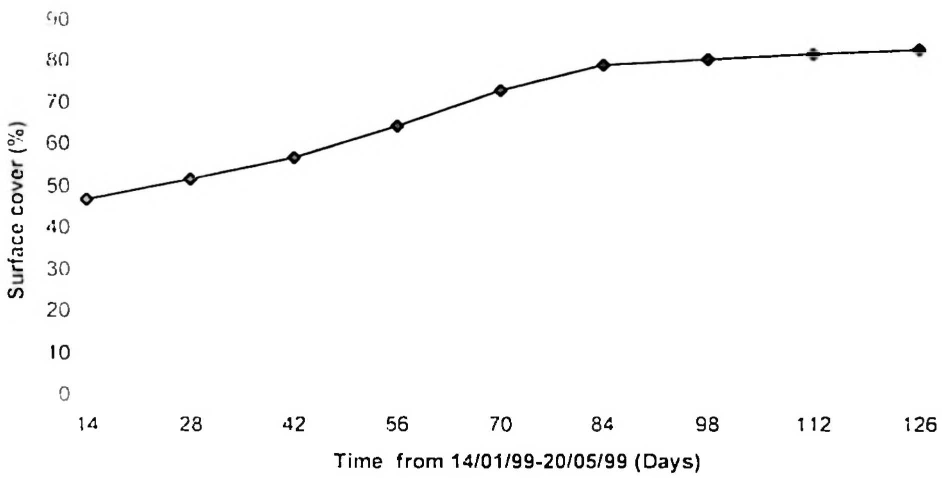

Figure 4.2: Percent cover by a mixture of vegetation at Muhu catchment

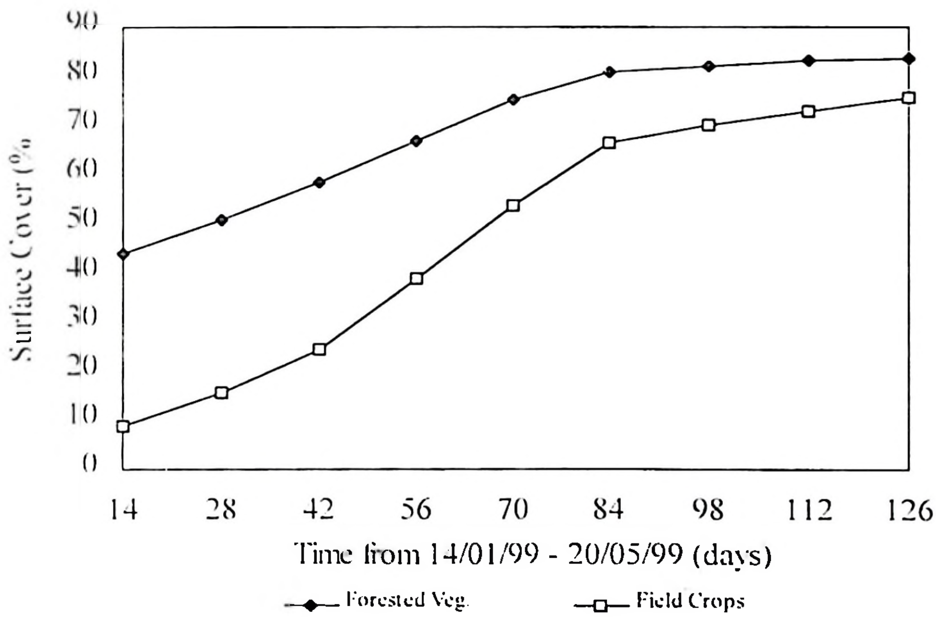

Figure 4.3:The percent surface cover for forest and field crops

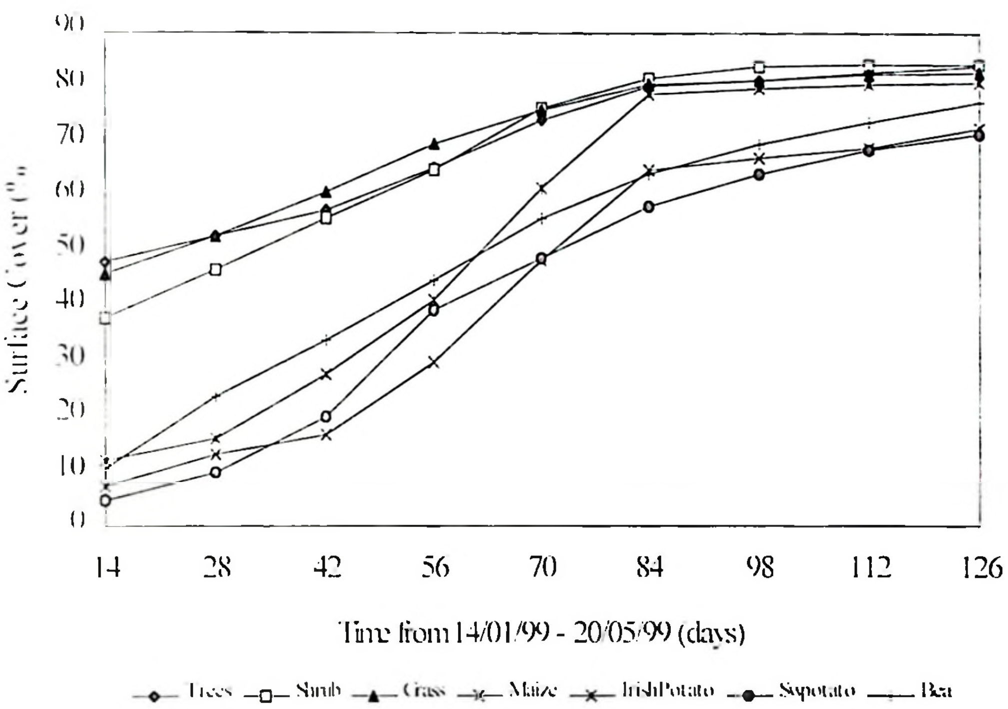

Figure 4.4: Surface cover by various types of vegetation

4.2.7 Slope

A topographic map is shown in Figure 4.5. The contour interval is 0.2 meters. The average catchment slope was calculated using Equation 3.3. The catchment in general has steep slopes with an average slope of 35% . Figures 4.6 (a) to (d) show development of sections A1A2, B1B2, C1C2 and D1D2 respectively. Slope variation across and along the escarpment is depicted in these figures. Figures 4.6b and 4.6c show typical steep slopes of the catchment while 4.6a and 4.6d show slopes slightly above and below the average slope. The valley along the tributaries, and the plateau at the peak are very narrow. According to Chow (1964), the steep slopes increase the velocity of water flow with consequent short time of concentration. The steep slopes combined with high rainfall intensity results in high runoff yield and soil loss (Ogrosselky and Mockusi, 1984).

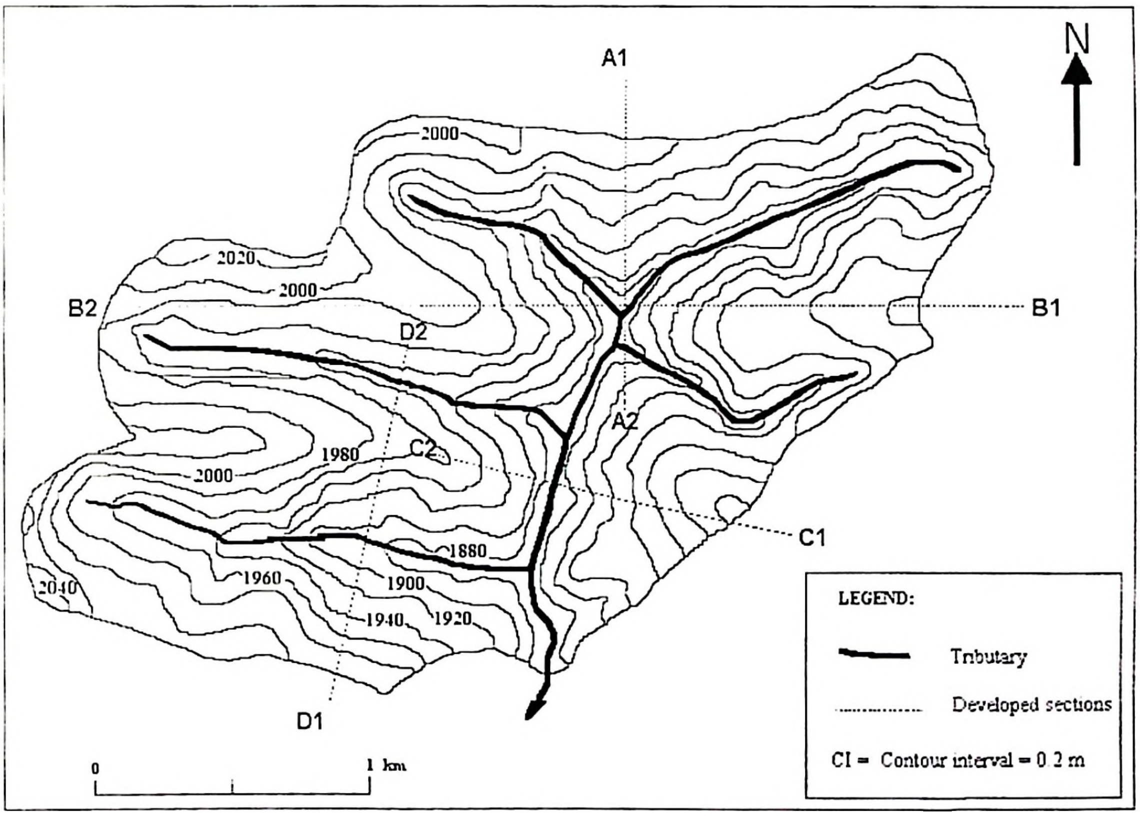

Figure 4.5: Contour map of Muhu catchment

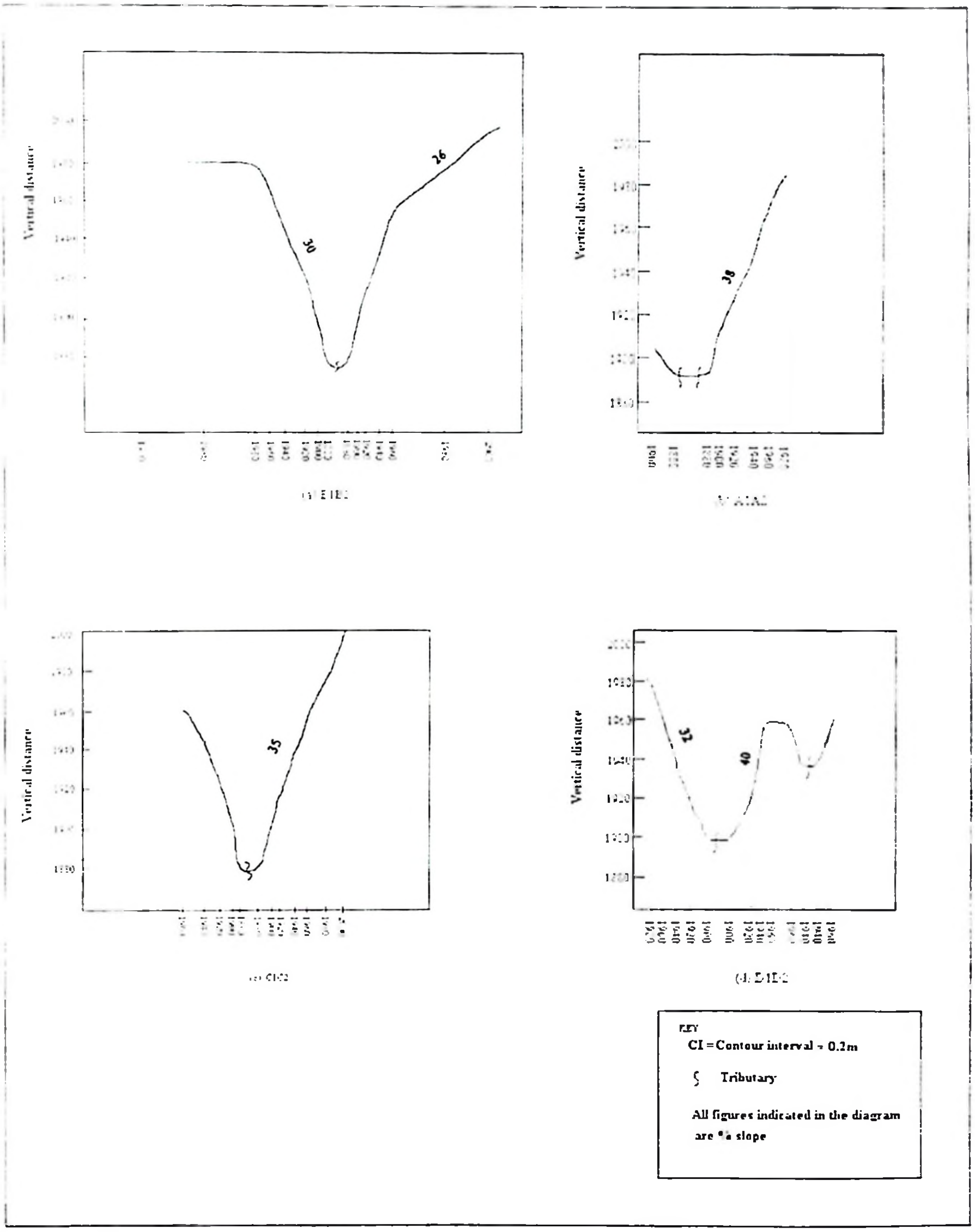

Figure 4.6: Section views of the study area

4.3 Climatic variables

The climatic variables considered and presented in this section include temperature, relative humidity, wind speed, radiation, rainfall amount, rainfall intensity, rainfall duration, and evapotranspiration. A summary of all the climatic variables is presented in Appendix B.

4.3.1 Temperature

The mean monthly temperature for the study area is shown in Figure 4.7. The mean temperature ranged from 10.7 °C to 17.5 °C over the past six years. July is the coldest month with a range of 10.7°C to 11.9°C. January is the hottest month with a range of 16.8 °C to 17.5 °C. The area is generally cool due to the high altitude of about 2000 meters above sea level. The cause of the vertical temperature change is explained by the 'lapse rate' theory which state that there is a decrease in temperature with height in the free atmosphere due dry and saturated adiabatic lapse rates. Crops such as maize take a long time to mature due to the cool temperatures.

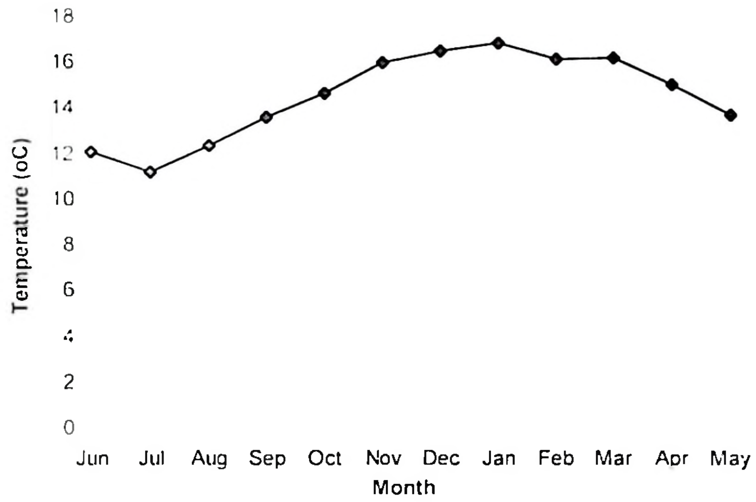

Figure 4.7: Mean monthly temperatures at Bomalang'mbe (1993/94 to 1998/99)

4.3.2 Relative humidity

Figure 4.8 shows the mean monthly relative humidity for the study area. It ranges from 63.2% to 92.9%. The lowest relative humidity is recorded in September which is the middle of the dry season. The highest is recorded in May, the last month of the wet season. The atmospheric condition in this catchment is generally humid. This can be attributed to the existence of four tributaries within the catchment contributing to the main stream, and light showers evenly distributed during the dry season.

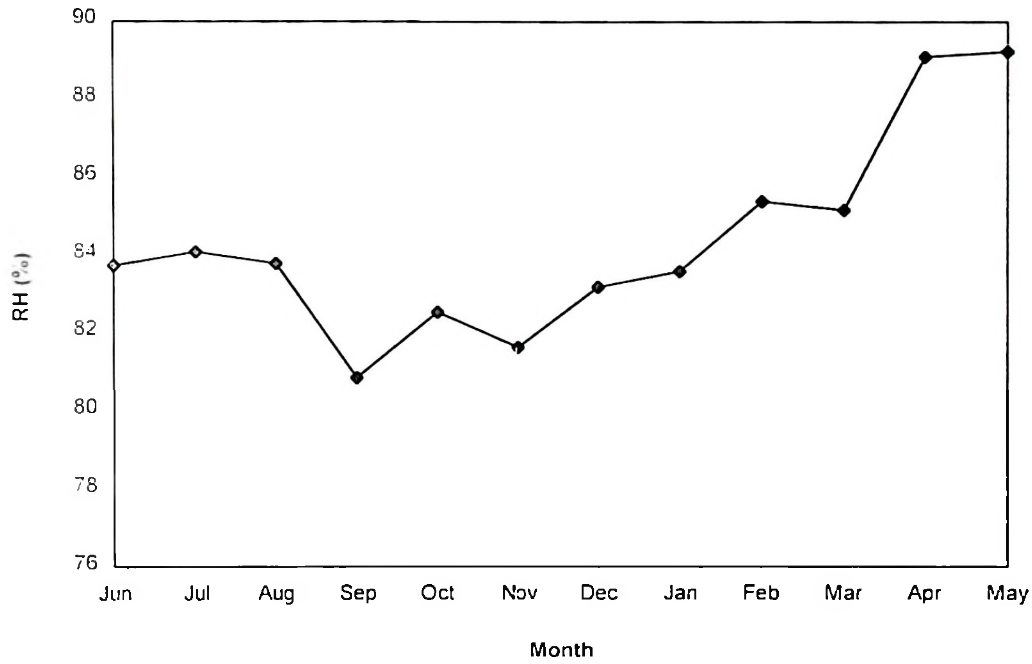

Figure 4.8: Mean monthly relative humidity at Bomalang'ombe (1993/94 to 1998/99)

4.3.3 Wind speed

The mean monthly wind speed ranges from 0.79 m/s to 1.79 m/s (Figure 4.9). Wind speed is generally high between August and November with a range of 1.6 to 1.79 m/s, and low between January and March, with a range of 0.79 to 1.0 m/s. Wind speed has influence on evapotranspiration (ETo). In general the wind speed is low in this area. Pereira (1962) observed that wind speed was generally low in the highlands of East Africa.

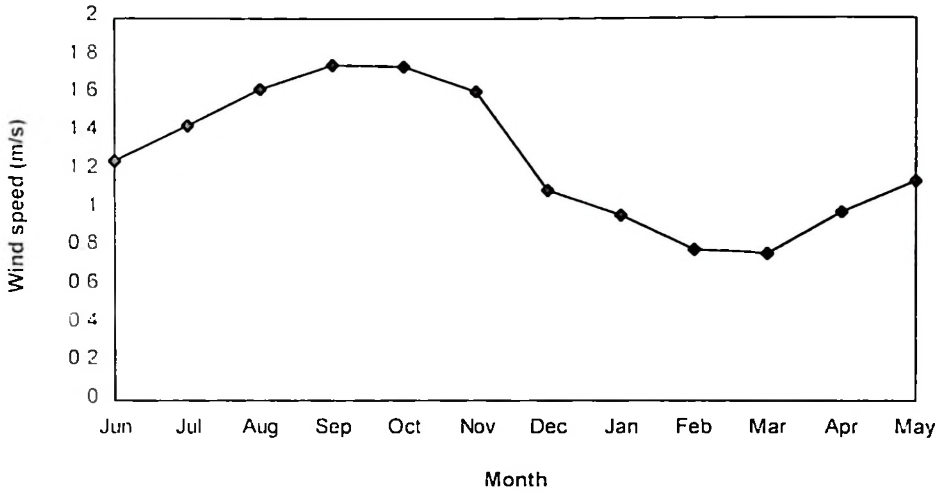

Figure 4.9: Mean monthly wind speed at Bomalang'ombe (1993/94 to 1998/99).

4.3.4 Radiation

Figure 4.10 shows the mean monthly radiation at the Muhu catchment in Bomalang'ombe. It ranged from 140 W/m^2 to 240 W/m^2. Radiation is high between September and January with November having the highest radiation. Radiation is lowest in May. Radiation is the most important energy source for the earth-atmosphere system having major influence on evaporation. According to the observation made in this study mean monthly evapotranspiration was highest in November, the same month in which temperature, wind speed and radiation were highest, and relative humidity was lowest. This agrees with the general concept that evapotranspiration is a function of radiation, temperature, saturation deficit and wind speed (Shaw, 1988).

