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Masters in Integrated Water Resources Management

Measuring forest floor and canopy interception in a savannah ecosystem (A case study of Harare, Zimbabwe)

By

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DECLARATION

I, Callister Tatenda Tsiko, declare that this thesis is my own work, a result of my own investigation. All the sources that I have used or quoted have been indicated and acknowledged by means of complete references. To the best of my knowledge, this work has not been submitted before for any other degree at any other university.

Signed: ……………………………

Date: ………………………………

DEDICATION

For mum and dad, Chester, Tinashe, Mandipa & Mark

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ABSTRACT

Interception is an important process that influences antecedent soil moisture conditions that are important for flood generation. It is however, one of the most underestimated processes of the hydrological cycle. Studies that consider interception focus on canopy interception and neglect forest floor interception. Most investigations on interception have been carried out in Europe and America but little is known about interception measurements in Africa. A study was carried out to measure forest floor and canopy interception in an African savannah ecosystem and to analyse the influence of meteorological factors and vegetation characteristics.

Thatching grass (*Hyparrhenia filipendula)* and Msasa (*brachystegia spiciformis*) tree leaf litter were used for the study. Two forest floor interception measuring devices were set up. Each device consists of two galvanized steel basins mounted above each other and continuously weighed with strain gauge sensors. Interception from the forest floor was determined by calculating the water balance of the upper and lower basin. Canopy interception was computed as the difference between gross and net precipitation. Sprinkler experiments were carried out to determine the storage capacity of the leaves and grass.

Forest floor interception was measured to be 20% of net rainfall for the Msasa leaf litter and 26% of gross rainfall for the Thatching grass. Canopy interception for the study period averaged 25% which is comparable to literature. The maximum water storage capacities for the Msasa leaf litter and Thatching grass were 1.8mm and 1.5mm respectively. The sprinkler experiments showed that water storage capacity increases with intensity until a threshold is reached then it starts decreasing. It is concluded from this study that interception is a threshold process which is affected by meteorological factors and vegetation characteristics.

The study also revealed that evaporation ‘loss’ from a litter layer is less than that from grass which is not as tightly packed as the leaf litter layer. However, vegetation with a higher Leaf Area Index (leaf litter) has a higher storage capacity than that with a lower Leaf Area Index (grass). Statistical analysis showed that there is a significant ($P<0.05$)* relationship between evaporation and canopy interception. Of most importance, the study revealed that combining canopy and forest floor interception yields a value of approximately half the amount of precipitation received thus interception should be given greater consideration in rainfall – runoff studies.

Key words: canopy, forest floor, interception, storage capacity

*P is probability

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DEFINITION OF TERMS

Antecedent soil moisture refers to the amount of residual water retained by the soil after a rainfall event.

Canopy refers to foliage above the ground surface on trees and shrubs.

Forest floor can consist of bare soil, short vegetation, grass or leaf litter.

Gross Precipitation is the precipitation, which falls on a catchment, measured above the canopy or in an open area.

Leaf Area Index is the ratio of leaf area to ground surface area.

Net precipitation is the precipitation, which reaches the soil surface, measured under the canopy.

Interception loss is the portion of gross precipitation retained by the canopy or litter and lost from the watershed as evaporation without adding moisture to the soil.

Canopy interception is the amount of rainfall which is stored and evaporated from the foliage above the ground.

Forest floor interception is the part of the net precipitation that is temporarily stored in the top layer of the forest floor and evaporated within a few hours or days during and after the rainfall event.

CHAPTER ONE

INTRODUCTION

1.1 Background of rainfall interception

The hydrological cycle involves many interconnected processes, separation points and feedback loops. Precipitation is regarded as the starting point of the cycle, from which the water is intercepted, "lost" as runoff or infiltrated in the first water partitioning point (Savenije, 2004a). Interception, the first of these processes, splits precipitation into that delivered to the land and water surfaces and returned to the atmosphere through evaporation.

In vegetated cases, interception is the amount of rainfall which is temporarily stored by a canopy and forest floor on a plot and evaporated shortly after or during a rainfall event (Savenije, 2005). It is characterised by time scales in the order of several hours to one day (De Groen and Savenije, 2006). Interception is a significant process that influences antecedent soil moisture conditions which are important for the generation of floods (Roberts and Klingeman, 1970).

Traditionally, investigators have adopted Leonard's (1961) attitude: 'We felt certain that at least one aspect of hydrology would not require study—interception … ' However, such a view was probably prompted by the fact that early studies were limited either by sampling (Helvey and Patric, 1965) or measurement techniques (Beven 2006) to provide much useful information.

Today, interception is one of the most underestimated processes in rainfall-runoff analysis (Savenije, 2004b). It has often been disregarded in hydrological models because it is difficult to measure (Lundberg et al., 1997; Llorens and Gallart, 2000). Models that consider interception take it as a minor flux and either combine it with evaporation and transpiration or take it as a fixed percentage of rainfall (Savenije, 2004b). The Sacramento model for instance, combines interception with the upper soil's tension water volume (Singh, 1995).

Disregarding or lumping up interception with other processes introduces errors in hydrological modelling. Penman (1963) and Leyton and Carlisle (1959) suggested that evaporation of intercepted precipitation merely replaced transpiration and that interception does not need to be considered as an additional 'loss' separate from transpiration. Savenije, (2004) argues that combining interception with transpiration is a conceptual mistake, because interception and transpiration are different evaporation processes and have different time scales. The time scale of interception is short, generally ending within a period of one day after rainfall (De Groen and Savenije, 2006), while transpiration has a much longer time scale (average residence times varying between weeks and months depending on the soil depth) (Savenije, 2006).

It is erroneous to consider interception as a minor process. Edwards et al., (1983) state that in areas of high wind speed, with aerodynamically 'rough' canopies, interception "loss" can be very rapid and in areas where the canopy is frequently wetted, the total quantity of intercepted water "lost" by evaporation can be a significant proportion of the total rainfall.

A study carried out by Owens et al., (2005) revealed that 35% of the bulk rainfall falling on juniper trees was intercepted by the tree canopy and 5% was intercepted by the coarse litter and duff beneath the tree.

Canopy interception has been investigated in many parts of the world, but forest floor interception has received little attention (Kiss et al., 2005; Gerrits et al., 2007) although it is an important mechanism that precedes infiltration or runoff. This is mainly because of the difficulties of carrying out on-site observations (for instance, Putuhena and Cordery, 1996; Schaap et al., 1997; Tobon-Marin et al., 2000). Rutter et al., (1975) found canopy interception values of 12% for a defoliated oak and 48% for a Norway spruce forest in the United Kingdom. Preliminary results for experiments carried out by Gerrits et al., (2007) to measure forest floor interception in a Beech forest indicate that evaporation from forest floor interception in Luxembourg was 34% of through fall. It is important to investigate this further because the sum of canopy and forest floor interception would then yield a higher interception value.

1.2 Problem Statement

Not much is known about rainfall partitioning by vegetation worldwide especially separating evaporation, transpiration and interception (Martinez-Meza and Whitford, 1996). Even less can be found on forest floor interception measurements (Gerrits et al., 2007). Most investigations on interception have been carried out in Europe and America but little is known about interception measurements in Africa.

1.3 Justification

It is important to better understand the process of rainfall interception so that it can be incorporated adequately in hydrological models. Partitioning gross rainfall into canopy interception, litter interception, stem flow and through fall allows an estimate of the physical impact of vegetation on the local hydrologic budget (Owens et al, 2005). Understanding rainfall interception is not only important to hydrology as a science, but also helps to better understand the ecosystem. This study therefore seeks to create a platform for further research on rainfall partitioning by vegetation in Southern Africa.

1.4 Objectives

1.4.1 Overall Objective

The main objective of the research is to determine forest floor and canopy interception in a savannah ecosystem and to analyse the influence of meteorological factors and vegetation characteristics.

1.4.2 Specific Objectives

1. To measure the amount of canopy interception
2. To measure the amount of forest floor interception
3. To compare interception by two different forest floors
4. To determine the water storage capacity of forest floor interception

1.5 Structure of the study report

Including this introductory chapter, this document contains five chapters. Chapter 2 is the literature review, which describes evaporation in general and interception in particular, as components of the hydrological cycle. The effects of meteorological and vegetation characteristics on interception are also discussed. In Chapter 3, a detailed description of the study area and methods is given. Chapter 4 contains the findings of the research, analysis and discussion of these results. The thesis ends with the conclusion and recommendations in Chapter 5.

CHAPTER TWO

LITERATURE REVIEW

2.1 Background of hydrology in Southern Africa

The hydrological cycle is the pathway of water as it moves in its various phases through the atmosphere to the earth and through the land, to the ocean and back to the atmosphere (Schulze, 1995). The main processes of the hydrological cycle are precipitation, evaporation, infiltration and runoff.