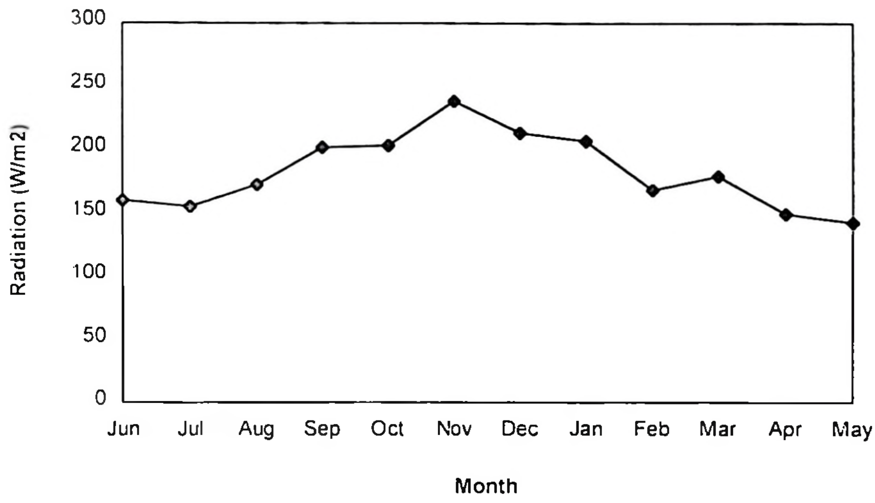

Figure 4.10: Mean Monthly Radiation at Bomalang'ombe (1993/94 to 1998/99).

4.3.5 Rainfall

Mean monthly rainfall and annual rainfall at Muhu catchment for the six years of monitoring are shown in Figures 4.11 and 4.12. The mean monthly rainfall ranged from 8.7mm to 256.1 mm (Figure 4.11). The mean monthly rainfall was highest in April and lowest in June (Figure 4.11). The highest recorded monthly rainfall during this period was 494.6mm in February 1997/98 with probability of exceedance of 7.7% and a return period of about 13 years (Appendix C1).

The annual totals ranged from 1071.1 mm to 1933.9 mm with an annual average of 1364.23mm (Figure 4.12). The highest annual rainfall was recorded in 1997/98. The wettest year was 1997/98 due to El-Niño phenomenon that occurred, bringing unusual heavy rains.

The dry season is between June and November with mean monthly rainfall ranging from 8.7mm to 42.4 mm (Figure 4.11). The wet season is between December and May with mean monthly rainfall of 105.8mm to 256.1 mm. The dry season and wet season are well contrasting and distinct. The catchment can be categorised as moist sub-humid since it has a wet period of six (6) months and annual average of 1346 mm (Raes, 1996).

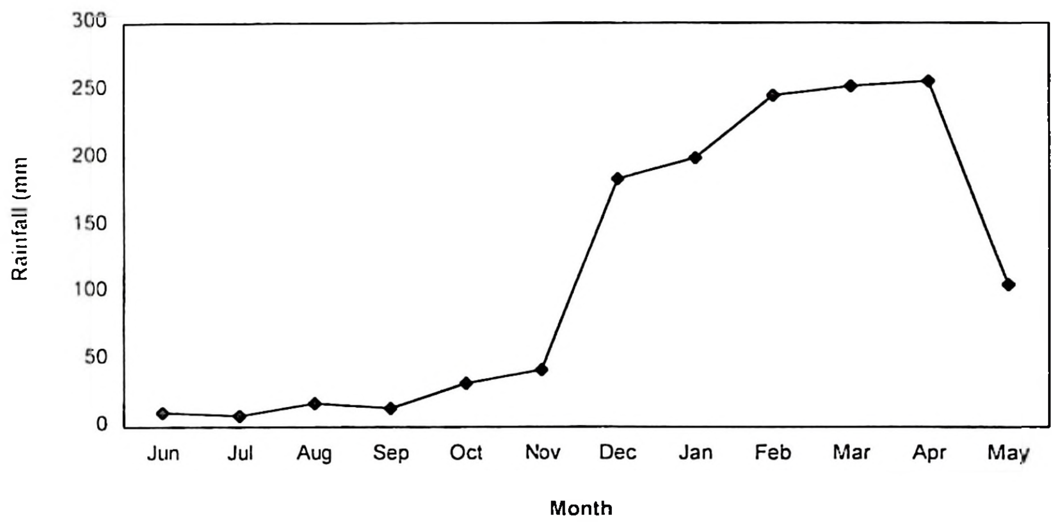

Figure 4.11: Mean monthly rainfall at Bomalang'ombe (1993/94 to 1998/99).

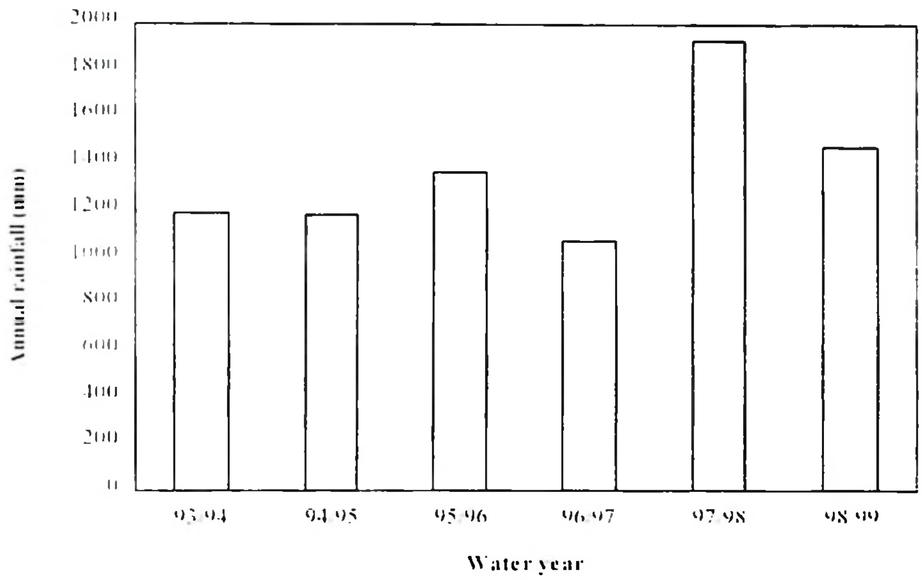

Figure 4.12: Annual rainfall at Bomalang'ombe (1993/94 to1998/99)

4.3.6 Rainfall intensity

The monthly average rainfall intensity results ranged from 2.02 mm/hr to 41.7 mm/hr while the 30 minutes maximum intensity (I30) ranged from 3.2 to 107 mm/hr (Figure 4.13). Rainfall intensity is generally low during the dry season (i.e. June to November). High rainfall intensities are recorded between December and April. The highest recorded monthly average rainfall intensity over the past six years was 49.43 mm/hr with probability of exceedance of 7.7 percent and a return period of 13 years (Appendix C3). When comparing the rainfall intensity with infiltration rate and hydraulic conductivity, it can be observed that on average rainfall intensity is only higher than the respective parameters between December and April. The rains of high intensity between December and January especially the I30 pose an erosion threat since it is immediately after the dry season, a period in which vegetal cover is minimal.

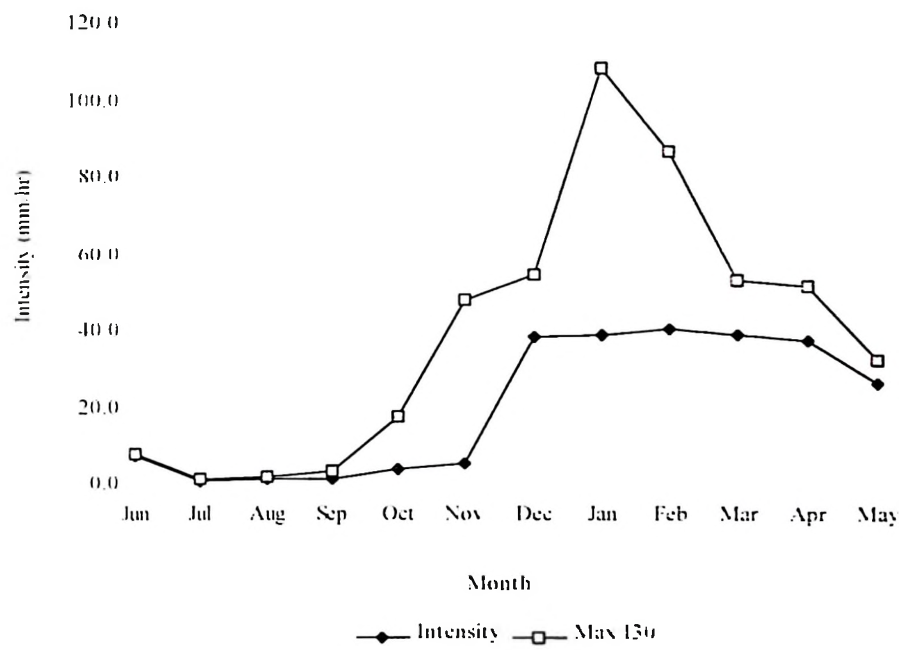

Figure 4.13: Mean monthly rainfall intensity at Bomalang'ombe) (93/94 to 98/99).

4.3.7 Rainfall duration

Figure 4.14 shows the mean monthly storm duration. It ranges from 1.4 hours to 8.4 hours. The lowest storm duration was recorded in June - the beginning of dry season. The highest was recorded in August – in the middle of the dry season. Some wet season months have relatively the same storm duration as dry season months even though rainfall amount is quite different. This is explained by the high rainfall intensity during the wet season. The highest recorded monthly storm duration over the past six years was 28 hours with the same probability of exceedance and return period as the highest intensity above (Appendix C4).

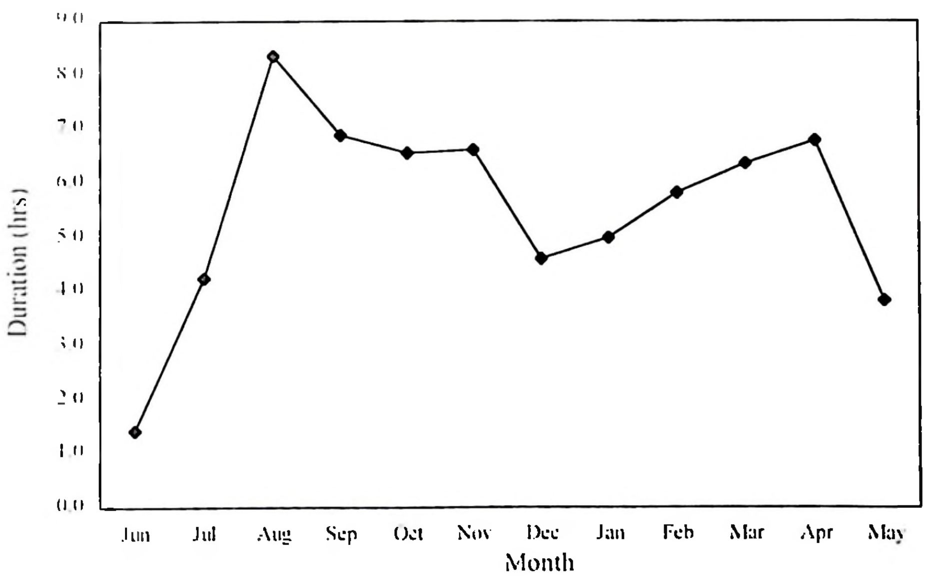

Figure 4.14: Mean storm duration over the study area (Rd) (93/94 to 98/99).

4.3.9 Evapotranspiration

Monthly and annual evapotranspiration (ETo) is shown in Figures 4.15 and 4.16. The maximum mean monthly ETo of 114.1mm was observed in November. The minimum ETo of 63.1 mm was observed in June (Figure 4.15). Both months where maximum and minimum ETo were observed are dry season months. Therefore November, the last month of the dry season, has a greater soil moisture deficit. The highest monthly ETo of 138.84 mm was recorded in December 1998/99 with probability of exceedance of 7.7% and a return period of 13 years (Appendix C2). The lowest monthly ETo was 55.86 mm with probability of exceedance of 92.3% and a return period of about 1.1 years. The annual ETo ranged from 995 mm to 1138 mm with an annual average of 1038 mm (Figure 4.16).

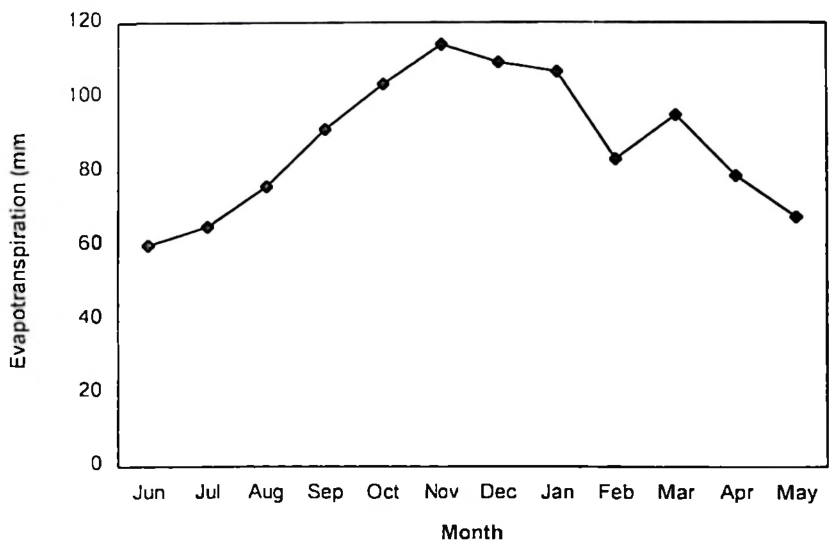

Figure 4.15: Mean monthly evapotranspiration at Bomalang,ombe.

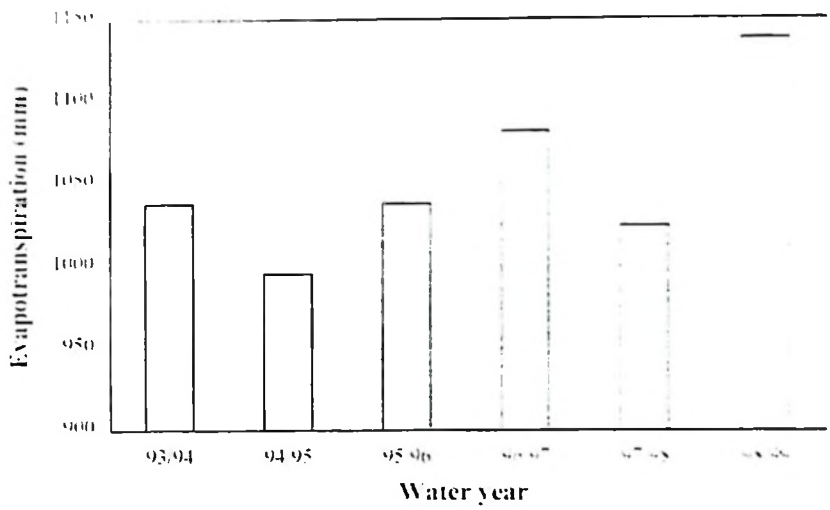

Figure 4.16: Annual evapotranspiration (1993/94 to 1998/99)

4.3.10 Comparison of rainfall and evapotranspiration

A comparison of the monthly and annual rainfall with evapotranspiration (ETo) is shown in Figures 4.17 and 4.18. On monthly basis ETo was higher than rainfall for all the dry season months (June to November) (Figure 4.17). During the wet season ETo is lower than rainfall (i.e. all surplus months). Therefore a greater soil moisture deficit was expected in September while a greater recharge was expected in April. The area is among the 4 % of the East African land surface described by Russell (1962) as receiving a mean annual rainfall greater than the ETo. On annual basis the rainfall was higher than ETo for all the years except 1996/97 (Figure 4.18). In 1996/97, the ETo was 11mm higher than rainfall.

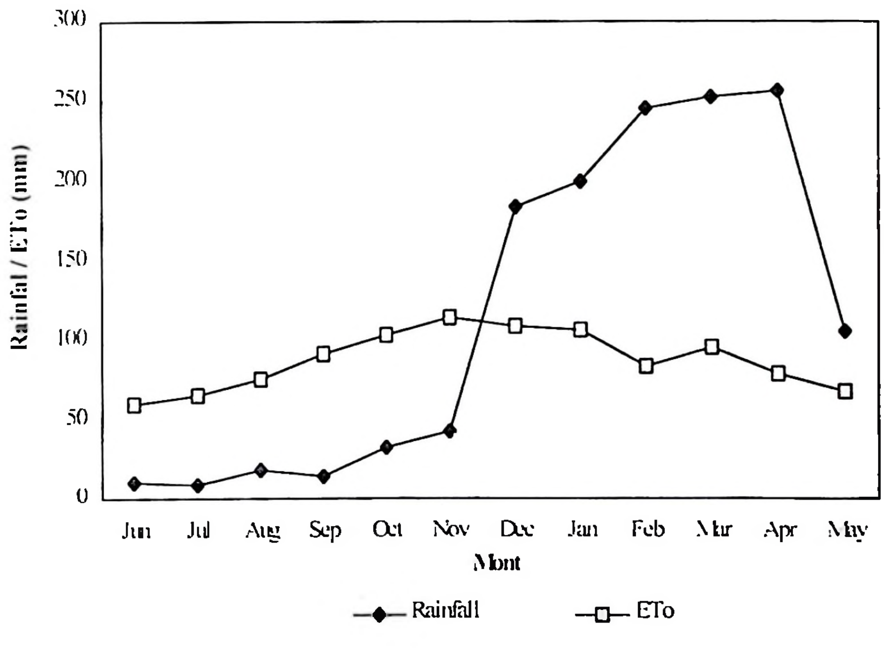

Figure 4.17: Comparison between monthly rainfall and evapotranspiration

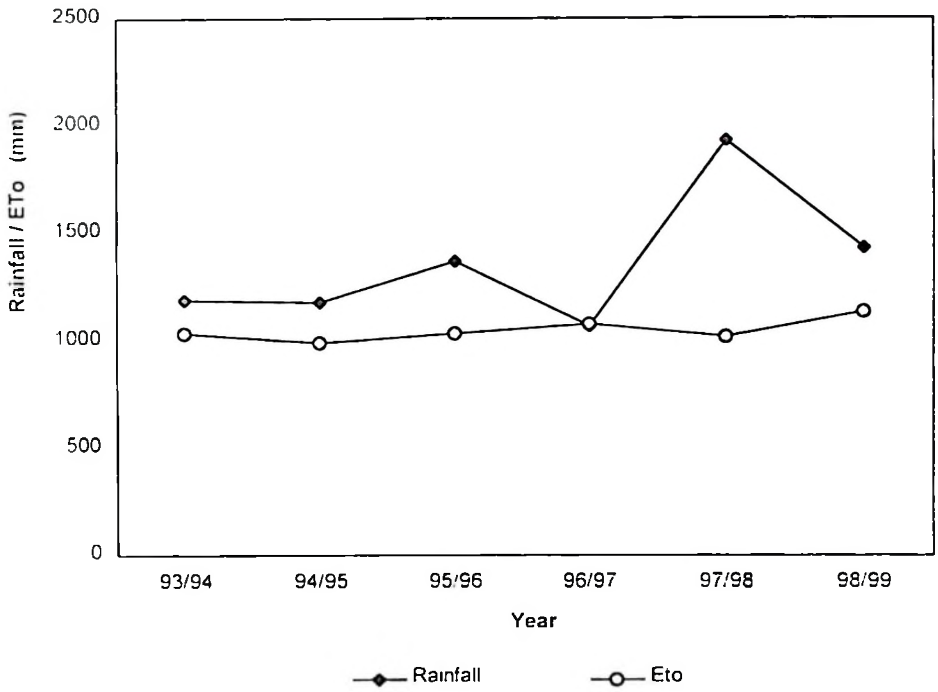

Figure 4.18: Comparison between annual rainfall and evapotranspiration (ETo)

4.4 Throughfall, stemflow and interception

4.4.1 Throughfall

Figure 4.19 gives a summary of throughfall for the four months of data collection during the 1998/99 wet season at Muhu catchment. The throughfall (T) was 128.5mm, 199.49mm, 205.38mm, and 88.477mm for February, March, April and May respectively. The mean monthly rainfall (P) for the respective months was 180.55mm, 300mm, 309.75mm, and 133.55mm respectively. Therefore throughfall was 71.17%, 66.5%, 66.31% and 66.25% of rainfall for the respective months. On average, throughfall was 67.31% of rainfall in this catchment. In a study conducted in Kenya with bamboo forest by Pereira (1962), an overall average of 80% throughfall was observed. Mahoo (1992) observed a throughfall of 59 to 74 % in a study conducted in Nigeria. Okhlayabin (1913) observed a throughfall of 77% with Spruce, 83 % with Beech and 67.5% with Pine. When comparing this study with other studies it can be shown that throughfall varies with type of stand which depends on the tree species and vegetation. The results of this study fall within the range of common values observed by other researchers.