Rainfall is the key input variable which activates flow in hydrological systems (O'Connell and Todini, 1996) and it is mainly driven by evaporation. Evaporation makes up the second largest process of the hydrological cycle (Edwards *et al*., 1983). Evaporation is defined as the process where liquid water is transformed into a gaseous state (Pidwirny, 2006). About 60% of the precipitation falling on the earth's land surface evaporates. This fraction changes from about 85% for the African continent where arid and semi-arid regions dominate to about 15% for the Antarctic continent which is permanently covered by ice (Gash and Shuttleworth, 2007).

Understanding evaporation and its controls can only proceed by using methods that separate the components of evaporation (Baird and Wilby, 1999) which are transpiration, surface evaporation, open water evaporation and evaporation from interception (Savenije, 2004b; De Groen and Savenije, 2006). It is important to quantify total evaporation in terms of each of these components because different biophysical and environmental characteristics exert dominant control on these components (Choudhury and Di Girolamo, 1998). Understanding evaporation is crucial because there has been a marked decline in hydro meteorological data collection and management (World bank, 1993, WMO, 1996 and Giles 2005) in Sub-Saharan Africa and this must be addressed.

Despite recognition of the potentially large effect of interception on the hydrologic budget, few studies have quantitatively evaluated interception and its associated components in semi arid savannas (Owens *et al.*, 2005). Baird and Wilby, (1999), identified two problems of interpreting what evaporation data there are for semi arid African forests. Usually only total evaporation data are available with no distinctions between evaporation of intercepted water and transpiration. Also, there are often substantial areas of bare soil, yet evaporation from the soil is included in the transpiration term. Pitman, (1973) states that interception in Southern African forests can be as much as 8 mm per day. De Groen (2002) gives a range of 2 to 5 mm per day but there is need to investigate this further.

2.2 The interception process

Interception can be considered in two ways: as a stock or as a flux (Savenije, 2005). If the stock is considered, interception is defined as the amount of rainfall which is temporarily stored by a canopy and forest floor. On the other hand, the flux is the amount of intercepted rainfall which is evaporated within a certain time usually one day. However, it is more appropriate to combine both the flux and storage so that the entire interception process can be determined (Savenije, 2005). The interception process thus equals the sum of the change in interception storage and the evaporation from this stock.

Studies carried out on interception measurements focus on either the interception stock or flux and disregard the entire interception process. For instance, Helvey (1964) found out that about 3% of the annual rainfall is evaporated from the forest litter. However, what was measured was not the flux but the storage capacity. Pathak et al., (1985) also measured storage capacity and found litter interception values of 8%-12%. There is need thus to carry out tests that combine the interception stock and flux.

2.3 Types of interception

In this study, interception is considered as occurring at two levels: in the canopy and on the forest floor

2.3.1 Canopy interception

Canopy interception is the amount of rainfall which is stored and evaporated from the foliage above the ground (Pidwiny, 2006). Intercepted moisture, stored in the canopy, is the first component of the hydrological cycle to be lost directly back to the atmosphere (Edwards *et al*., 1983). Canopy interception is the difference between gross precipitation and through fall. When rain first begins, the water striking the leaves spreads over the surfaces in a thin layer or it collects at points or edges. When the maximum surface storage capacity on the surface of the material is exceeded, the material stores additional water in growing drops along its edges. Eventually the weight of the drops exceeds the surface tension and water falls to the ground. Link et al., (2004) estimate canopy interception in humid and temperate climates to vary between 10 and 50% of the annual rainfall.

2.3.2 Forest floor interception

Forest floor interception on the other hand, is the part of the net precipitation that is temporarily stored in the top layer of the forest floor and evaporated within a few hours or days during and after the rainfall event. The forest floor can consist of bare soil, short vegetation, grass or leaf litter (Gerrits *et al*., 2007).

The forest floor is an important hydrological component in controlling water from the sub-canopy atmosphere and the soil (Pitman, 1989; Viney and Hatton, 1990). Forest litter is estimated to store between 100% and 150% of its dry mass in water (Helvey and Patric 1965). The deadwood on the forest floor is estimated to intercept and store 2%–5% of gross precipitation (Harmon and Sexton, 1995). The litter layer prevents soil erosion by absorbing the impact energy of raindrops (Geddes and Dunkerley, 1999; Miura 2000). In this way; the forest floor also ensures rapid infiltration (Baird and Wilby, 1999). In most hydrological studies the forest floor is neglected or treated as part of mineral soil. Only a few studies deal with determination of water storage capacity and temporal variability of water retention by the forest floor and these mainly pertain to coniferous and other temperate forests (Putuhena and Cordery, 1996).

2.4 Importance of interception

Rainfall partitioning by vegetation plays an important role affecting the water balance at local and catchment scale. Vegetation modifies both evaporation and the redistribution of incident rainfall (Llorens and Domingo, 2007).

Evaporation from interception is an important process in moisture recycling to support continental rainfall. According to Eltaher and Bras, (1994) and Savenije, (2004a) rainfall in the Sahel relies primarily on interception. Interception retains the water before it can continue its path in the water cycle and it allows for a direct feedback loop to the atmosphere. Shuttleworth, (1993) observed that half the amount of evaporation from interception occurs during the storm itself providing instant moisture feedback. Interception is also a major factor in reducing soil erosion. This has an indirect effect on the hydrological cycle, in that, by conserving surface soil, infiltration is maintained (Edwards et al., 1983).

2.5 Role of interception in Hydrological Modeling

Hydrologic models are simplified, conceptual representations of a part of the hydrologic cycle. They are used for hydrologic prediction and for understanding hydrologic processes. The main objective of hydrological modeling is to explain the variability of catchment response in terms of the factors that may influence it (Beven, 2006).

Interception accounts for an important component of the water balance but is often neglected in model applications (Savenije, 2004b). Some water balance models such as CROPWAT (Clarke et al.,1998) which is used to determine irrigation requirements uses as effective rainfall the rainfall minus the 'initial loss'. Empirical relations are then used to determine the interception. However, such empirical relations are a blanket recommendation and do not account for rainfall variability (De Groen and Savenije, 2006).

Lack of data is one of the main limitations for hydrological modeling. According to Fenicia et al., (2008) one of the reasons for neglecting interception in hydrological models is the need to keep the model as simple as possible, so as to reduce the number of calibration parameters. However, Zhang and Savenije (2005) found that the introduction of an interception component in a model structure improved model performance.

2.6 Measuring forest interception

The traditional way to measure forest evaporation is to conduct catchment experiments to solve the water balance equation:

$$P - E - R = \frac{dS}{dt} \qquad \text{(Equation 2.1)}$$

where E is the evaporation, P is precipitation, dS/dt is the change in water storage of the soil or catchment and R is runoff and drainage (Baird and Wilby, 1999).

Measurements of interception “losses” from forests are usually made at a scale smaller than that of a catchment. These measurements can be at leaf, tree or plot scale (Baird and Wilby, 1999). Models would then be used to exploit the information from these measurements at larger scales. This is because the spatial variability of the amount and composition of different canopies and litter layers makes it difficult to measure interception for a whole catchment (Putuhena and Cordery1996).

Estimation of interception “loss” requires direct measurement of gross precipitation, through fall, stem flow and change in litter moisture content before, during and after storms. Gross rainfall caught by the canopy is redistributed as through fall, stem flow, and evaporation from the standing vegetation. The remainder is caught on the litter layer and evaporated without adding to moisture in the mineral soil (Helvey, 1965). Gross precipitation and through fall are measured using rain gauges. Stem flow is measured by fixing collars around tree or shrub main stems and funnelling the water into a collection gauge (Rangeland Watershed Program fact sheet, 1996).

Interception measurements have been conducted in both the field and laboratory (Aston, 1979; Lloyd et al., 1988 and Li et al., 1997) but results have been limited by inadequate measurement techniques. In the field, point measurements for canopy interception are obtained by using funnels or rain gauges directly beneath the canopy. This method is easy to perform but does not show the spatial variability. Area measurements using plastic sheets or troughs associated with tipping bucket or weighing type gauges yield spatially correct averages, but adhesion of rainwater to the sheeting combined with possible blockage of the collection gutter during large storms (Teklehaimanot et al., 1991) may induce large measurement errors.

Canopy interception “loss” is calculated as the difference between gross precipitation, through fall and stem flow (Gash et al., 1980). Litter interception loss is estimated by collecting litter from a plot of known area immediately before, during, and after a storm. The litter is weighed, dried, and weighed again. The difference between the wet weight and the dry weight is the water content of the litter. The change in litter water content over time is determined and litter interception loss calculated.

2.7 Factors affecting interception

Interception is influenced by climatic conditions and vegetation characteristics (Dabral et al, 1963; Pradhan, 1973).