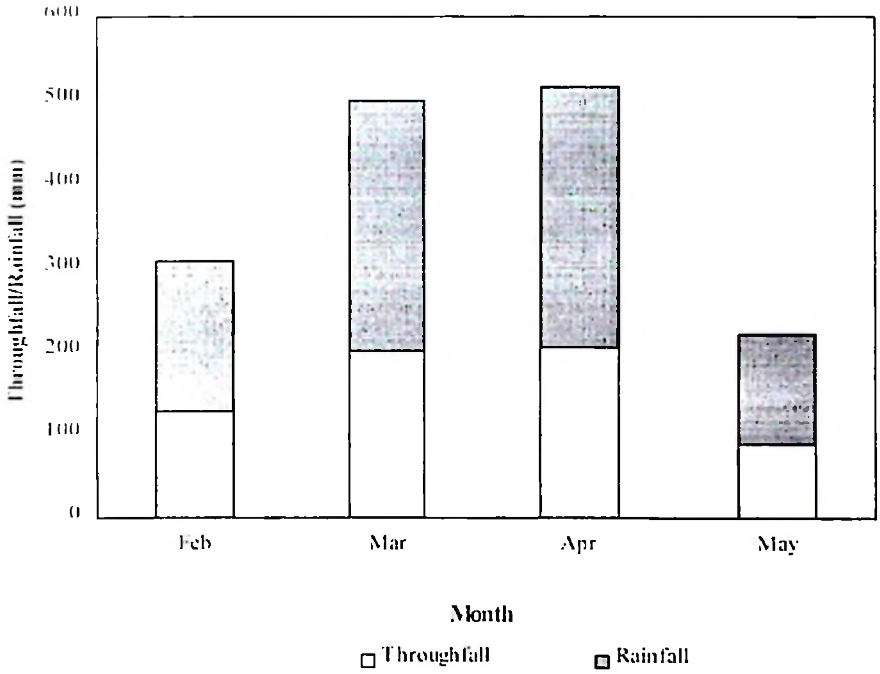

Figure 4.19: Amount of throughfall recorded at Muhu catchment

4.4.2 Throughfall - rainfall relationship

The relationship between throughfall and rainfall is depicted in Figure 4.20. There is a high correlation between rainfall and throughfall (R^2 = 0.98).The relationship is described by the regression equation below which was fitted to daily data shown in Appendix E.

$$T = 0.7130P - 0.4946 ; \qquad R^2 = 0.98 \qquad (4.1)$$

About 98 percent of the variances were explained by the regression equation, indicating a high potential of the equation to predict throughfall. The coefficient of regression (β) was significantly different from zero ($\beta \neq 0$) at 1% level as shown by ANOVA in Appendix E1. The storage capacity calculated according to Equation 2.5 which requires the slope of the regression line and intercept relating throughfall and rainfall was 0.7 mm. It is estimated that rains of 0.7 mm and below will be intercepted , thus no throughfall will be realised. According to Hamilton and Rowe (1949), storage capacity amounts range between 0.25 mm and 9.14 mm.

4.4.3 Comparison between observed throughfall and predicted throughfall

Equation 4.1 was used to predict throughfall. A comparison was made between the two data sets (i.e. observed and predicted) as shown in Figure 4.21. A reference to Figure 4.21 and Table 4.4 shows that there was no significant difference between observed and predicted throughfall at 5% level. Therefore equation 4.1 can be used to predict throughfall. This will facilitate in determing the effect of throughfall on water balance.

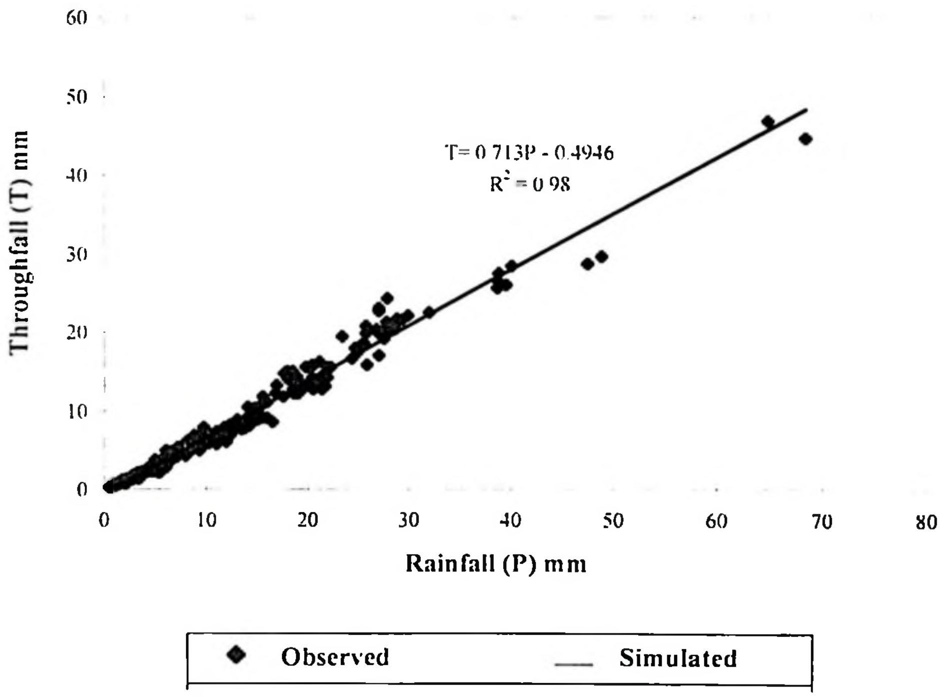

Figure 4.20: Throughfall - Rainfall relationship

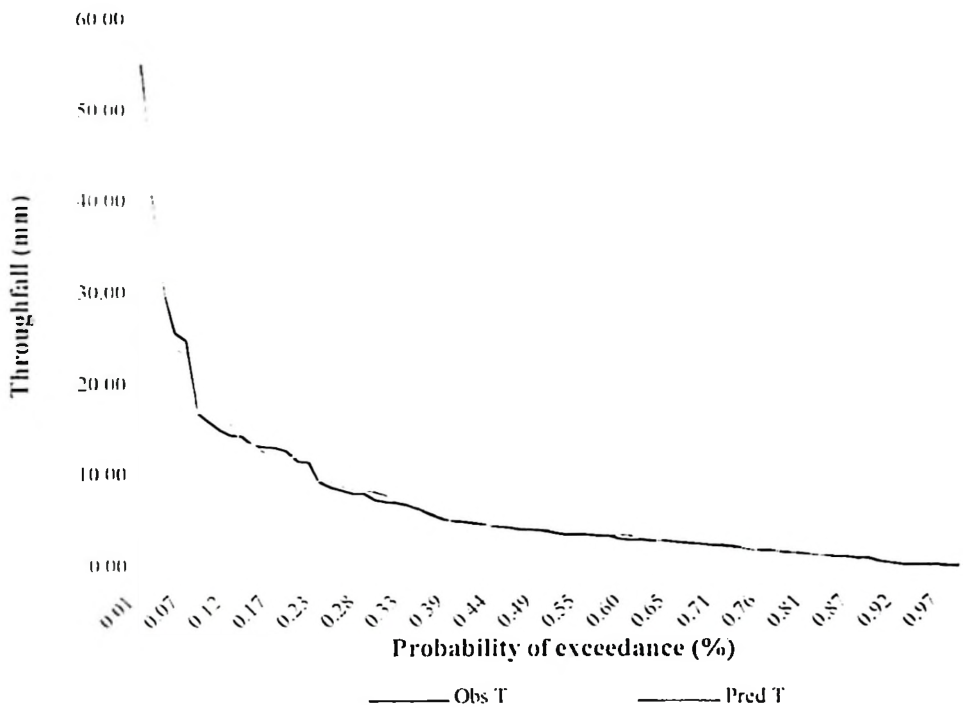

Figure 4.21: Comparison between observed and predicted throughfall

Table 4.4: Test statistics for significant difference between observed and predicted throughfall

Df	*p*	*t Stat*	*t Crictical*	*Significance*
146	0.05	-0.024	1.98	n.s.d.

4.4.4 Stemflow

The results of stemflow are presented in Figures 4.22. Stemflow was 5.97 mm (3.31%). 8.60 mm (2.87%), 11.213mm(3.62%) and 4.40mm (3.30%) for February, March, April and May respectively. The highest propotion of stemflow was recorded in April and the lowest propotion in March. The overall percent stemflow in this catchment was 3.27 % (Figure 4.22). Kitridge (1948) observed stemflow of 2 to 3 % for rough barked pine. Rowe (1941) observed that in case of some smooth barked trees, like beech, stemflow can go up to 15%. In some studies it has been neglected due to the claim that it contributes 1% or less (Jackson, 1971). There is variation of the reported stemflow among researchers, and it is erroneous to ignore it as it is significant in some instances.

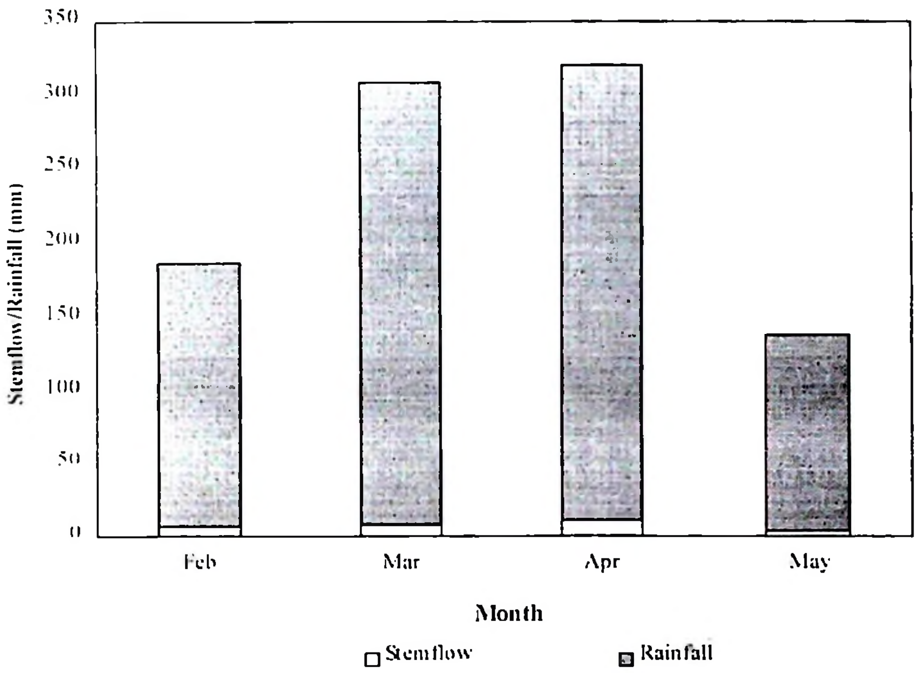

Figure 4.22 : Amount of stemflow at Muhu catchment

4.4.5 Stemflow - rainfall relationship

The relationship between stemflow and rainfall is depicted in Figure 4.23. Details of the fitted line are shown in Appendix F2. The correlation between stemflow and rainfall was fairly high ($R^2 = 0.68$). The relationship is explained by the equation 4.2:

$$S = 0.0335P - 0.014 \; ; \qquad R^2 = 0.68 \qquad (4.2)$$

Sixty-eight per cent of the variances were explained by the regression equation. From Figure 4.23 there are few points that fall on the regression line for bigger storms. thus thirty two percent of the variation is not explained by the regression. However the equation can be used to predict stemflow since its coefficient of determination (R^2) is categorised as moderately high. In addition the coefficient of regression (β) was significantly different from zero ($\beta \neq 0$) at 1% level as shown by ANOVA in Appendix E2.

4.4.6 Comparison between observed stemflow and predicted stemflow

Equation 4.2 was used to predict stemflow. The predicted stemflow was compared with observed stemflow using a t-test at 95% confidence interval to evaluate and validate the capability of equation 4.2 to predict stemflow. Results are shown in Figure 4.24 and Table 4.5 below.

It can be shown from Table 4.5 that observed and predicted stemflow are statistically not different from each other at 5% level. Therefore equation 4.2 can be used to predict stemflow. Also this will facilitate to determine the effect of stemflow on water balance.

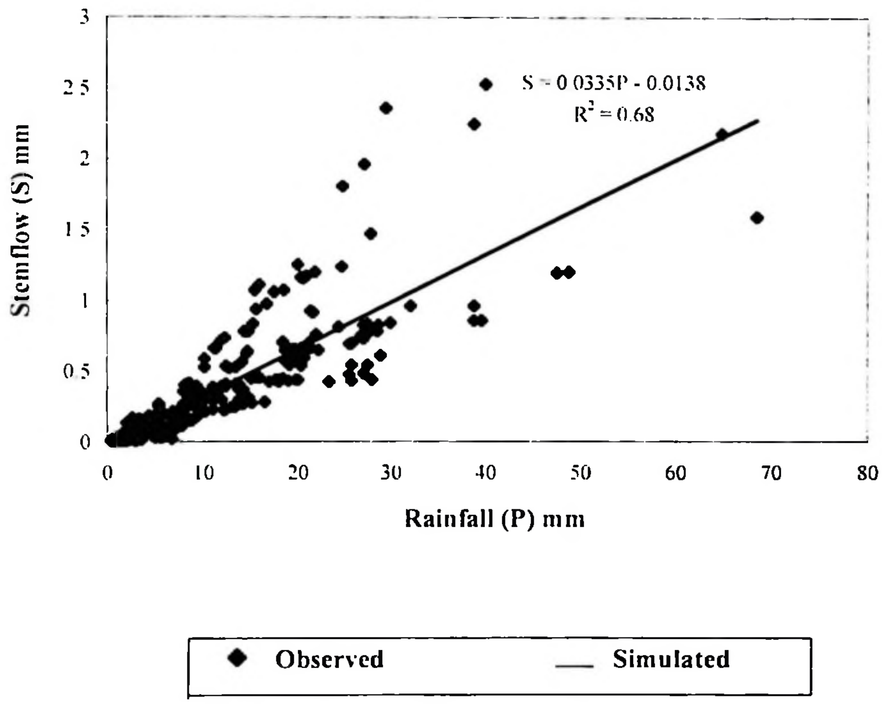

Figure 4.23: Stemflow - rainfall relationship

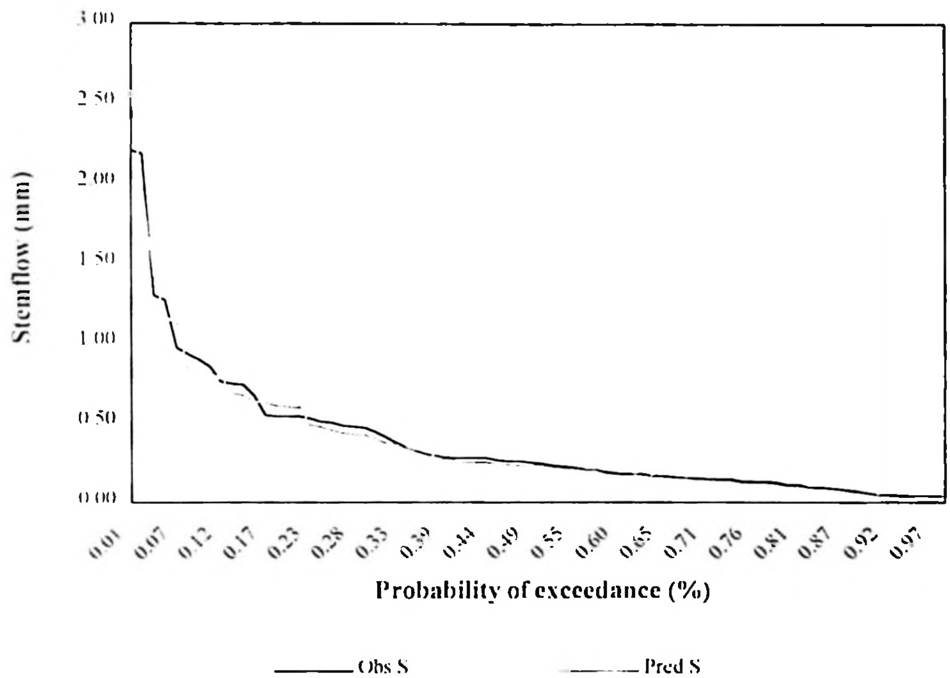

Figure 4.24: Comparison between observed and predicted stemflow

Table 4.5: Test statistics for significant difference between observed and predicted stemflow

df	*p*	*t Stat*	*t Crictical*	*Significance*
146	0.05	0.088	1.98	n.s.d.

4.4.7 Interception

The results of interception are presented in Figure 4.25. The amount of rainfall intercepted was 46.08mm (25.52%), 91.91mm (30.64%), 93.15mm (30.07%) and 40.67mm (30.45%) for February, March, April and May respectively. The highest percent of intercepted rainfall was recorded in March and the lowest was recorded in February. The overall percent interception in this catchment was 29.42 % (Figure 4.25). A study by Edwards (1979) conducted in Kenya in a bamboo forest showed that 20% of the rainfall was intercepted. According to Eschener (1967), tree cover of most forest regions intercept 10 to 30 % of the annual precipitation. A study by Mahoo (1992) in Nigeria showed that about 26 to 32% of the rainfall was intercepted. Although there is quite variation of interception, there is a common range of 10 – 30% and results reported in this study are within this range.

4.4.8 Interception - rainfall relationship

Figure 4.26 shows the relationship between interception and rainfall. Details of the fitted line are shown in Appendix E3. There is a high correlation between interception and rainfall ($R^2 = 0.84$). The relationship is explained by the regression equation 4.3:

$$I = 0.2533P - 0.5079 \;;\quad R^2 = 0.84 \qquad (4.3)$$

Eighty four percent of the variances were explained by the regression equation. Only sixteen per cent of the variation is not explained by the regression. The coefficient of regression (β) was significantly different from zero ($\beta \neq 0$) at 1% level as shown by ANOVA in appendix E3.

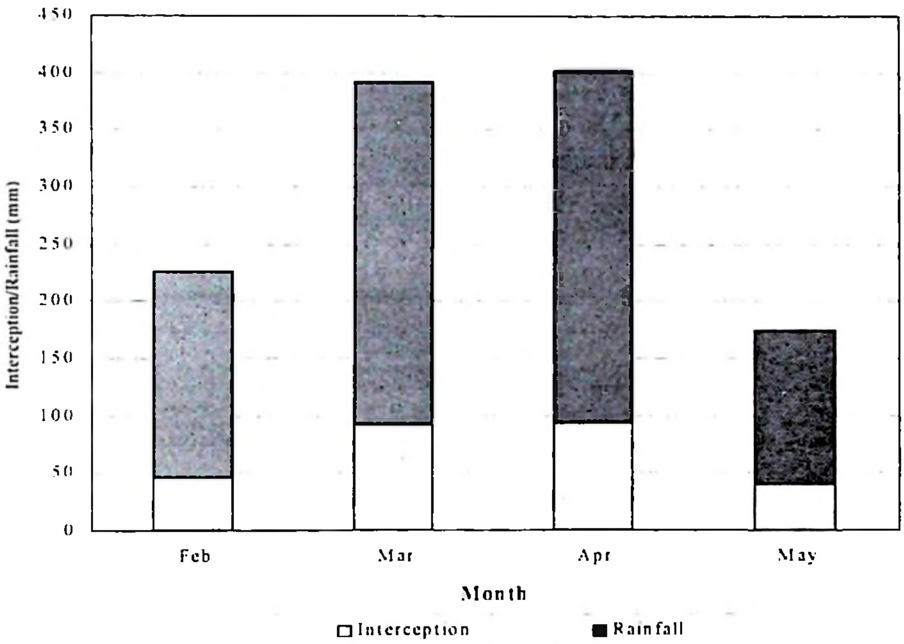

Figure 4.25: Amount of intercepted rainfall at Muhu catchment

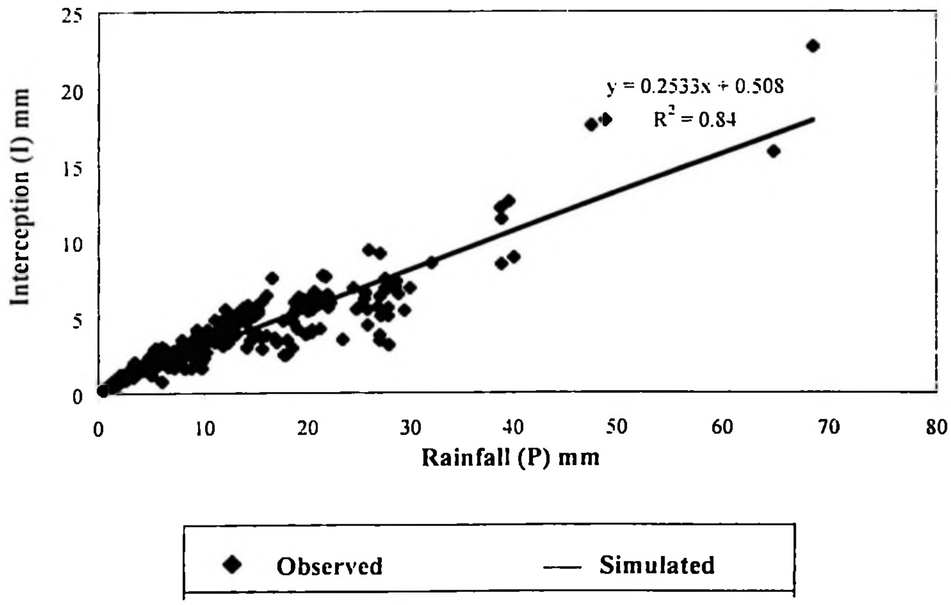

Figure 4 26 : Interception - rainfall relationship

4.4.9 Comparison between observed interception and predicted interception

Equation 4.3 was used to predict interception. The predicted interception was compared with interception calculated using measured variables (i.e. rainfall, throughfall and stemflow). A t-test was used at 95% confidence interval to evaluate and validate the capability of equation 4.3 to predict interception. Results are shown in Figure 4.27 and Table 4.6.

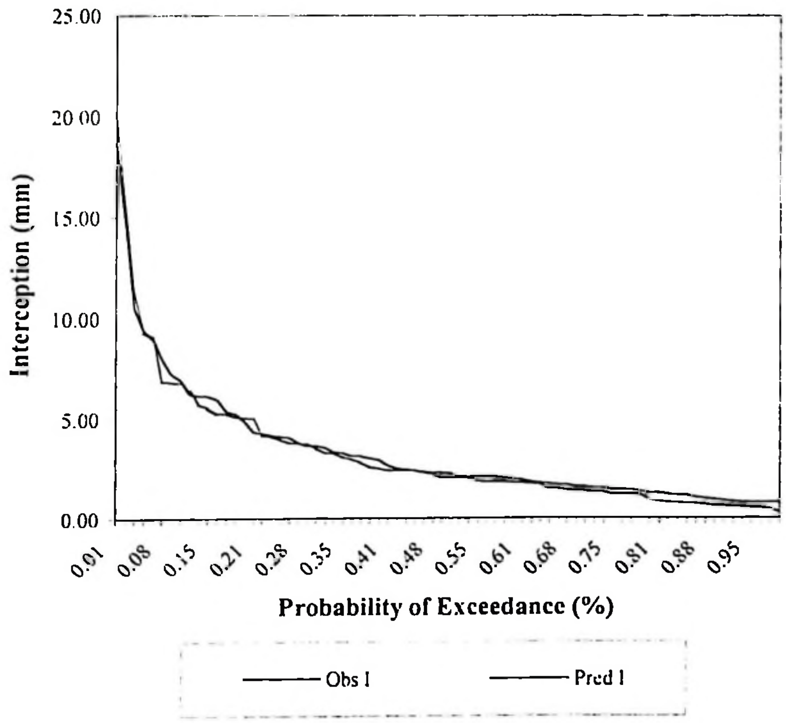

Figure 4.27: Comparison between observed and predicted interception

Table 4.6: Test statistics for significant difference between observed and predicted interception

df	*p*	*t Stat*	*t Crictical*	*Significance*
146	0.05	-0.162	1.98	n.s.d.

From Table 4.6, the observed and predicted interception were statistically not different from each other at 5% level. Therefore equation 4.3 can be used to predict interception. It will facilitate to determine the effect of interception on the water balance.

4.4.10 Effect of stem size on stemflow

Trees with small diameter at breast height yielded higher stemflow than those with larger diameter at breast height (Figure 4.28). The results showed that there was a negative association between stem size and corresponding stemflow. A significant difference was observed between various stem sizes on stemflow yield at 1% level (Appendix G1). The features of trees used for stemflow measurements are shown in Appendix G. The difference in stemflow yield can be attributed to the difference in the level of branching. Big trees have a lot of branches, resulting in less rain water reaching the bottom of the tree as stemflow. Another factor is the thickness of the bark and its potential to absorb water. Generally big trees have thicker rough barks. absorbing more water. Bruinzell (1990) made a similar observation whereby smaller stemmed trees had higher stemflow.

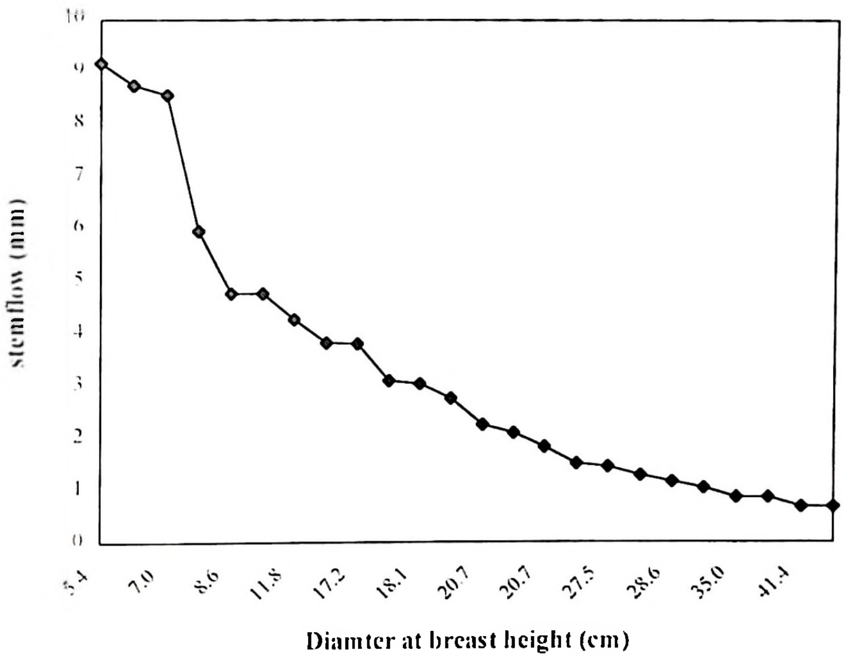

Figure 4.28: The effect of stem size on stemflow

4.4.11 The Effect of surface cover on throughfall

Throughfall and surface cover are inversely related with a negative slope (Figure 4.29). The fitted regression line shows that 95 % of the variation between throughfall and surface cover is explained by the regression equation. Therefore reduction in surface cover increases net rainfall. This may have both positive and negative effects. It may increase the amount of water infiltrating into the soil thus increasing the contribution to ground water storage and soil moisture storage. On the other hand it can result in water being lost as surface runoff thus increasing erosion.

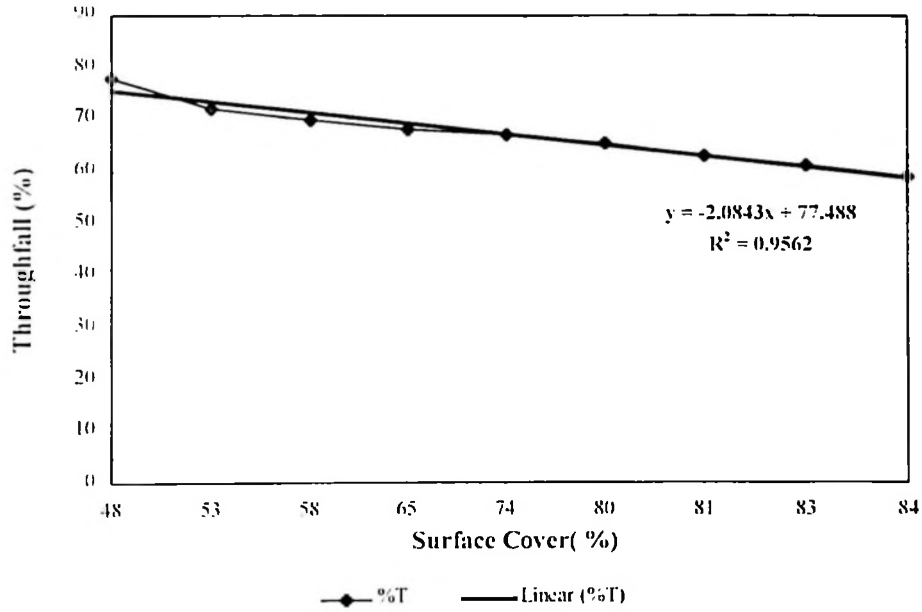

Figure 4.29: The effect of surface cover on throughfall

4.4.12: The effect of surface cover on interception

Surface cover and interception are positively correlated with a positive slope as shown in Figure 4.30. Increase in percent surface cover leads to an increase in interception. Ninety seven percent of the variation could be explained by the fitted regression line. The increase in interception as a result of increased vegetal cover was due to increase in the number of leaves which increase the amount of rain water stored on the leaf blades. This leads to reduction in throughfall and increase in interception as shown in Figure 4.30.

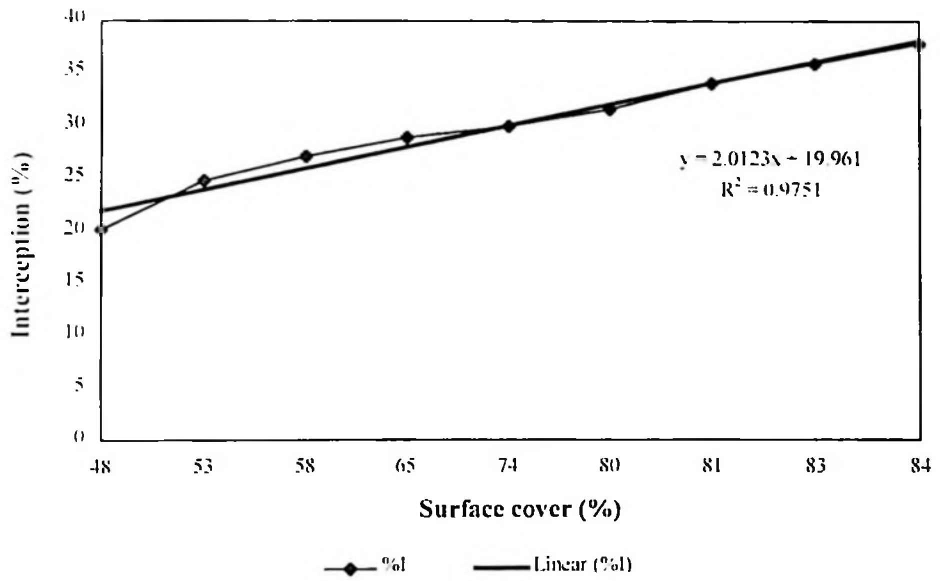

Figure 4.30: The effect of surface cover on interception

4.5 Stream flow characteristics

The stream flow characteristics analysed were monthly and annual water yield: minimum, maximum and mean stream flow; and runoff. The results are presented in the following subsections.

4.5.1 Catchment water yield

The variability in monthly and annual water yield is shown in Table 4.7 and Figures 4.31 and 4.32 respectively. Mean monthly stream flow ranged from 1.6 m^3/s to 2.5

m^3/s. The highest mean monthly flow of $2.5m^3/s$ was observed in April while the lowest mean monthly flow of $1.6m^3/s$ was observed in November (Table 4.7). The lowest stream flow had a 7.7 % probability to be exceeded while the highest had a probability of 92.3% to be exceeded (Appendix C4). Stream flow increased between November and April, declined between April and September and stabilised between September and November (Figure 4.31). The decline between April and September indicated the recession period of the stream after the wet season. During this period there was little rainfall, however, there was high evapotranspiration. Therefore stream flow during this period was sustained mainly by ground water (base flow) contribution.

Annual total stream flow ranged from 19.13 to 26.49 m^3/s (Figure 4.32). Stream flow decreased between 1993/94 and 1994/95, increased gradually from 1994/95 to 1998/99 and peaked in 1997/98. The variability was due to combined effects of climatic changes and catchment degradation processes. In terms of rainfall, the lowest annual rainfall was recorded in 1996/97 which was a drought year in Tanzania. The highest rainfall was recorded in 1997/98, the year of El-Niño rains. Annual rainfall increased between 1993/94 and 1995/96. Therefore rainfall alone is not enough in explaining the variability in stream flow. However when the processes of catchment degradation are integrated, a better explanation can be given. Many studies have shown that catchment degradation has a significant effect on stream flow over time (Pereira, et al., 1962; Malongo, 1997; Anderson and Spencer, 1989;

Lal, 1981; Temple and Sundeborg, 1972). The decrease in stream flow between 1993/94 and 1994/95 can be associated with the planting of trees and adoption of conservation measures promoted by the catchment conservation project under HIMA (HIMA, 1994). However stream flow started to increase gradually in subsequent years, which meant that degradation processes such as forest clearance began to increase as observed by HIMA (HIMA, 1997).

The maximum, minimum and mean daily flows for the past six years are shown in Table 4.8. The lowest flow of $0.27m^3/s$ was recorded in December, 1994/95. The highest flow of $0.31m^3/s$ was recorded in February, 1997/98 - the wettest year. There is a lot of variation between dry season flow and wet season flow.

Table 4.7: Monthly total stream flow (m^3/s)

Year/Month	93/94	94/95	95/96	96/97	97/98	98/99	Average
June	2.51	1.62	1.50	1.74	1.97	2.17	1.92
July	2.99	1.60	0.88	1.69	1.92	2.17	1.87
August	2.41	1.52	1.42	1.70	1.85	1.74	1.77
Sept	1.79	1.44	1.38	1.60	1.58	1.91	1.62
Oct	1.86	1.49	1.44	1.68	1.65	1.94	1.68
Nov	1.91	1.38	1.33	1.53	1.64	1.88	1.61
Dec	1.93	1.52	1.74	1.67	2.69	1.59	1.86
Jan	1.79	1.64	1.53	1.88	3.33	2.23	2.07
Feb	1.64	1.46	1.94	2.33	2.04	2.14	1.93
Mar	2.40	1.88	1.85	2.56	3.04	2.50	2.37
April	1.91	1.84	2.84	2.78	2.39	3.26	2.50
May	2.01	1.74	2.29	2.20	2.38	2.70	2.22
Ann. Streamflow	25.13	19.13	20.15	23.35	26.49	26.246	23.42

Source: HIMA, 1997

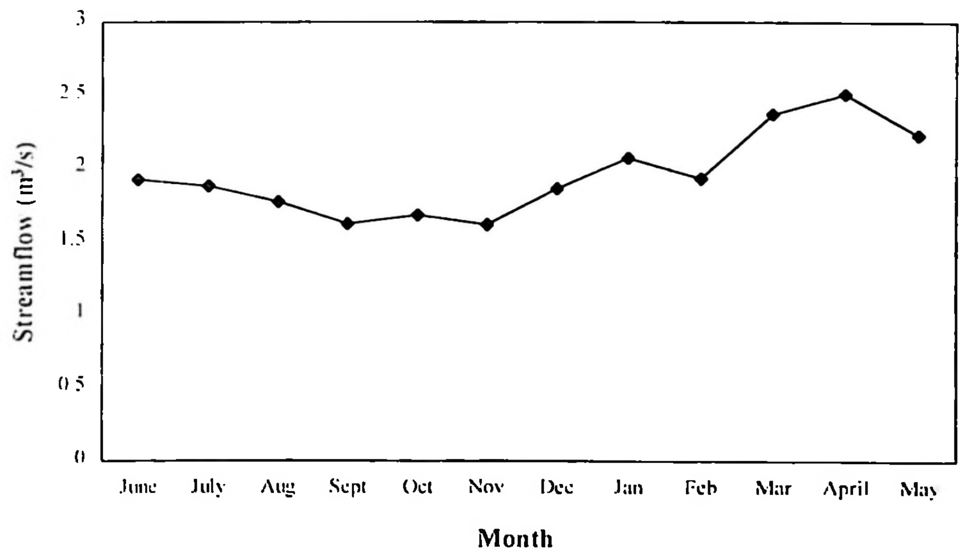

Figure 4.31: Monthly stream flow

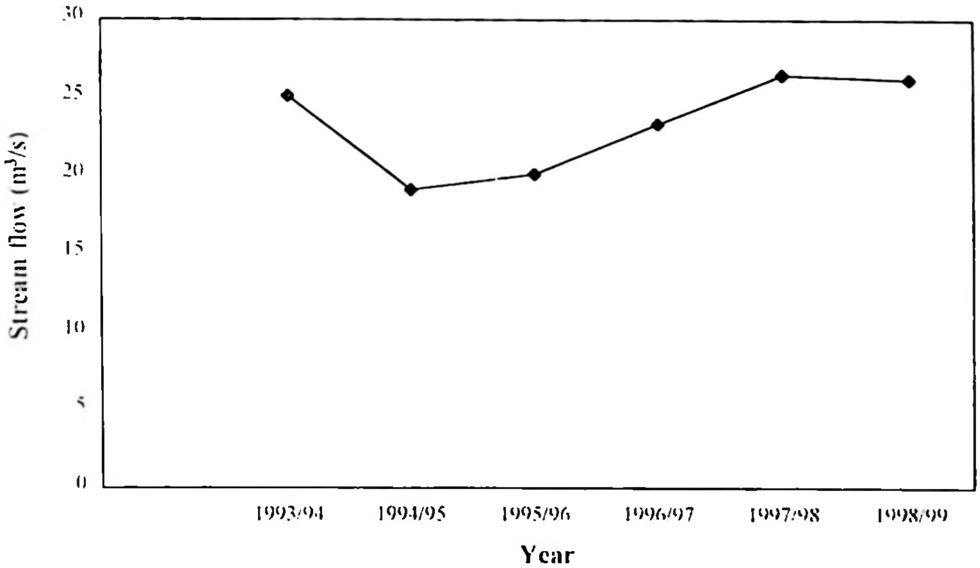

Figure 4.32: Annual stream flow

Table4.8: Minimum and maximum stream flow (m^3/s)

Year/Month	93/94		94/95		95/96		96/97		97/98		98/99	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
June	0.079	0.086	0.054	0.057	0.048	0.056	0.054	0.066	0.061	0.075	0.069	0.075
July	0.072	0.106	0.050	0.054	0.027	0.029	0.054	0.056	0.061	0.066	0.065	0.071
August	0.063	0.090	0.047	0.052	0.044	0.051	0.054	0.055	0.054	0.061	0.058	0.065
Sept	0.056	0.063	0.047	0.049	0.043	0.053	0.051	0.057	0.048	0.055	0.059	0.102
Oct	0.049	0.069	0.044	0.067	0.043	0.049	0.053	0.057	0.048	0.066	0.060	0.069
Nov	0.058	0.076	0.043	0.060	0.044	0.048	0.049	0.057	0.044	0.147	0.055	0.076
Dec	0.049	0.140	0.028	0.039	0.043	0.126	0.051	0.067	0.046	0.168	0.041	0.062
Jan	0.047	0.083	0.043	0.130	0.039	0.074	0.045	0.155	0.058	0.247	0.042	0.153
Feb	0.052	0.092	0.047	0.065	0.044	0.117	0.040	0.148	0.065	0.314	0.061	0.124
Mar	0.039	0.048	0.031	0.043	0.049	0.099	0.056	0.167	0.063	0.138	0.057	0.119
April	0.056	0.077	0.049	0.094	0.062	0.217	0.066	0.165	0.062	0.149	0.080	0.206
May	0.057	0.084	0.052	0.085	0.065	0.096	0.063	0.084	0.065	0.156	0.070	0.122
Lowest	0.039	0.048	0.028	0.039	0.027	0.029	0.040	0.055	0.04	0.06	0.04	0.06
Highest	0.079	0.106	0.054	0.130	0.065	0.217	0.066	0.167	0.07	0.31	0.08	0.21

Source: HIMA, 1997

4.5.2 Runoff

Monthly and annual total runoff, base flow, and direct runoff are presented in Tables 4.9, 4.10 and 4.11 respectively. Appendices C5, C6 and C7 show the probability of exceedance and return period for the monthly total runoff, base flow and direct runoff respectively. Direct runoff (DRO) increased gradually from July to April, reaching its peak in January. This is also shown by the distance between total runoff curve and the base flow curve (Figure 4.33). DRO was relatively stable between February and April but there was a sharp drop between April and May. Generally the wet season had a higher direct runoff as expected than the dry season due to differences in rainfall. However base flow and total runoff did not show the same response. This was due to differences in the time of response by the catchment to yield the various components of runoff. Direct runoff is quickly generated during a rainfall event and an instantaneous increase in the stream flow is realised. When DRO declined , base flow began to increase gradually as it took a longer time to reach the stream outlet (Figure 4.33). Base flow continued to increase even when DRO had ceased. The decline in base flow was gradual, and it took longer time - extending to the dry season of the following water year. Such a characteristic gives an indication about the catchment hydrologic properties of the soil. Water movement in the deeper layers of the soil is relatively moderate indicating a moderate saturated hydraulic conductivity. This makes it possible for the flow to be perennial with base flow supporting the dry season flow.

Total runoff, base flow and direct runoff decreased between 1993/94 and 1994/95; increased gradually between 1994/95 and 1998/99 with highest peak in 1997/98 - the wettest year (Figure 4.34). The decrease between 1993/94 and 1994/95 can not be attributed to rainfall since the rainfall was 1193mm and 1182mm in both years respectively. Rather the explanation could be due to improvement in catchment management. This is can be explained by the fact that forest cover increased, thus reducing surface runoff. This is in line with what some researchers have reported in that increase in vegetal cover reduces surface runoff (Tischendorf, 1969; Rewitz et al., 1970; Kirby and Chorley, 1967). However the forest cover was gradually cleared in the subsequent years, resulting in gradual increase in runoff.