2.7.1 Meteorological factors

Climatic factors which affect interception loss are:

- **Evaporation and potential evaporation**

Evaporation is the process where liquid water is transformed into a gaseous state. Evaporation can only occur when water is available. It also requires that the humidity of the atmosphere be less than that of the evaporating surface (Pidwirny, 2006). Potential evaporation is a measure of the ability of the atmosphere to remove water from a surface through the process of evaporation assuming no control on water supply (Thornthwaite, 1948). Interception “loss” will be high if evaporation proceeds rapidly and the potential evaporation is high. Evaporation is a function of wind speed, temperature and humidity.

- **Wind speed**

High winds during evaporation can either shake water loose or increase the rate of evaporation (Horton, 1919; Klaasen *et al.,* 1996). As the water vaporises into the atmosphere, the boundary layer between earth and air becomes saturated and this layer must be removed and continuously replaced by drier air if evaporation is to proceed. This movement of the air in the boundary layer is a function of wind speed (Wilson, 1990). According to Stewart, (1977) interception can play a major role in the water balance of catchments where the aerodynamic component of the energy balance is large relative to net radiation.

- **Temperature**

An energy input is necessary for evaporation to proceed. If the ambient temperature of the air and ground are high, evaporation will proceed more rapidly than if they are low since heat energy is more readily available (Wilson, 1990).

- **Humidity**

As the air's humidity rises, its ability to absorb more water vapour decreases and the rate of evaporation slows (Wilson, 1990). During and immediately after rainstorms humidity deficits in the atmosphere are small and gradients in the atmosphere are difficult to measure (Baird and Wilby, 1999).

- **Storm duration**

Interception increases exponentially during a storm until the interception capacity is achieved and the weight of more rain overcomes the surface tension holding the water on the plants. When capacity is reached, any additional input of rainfall becomes runoff or infiltration into the soil (Rangeland Watershed Program fact sheet, 1996). Nearly all the precipitation from a very short storm can be intercepted resulting in no drippage or stem flow.

- **Storm frequency**

In wet vegetation part of the interception capacity is already occupied before a storm. Therefore, maximum interception occurs with short duration precipitation events that are spaced sufficiently far apart so that vegetation dries out (Baird and Wilby, 1999). Less interception loss will occur if the second storm occurs before the water intercepted during the first storm has evaporated (Rangeland Watershed Program fact sheet, 1996).

- **Storm intensity**

A high intensity precipitation event will have lower interception "loss" than a low intensity event. The percentage of total interception ranges from nearly 100% where the total rainfall does not exceed the interception storage capacity to about 25 % as an average constant rate for most trees in heavy rains of long duration (Horton, 1919).When the intensity is too high water can be delivered too quickly for the plants to accommodate thus high intensity is associated with low interception. Table 2.1 below shows the effect of rainfall intensity on interception:

Table 2.1 Storm size and interception in a tropical forest in Tanzania

Storm size (mm)	0-5.0	5.1-10	10.1-15	15.1-20	20.1-30	30.1-40	40.1-50		
Gross rainfall and interception									
Gross rainfall (mm)	1	2.5	5.0	7.5	10.0	15.0	20.0	30.0	40.0
Interception loss (mm)	0.7	0.9	1.2	1.5	1.8	2.4	3.0	4.2	5.4
Interception (%)	70	36	24	20	18	16	15	14	13.5

(Source: Jackson, 1971)

2.7.2 Vegetation characteristics

Interception capacity is a function of:

- **Species**

Variation in species characteristics creates variation in interception between species. For instance, conifers have a greater interception capacity than broadleaf species (Horton, 1919). On broadleaves, raindrops can run together forming large drops which fall from the leaf as through fall, but the needles of conifers do not allow this (Rangeland Watershed Program Fact Sheet, 1996). The leaves of deciduous trees are reported to intercept between 20-30% of the falling rain (Pidwirny, 2006). According to Warburton, (2007) coniferous trees intercept 25-35% of annual precipitation whilst deciduous trees intercept 15 % - 25 %. Zinke, (1967) gives an interception range of 10-20% for hardwoods and 20-40% for conifers.

- **Seasonality**

Seasonality affects interception because deciduous trees shed their leaves whilst evergreen trees retain their leaves throughout the year. A deciduous tree will have a lower interception capacity when it is dormant than when it is growing. An evergreen tree on the other hand, maintains a fairly constant interception capacity throughout the year (Rangeland Watershed Program Fact Sheet, 1996). Grasses have high interception capacity during the growing season but then they either die (annual plants) or lose mass (perennial plants). During winter interception does not play a significant role, due to the lack of available energy.

- **Leaf Area Index**

The amount of direct through fall is controlled by the canopy coverage of an area, a measure which is the Leaf Area Index (LAI). LAI is the ratio of leaf area to ground surface area. Interception storage increases with increasing Leaf Area (Aston, 1979; Herwitz, 1985; Llorens and Gallart, 2000). The Leaf Area Index is commonly used in measuring interception.

- **Leaf surface roughness**

Leaf surface roughness is important because a rough leaf will hold more water than a smooth leaf. Pubescence, or hair, on grass blades contributes to roughness.

- **Leaf litter**

Limited information is available on the leaf litter interception capacity (Gerrits *et al*., 2007). Generally it is dependent upon the thickness and water holding capacities of the litter. The water holding capacity of litter is a function of the vegetation type, the species from which it came and its decomposition rate (Warburton, 2007). Litter under hardwoods tends to have a slightly lower interception capacity than litter under conifers. Helvey and Patric (1965) estimated forest floor interception of approximately 5% on hardwoods in eastern USA.

2.8 Interception storage capacity

The interception storage capacity is the maximum amount of water that can be stored by the canopy (when through fall has ceased,) or forest floor in conditions of zero evaporation (Horton, 1919). Gerrits et al, (2008) describe interception as a threshold process because a certain amount of water is required before successive processes such as infiltration or runoff can take place.

The interception storage capacity of canopy is high in summer and low in winter. (Gerrits et al., 2008) suggest that it is close to zero in winter. Interception capacity depends on rainfall intensity (Calder et al. 1996). This concedes with earlier studies by Laws and Parsons (1943); Best (1950) and Mason and Andrews (1960) who state that higher rainfall intensities have larger drop sizes that should impart a greater force to the surface of a leaf. Therefore, it has been hypothesized that at higher rainfall intensities the water stored on a branch will decrease because the bigger raindrops will splash greater quantities of water off of the surface (Rutter et al., 1971; Calder et al., 1996). Research has also affirmed that interception storage is negatively associated with increasing wind speeds (Calder et al., 1996; Rutter et al., 1971). High wind speeds shake the foliage and dislodge the stored water. The storage capacity of the forest floor depends on vegetation type, the species from which it came and its decomposition rate (Warburton, 2007).

Various techniques have been applied to measure interception storage capacity (Dunkerley, 2000), including artificial rain experiments and weighing of whole trees or single branches after precipitation (e.g. Aston 1979, Teklehaimanot and Jarvis 1991). For instance, Putuhena and Cordery, (1996) measured the forest floor interception capacity of a 15-year-old Pinus radiata plantation and a native dry sclerophyll eucalypt forest at Lidsdale State Forest, Australia, in the laboratory using a technique of applying artificial rain to undisturbed samples of the forest floor. The interception capacity of the pine catchment was 2.8 mm for the pine and 1.7 mm for the eucalypt. The contribution of leaf litter, stem and branch litter, and grass vegetation to the overall interception capacity was similar for both catchments at 47 %, 8 % and 45 %, respectively.

Helvey, (1964) performed a drainage experiment on the forest floor after it was saturated. During drainage the samples were covered and after drainage had stopped (assumed 24 h), the samples were taken to the laboratory, where they were weighed and successively dried until a constant weight was reached.

By knowing the oven dry weight of the litter per unit area and the drying curve, the evaporation from interception could be calculated. In this way they found that about 3% of the annual rainfall evaporated from the litter. Pathak et al., (1985), measured the weight of a sample tray before and after a rainfall event and found litter interception values of 8 %–12 % of the net precipitation.

In areas of shorter vegetation interception storage is likely to be small, and the rate of loss may not exceed the potential evaporation rate. Thus in rangelands, interception storage is unlikely to be a measurable quantity in the water balance.

According to Putuhena and Cordery (1996), there are two types of forest floor interception capacities, defined as the maximum storage capacity (C_{max}) and minimum storage capacity (C_{min}). C_{max} is the maximum interception storage capacity of the litter layer, taken as the amount of water detained in the litter layer when the litter interception stopped increasing during the rainfall event. It includes gravitational water. It is therefore a dynamic storage. C_{min} is the minimum interception storage capacity of the litter layer, taken as the amount of water detained in the litter layer when free drainage ceased after rain. This amount is a static storage and can only be removed by evaporation. Putuhena and Cordery, (1996) argue that C_{min} is more important than C_{max} because gravitational water is readily drained within about 6 to 30 minutes after the cessation of rainfall. C_{max} is significant only when the evaporation rate is very high.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Description of the site

The study was carried out at the Meteorological Services Department in Belvedere and at Kutsaga Research Station in Harare, Zimbabwe as shown below in Figure 3.1:

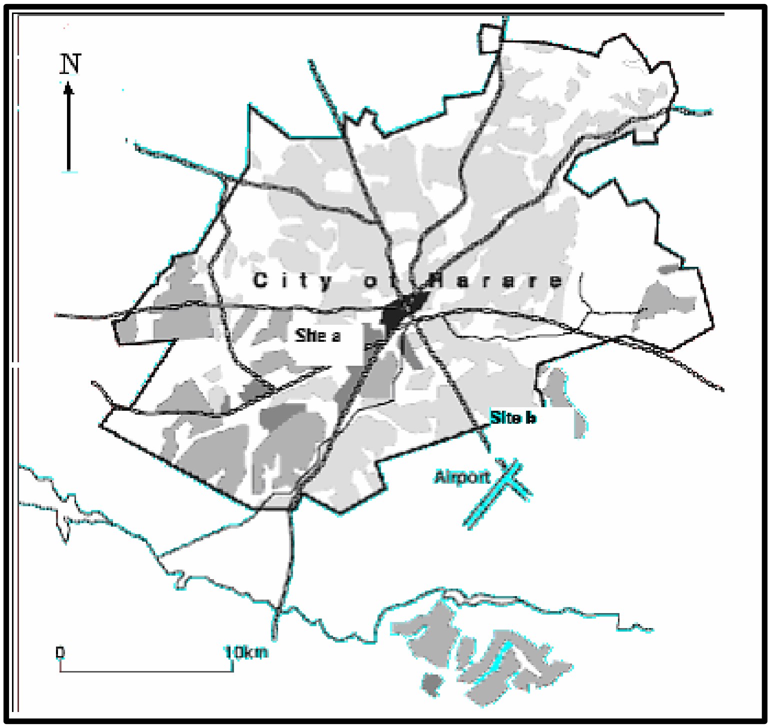

Figure 3.1 Location of the study area, site a (Belvedere Meteorological Services Department) and site b (Kutsaga Research Station)

Harare lies in the upper Manyame catchment in Natural Region IIa of Zimbabwe. It is characterised by a summer rainy season which lasts from mid-November to March. This is followed by a cold dry season from April to July and a hot dry season from August to mid-November. The mean annual rainfall is 825mm and the mean daily temperature ranges between 7°C and 20°C in winter and 13°C and 28°C in summer. The altitude is 1479m above sea level.

The rainfall in Zimbabwe is strongly related to the seasonal fluctuations of the Inter tropical Convergence Zone (ITCZ). The ITCZ is the zone where airstreams originating from both hemispheres meet. It is a zone of intense rain-cloud development created when the Southeast trade winds collide with the Northeast monsoons. The movement of the ITCZ southward away from the equator marks the start of the main rainy season in the southern hemisphere. Convection accounts for about 90% of the Zimbabwean rainfall, although not all of this is related to the ITCZ (Torrance, 1981). Apart from the ITCZ, Indian Ocean cyclones also influence Zimbabwe rainfall. The cyclone season is usually from December to April.

Zimbabwe is predominantly savanna (tropical grassland), with a generous tree growth encouraged by the wet summers (Encyclopaedia Britannica, 2008). Savanna vegetation consists of plant formations comprising a continuous stratum of herbaceous plants especially grasses and sedges and a stratum of woody plants. Harare supports a natural vegetation of open woodland. Grasses are also a dominant feature of this ecological zone. An ecological zone is a natural unit that makes up the environment. It is controlled by a set of common processes, mostly climatic and is dominated by life forms with similar physical adaptations to those processes. Savanna is the biggest ecological zone in southern Africa and the average rainfall amount received ranges between 400–1400mm per year.

3.2 Description of the tree and forest floor under study

The research focused on interception by grass and leaf litter interception and was analysed by the use of field experiments. The study was carried out at tree and plot levels due to limited sensors and data loggers. Also, the spatial variability of the amount and composition of different canopies and litter layers makes it difficult to measure interception for a whole catchment (Putuhena and Cordery1996). A 60 year old Msasa (*brachystegia spiciformis*) tree was subjected to canopy interception measurements. The Msasa is a seasonal broadleaf tree with an annual cycle of leaf-on, leaf- off periods. The tree under study has a height of 6m and an average canopy cover diameter of 10m. The tree has small and broad leaves about 4-6cm long and 2.5-4.5cm wide. The upper surface of the leaf has a smooth texture and the lower surface has a leathery texture.

Msasa (*brachystegia spiciformis*) tree leaf litter and “dead” Thatching grass (*Hyparrhenia filipendula)* were used for the forest floor interception experiments. The Msasa litter consist of leaves and pods that are partially decomposed. The Thatching grass is perennial and grows up to 2m tall. The grass flowers between November and April (Gibbs-Russell, 1990).

3.2 Period of study

Data was collected for a period of four and half months starting from mid-November 2007 to March 2008.

3.3 Determination of canopy interception

Canopy interception for the Msasa (*brachystegia spiciformis*) tree was computed as the difference between gross precipitation and net precipitation. Gross precipitation was measured using an autographic recorder under open sky. The autographic recorder consists of a clockwork-driven drum on which a pen records the total water collected (see Figure 3.2 below). Net precipitation was measured using a standard rain gauge installed under the Msasa tree.

Figure 3.2 Autographic recorder under open sky (left) main frame (right) chart and recording pen.

3.4 Determination of forest floor interception

A Forest Floor Interception device was used to determine the forest floor interception. Two experimental sites were selected for the forest floor sampling plots. At *site A* (Belvedere Meteorological Station) the device was placed under a tree and received through fall. It was filled with Msasa (*brachystegia spiciformis*) tree leaf litter. A standard rain gauge was placed next to the device to measure the through fall.

At *site B* (Kutsaga Research Station) the device was set up under free sky. The amount of rainfall received was also determined using a standard and an automatic rain gauge placed near the device. Daily evaporation measurements were obtained from Standard Class A evaporation pans at both sites. Daily series of humidity, temperature and wind speed data were obtained from both stations. In February 2008, the device at Kutsaga station was relocated to Belvedere and the Msasa tree leaf litter for that basin was replaced with Thatching grass (*Hyparrhenia filipendula)*.

The Forest Floor Interception device consists of two galvanized steel basins, which are mounted above each other and are weighed accurately with 2 sets of 3 strain gauge sensors (Figure 3.3).

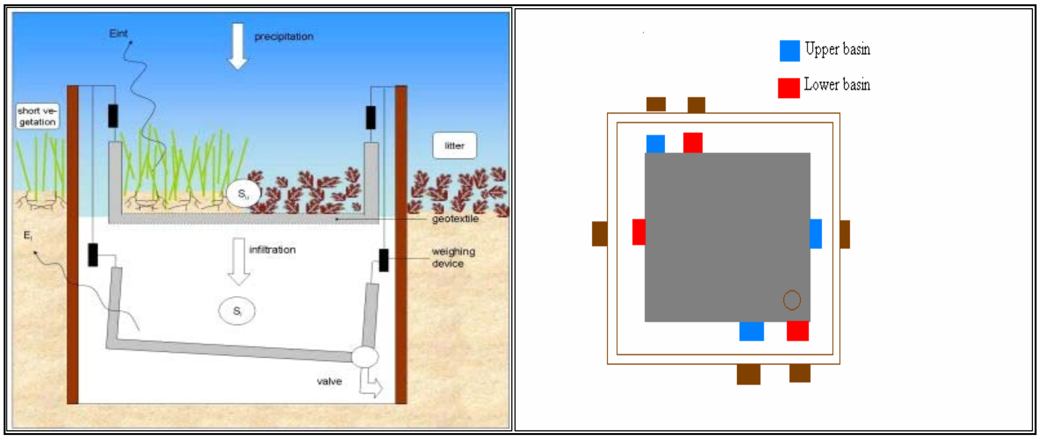

Figure 3.3: (left) Schematic drawing of the FFI device with E_i the evaporation from interception, E_l the evaporation from the lower basin and S_u and S_l the storage in respectively the lower and upper and lower basin (right)Top view of the FFI device

The upper basin which has a permeable bottom of chicken wire was covered with hessian sack and filled with Msasa (*brachystegia spiciformis*) tree leaf litter / Thatching (*Hyparrhenia filipendula)* grass. During a rainfall event, the weight of the upper basin increased and if the litter or grass was saturated water percolated into the lower basin. The weight of the lower basin also increased as a result. In this lower basin a valve was installed, which emptied three times every day for fifteen minutes to avoid overtopping and evaporation from the lower basin as much as possible. The space between the supporting structure and the galvanised steel basins was also minimised using wooden boards to avoid evaporation by turbulent wind fluxes.