Table 4.9: Monthly total runoff (TR) (mm)

Year/Month	1993/94	1994/95	1995/96	1996/97	1997/98	1998/99	Average
June	44.54	28.76	26.69	30.02	32.93	36.38	33.22
July	53.02	28.29	15.58	30.03	32.02	32.03	31.83
August	42.71	26.91	25.25	29.35	30.95	31.80	31.16
Sept	31.71	25.54	24.51	27.64	26.57	30.37	27.72
Oct	32.94	26.40	24.91	29.02	27.69	30.07	28.51
Nov	33.82	24.51	23.55	25.57	27.50	33.42	28.06
Dec	34.26	27.02	30.10	28.01	45.09	28.28	32.13
Jan	31.66	29.12	26.40	31.55	59.20	39.60	36.26
Feb	29.14	25.95	33.56	31.19	51.17	37.98	34.83
Mar	42.50	33.29	31.88	41.92	42.82	44.25	39.44
April	33.91	32.65	49.01	49.23	40.08	57.87	43.79
May	35.65	30.86	39.58	36.77	39.83	47.98	38.45
Annual TR	445.86	339.30	351.02	390.30	455.85	450.03	405.39

Table 4.10: Monthly base flow (BF) (mm)

Year/Month	1993/94	1994/95	1995/96	1996/97	1997/98	1998/99	Average
June	43.37	28.72	26.06	29.27	31.51	35.03	32.33
July	51.46	28.18	15.31	29.82	31.55	30.75	31.18
August	42.07	26.60	24.01	29.35	30.36	29.99	30.40
Sept	30.59	25.17	22.47	27.00	26.16	26.88	26.38
Oct	26.07	23.58	24.08	28.70	24.64	28.56	25.94
Nov	27.50	19.01	23.32	24.88	21.82	31.20	24.62
Dec	26.86	22.46	23.41	26.66	27.10	26.81	25.55
Jan	16.33	18.40	22.11	24.72	27.73	24.24	22.25
Feb	17.44	22.35	18.60	16.23	30.59	31.04	22.71
Mar	19.47	24.99	25.97	27.42	33.81	32.64	27.38
April	29.30	21.72	33.11	33.71	30.16	41.87	31.65
May	31.21	25.59	33.96	34.53	35.63	40.39	33.55
Annual BF	361.67	286.77	292.41	332.29	351.06	379.40	333.93

Table 4.11: Monthly direct runoff (DRO) (mm)

Year/Month	1993/94	1994/95	1995/96	1996/97	1997/98	1998/99	Average
June	1.17	0.04	0.63	0.75	1.42	1.35	0.89
July	1.56	0.11	0.27	0.21	0.47	1.28	0.65
August	0.64	0.31	1.24	0.00	0.59	1.81	0.77
Sept	1.12	0.37	2.04	0.64	0.41	3.50	1.35
Oct	6.87	2.82	0.83	0.32	3.05	1.51	2.57
Nov	6.32	5.50	0.23	0.69	5.68	2.22	3.44
Dec	7.40	4.56	6.69	1.35	17.99	1.47	6.58
Jan	15.30	10.72	4.29	6.83	31.47	15.36	14.00
Feb	11.70	3.60	14.96	14.96	20.58	6.94	12.12
Mar	23.03	8.30	5.91	14.50	9.01	11.61	12.06
April	4.61	10.93	15.90	15.52	9.92	16.00	12.15
May	4.44	5.27	5.62	2.24	4.20	7.59	4.89
Annual DRO	84.18	52.53	58.61	58.01	104.79	70.64	71.46

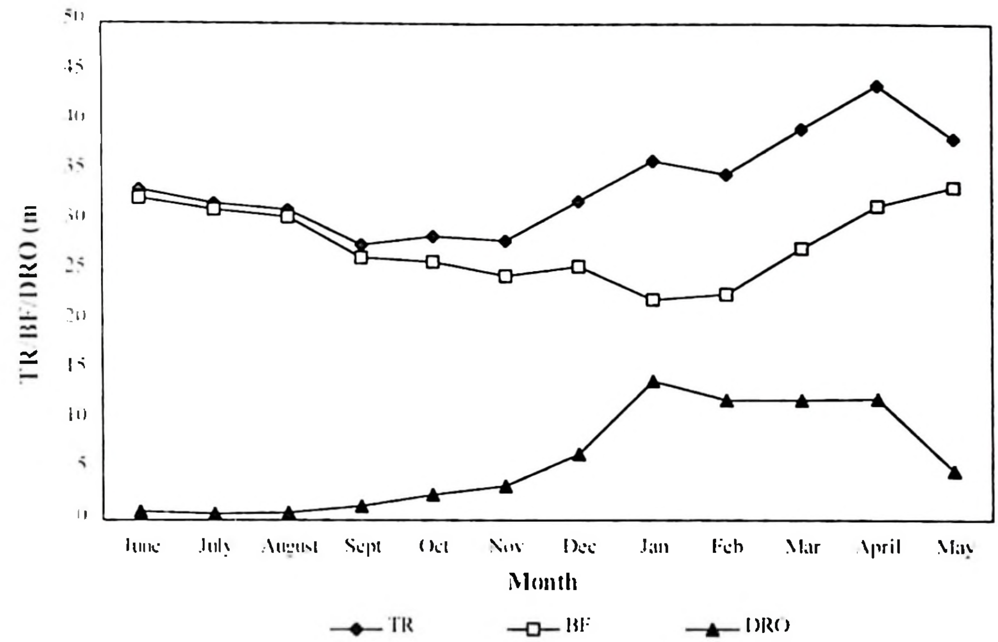

Figure 4.33: The components of monthly runoff

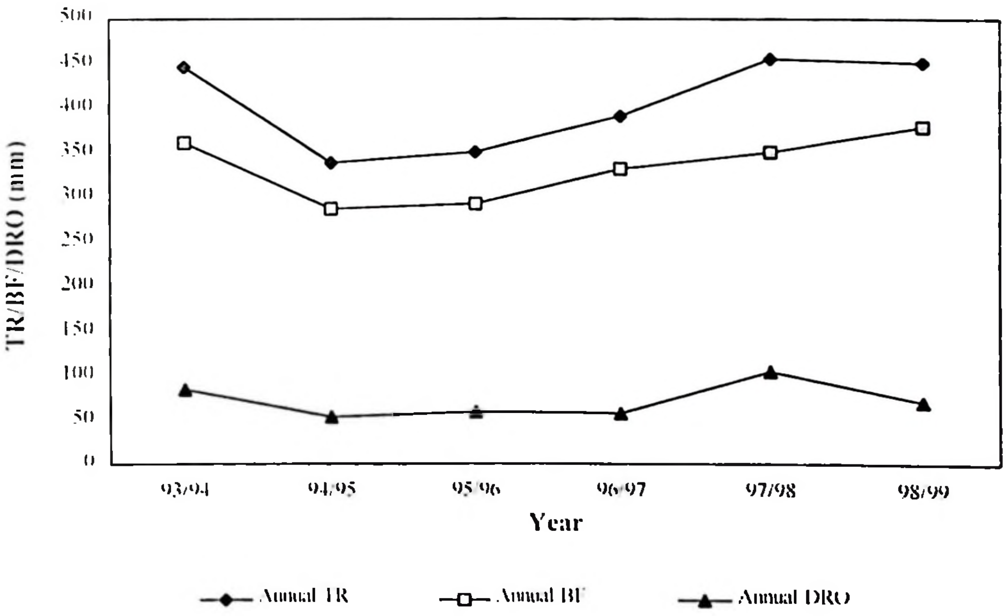

Figure 4.34: The annual runoff components

4.5.2.1 Runoff curve numbers

Runoff curve numbers were calculated using Equation 4.4 below:

$$CN = \frac{1000}{10 + S/2.54} \quad (4.4)$$

where: CN = runoff curve number

S = potential maximum retention after runoff begin

$$S = 5[P + 2Q - (4Q^2 + 5PQ)^{0.5}] \quad (4.5)$$

where: P = rainfall (mm).

Q = runoff (mm).

The results are shown in Figures 4.35 and 4.36, and Table 4.12. The calculated values of S are shown in Appendix H. The monthly curve numbers ranged from 25.89 to 91.94 (Figure 4.35). June had the highest runoff curve number while April had the lowest. Curve numbers indicate the soil cover complexes and level of runoff. High values indicate either high soil cover or low runoff or a combination of the two. The high runoff curve numbers after the wet season are a result of high surface cover. This is reasonable as growth is encouraged during the wet season , and run off is low during the dry season as rainfall is low.

The annual curve number was maximum in 1996/97 - the drought year and lowest in 1997/98 - the wettest year (Figure 4.36). The differences in curve numbers between the two years was due to rainfall. Comparing 1993/94, 1994/95 and 1995/96, runoff curve numbers decreased gradually, indicating an increase in runoff. The annual rainfall in the respective years did not provide enough basis for this trend. Therefore the increase was due to decrease in the soil cover complexes as a result of gradual forest clearance.

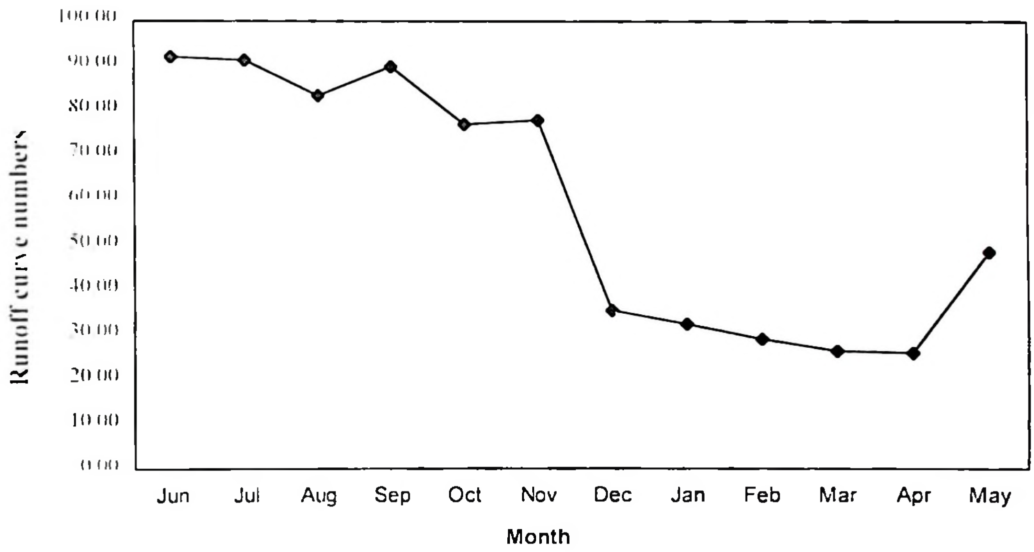

Figure 4.35: Monthly runoff curve numbers

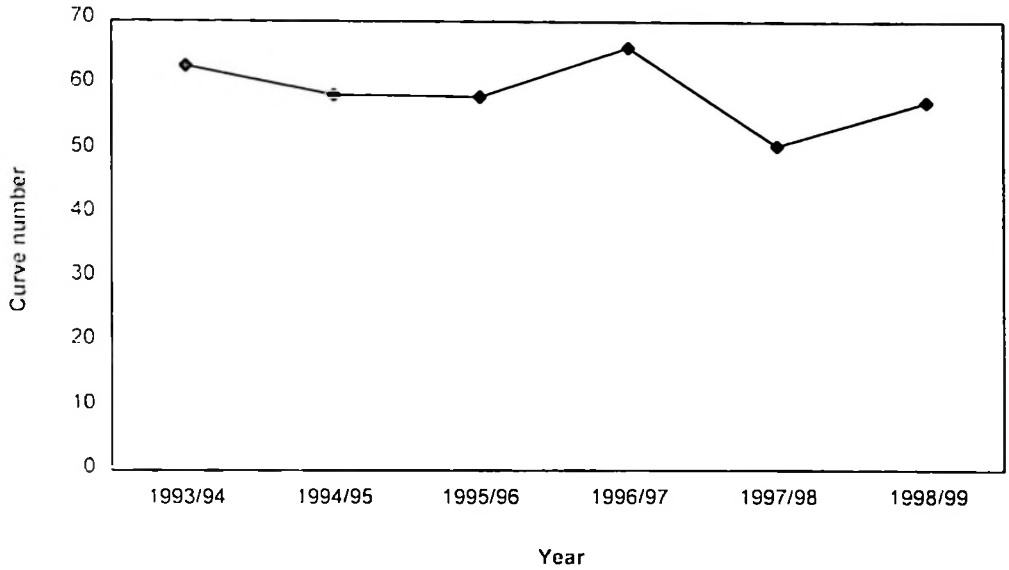

Figure 4.36: Annual runoff curve number

Table 4.12: Curve numbers for Muhu catchment

Year/ Month	93/94	94/95	95/96	96/97	97/98	98/99	Average
Jun	95.26	98.16	99.27	99.09	63.83	96.03	91.94
Jul	94.40	85.97	94.58	94.35	83.95	94.08	91.22
Aug	89.80	83.87	65.57	100.0	85.99	75.19	83.40
Sep	96.86	93.53	88.84	99.44	94.23	65.58	89.75
Oct	82.61	68.75	82.01	81.55	53.41	92.80	76.86
Nov	87.09	73.01	92.98	83.85	34.03	96.67	77.94
Dec	51.89	29.34	35.01	56.98	16.80	22.17	35.37
Jan	35.03	34.03	37.07	32.53	26.07	29.62	32.39
Feb	34.22	37.85	23.30	31.49	14.22	33.01	29.01
Mar	21.29	25.99	29.74	22.11	35.62	22.95	26.29
Apr	35.27	23.80	18.43	26.92	28.66	22.25	25.89
May	32.96	47.84	32.89	64.11	72.77	39.52	48.35
Mean	63.06	58.51	58.31	66.04	50.80	57.49	59.03
SD=	30.15	28.23	31.64	31.02	28.59	32.15	

4.5.2.2 Relationship between runoff and rainfall parameters

The degree of association that exists between runoff and rainfall parameters which include rainfall amount, rainfall intensity, storm duration, throughfall and stemflow was assessed using a correlation test. This was done as a preliminary exercise to determine parameters that can be used to develop a runoff model for the catchment. Correlation coefficients between runoff and the rainfall parameters are shown in Table 4.13.

Table 4.13: Correlation coefficients between runoff and rainfall parameters

Parameter	Correlation coefficient r
Rainfall (P)	0.96
Intensity (Ri)	0.78
Duration (Rd)	0.54
Throughfall (T)	0.96
Stemflow (S)	0.96
Interception	0.96

From Table 4.13, duration had the lowest correlation coefficient (r = 0.54) while rainfall, throughfall, interception and stemflow had the highest correlation coefficient (r = 0.96). Generally runoff was closely associated with the rainfall parameters.

4.5.2.3 Runoff model

From section 4.5.2.2. it is clear that runoff is related to a number of climatic variables that can be used to estimate runoff. A multiple regression based model which included the climatic parameters above was developed. The output from the regression analysis is shown in Appendix I-1 and Appendix I-2. The slope for stemflow and interception had high standard errors of 38.91 and 35.90 respectively. The two parameters with such standard errors reduce the level of precision if included in the model. Throughfall had a standard error of zero indicating that the coefficient of regression (β) for throughfall is not useful in predicting runoff(Appendix I-1). Therefore the model was based on those coefficients of parameters in Appendix I-2.

$$DRO = 0.0559P + 0.3414Rd - 0.0740Ri - 0.671; \quad \mathbf{R^2 = 0.94} \qquad (4.6)$$

where: DRO = direct runoff

Rd = Rainfall duration

Ri = Rainfall intensity

P = Rainfall amount

R^2 = coefficient of determination

4.5.2.4. Runoff model evaluation and validation

Gendavaki catchment was used to validate the model. The developed model. equation 4.6. was used to predict DRO. and a comparison was made between predicted DRO and calculated DRO using observed or measured parameters. The comparison was done using t-test and the results are shown in Figure 4.37 and Table 4.14.

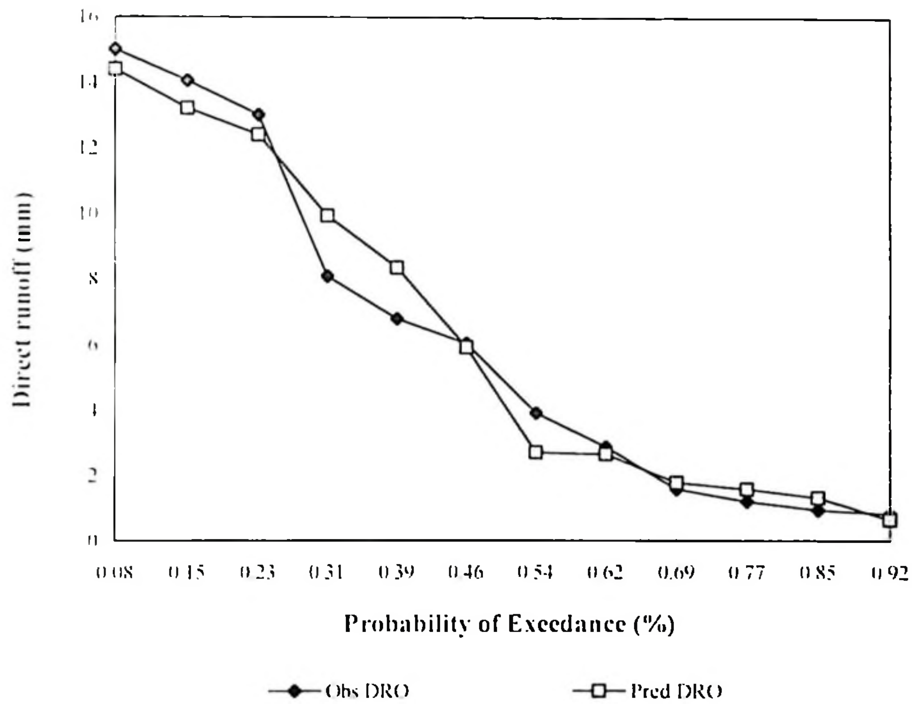

Figure 4.37: Comparison between observed and predicted runoff

Table 4.14: Test statistics for significant difference between observed and predicted runoff

df	*p*	*t Stat*	*t Crictical*	*Significance*
22	0.05	-0.0.25	2.07	n.s.d.

It is evident from Table 4.14 that observed and predicted DRO are not significantly different from each other at 5% level. The ANOVA from Appendix I-2 shows that the coefficient of regression (β) was significantly different from zero (0) at 1% level. The above evidence suggests that the model is useful in estimating runoff.

4.6 The Water Balance

The mean monthly and annual values of the calculated water balance are shown in Figures 4.38 and 4.39. Positive water balance is experienced between December and May (Figure 4.38). The highest water balance is recorded in April while the lowest water balance is in September (Figure 4.38). Table 4.15 shows the monthly water balance over the past six years. The positive water balance is experienced during the wet season months. The annual water balance ranged from -401.18 mm in 1996/97 to 453.8 mm in 1997/98 (Figure 4.39). The water year 1996/97 is the only one where annual evapotranspiration exceeded the annual rainfall, and it was a drought year in Tanzania with a negative effect on crop yield. The water year 1997/98 was the wettest one as explained in the previous sections. The probability of exceedance and return period for the mean monthly water balance is shown in Appendix C8.

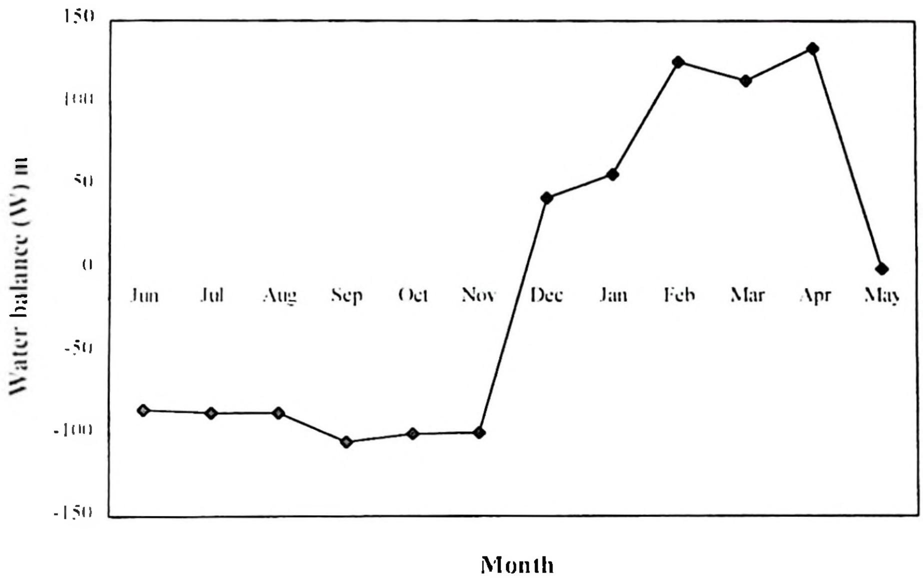

Figure 4.38: Mean monthly water balance

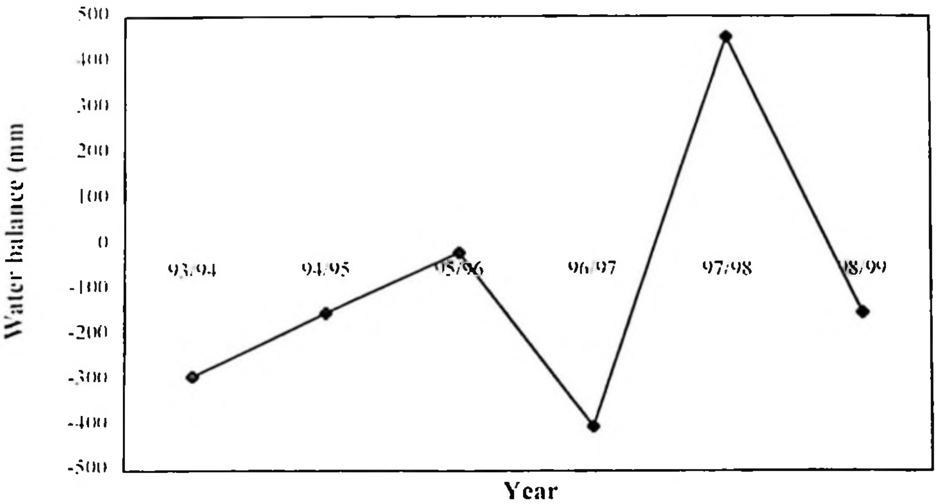

Figure 4.39: Annual water balance.

Table 4.15: Monthly water balance (mm)

Year/Month	1993/94	1994/95	1995/96	1996/97	1997/98	1998/99	Average
Jun	-93.40	-97.45	-90.68	-88.00	-45.04	-100.64	-85.87
Jul	-102.80	-80.61	-74.25	-91.79	-80.91	-93.20	-87.26
Aug	-94.01	-80.68	-62.18	-121.15	-102.54	-65.33	-87.65
Sep	-132.61	-108.98	-101.87	-119.13	-119.26	-48.81	-105.11
Oct	-141.34	-73.79	-117.44	-106.08	-39.86	-122.01	-100.09
Nov	-116.88	-84.19	-142.00	-134.97	22.56	-142.98	-99.74
Dec	-49.65	46.88	18.10	-85.94	279.55	48.18	42.85
Jan	51.85	51.09	2.56	18.94	151.94	64.78	56.86
Feb	76.99	15.34	172.32	97.95	364.70	23.31	125.10
Mar	218.98	96.50	56.09	158.93	23.01	131.63	114.19
Apr	30.66	160.49	255.07	125.20	75.52	153.73	133.45
May	61.44	3.56	64.23	-55.15	-75.86	-0.18	-0.32
Annual	-290.77	-151.84	-20.01	-401.18	453.80	-151.52	-93.59

4.6.1 The relationship between water balance and rainfall - runoff parameters

According to equation 2.1 rainfall, evapotranspiration and runoff have an effect on the water balance. However the equation does not imply a linear relationship between water balance and these factors. Therefore regression analysis was done to assess linearity between water balance and each of these parameters. Other parameters related to rainfall and runoff were included to increase the prediction ability of the model.

Table 4.16 shows the regression coefficients and coefficients of determination of the respective equations relating water balance and rainfall, evapotranspiration, intensity, duration, throughfall, stemflow, interception, total runoff, direct runoff and base flow. It can be observed that the water balance is linearly related to rainfall, throughfall, stemflow, interception, direct runoff, total runoff, and intensity. This is evidenced by the regression coefficients which are statistically different from zero ($P < 0.05$) and moderately high coefficients of determination for the respective equations (Table 4.16). There is a poor linear relationship between water balance and duration of rainfall ($R^2 = 0.37$). Water balance and evapotranspiration and base flow are not linearly related in this catchment. This is evidenced by the regression coefficients which are not statistically different from zero at 5% level and very low coefficients of determination for the respective equations (Table 4.16). Therefore the relationship between water balance and evapotranspiration can be pegged on other kinds of relationships. Since in this study the model was based on multiple regression which imply a linear relationship, evapotranspiration and base flow were not included.

Table 4.16: Regression coefficients and coefficients of determination of respective Equations

Parameters (Independent variables)	Regression equations (Dependant variable: W = water balance)	Coefficient of Determination (R^2)	Significance at 5% level of regression coefficient ($\beta \neq 0$)
Rainfall (P)	W = 0.72P – 112.4	0.97	Significant
Evapotranspiration (E)	W = 0.5E - 51.37	0.01	n.s.d.
Intensity (Ri)	W = 5.24Ri – 118.6	0.91	Significant
Duration (Rd)	W = 7.28Rd – 128.4	0.37	Significant
Throughfall (T)	W = 1.28T – 111.5	0.97	Significant
Stemflow (S)	W = 27.3S – 111.7	0.97	Significant
Interception	W = 3.6I – 113.95	0.97	Significant
Total runoff (TR)	W = 16.1TR – 549.5	0.67	Significant
Direct runoff (DRO)	W = 17.4DRO – 111.3	0.86	Significant
Base flow (BF)	W = 134.8 – 5.13BF	0.04	n.s.d.

4.6.2. Water balance model.

It has been shown in section 4.6.1 that the water balance is linearly related to a number of rainfall - runoff parameters that can be used to estimate the former. A multiple regression based empirical model which included the parameters above was developed. The output from the regression analysis is shown in Appendix 13 and Appendix 14. The slope for stemflow and interception had high standard errors of 36.33 and 33.64 respectively (Appendix 13). The two parameters with such standard errors will normally reduce the level of precision if included in the model. Throughfall had a standard error of zero indicating that the coefficient (β) of throughfall is not useful in predicting water balance (Appendix 13). Although interception, stemflow and throughfall had a linear relationship with water balance when analysed singly, their effectiveness in predicting water balance when combined with other factors tend to reduce. Therefore the three parameters, interception, stemflow and throughfall were eliminated to increase the level of precision of the model. Therefore the model developed is shown below (Equation 4.7). The coefficients are shown in the regression output in Appendix I4.

$$W = 0.7855P - 5.3641Rd + 5.0175TR + 0.628Ri - 2.2199DRO - 231.25;$$

$$R^2=0.97 \qquad (4.7)$$

where:

W = water balance

DRO = direct runoff

TR = total runoff

Rd = Rainfall duration

Ri = Rainfall intensity

P = Rainfall amount

R^2 = coefficient of determination

4.6.3 Model evaluation and validation.

The Gendavaki data was used for the validation of the model. The calculated water balance using measured parameters was compared with predicted water balance using Equation 4.7. The results are shown in Figure 4.40 and Table 4.17.

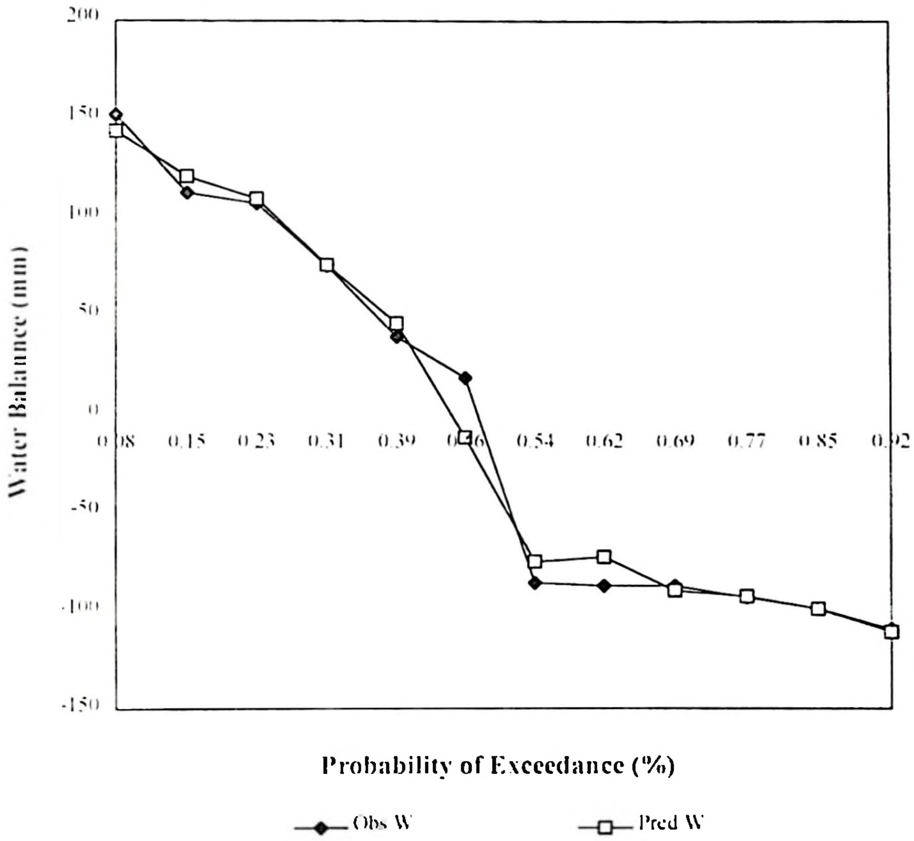

Figure 4.40: Comparison between observed and predicted water balance

Table 4.17: Test statistics for significant difference between observed and predicted water balance

Df	*p*	*t Stat*	*t Crictical*	*Significance*
22	0.05	-0.00.25	2.07	n.s.d.

The results show that there was no significant difference between predicted water balance and observed water balance at 5% level. In addition regression coefficient (β) was significantly different from zero at 1% level as shown by ANOVA in Appendix 14. Therefore the model can be useful in estimating the water balance.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following conclusions can be drawn from this study:

1. The soil physical and hydrological properties of the catchment suggest good drainage and permeability. This is indicated by the predominance of the sandy clay texture, high organic matter content, moderately rapid hydraulic conductivity of 4.2 cm/h and a moderately rapid infiltration rate of 3.8 cm/h.

2. As expected, the bulk density increased with depth with an overall average of 0.9 g/cm^3 for 0 - 15 cm depth, 1.11g/cm^3 for 15 - 30 cm depth and 1.30 g/cm^3 for 30 - 45 cm depth. It falls within the acceptable range for root penetration. The high organic matter content contributed to the low bulk density of the top layer.

3. Surface runoff is mainly generated from the sites with clay and sandy clay texture which have an infiltration rate that is lower than rainfall intensity, and this occurs during the first five months of the wet season.

4. The catchment is characterised by a shorter time of concentration due to steep slopes of about 35 % resulting in rapid response of the stream in case of a rainfall event.

5. The area can be categorised as moist sub - humid with six months of rainfall. The wet season is distinct from the dry season . The distribution of rainfall throughout the season gives better support to crops.

6. Rainfall is linearly related to throughfall, stemflow, and interception as depicted by the respective regression equations. Seventy percent of the rainfall reaches the forest floor as net rainfall (throughfall and stemflow) while the remainder is intercepted by the forest canopy. Throughfall, which is realised with a rainfall event of more than 0.7mm decreases with increasing vegetal cover while the opposite is true with interception. Trees with small stem sizes had high amount of stemflow.

7. Baseflow plays a significant contribution to total runoff compared to direct runoff. This is evidenced by the perennial nature of the main stream – Muhu inspite of the fact that there is evidence of catchment degradation in terms of forest clearing.

8. Water balance was only positive during the first five months of the wet season. This period is considered adequate to support a crop without the expense of irrigation.

9. There is fairly good agreement between observed and modelled direct runoff and water balance with correlation coefficients (R^2) of 0.94 and 0.99 respectively. This shows that the developed models are valid and useful in estimating the respective parameters in the highlands of Tanzania with sub-humid climate.

5.2 Recommendations

1. Given that cultivation is done on steep slopes without erosion control measures, it is recommended that extension officers in collaboration with other rural development projects should put more effort in encouraging farmers to use

terracing in their cultivation. It will help to conserve water, minimise runoff and soil erosion.

2. As the HIMA project phases out, it is recommended that government should ensure that the water resource monitoring programme continues for the next two decades. It will facilitate generating more data that can help to better assess the effects of changes in land use.

3. Government should take strong measures against the interference with the forests and vegetation cover in the highlands of Tanzania since most of the large rivers originate from these highlands. The action is necessary because the highlands play a major role in water supply, and hence the need to manage the highlands properly.

4. Government should use the motivation approach to ensure that the land users become stewards of the catchment resources for the present and future generations.

5. Models developed from this study should be tested in other catchments in Tanzania for possible adoption.

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APPENDICES

Appendix A: Equations for generating infiltration curves

Site	Infiltration rate	Cumulative infiltration	Site	Infiltration rate	Cumulative infiltration
1	Y = 95.59e-0.013x	Y = 25.7Ln(x) - 37.36	28	Y = 94.61e-0.027x	Y = 15.73Ln(x) - 17.65
2	Y = 87.19e-0.023x	Y = 15.51Ln(x) - 18.50	29	Y = 31.23e-0.025x	Y = 4.05Ln(x) - 2.23
3	Y = 36.36e-0.041x	Y = 3.26Ln(x) - 0.079	30	Y = 110e-0.009x	Y = 36.37Ln(x) - 55.33
4	Y = 61.33e-0.071x	Y = 8.53Ln(x) - 8.1	31	Y = 99.79e-0.02x	Y = 21.99Ln(x) - 25.11
5	Y = 79.13e-0.022x	Y = 14.96Ln(x) - 20.07	32	Y = 61.27e-0.02x	Y = 11.04Ln(x) - 9.8
6	Y = 26.67e-0.0003x	Y = 2.9Ln(x) - 1.2	33	Y = 76.68e-0.022x	Y = 14.39Ln(x) - 16.9
7	Y = 68.46e-0.026x	Y = 10.67Ln(x) - 11.7	34	Y = 94.25e-0.026x	Y = 15.24Ln(x) - 18.17
8	Y = 41.11e-0.018x	Y = 7.48Ln(x) - 7.82	35	Y = 30.58e-0.017x	Y = 6.12Ln(x) - 5.30
9	Y = 43.06e-0.02x	Y = 6.15Ln(x) - 4.94	36	Y = 49.99e-0.015x	Y = 11.5Ln(x) - 14.99
10	Y = 28.08e-0.019x	Y = 4.55Ln(x) - 4.03	37	Y = 55.46e-0.025x	Y = 8.42Ln(x) - 7.25
11	Y = 42.88e-0.023x	Y = 7.50Ln(x) - 6.11	38	Y = 69.9e-0.016x	Y = 15.37Ln(x) - 19.43
12	Y = 64.51e-0.02x	Y = 12.1Ln(x) - 13.02	39	Y = 79.53e-0.020x	Y = 15.78Ln(x) - 20.89
13	Y = 41.04e-0.021x	Y = 7.07Ln(x) - 5.4	40	Y = 30.64e-0.021x	Y = 4.57Ln(x) - 2.56
14	Y = 61.47e-0.019x	Y = 12.18Ln(x) - 12.93	41	Y = 108.86e-0.026x	Y = 17.7Ln(x) - 19.88
15	Y = 59.67e-0.025x	Y = 9.4Ln(x) - 6.69	42	Y = 32.43e-0.025x	Y = 4.02Ln(x) - 2.6
16	Y = 35.19e-0.022x	Y = 5.52Ln(x) - 4.45	43	Y = 87.56e-0.025x	Y = 14.41Ln(x) - 16.04
17	Y = 46.64e-0.024x	Y = 6.79Ln(x) - 4.83	44	Y = 82.71e-0.018x	Y = 18.20Ln(x) - 24.94
18	Y = 73.79e-0.02x	Y = 14.16Ln(x) - 15.36	45	Y = 65.07e-0.022x	Y = 11.62Ln(x) - 13.13
19	Y = 47.61e-0.021x	Y = 7.94Ln(x) - 7.50	46	Y = 52.17e-0.012x	Y = 14.15Ln(x) - 19.51
20	Y = 33.62e-0.019x	Y = 5.9Ln(x) - 3.84	47	Y =93.50e-0.021x	Y = 17.56Ln(x) - 21.25
21	Y = 45.71e-0.022x	Y = 7.9Ln(x) - 8.16	48	Y = 91.49e-0.017x	Y =21.70Ln(x) -26.25
22	Y = 48.44e-0.025x	Y = 7.15Ln(x) - 6.2	49	Y = 98.84e-0.027x	Y = 15.63Ln(x) - 18.24
23	Y = 47.46e-0.016x	Y = 8.98Ln(x) - 8.90	50	Y =79.35e-0.018x	Y = 16.54Ln(x) - 21.92
24	Y = 64.35e-0.019x	Y = 12.69Ln(x) - 14.27	51	Y = 76.40e-0.022x	Y = 14.50Ln(x) - 15.076
25	Y =60.78e-0.019x	Y = 12.77Ln(x) - 13.35	52	Y =41.77e-0.018x	Y = 7.2Ln(x) - 6.93
26	Y = 95.77e-0.026x	Y = 15.73Ln(x) - 19.21	53	Y = 63.02e-0.015x	Y = 15.66Ln(x) - 21.94
27	Y = 75.13e-0.02x	Y = 14.34Ln(x) - 14.11	54	Y = 99.33e-0.0075x	Y = 43.89Ln(x) - 83.7

Appendix B: The Summary of Climatic Parameters of Bomalang'ombe Weather Station

Year						1993/94						
Climatic parameters	Jun-93	Jul-93	Aug-93	Sep-93	Oct-93	Nov-93	Dec-93	Jan-94	Feb-94	Mar-94	Apr-94	May-94
Mean Temp (oC)	11.8	10.7	13.5	14.5	15.4	16.2	16.6	16.9	16.2	16.1	15.0	13.6
Mean RH %	89.1	87.8	84.6	84.0	86.0	84.9	89.3	88.1	90.7	92.4	92.3	92.9
Mean radiation W/m2	159.8	159.3	166.3	228.2	231.2	244.2	204.7	199.4	149.5	169.4	167.6	117.8
Mean wind speed (m/s)	1.29	1.52	1.87	1.93	1.82	1.71	1.30	1.09	1.01	0.66	1.25	1.34
Total rainfall (mm)	7	8.7	10.4	5.3	33.6	26.4	92.7	187.2	179.3	346.8	142.0	153.5
ETo. (mm)	55.86	58.5	61.7	106.2	142.0	109.5	108.1	103.7	73.2	85.3	77.4	56.4
Duration (hr)	0.73	4.29	4.0	2.42	7.0	3.8	3.0	4.70	4.42	8.90	3.56	5.21
Intensity (mm/hr)	9.65	2.03	2.61	2.25	4.80	6.90	30.97	39.92	40.58	38.87	39.87	29.45
Year						1994/95						
Climatic parameters	Jun-94	Jul-94	Aug-94	Sep-94	Oct-94	Nov-94	Dec-94	Jan-95	Feb-95	Mar-95	Apr-95	May-95
Mean Temp (oC)	12.0	11.5	12.0	13.4	15.1	15.8	16.4	17.0	16.6	16.3	15.4	13.9
Mean RH %	88.3	88.6	90.0	86.3	88.3	84.5	90.4	88.6	88.3	89.0	91.6	89.8
Mean radiation W/m2	181.6	146.1	146.4	195.3	172.9	209.9	204.9	181.9	171.3	193.3	141.1	128.7
Mean wind speed (m/s)	1.39	1.54	1.62	1.81	1.81	1.59	1.33	1.04	0.91	0.75	1.10	1.31
Total rainfall (mm)	1.4	10.5	13.8	6.3	42.6	44.4	177.5	176.7	124.0	226.4	262.5	96.3
ETo. (mm)	70.1	62.8	67.6	89.7	90.0	104.1	103.6	96.5	82.7	96.6	69.4	61.9
Duration (hr)	0.16	5.02	5.42	3.05	10.95	6.34	4.49	4.4	2.95	5.65	6.9	3.55
Intensity (mm/hr)	8.52	2.09	2.15	2.06	3.89	7.02	39.5	40.02	41.91	40.01	38.35	27.40
Year						1995/96						
Climatic parameters	Jun-95	Jul-95	Aug-95	Sep-95	Oct-95	Nov-95	Dec-95	Jan-96	Feb-96	Mar-96	Apr-96	May-96
Mean Temp (oC)	12.4	11.5	12.6	13.5	15.0	16.4	16.8	16.8	16.5	16.6	14.7	13.8
Mean RH %	87.1	89.2	88.3	87.0	86.7	85.3	88.1	88.4	90.3	88.7	91.2	91.3
Mean radiation W/m2	171.2	146.6	171.9	208.4	228.3	258.3	204.6	200.1	164.5	185.6	126.4	114.5
Mean wind speed (m/s)	1.09	1.43	1.65	1.67	1.80	1.85	1.27	0.82	0.64	0.83	1.28	1.28
Total rainfall (mm)	1.8	5.0	40.2	15.5	18.4	6.1	153.9	131.5	286.8	182.6	366.8	160.5
ETo. (mm)	65.8	63.7	77.1	92.9	110.9	124.5	105.7	102.5	80.9	94.6	62.7	56.7
Duration (hr)	0.2	2.7	16.08	6.25	3.79	0.89	3.87	3.36	6.86	4.67	9.4	5.92
Intensity (mm/hr)	8.87	1.85	2.50	2.48	4.86	6.80	39.8	39.69	41.85	39.92	38.87	27.64

Year	1996/97											
Climatic parameters	Jun-96	Jul-96	Aug-96	Sep-96	Oct-96	Nov-96	Dec-96	Jan-97	Feb-97	Mar-97	Apr-97	May-97
Mean Temp (oC)	11.9	11.2	12.1	13.7	14.0	16.2	17.1	17.5	16.6	16.3	15.4	13.7
Mean RH %	88.9	88.0	85.2	87.3	88.6	84.9	87.2	86.8	90.3	88.1	89.5	89.4
Mean radiation W/m2	145.6	162.8	222.4	206.8	189.7	264.5	221.5	229.3	166.2	197.9	158.4	144.9
Mean wind speed (m/s)	1.37	1.45	1.52	1.69	1.74	1.70	1.07	1.20	0.86	0.99	0.78	1.15
Total rainfall (mm)	2.2	4.9	0.0	1.6	15.9	16.0	55.1	168.8	209.2	300.3	249.4	47.4
ETo. (mm)	60.2	66.7	91.8	93.1	93.0	125.4	113.1	118.4	80.1	99.5	75.0	65.8
Duration (hr)	0.25	2.29	0.0	0.57	3.32	2.34	1.50	4.36	5.46	7.69	6.5	1.88
Intensity (mm/hr)	8.67	2.14	0.0	2.80	4.78	6.76	37.32	38.68	38.32	39.02	38.67	25.36
Year	1997/98											
Climatic parameters	Jun-97	Jul-97	Aug-97	Sep-97	Oct-97	Nov-97	Dec-97	Jan-98	Feb-98	Mar-98	Apr-98	May-98
Mean Temp (oC)	12.7	11.4	12.7	13.9	14.6	16.5	16.5	17.3	16.1	17.4	15.6	14.7
Mean RH %	79.6	79.1	79.1	70.2	75.2	80.5	81.0	79.6	86.4	80.5	88.7	90.0
Mean radiation W/m2	128.8	150.6	199.3	220.6	168.2	218.6	167.1	198.1	141.3	186.3	127.4	175.4
Mean wind speed (m/s)	1.23	1.53	1.41	1.66	1.55	0.95	0.65	0.64	0.45	0.55	0.56	0.85
Total rainfall (mm)	43.8	14.7	13.5	5.9	71.9	154.3	411.2	311.2	494.6	160.8	210.8	41.2
ETo. (mm)	55.9	63.6	85.1	98.5	84.1	104.2	86.6	100.1	78.7	95.0	95.2	77.2
Duration (hr)	6.54	7.03	5.11	1.3	1.22	26.15	10.3	7.80	11.0	4.0	6.02	1.52
Intensity (mm/hr)	6.70	2.09	2.04	4.66	5.90	5.90	39.83	39.90	45.44	39.93	35.72	27.47
Year	1998/99											
Climatic parameters	Jun-98	Jul-98	Aug-98	Sep-98	Oct-98	Nov-98	Dec-98	Jan-99	Feb-99	Mar-99	Apr-99	May-99
Mean Temp (oC)	12.6	11.9	12.4	13.7	14.9	16.1	16.7	17.1	16.4	15.8	15.4	14.0
Mean RH %	69.4	71.8	75.6	70.4	70.6	69.8	63.2	70.2	66.4	72.1	81.3	82.1
Mean radiation W/m2	175.0	169.4	131.5	154.1	230.9	237.1	277.5	234.2	218.6	146.3	176.8	175.2
Mean wind speed (m/s)	1.16	1.17	1.71	1.76	1.77	1.90	1.00	1.01	0.86	0.84	0.96	0.95
Total rainfall (mm)	6.6	8.4	30.0	50.1	10.2	7.4	215.3	225.0	166.5	276.0	305.0	136.0
ETo. (mm)	70.9	69.6	63.6	68.5	102.1	117.0	138.8	120.6	105.2	100.1	93.4	88.2
Duration (hr)	0.76	4.18	10.24	27.83	2.10	0.15	4.46	5.36	4.30	7.31	8.31	4.90
Intensity (mm/hr)	8.70	2.01	2.93	1.80	4.91	6.70	48.32	41.36	41.94	40.92	38.71	27.40

APPENDIX C: Probability of exceedance and return period.