After a rainfall event the weight increase in the basins was measured. Recordings from the sensors were made to a data logger which recorded at a five-minute time interval. In addition to the weight; temperature was measured by two temperature sensors and saved on the data logger every five minutes. A dummy sensor was installed in order to establish the relationship between temperature and sensor output.

Evaporation from the forest floor was determined by calculating the water balance of the upper and lower basin. Evaporation from interception was computed as net precipitation minus the discharged water from the valve, minus the change in weight of the 2 basins:

$$E_i = P_{net} - \left[\frac{\mathrm{d}S_u}{\mathrm{d}t} + \frac{\mathrm{d}S_l}{\mathrm{d}t} \right] - \mathrm{R}_{\mathrm{valve}} \qquad \text{(Equation 3.1)}$$

where E_i is the evaporation from interception, P_{net} the net precipitation, S_u and S_l the storage in respectively the lower and upper and lower basin and R_{valve} the drainage from the valve.

The setup of the forest floor interception device is shown in Figure 3.4 and 3.5 below:

Figure 3.4 Setup of the forest floor interception device with upper basin containing Msasa (*brachystegia spiciformis*) leaf litter

Figure 3.5 Setup of the forest floor interception device with upper basin containing Thatching (*Hyparrhenia filipendula)* grass

*note the Thatching grass stand in the background

3.5 Determination of water storage capacity

Sprinkler experiments were carried out to measure the water storage capacity of the Msasa (*brachystegia spiciformis*) tree leaf litter and the Thatching grass (*Hyparrhenia filipendula).* The equipment used for the experiment consisted of a reservoir mounted on a ladder to increase water pressure. The reservoir was calibrated and filled with a known volume of water. A garden hose connected the reservoir to a shower head from which water was applied to the upper basin as shown below in Figure 3.6:

Figure 3.6: (left) Reservoir mounted on ladder;(right) Application of water using a showerhead connected by hose to reservoir

During each test run, water from the reservoir was applied evenly over the basin. The test was carried out for twenty minutes and recordings were made for forty minutes in order to record the recession after water application. The test was carried out on dry days. The dynamic and static threshold of the leaf litter and grass were computed.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Rainfall Distribution

The amount of gross rainfall received at Belvedere and Kutsaga stations from November 2007 to March 2008 was 1208.6 mm and 657.1 mm respectively. 79 rain days were recorded for Belvedere station and 71 rain days for Kutsaga during this period. Figure 4.1 below shows the monthly rainfall distribution for the two stations:

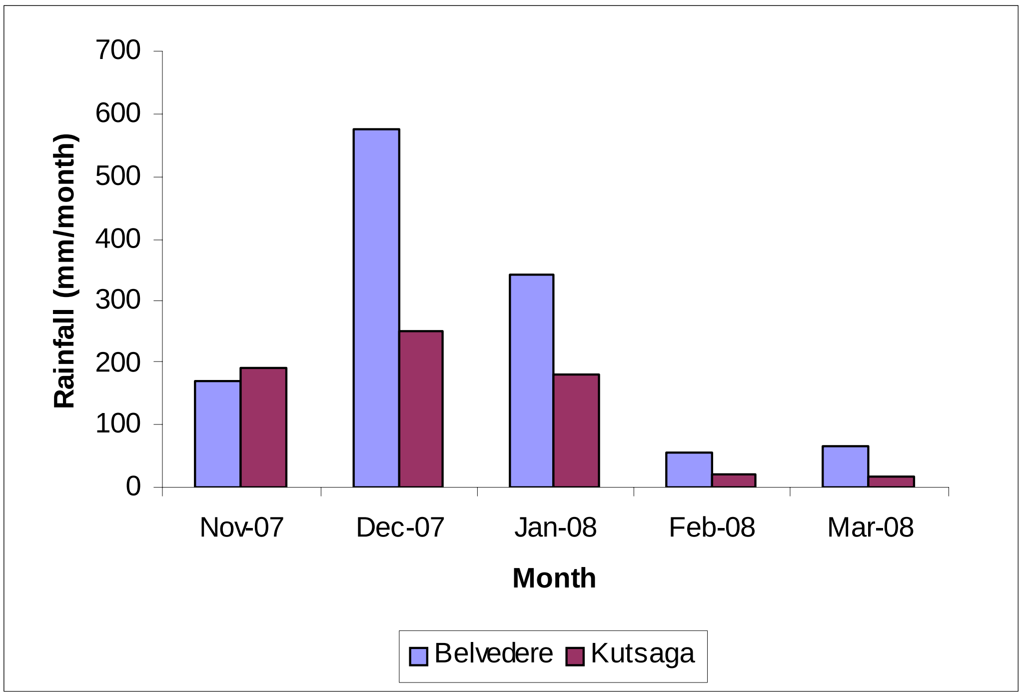

Figure 4.1 Monthly rainfall distribution at Belvedere and Kutsaga (November 2007 to March 2008)

Though the stations are only a few km apart, the amounts of rainfall received were substantially different. December was the wettest month for both stations. Daily rainfall distribution data is shown in Appendix 1.

Figure 4.2 below shows the cumulative monthly rainfall for the two stations:

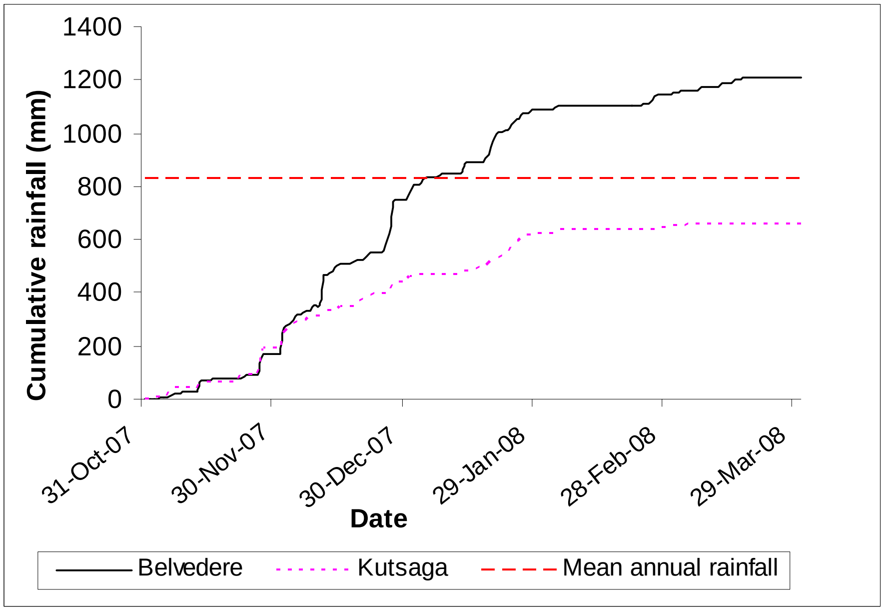

Figure 4.2 Cumulative rainfall at Belvedere and Kutsaga (November 2007 to March 2008)

As shown in Figure 4.2 above, Belvedere station received more rainfall (1208.6 mm) than Kutsaga station (657.1 mm) for the period November 2007 to March 2008. As indicated on the graph, Belvedere station received more than the mean annual rainfall (825 mm) of Harare whilst Kutsaga station received less than the mean annual rainfall. Thus the season was substantially wet at Belvedere station.

4.2 Canopy Interception

Canopy interception was computed as the difference between the gross and net rainfall. Appendix 2 shows the gross and net rainfall data for Belvedere station where the study was carried out under a Msasa tree. Figure 4.3 below shows the monthly gross rainfall, net rainfall and canopy interception distribution at Belvedere station.

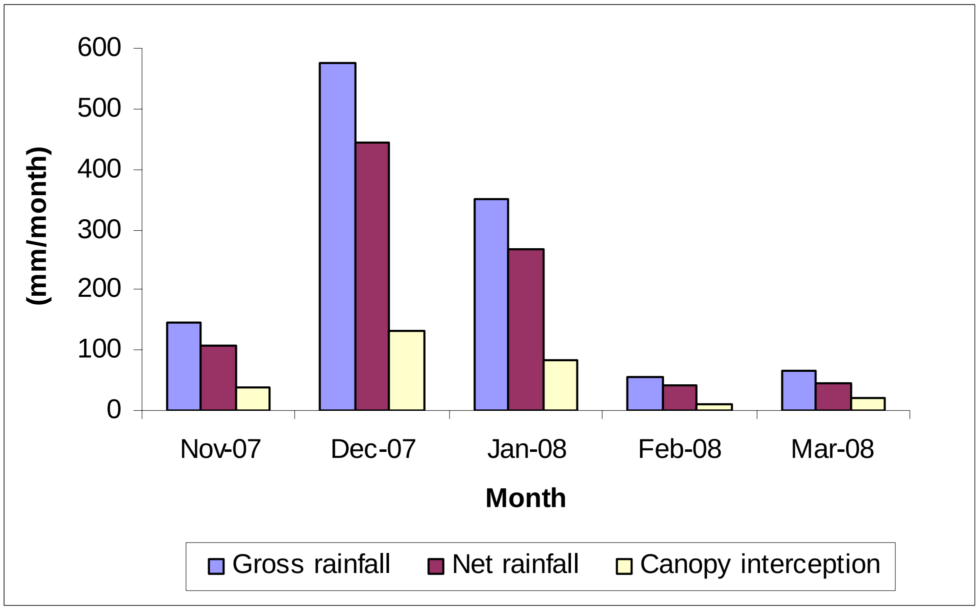

Figure 4.3 Monthly gross rainfall, net rainfall and canopy interception distribution at Belvedere station