Appendix C-1: Monthly Rainfall probability of exceedance and return period

P	Tr	93/94	94/95	95/96	96/97	97/98	98/99
0.077	12.987	346.78	262.54	366.78	300.33	494.6	309.75
0.154	6.4935	187.21	226.39	286.79	249.42	411.2	300
0.231	4.329	179.33	177.51	182.57	209.23	311.2	225
0.308	3.2468	153.49	176.71	160.54	168.84	210.8	215.3
0.385	2.5974	141.97	123.99	153.9	55.124	160.8	180.55
0.462	2.1645	92.71	96.32	131.46	47.44	154.3	133.55
0.538	1.8587	33.60	44.424	40.174	15.952	71.884	50.06
0.615	1.626	26.44	42.602	18.37	15.944	43.814	30.02
0.692	1.4451	10.40	13.823	15.538	4.941	41.2	10.2
0.769	1.3004	8.70	10.484	6.05	2.216	14.726	8.4
0.846	1.182	7.00	6.258	5.034	1.614	13.52	7.41
0.923	1.0834	5.30	1.41	1.814	0	5.85	6.6

P : Probability of exceedance
Tr : Return Period

Appendix C- 2: Monthly evapotranspiration probability of exceedance and return period

P	Tr	93/94	94/95	95/96	96/97	97/98	98/99
0.077	12.987	142	104.1	124.5	125.35	104.24	138.84
0.154	6.4935	109.5	103.6	110.9	118.35	100.06	120.62
0.231	4.329	108.1	96.6	105.7	113.05	98.54	116.97
0.308	3.2468	106.2	96.5	102.5	99.48	95.2	105.21
0.385	2.5974	103.7	90	94.6	93.1	94.97	102.14
0.462	2.1645	85.3	89.7	92.9	93	86.56	100.12
0.538	1.8587	77.4	82.7	80.9	91.8	85.11	93.4
0.615	1.626	73.2	70.1	77.1	80.09	84.06	88.2
0.692	1.4451	61.7	69.4	65.8	74.99	78.73	70.86
0.769	1.3004	58.48	67.6	63.7	66.7	77.23	69.57
0.846	1.182	56.4	62.8	62.7	65.82	63.62	68.5
0.923	1.0834	55.86	61.9	56.7	60.2	55.92	63.55

P : Probability of exceedance
Tr : Return Period

Appendix C- 3: Monthly rainfall intensity probability of exceedance and return period

P	Tr	93/94	94/95	95/96	96/97	97/98	98/99
0.077	12.987	40.58	41.90	41.90	39.00	45.40	48.30
0.154	6.4935	39.90	40.00	39.90	38.60	39.90	41.90
0.231	4.329	39.80	39.20	39.80	38.50	39.80	40.90
0.308	3.2468	38.90	39.00	39.60	38.30	39.70	40.80
0.385	2.5974	30.90	38.40	38.80	37.80	35.70	38.70
0.462	2.1645	29.40	27.40	27.60	25.30	27.40	27.40
0.538	1.8587	9.70	8.50	8.90	8.70	6.70	8.70
0.615	1.626	6.90	7.00	6.80	6.70	5.90	6.70
0.692	1.4451	2.60	2.20	2.60	2.80	4.70	2.90
0.769	1.3004	2.30	2.10	2.50	2.80	4.60	2.80
0.846	1.182	2.20	2.08	2.40	2.10	2.10	2.00
0.923	1.0834	2.00	2.05	1.90	0.00	2.00	1.80

P : Probability of exceedance
Tr : Return Period

Appendix C-4: Monthly rainfall duration probability of exceedance and return period

P	Tr	93/94	94/95	95/96	96/97	97/98	98/99
0.077	12.987	8.90	10.90	16.08	7.70	26.15	27.83
0.154	6.4935	7.00	6.90	9.42	6.60	12.18	10.24
0.231	4.329	5.20	6.40	6.91	5.50	11.01	8.30
0.308	3.2468	4.70	6.34	6.31	4.40	10.30	7.35
0.385	2.5974	4.40	5.70	5.95	3.30	7.80	5.35
0.462	2.1645	4.30	5.21	4.72	2.40	7.00	4.90
0.538	1.8587	4.00	4.52	3.91	2.30	6.50	4.50
0.615	1.626	3.80	4.41	3.80	1.92	6.00	4.30
0.692	1.4451	3.60	3.60	3.45	1.55	5.10	4.20
0.769	1.3004	3.00	3.15	2.75	0.65	4.00	2.10
0.846	1.182	2.40	3.02	0.90	0.35	1.55	0.80
0.923	1.0834	0.73	0.16	0.15	0.00	1.32	0.20

P . Probability of exceedance
Tr : Return Period

Appendix C-5: Total runoff (TR) probility of exceedance and return period

Prob of Exc	Tr	93/94	94/95	95/96	96/97	97/98	98/99
0.077	12.987	53.02	33.29	49.01	49.23	59.2	57.87
0.154	6.4935	44.54	32.65	39.58	41.92	51.17	47.98
0.231	4.329	42.71	30.86	33.56	36.77	45.09	44.25
0.308	3.2468	42.5	29.12	31.88	31.55	42.82	39.6
0.385	2.5974	35.65	28.76	30.1	31.19	40.08	37.98
0.462	2.1645	34.259	28.29	26.69	30.03	39.83	36.38
0.538	1.8587	33.91	27.02	26.4	30.02	32.93	33.42
0.615	1.626	33.82	26.907	25.25	29.35	32.02	32.03
0.692	1.4451	32.94	26.4	24.91	29.02	30.95	31.8
0.769	1.3004	31.706	25.95	24.51	28.01	27.69	30.37
0.846	1.182	31.66	25.54	23.55	27.64	27.5	30.07
0.923	1.0834	29.14	24.51	15.58	25.57	26.57	28.28

P : Probability of exceedance
Tr : Return Period

Appendix C-6: Direct Runoff (DRO) probability of exceedance and return period

Prob of Exc	Tr	93/94	94/95	95/96	96/97	97/98	98/99
0.077	12.987	23.03	10.93	15.9	15.52	31.47	16
0.154	6.4935	15.33	10.72	14.96	14.96	20.58	15.36
0.231	4.329	11.7	8.3	6.69	14.5	17.99	11.61
0.308	3.2468	7.398	5.5	5.91	6.83	9.92	7.59
0.385	2.5974	6.87	5.27	5.62	2.24	9.01	6.94
0.462	2.1645	6.32	4.56	4.29	1.35	5.68	3.495
0.538	1.8587	4.61	3.6	2.04	0.75	4.2	2.22
0.615	1.626	4.44	2.82	1.24	0.69	3.05	1.81
0.692	1.4451	1.56	0.37	0.83	0.64	1.42	1.51
0.769	1.3004	1.17	0.31	0.63	0.32	0.59	1.47
0.846	1.182	1.12	0.11	0.27	0.21	0.47	1.35
0.923	1.0834	0.64	0.04	0.23	0	0.41	1.28

P : Probability of exceedance
Tr : Return Period

Appendix C-7: Base flow (BF) probability of exceedance and return period

Prob of Exc	Tr	93/94	94/95	95/96	96/97	97/98	98/99
0.077	12.987	51.46	28.72	33.96	34.53	35.63	41.87
0.154	6.4935	43.37	28.18	33.11	33.71	33.81	40.39
0.231	4.329	42.07	26.597	26.06	29.82	31.55	35.03
0.308	3.2468	31.21	25.59	25.97	29.35	31.51	32.64
0.385	2.5974	30.586	25.17	24.08	29.27	30.59	31.2
0.462	2.1645	29.3	24.99	24.01	28.7	30.36	31.04
0.538	1.8587	27.5	23.58	23.41	27.42	30.16	30.75
0.615	1.626	26.861	22.46	23.32	27	27.73	29.99
0.692	1.4451	26.07	22.35	22.47	26.66	27.1	28.56
0.769	1.3004	19.47	21.72	22.11	24.88	26.16	26.875
0.846	1.182	17.44	19.01	18.6	24.72	24.64	26.81
0.923	1.0834	16.33	18.4	15.31	16.23	21.82	24.24

P : Probability of exceedance
Tr : Return Period

Appendix C-8: Water balance probility of exceedance and return period

Prob of	Tr	93/94	94/95	95/96	96/97	97/98	98/99	Average
0.08	12.99	218.98	160.49	255.07	158.93	364.70	153.73	218.65
0.15	6.49	76.99	96.50	172.33	125.20	279.55	131.63	147.03
0.23	4.33	61.44	51.09	64.26	97.95	151.94	64.78	81.91
0.31	3.25	51.85	46.89	56.09	18.94	75.52	48.18	49.58
0.39	2.60	30.66	15.34	18.10	-55.15	23.01	23.31	9.21
0.46	2.16	-49.65	3.56	2.56	-85.94	22.56	-0.18	-17.85
0.54	1.86	-93.40	-73.80	-62.18	-88.00	-39.87	-48.81	-67.68
0.62	1.63	-94.01	-80.61	-74.25	-91.79	-45.04	-65.33	-75.17
0.69	1.45	-102.80	-80.68	-90.68	-106.08	-75.86	-93.20	-91.55
0.77	1.30	-116.88	-84.19	-101.87	-119.13	-80.91	-100.64	-100.60
0.85	1.18	-132.61	-97.45	-117.44	-121.15	-102.54	-122.01	-115.53
0.92	1.08	-141.34	-108.98	-142.00	-134.97	-119.26	-142.98	-131.59

P : Probability of exceedance
Tr : Return Period

Appendix D: Daily Throughfall (T), Stemflow (S) and Interception (I)

Appendix D-1: Average daily throughfall (T), stemflow (S), interception (I) gross rainfall(P) for plot I

Day	February				March				April				May			
	P	T	S	I	P	T	S	I	P	T	S	I	P	T	S	I
1	20.4	13.4	1.17	5.85	0	0	0	0	12.3	8.23	0.74	3.33	14.8	10.4	0.79	3.65
2	0	0	0	0	0	0	0	0	8.3	5.18	0.41	2.71	15.5	10.8	1.07	3.64
3	0	0	0	0	0	0	0	0	17.6	11.8	1.06	4.76	14.7	10.3	0.79	3.58
4	0	0	0	0	0	0	0	0	15.3	10.7	0.84	3.8	1	0.42	0.01	0.57
5	0	0	0	0	0	0	0	0	18.6	12.9	1.07	4.65	1.5	0.63	0.02	0.85
6	0	0	0	0	2.4	1.18	0.1	1.11	3.2	1.52	0.16	1.53	0	0	0	0
7	0	0	0	0	10.1	6.77	0.59	2.75	2.1	0.72	0.13	1.25	11.2	7.13	0.66	3.4
8	21	14	1.17	5.81	21.4	12.8	0.92	7.73	3.3	1.6	0.17	1.53	16	11.1	1.11	3.79
9	0	0	0	0	21.7	13.1	0.92	7.65	4.3	2.48	0.19	1.63	0	0	0	0
10	0	0	0	0	14.7	10.4	0.64	3.71	8.1	6.05	0.4	1.65	8	5.87	0.36	1.78
11	21.9	14.2	1.2	6.48	14.6	9.95	0.63	4.02	24.9	17.5	1.81	5.58	11.4	7.28	0.66	3.45
12	0	0	0	0	1.1	0.43	0.01	0.65	8.2	5.18	0.35	2.67	20	13.4	1.25	5.36
13	0	0	0	0	12.8	8.22	0.53	4.06	9.3	6.13	0.39	2.77	1.3	0.53	0.02	0.75
14	0	0	0	0	10.1	6.33	0.53	3.23	14.4	10.2	0.78	3.47	0	0	0	0
15	0	0	0	0	12.4	7.32	0.54	4.54	1	0.42	0.01	0.57	0	0	0	0
16	0	0	0	0	2.3	1.35	0.1	0.85	3.3	2.08	0.16	1.05	0	0	0	0
17	0	0	0	0	0	0	0	0	5.2	2.73	0.21	2.26	0	0	0	0
18	0	0	0	0	0.5	0.28	0.01	0.21	8.6	5.07	0.42	3.12	0	0	0	0
19	7.8	5.18	0.2	2.41	0.5	0.27	0.01	0.22	29.4	21.6	2.36	5.41	0	0	0	0
20	40	28.5	2.66	8.87	8.6	5.25	0.41	2.94	3.7	2.03	0.16	1.51	2	1.03	0.02	0.95
21	20.7	13.4	1.17	6.12	8.7	5.5	0.41	2.79	8.2	6.23	0.35	1.62	0	0	0	0
22	0.7	0.33	0.01	0.36	14.1	10.5	0.57	3.01	8.3	5.27	0.39	2.65	0	0	0	0
23	0		0	0	2.6	1.57	0.17	0.86	38.8	27.5	2.87	8.45	0	0	0	0
24	0		0	0	5.3	2.15	0.25	2.9	27.8	20.6	2.16	5.06	0	0	0	0
25	16.8	12.2	0.98	3.62	5.4	2.17	0.27	2.97	8	5.87	0.36	1.78	11.8	7.97	0.72	3.11
26	7	4.73	0.18	2.08	8.6	5.45	0.35	2.8	5.2	2.63	0.2	2.36	0	0	0	0
27	20.6	12.8	1.16	6.66	24.7	18	1.24	5.49	11.2	7.13	0.66	3.4	0	0	0	0
28	0	0	0	0	6.8	4.77	0.21	1.82	4.2	2.4	0.18	1.62	0	0	0	0
29					0	0	0	0	27.1	19.9	2.16	5.06	6	5.03	0.19	0.77
30					15.6	11.8	0.94	2.91	7.2	5.33	0.21	1.66	8	5.87	0.36	1.78
31					64.8	46.8	2.18	15.8					2	1.03	0.02	0.95
Total	177	119	9.91	48.3	290	192	12.5	85	347	237	21.3	88.9	145	98.8	8.04	38.4

Appendix D-2: Average daily throughfall (T), stemflow (S), interception (I) gross rainfall(P) for plot 2

Day	February				March				April				May			
	P	T	S	I	P	T	S	I	P	T	S	I	P	T	S	I
1	19.4	13.2	0.59	5.61	0	0	0	0	13.3	8.28	0.25	4.77	14	9.08	0.27	4.65
2	0	0	0	0	0	0	0	0	8.2	4.98	0.16	3.06	16.5	8.65	0.29	7.56
3	0	0	0	0	0	0	0	0	15.2	9.65	0.28	5.27	13.2	8.33	0.25	4.62
4	0	0	0	0	0	0	0	0	3.6	2.12	0.06	1.43	2.3	1.27	0.09	0.94
5	0	0	0	0	0	0	0	0	19.1	12.2	0.55	6.32	2.6	1.45	0.05	1.1
6	0	0	0	0	0	0	0	0	3	1.75	0.06	1.19	0	0	0	0
7	0	0	0	0	8.2	4.8	0.15	3.25	1.1	0.45	0.02	0.63	8.1	4.8	0.15	3.15
8	20.7	13.7	0.6	6.38	8.2	4.85	0.15	3.2	3.4	2	0.06	1.34	0	0	0	0
9	0	0	0	0	9.3	4.93	0.18	4.19	4.3	2.53	0.06	1.7	0	0	0	0
10	0	0	0	0	10.3	5.9	0.22	4.18	8.1	5	0.15	2.95	2.8	1.75	0.06	0.99
11	20.3	13.3	0.66	6.36	15.2	9.48	0.28	5.44	25.9	15.8	0.7	9.4	4.6	2.73	0.06	1.8
12	0	0	0	0	1.2	0.55	0.03	0.62	6.4	3.52	0.09	2.79	11	6.85	0.23	3.92
13	0	0	0	0	25.6	18.4	0.69	6.54	9.2	5.32	0.18	3.71	2.4	1.35	0.05	1
14	0	0	0	0	9.4	5.25	0.18	3.97	14.3	9.08	0.27	4.95	0	0	0	0
15	0	0	0	0	13	8.89	0.24	3.86	1.1	0.45	0.03	0.62	0	0	0	0
16	0	0	0	0	3.8	2.22	0.05	1.53	3.2	1.8	0.06	1.34	0	0	0	0
17	0	0	0	0	0	0	0	0	4.2	2.43	0.06	1.71	0	0	0	0
18	0	0	0	0	10.2	7.27	0.22	2.72	8.6	5.3	0.16	3.14	0	0	0	0
19	8	5.03	0.25	2.71	0.6	0.25	0.02	0.33	19.5	12.7	0.6	6.16	0	0	0	0
20	28.6	20.4	0.83	7.34	0	0	0	0	3.7	2.32	0.06	1.32	1.8	0.87	0.07	0.86
21	18.7	12.2	0.57	5.96	6.3	3.3	0.09	2.91	8.3	5.12	0.15	3.03	0	0	0	0
22	0.5	0.23	0.01	0.26	13.3	8.33	0.25	4.72	8.2	5.07	0.15	2.98	0	0	0	0
23	0	0	0	0	5.1	2.78	0.07	2.24	38.8	26.4	0.96	11.4	0	0	0	0
24	0	0	0	0	0	0	0	0	27.8	21.4	0.79	5.61	0	0	0	0
25	11.5	6.47	0.32	4.72	8.2	5.4	0.16	2.64	7.1	4.2	0.09	2.81	0	0	0	0
26	7.9	4.47	0.25	3.18	25.5	18.6	0.7	6.19	5.2	3.15	0.07	1.98	8.8	5.4	0.15	3.25
27	22.2	15.6	0.65	5.93	6.2	3.72	0.1	2.39	11.1	6.85	0.23	4.02	0	0	0	0
28	0	0	0	0	7.9	4.23	0.15	3.51	4.2	2.55	0.07	1.58	0	0	0	0
29					0	0	0	0	27	19.9	0.73	6.37	12.2	7.35	0.22	4.63
30					12.4	6.92	0.23	5.25	4.2	2.63	0.07	1.49	9	5.32	0.17	3.52
31					68.5	44.7	1.15	22.7					2	0.97	0.08	0.96
Total	158	105	4.74	48.4	268	171	5.31	92.4	317	205	7.17	105	111	66.2	2.2	42.9

Appendix D-3: Average daily throughfall (T), stemflow (S), interception (I) gross rainfall (P) for plot 3