The month of December had the highest canopy interception loss followed by January with a comparatively high value. Percentage canopy interception values for the five months at Belvedere station are presented below in table 4.1:

Table 4.1 Percentage canopy interception values for Belvedere station

Month	Gross rainfall (mm)	Net rainfall (mm)	Canopy interception (mm)	% Canopy interception
Nov-07	145.8	108.6	37.2	25.5
Dec-07	576.5	445.6	130.9	22.7
Jan-08	352.0	267.8	84.2	23.9
Feb-08	53.9	42.4	11.5	21.3
Mar-08	64.6	44.4	20.2	31.3

The percentage canopy interception values are comparable to literature. Warburton, (2007) suggested a range of 15-25% canopy interception for deciduous trees whilst Pidwirny, (2006) gave a range of 20-30% for deciduous trees. Coniferous trees have a higher range of 25-35%. The cumulated values for gross rainfall, net rainfall and canopy interception at Belvedere station are shown below in Figure 4.4:

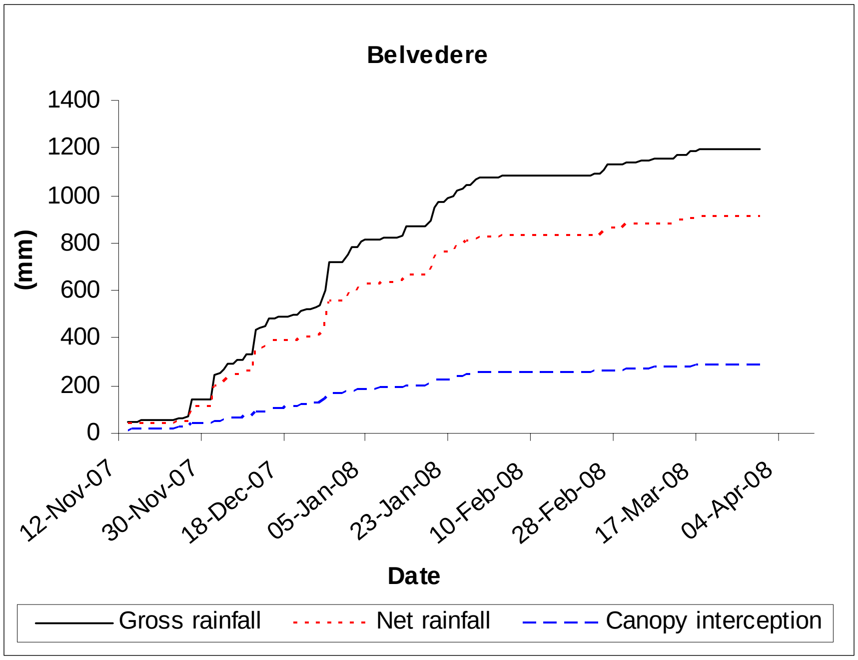

Figure 4.4 Cumulative canopy interception compared to gross and net rainfall at Belvedere station

The canopy interception for the study period was 25% of gross rainfall as shown in table 4.2 below:

Table 4.2 Canopy interception value from mid-November 2007 to March 2008

Gross rainfall	1192.8 mm
Net Rainfall	908.8 mm
Canopy interception	284.0 mm
% Canopy interception	25

4.2.1 Effects of meteorological factors on canopy interception

Interception is influenced by meteorological factors chief of which is temperature which affects the rate at which water evaporates. The relationship between canopy interception, mean daily temperature and daily evaporation is shown in figure 4.5 below:

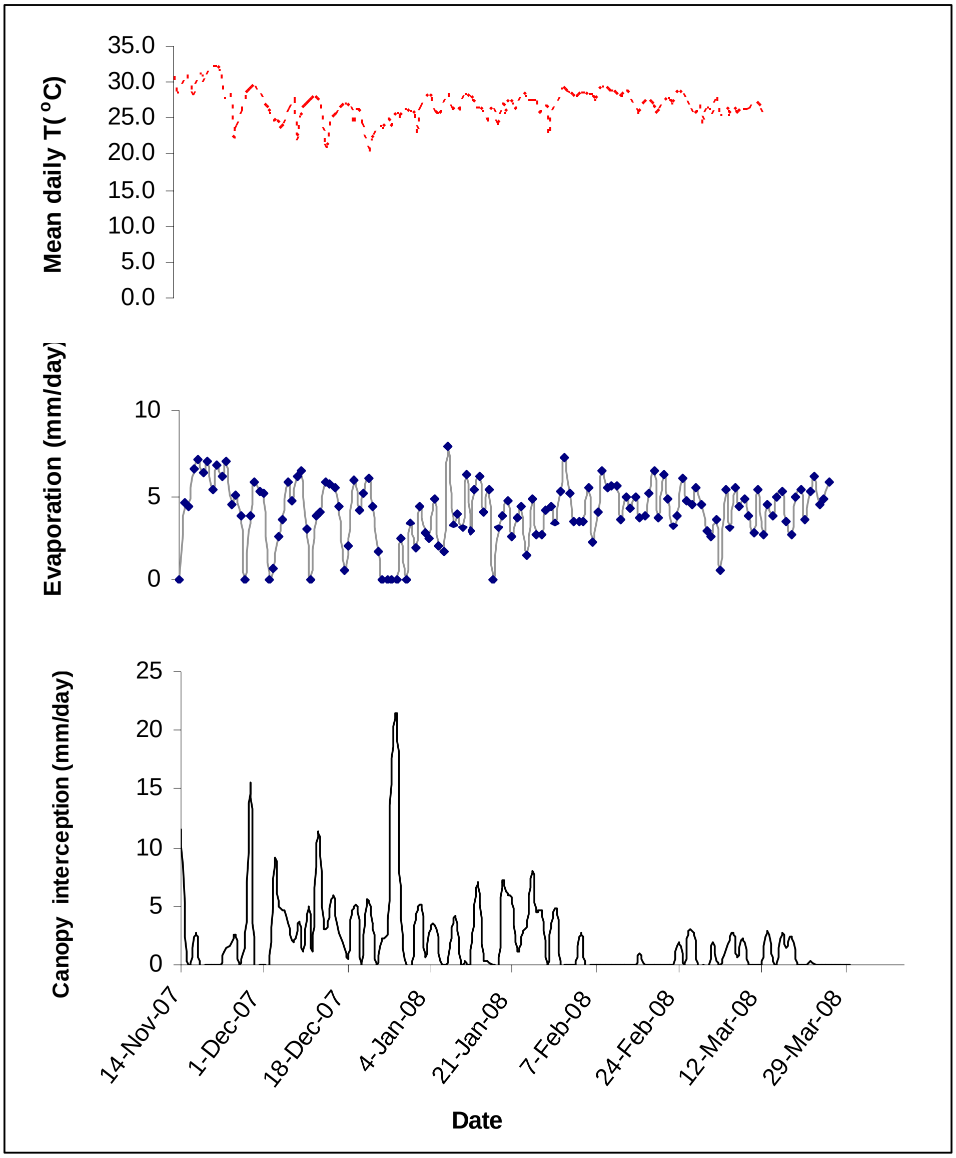

Figure 4.5 Effect of mean daily temperature and daily evaporation on canopy interception.

Generally, the amount of canopy interception was high when temperature and evaporation were high except where canopy interception peaks were very great. This concurs with Wilson's,(1990) view that if the ambient temperature of the air and ground are high, evaporation will proceed more rapidly than if they are low since heat energy is more readily available for evaporation to take place. The average evaporation rate for the study period was 5mm.

Regression analysis was carried out to establish a relationship between evaporation and interception as shown in Appendix 3. The analysis shows a significant ($P<0.05$) relationship between evaporation and canopy interception. A correlation coefficient of ($r=0.53$) was observed showing that evaporation has an influence on canopy interception.

High canopy interception values computed for the 28th of November and the 12th and 28th of December 2007 may have been a result of the substantial amount of rainfall received on these days which were 77.6mm, 106.3mm and 117.2mm respectively. However, according to The Rangeland Watershed Program fact sheet, (1996), rainfall amount does not influence interception loss once interception storage capacity is reached. Another explanation for these peaks was probably the storm frequency. Two or three storms may occur in one day and if the storms are spaced sufficiently far apart so that vegetation dries out (Baird and Wilby, 1999) interception “loss” will be high.

The relationship between canopy interception, humidity and wind speed was also established (figure 4.6) as these factors also influence canopy interception.

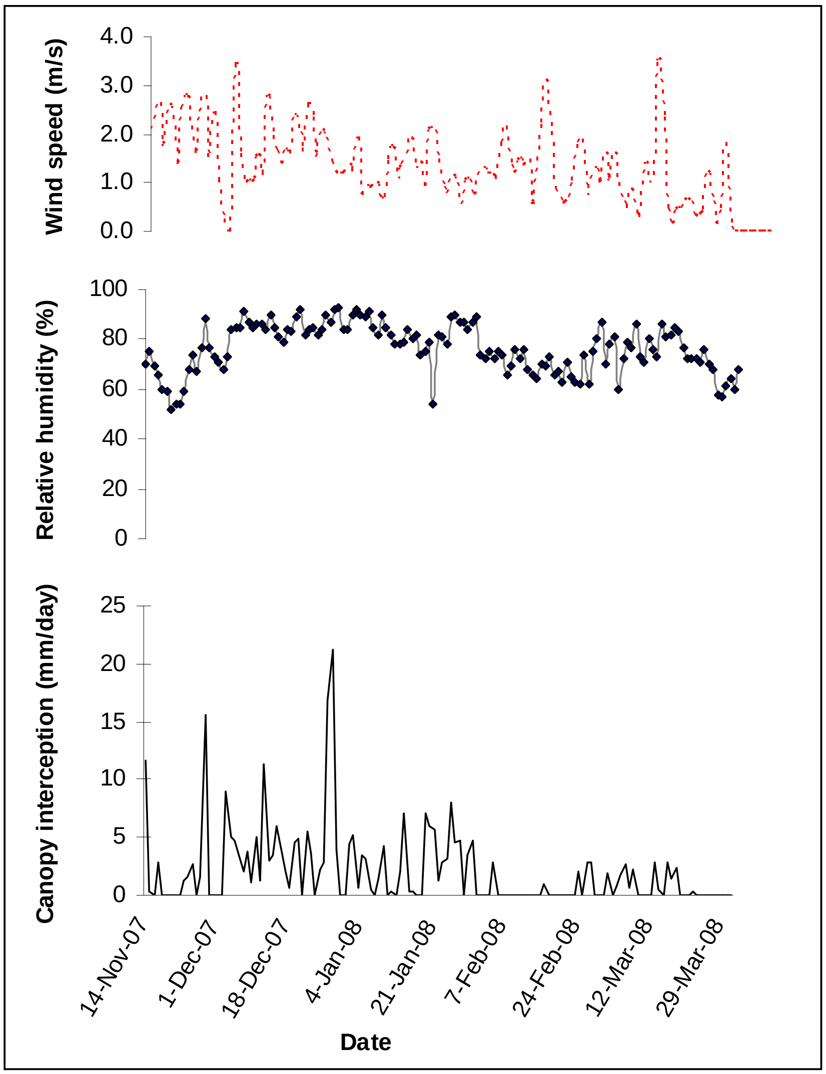

Figure 4.6 Effect of wind speed and humidity on canopy interception

It can be observed from Figure 4.6 that canopy interception increased with increasing wind speed. This is because high winds during evaporation increase the rate of evaporation (Horton, 1919; Klaassen et al., 1996). As water vaporises into the atmosphere, the boundary layer between earth and air becomes saturated and this layer must be removed and continuously replaced by drier air if evaporation is to proceed. This movement of the air in the boundary layer is a function of wind speed (Wilson, 1990).

There was an inverse relationship between canopy interception and humidity. More rain was intercepted by the canopy on less humid days. This was due to the fact that as the air's humidity fell its ability to absorb more water vapour increased and the rate of evaporation became faster (Wilson, 1990).

4.3 Forest floor Interception

Msasa leaf litter interception at Belvedere station for the period 14 November 2007 to 31 January 2008 was 14% of net precipitation (Figure 4.7). At Kutsaga, the Msasa leaf litter under open sky lost 19% of gross rainfall to interception (Figure 4.8):

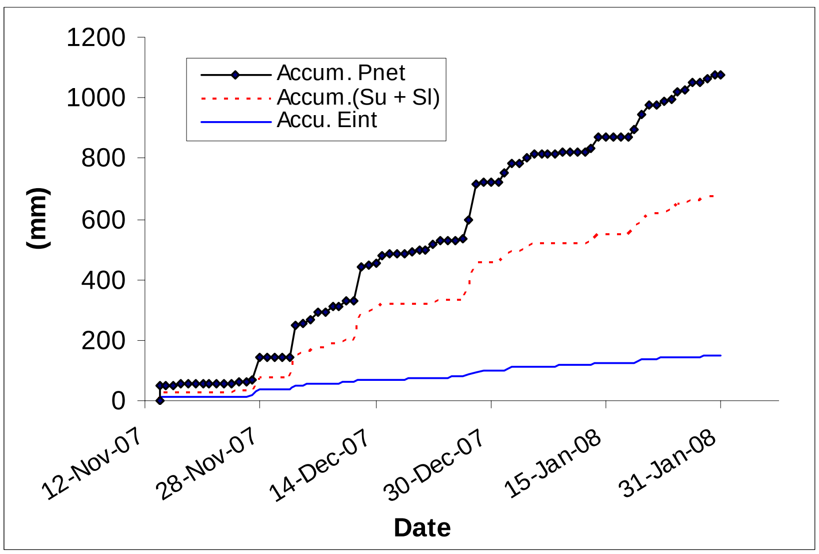

Figure 4.7 Accumulated interception by Msasa leaf litter at Belvedere station for the period 14 November to 31 January 2008

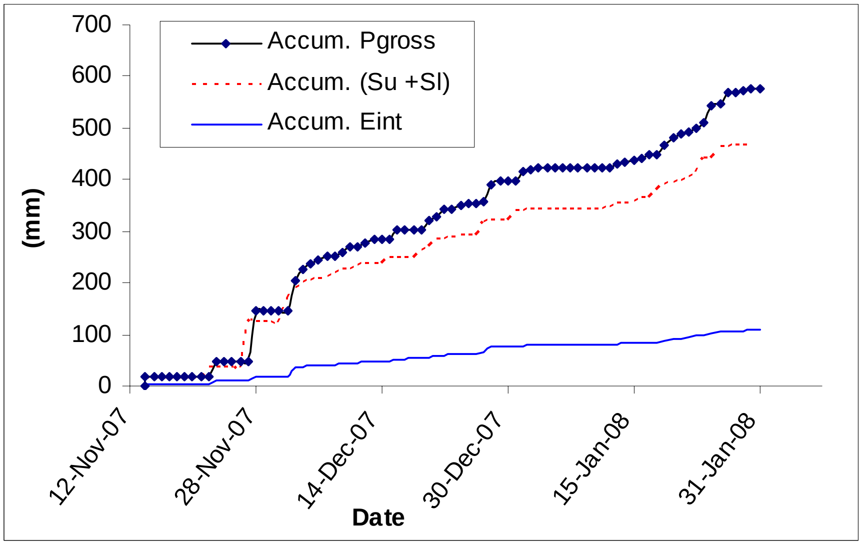

Figure 4.8 Accumulated interception by Msasa leaf litter at Kutsaga station for the period 14 November to 31 January 2008

Kutsaga station lost a higher percentage of the received rainfall to evaporation mainly because it was under open sky whereas at Belvedere station some of the precipitation was intercepted by the canopy since the device was located under a tree. The canopy also intercepted some of the radiation reaching the surface. Appendix 4 and 5 show the raw data from which the leaf litter interception computations were made.

In February, the forest floor interception device at Kutsaga station was relocated to Belvedere station and the Msasa leaf litter for the basin was replaced with 'dead' Thatching grass. Dead grass was used in order to exclude transpiration from the measurements. However, most of the data for February was lost due to failure of the data logger.