Day	February				March				April				May			
	P	T	S	I	P	T	S	I	P	T	S	I	P	T	S	I
1	23.4	19.5	0.42	3.51	0	0	0	0	17.8	14.9	0.44	2.48	17.8	14.9	0.44	2.48
2	0	0	0	0	0	0	0	0	11.2	7.23	0.37	3.6	18.5	15.1	0.44	2.97
3	0	0	0	0	0	0	0	0	9.8	7.12	0.31	2.37	17.7	14.7	0.44	2.53
4	0	0	0	0	0	0	0	0	8.8	6.9	0.27	1.63	1.5	0.78	0.01	0.71
5	0	0	0	0	0	0	0	0	9.8	7.4	0.31	2.09	2	1.05	0.01	0.94
6	0	0	0	0	7.7	5.15	0.14	2.41	7.8	5.32	0.22	2.26	0	0	0	0
7	0	0	0	0	8.9	6.38	0.15	2.36	0	0	0	0	14.2	8.03	0.37	5.79
8	25.8	19.9	0.43	5.48	0	0	0	0	8	5.17	0.23	2.6	20	15.6	0.44	3.91
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	38.7	25.7	0.86	12.1	27.5	20.1	0.55	6.9	6	4	0.04	1.96
11	27.9	24.3	0.44	3.16	25.8	20.8	0.55	4.45	11.5	6.85	0.37	4.28	9.4	6.2	0.29	2.91
12	0	0	0	0	9.7	7.73	0.28	1.69	3.5	1.45	0.01	2.04	18	15	0.44	2.58
13	0	0	0	0	28.8	21.7	0.61	6.51	13.8	7.78	0.37	5.65	1.1	0.65	0.01	0.44
14	0	0	0	0	0	0	0	0	3.4	1.38	0.01	2	0	0	0	0
15	0	0	0	0	20.4	15.9	0.54	4	2.2	1.18	0.01	1	0	0	0	0
16	0	0	0	0	11.2	7.25	0.3	3.65	2	1.05	0.01	0.94	0	0	0	0
17	3	1.82	0	1.18	0	0	0	0	3.4	1.33	0.01	2.05	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	6.9	4.52	0.15	2.24	19	14.4	0.43	4.22	6.5	4.2	0.04	2.26	0	0	0	0
20	27	23.1	0.48	3.45	14.8	9.42	0.32	5.07	5	3.77	0.03	1.2	2.4	1.22	0.01	1.17
21	10	7.32	0.34	2.34	0	0	0	0	6.7	4.25	0.03	2.42	0	0	0	0
22	0	0	0	0	12	7.63	0.3	4.07	12	6.97	0.38	4.65	0	0	0	0
23	0	0	0	0	4.8	3.23	0.08	1.49	17	13.2	0.43	3.34	0	0	0	0
24	0	0	0	0	0	0	0	0	2	1.15	0.01	0.84	0	0	0	0
25	19.8	15.5	0.44	3.85	11	7.37	0.29	3.34	3.5	1.52	0.01	1.97	9.7	7.12	0.31	2.27
26	27	22.7	0.48	3.8	13.8	8.13	0.3	5.37	11.8	6.62	0.39	4.8	0	0	0	0
27	25.5	18.4	0.48	6.67	9.8	7.88	0.28	1.64	9.2	6.2	0.29	2.71	0	0	0	0
28	0	0	0	0	0	0	0	0	9.8	7.25	0.32	2.23	0	0	0	0
29					12.4	7.52	0.4	4.49	9.9	7.23	0.32	2.35	5.6	3.75	0.03	1.82
30					39.5	26.1	0.86	12.6	18	14.1	0.43	3.49	7.7	5.13	0.14	2.43
31					20.4	15.7	0.55	4.15					1.7	0.95	0.01	0.74
Total	196	157	3.67	35.7	309	218	7.22	83.6	252	172	6.18	74.2	153	114	3.43	35.7

Appendix D-4: Average daily throughfall (T), stemflow (S), interception (I) gross rainfall(P) for plot 4

Day	February				March				April				May			
	P	T	S	I	P	T	S	I	P	T	S	I	P	T	S	I
1	21.4	14.4	0.67	6.3	0	0	0	0	18.5	12.7	0.7	5.08	16	9.12	0.46	6.43
2	0	0	0	0	0	0	0	0	11	5.78	0.39	4.83	18.5	12.7	0.71	5.14
3	0	0	0	0	0	0	0	0	9.8	5.73	0.28	3.78	15	8.8	0.45	5.75
4	0	0	0	0	0	0	0	0	9.7	5.6	0.28	3.82	1.8	1.17	0.06	0.57
5	0	0	0	0	0	0	0	0	8.5	5.65	0.26	2.59	2.2	1.28	0.08	0.84
6	0	0	0	0	7.7	5.55	0.11	2.04	8	5.32	0.27	2.41	0	0	0	0
7	0	0	0	0	9.7	6.82	0.27	2.62	0	0	0	0	9.8	6.03	0.28	3.49
8	26.8	20.4	0.75	5.66	0	0	0	0	9	5.47	0.27	3.26	8.4	5.18	0.27	2.95
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	47.5	28.8	1.2	17.5	27.5	19.2	0.84	7.5	2.8	1.45	0.1	1.25
11	27	19.9	0.75	6.32	19.5	13.1	0.65	5.76	18.5	12.6	0.71	5.17	4.8	2.3	0.1	2.4
12	0	0	0	0	6.6	4.78	0.1	1.72	2.8	1.23	0.09	1.48	10	6.28	0.29	3.43
13	0	0	0	0	27.7	20.1	0.78	6.85	21.2	16.3	0.7	4.23	2.1	1.2	0.08	0.82
14	0	0	0	0	0	0	0	0	4	2.27	0.09	1.64	0	0	0	0
15	0	0	0	0	19.2	13	0.65	5.55	2	1.17	0.06	0.77	0	0	0	0
16	0	0	0	0	15.6	9.07	0.45	6.08	2.5	1.33	0.07	1.1	0	0	0	0
17	7	4.72	0.11	2.17	0	0	0	0	5.5	2.6	0.11	2.79	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	7	4.82	0.11	2.07	20.4	14.3	0.67	5.47	8.5	5.05	0.17	3.28	0	0	0	0
20	29.9	22.2	0.84	6.89	13.7	7.93	0.41	5.36	3	1.53	0.08	1.38	2	1.15	0.08	0.77
21	18.7	12.8	0.65	5.29	0	0	0	0	6	2.88	0.09	3.03	0	0	0	0
22	0	0	0	0	9.3	6.1	0.26	2.94	10	6.23	0.28	3.48	0	0	0	0
23	0	0	0	0	4.3	2.23	0.07	1.99	27	17	0.83	9.17	0	0	0	0
24	0	0	0	0	0	0	0	0	5.5	2.55	0.14	2.81	0	0	0	0
25	13.8	7.88	0.41	5.51	9	6.05	0.26	2.69	3.5	1.8	0.12	1.58	9	5.52	0.27	3.21
26	18.8	12.7	0.64	5.49	19.7	13.3	0.65	5.8	22	15.6	0.76	5.62	0	0	0	0
27	20.8	13.9	0.66	6.23	12.4	8.12	0.41	3.87	24.4	16.7	0.78	6.92	0	0	0	0
28	0	0	0	0	0	0	0	0	8.9	5.35	0.28	3.27	0	0	0	0
29					13.5	7.63	0.41	5.46	13.4	7.9	0.53	4.97	12	6.08	0.39	5.52
30					48.8	29.7	1.2	17.9	32	22.5	0.96	8.52	8.5	5.65	0.26	2.59
31					28.5	20.7	0.78	7					1.5	0.93	0.05	0.52
Total	191	134	5.59	51.9	333	217	9.34	107	323	208	10.2	104	124	74.8	3.94	45.7

APPENDIX E: Relationship between Rainfall and Throughfall, Stemflow and Interception

Appendix E-1: Regression output for the Throughfall -Rainfall relationship

Regression Statistics	
Multiple R	0.98
R Square	0.97
Adjusted R Square	0.97
Standard Error	1.06
Observations	298

ANOVA for the regression

Source of Variation	*df*	*SS*	*MS*	*F*	*F Crict*
Regression	1	15060.1	15060.1	13222.66	1.11E-247
Residual	296	337.13	1.14		
Total	297	15397.2			

NB: ** = significant at 0.01

Variable	*Coefficients*	*SE*	*T Stat*	*P-value*
Intercept	-0.4946	0.0987	-5.013	9.2E-07
Rainfall (P)	0.713	0.0062	114.990	1.1E-247

Appendix E-2: Regression output for the Stemflow -Rainfall relationship

Regression Statistics	
Multiple R	0.82
R Square	0.68
Adjusted R Square	0.68
Standard Error	0.23
Observations	298

ANOVA for the regression

Source of Variation	*df*	*SS*	*MS*	*F*	*F Crict*
Regression	1	33.21	33.21	622.69 **	8.95E-
Residual	29	15.78	0.053		
Total	297	49.0			

NB: ** = significant at 0.01

Variable	*Coefficients*	*SE*	*T Stat*	*P-value*
Intercept	-0.01384	0.021	-0.65	0.05
Rainfall (P)	0.03348	0.0013	24.95	8.9E-75

Appendix E-3: Regression output for the Interception -Rainfall relationship

Regression Statistics	
Multiple R	0.92
R Square	0.84
Adjusted R Square	0.84
Standard Error	1.11
Observations	298

ANOVA for the regression

Source of Variation	*df*	*SS*	*MS*	*F*	*F Crict.*
Regression	1	1900	1900	1549.7 **	1.15E-
Residual	29	362.9	1.23		
Total	297	2262.9			

NB: ** = significant at 0.01

Variable	*Coefficients*	*SE*	*T Stat*	*P-value*
Intercept	0.50799	0.10236	4.96	1.17E-06
Rainfall (P)	0.25325	0.0064	39.37	1.15E-119

APPENDIX F : Comparison of Throughfall, Stemflow and Interception between months

Appendix F-1: ANOVA for comparing percent throughfall between months

Source of Variation	*df*	*SS*	*MS*	*F*	*F crit*
Between months	3	104.66	34.89	0.806 ns	3.098
Error	20	865.51	43.27		
Total	23	970.18			

NB: ns = not significantly different at 5% level

Appendix F-2: ANOVA for comparing percent stemflow between months

Source of Variation	*df*	*SS*	*MS*	*F*	*F crit*
Between months	3	1.72	0.57	0.58 ns	3.098
Error	20	19.80	0.99		
Total	23	21.53			

NB: ns = not significantly different at 5% level

Appendix F-3: ANOVA for comparing percent interception between months

Source of Variation	*df*	*SS*	*MS*	*F*	*F crit*
Between months	3	107.58	35.86	1.06 ns	3.098
Error	20	674.41	33.72		
Total	23	781.99			

NB: ns = not significantly different at 5% level

APPENDIX G: Features of the twenty-four(24) trees used in the study of throughfall, interception, and stemflow

PLOT 1	DBH	Crown Area	Bark	English	Scientific name
Tree1	27.5	3.46	smooth	cypress	Cupressus lusitanica
Tree2	41.38	30.2	rough	euculyptus	Eucalytus tereticornis
Tree3	6.4	2.54	smooth	euculyptus	Eucalytus tereticornis
Tree4	20.7	3.46	smooth	euculyptus	Eucalytus tereticornis
Tree5	31.83	8.04	rough	Slash pine	Pinu caribaea
Tree6	27.7	22.9	rough	Slash pine	Pinu caribaea
PLOT 2	DBH	Crown Area	Bark	Name	Scientific name
Tree1	8.6	10.04	smooth	blackwattle	Acacia mearsii
Tree2	35	35.39	rough	pine	Pinus oocarpa
Tree3	37.88	51.5	rough	euculyptus	Eucalytus tereticornis
Tree4	21.96	4.27	smooth	cypress	Cupressus lusitanica
Tree5	28.64	20.1	rough	Slash pine	Pinu caribaea
Tree6	11.78	4.54	smooth	cypress	Cupressus lusitanica
PLOT 3	DBH	Crown Area	Bark	Name	Scientific name
Tree1	18.14	10.55	smooth	blackwattle	Acacia mearsii
Tree2	20.7	21.74	smooth	blackwattle	Acacia mearsii
Tree3	5.4	4.77	smooth	blackwattle	Acacia mearsii
Tree4	18.8	28.27	smooth	blackwattle	Acacia mearsii
Tree5	11	5.14	smooth	blackwattle	Acacia mearsii
Tree6	17.2	16.62	rough	pine	Pinus oocarpa
PLOT 4	DBH	Crown Area	Bark	Name	Scientific name
Tree1	49	30.2	rough	euculyptus	Eucalytus tereticornis
Tree2	28.64	5.46	smooth	blackwattle	Acacia mearsii
Tree3	7	10.04	smooth	blackwattle	Acacia mearsii
Tree4	6.36	3.95	smooth	blackwattle	Acacia mearsii
Tree5	16.55	20.1	smooth	blackwattle	Acacia mearsii
Tree6	8.6	4.33	smooth	blackwattle	Acacia mearsii

NB: DBH = Diameter at breast height

APPENDIX G -1: ANOVA for comparing of stemflow between various stem sizes

Source of Variation	*df*	*SS*	*MS*	*F*	*F crit*
Between Stems	23	624.014	27.13104	43.34 **	1.68
Error	72	45.077	0.62606		
Total	95	669.09048			

NB: ** = Significantly different at 0.01

APPENDIX H: Potential maximum retention (S) cm

Year/Month	93/94	94/95	95/96	96/97	97/98	98/99	Average
Jun	1.26	0.48	0.19	0.23	14.39	1.05	2.93
Jul	1.51	4.15	1.46	1.52	4.85	1.60	2.51
Aug	2.89	4.89	13.34	0.00	4.14	8.38	5.61
Sep	0.82	1.76	3.19	0.14	1.56	13.33	3.47
Oct	5.35	11.55	5.57	5.75	22.16	1.97	8.72
Nov	3.77	9.39	1.92	4.89	49.25	0.88	11.68
Jan	47.11	49.25	43.13	52.67	72.04	60.36	54.09
Feb	48.83	41.70	83.61	55.26	153.22	51.56	72.36
Mar	93.89	72.32	60.00	89.47	45.91	85.27	74.48
Apr	46.62	81.32	112.44	68.96	63.24	88.78	76.89
May	51.66	27.70	51.84	14.22	9.50	38.88	32.30
Mean	25.31	25.37	31.39	24.43	36.69	29.34	28.75
SD	31.51	29.35	38.87	33.23	45.18	34.57	

Appendix H-1: A composite Table showing means for all parameters used in the models

Prob of Exc	Tr	W	Rainfall	Ri	Rd	TR	DRO	S	T	I	Eto	BF
0.08	12.99	133.45	256.10	41.6	8.4	43.79	14.00	8.59	182.66	65.57	114.11	33.55
0.15	6.49	125.10	248.80	39.9	6.9	39.44	12.15	8.46	179.76	64.55	109.31	32.33
0.23	4.33	114.19	243.40	39.8	6.8	38.45	12.12	8.22	174.72	62.76	106.96	31.65
0.31	3.25	56.86	200.10	39.4	6.6	36.26	12.06	6.69	142.16	51.19	103.68	31.18
0.39	2.60	42.85	184.30	38.4	6.6	34.83	6.58	6.16	130.90	47.19	95.18	30.40
0.46	2.16	-0.32	105.80	37.5	6.4	33.22	4.89	3.52	74.67	27.21	91.49	27.38
0.54	1.86	-85.87	42.40	8.5	5.8	32.13	3.44	1.41	29.76	11.26	83.47	26.38
0.62	1.63	-87.26	32.10	6.7	5.0	31.83	2.57	1.06	22.39	8.64	78.85	25.94
0.69	1.45	-87.65	18.00	4.9	4.6	31.16	1.35	0.59	12.33	5.06	76.12	25.55
0.77	1.30	-99.74	14.10	2.7	4.3	28.51	0.89	0.46	9.56	4.08	67.71	24.62
0.85	1.18	-100.09	10.50	2.4	3.8	28.06	0.77	0.34	6.97	3.16	65.30	22.71
0.92	1.08	-105.11	8.70	2	1.4	27.72	0.65	0.28	5.72	2.72	60.35	22.26

P : Probability of exceedance
Tr : Return Period

APPENDIX I: Regression output related to the development to of the models

Appendix I-1: Regression output for the development of the runoff model

Regression Statistics		ANOVA for the Regression						
Multiple R	0.98	**Source of Variation**	*Df*	*SS*	*MS*	*F*	*Fcrit*
R Square	0.96	Regression	6	287.94	47.99	20.52**	0.002
Adjusted R Square	0.91	Residual	5	11.69	2.34		
Standard Error	1.53						
Observations	12	Total	11	299.64			

NB: ** = Significantly different at 0.01

Variables	*Coefficients*	*Standard Error*	*t Stat*	*P Value*
Intercept	-0.2671	16.11	-0.01.7	0.82
Rainfall (P)	0.3558	0.58	0.612	0.57
Intensity (Ri)	-0.0982	0.09	-1.049	0.34
Duration (Rd)	0.2871	0.49	0.588	0.59
Throughfall (T)	-0.3613	0.00	0.00	0.00
Stemflow (S)	4.0188	38.91	0.010	081
Interception (I)	-0.670	35.90	0.019	0.82

Appendix I-2: Regression output of selected parameters for the development of the runoff model (DRO)

Regression Statistics		ANOVA for the Regression					
Multiple R	0.98	**Source of Variation**	*Df*	*SS*	*MS*	*F*	*Fcrit.*
R Square	0.96	Regression	3	287.33	95.77	62.59**	6.9E-06
Adjusted R Square	0.94	Residual	8	12.31	1.53		
Standard Error	1.24						
Observations	12	Total	11	299.64			

NB: ** = Significantly different at 0.01

Variables	*Coefficients*	*Standard Error*	*t Stat*	*P Value*
Intercept	-0.671	1.551	-0.432	0.68
Rainfall (P)	0.0559	0.011	4.979	0.001
Intensity (Ri)	-0.074	0.066	-1.125	0.29
Duration (Rd)	0.3414	0.386	0.883	0.40

Appendix I-3:Regression output for the development of the water balance model.

Regression Statistics		ANOVA for the Regression					
Multiple R	0.95	**Source of Variation**	*Df*	*SS*	*MS*	*F*	*Fcrit*
R Square	0.95	Regression	8	1040.66	130.08	8.52**	0.002
Adjusted R Square	0.92	Residual	3	454.56	15.15		
Standard Error	12.3						
Observations	12	Total	11	14895.22			

NB: ** = Significantly different at 0.01

Variables	*Coefficients*	*Standard Error*	*t Stat*	*P Value*
Intercept	-240.77	12.96	-0.001	0.81
Rainfall (P)	-5.610	4.851	-1.156	0.33
Intensity (Ri)	1.227	0.894	1.372	0.26
Duration (Rd)	-4.673	5.408	-0.864	0.45
Total runoff (TR)	5.102	3.333	1.530	0.22
Direct runoff (DRO)	-1.187	3.862	-0.307	0.78
Stemflow (S)	-19.96	36.33	-0.001	0.83
Interception (I)	15.563	33.64	0.005	0.82
Throughfall (Γ)	4.879	0.00	0.00	0.00

Appendix I-4:Regression output of selected parameters for the development of the water balance (W) model

Regression Statistics		ANOVA for the Regression					
Multiple R	0.99	**Source of Variation**	*Df*	*SS*	*MS*	*F*	*Fcrit*
R Square	0.98	Regression	5	1038.02	207.60	17.32**	0.002
Adjusted R Square	0.97	Residual	6	718.52	11.98		
Standard Error	9.4						
Observations	12	Total	11	14895.22			

NB: ** = Significantly different at 0.01

Variables	*Coefficients*	*Standard Error*	*t Stat*	*P Value*
Intercept	-231.25	7.4250	-1.19	0.02
Rainfall (P)	0.7855	0.2129	3.67	0.01
Intensity (Ri)	0.6280	0.6853	0.92	0.39
Duration (Rd)	-5.3640	4.7857	-1.12	0.31
Total runoff (TR)	5.0175	2.9631	1.69	0.14
Direct runoff (DRO)	-2.2199	3.3627	-0.66	0.53

APPENDIX J: Gendavaki catchment parameters used to validate the models

Prob of Exc	Tr	P	Rd	Ri	W	TR	DRO	BF	Eto	T	S	I
0.08	12.99	258.00	11.00	38.50	152.00	44.10	15.02	37.08	109.00	171.57	8.77	75.08
0.15	6.49	248.00	9.91	37.80	112.51	42.02	14.06	35.69	102.00	164.92	8.43	72.17
0.23	4.33	236.30	8.26	36.40	107.20	39.00	13.01	32.22	99.95	157.14	8.03	68.76
0.31	3.25	207.57	7.09	36.20	75.47	38.00	8.09	31.09	99.00	138.03	7.06	60.40
0.39	2.60	176.17	6.44	35.90	39.17	38.00	6.78	31.00	98.49	117.15	5.99	51.26
0.46	2.16	114.60	6.25	25.60	18.60	36.50	6.02	27.34	93.47	76.21	3.90	33.35
0.54	1.86	39.00	5.78	8.70	-86.11	32.20	3.90	27.00	85.00	25.94	1.33	11.35
0.62	1.63	38.49	5.42	7.20	-87.30	32.15	2.86	24.06	75.00	25.60	1.31	11.20
0.69	1.45	19.82	4.87	3.50	-87.38	28.90	1.56	23.94	72.30	13.18	0.67	5.77
0.77	1.30	17.84	4.48	2.70	-93.18	28.00	1.20	22.74	69.00	11.86	0.61	5.19
0.85	1.18	13.82	3.57	2.40	-99.15	25.60	0.92	21.98	68.00	9.19	0.47	4.02
0.92	1.08	9.65	1.59	1.80	-109.55	24.30	0.81	20.40	57.00	6.42	0.33	2.81