Figure 4.9 below makes a comparison of the evaporation from interception between the Msasa leaf litter and Thatching grass from 19 February to 31 March 2008:

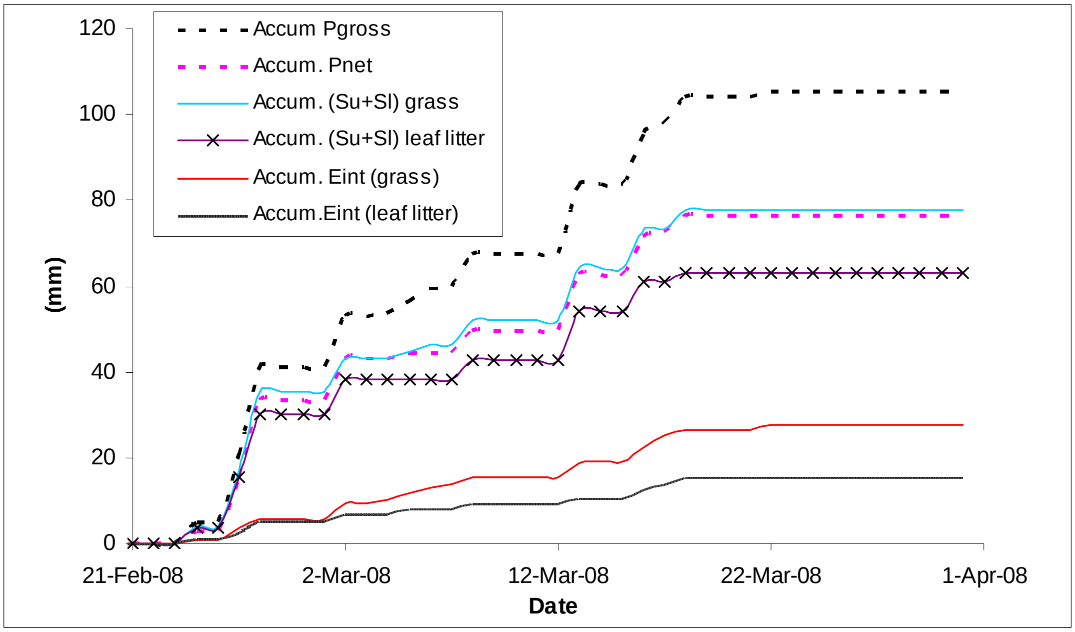

Figure 4.9 Comparison of the evaporation from interception between the Msasa leaf litter and Thatching grass (19 February to 31 March 2008)

The Thatching grass had a higher percentage of interception loss (26%) compared to the Msasa leaf litter (20%). This was probably due to the fact that the grass was under open sky and received more rain than the leaf litter which received only the through fall as it was located under a tree. Also, it was observed during sprinkler tests carried out that the dry grass dried out faster than the leaf litter layer since it is less closely packed than the litter allowing wind to flow through it. The nature of the intercepting material thus influences interception. Appendix 6 and 7 show the source data from which the interception values were computed.

4.4 Interception storage capacity

4.4.1 Effect of vegetation type on water storage capacity

Sprinkler tests were carried out to determine the water storage capacity. The tests for Thatching grass were carried out on the 19th of May 2008 and those for Msasa leaf litter were carried out on the 21st of May 2008 .The tests indicate that water storage increases exponentially during a storm until the storage capacity is reached. When rainfall stops there is rapid initial drainage which then slows and ends at a lower static storage. The Msasa leaf litter had a higher water storage capacity than the Thatching grass (see Appendix 8 for source data) for the three experiments carried out as shown below in Figure 4.10:

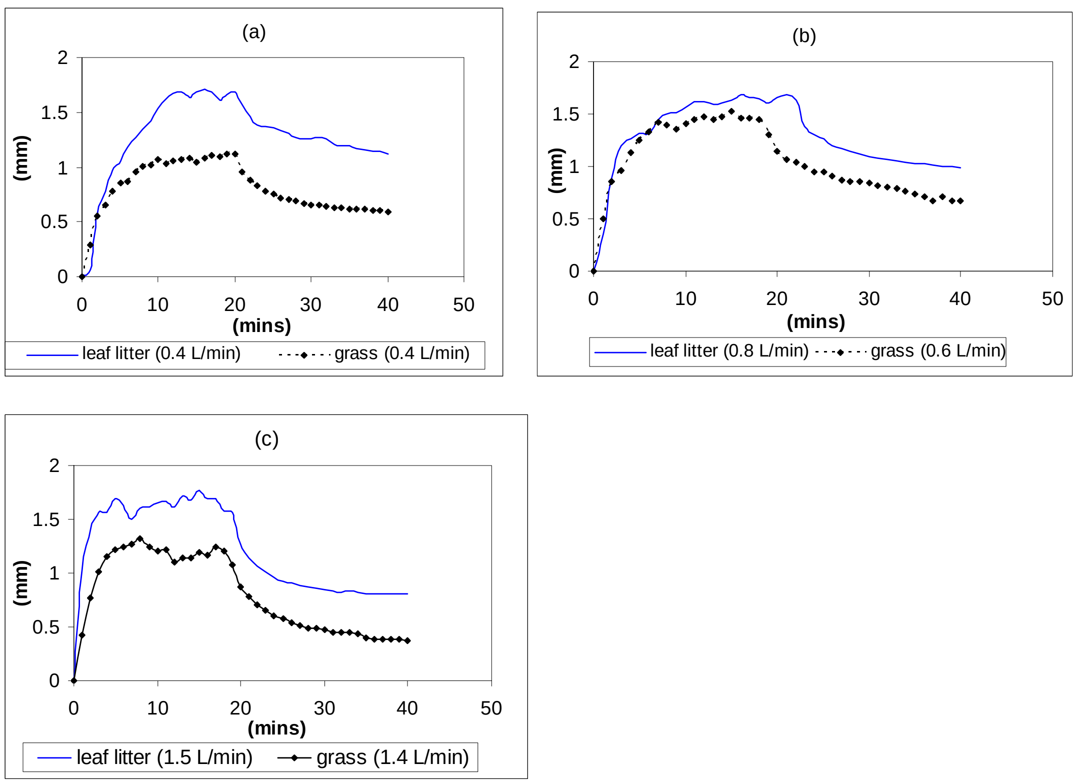

Figure 4.10 Water storage capacities of Msasa leaf litter and Thatching grass for three experiments

The results of all three experiments indicate that Msasa leaf litter water storage capacity was higher than interception by Thatching grass. This confirms the observation by Horton, (1919), that large broadleaved plants tend to hold water well on their leaves while grass holds less water.

As can be seen from Figure 4.11, the highest dynamic threshold of interception achieved was 1.8 mm. This was achieved at the highest intensity rainfall of 1.5L/min by the Msasa tree leaf litter. However after drainage of the leaves, the static threshold was highest at lower intensities of 0.4 L/min and 0.8 L/min with a value of 1mm at both intensities. The highest dynamic threshold for the grass was 1.5mm at a rainfall intensity of 0.6 L/min. The highest static threshold for the grass was 0.7mm at an intensity of 0.6 L/min.

It must be emphasized however, that the second and third experiments for both the leaf litter and grass were carried out at slightly different intensities and were thus difficult to compare.

4.4.2 Effect of rainfall intensity of water storage capacity

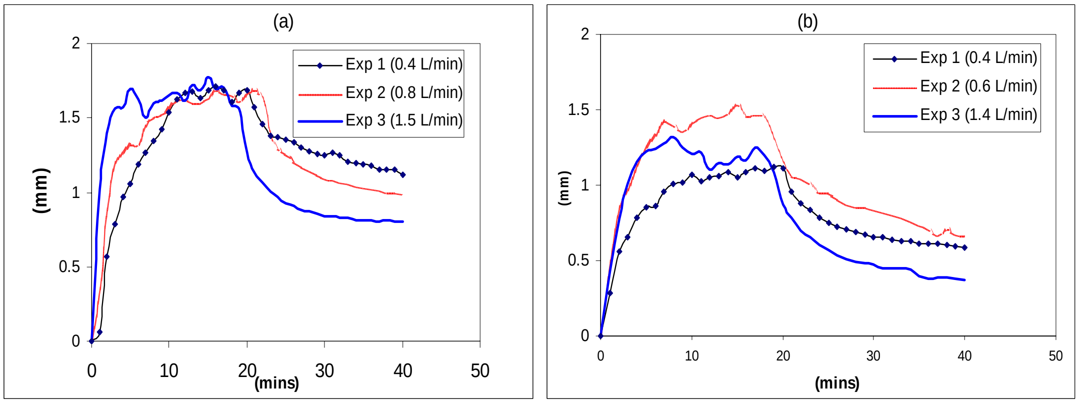

Figure 4.11 Effect of rainfall intensity on water storage capacity

Figure 4.11 shows that the interception capacity depends on rainfall intensity as supported by Calder et al., (1996). The static water storage threshold for the Msasa leaf litter was highest with the lowest intensity rainfall events. This is comparable to studies carried out by Jackson, (1971) in a tropical forest in Tanzania (see table 2:1). In this study, the static threshold is more important than the dynamic threshold because it represents the storage which can only be lost by evaporation (Putuhena and Cordery, 1996).

The least static threshold was observed for the highest intensity (1.5 L/min storm). This can be explained by the fact that at higher rainfall intensities the water stored on the litter will decrease because the bigger raindrops will splash greater quantities of water off the surface (Rutter et al., 1971; Calder et al., 1996).

The Thatching grass had a higher static threshold at an intensity of 0.6 L/min and the least threshold at an intensity of 1.4 L/min. A low static threshold was recorded for an intensity of 0.4 L/min. This disparity may have been caused by less grass being used for this experiment compared to the other experiments. This is because dry grass was used for each experiment since antecedent soil moisture conditions affect water storage capacity.

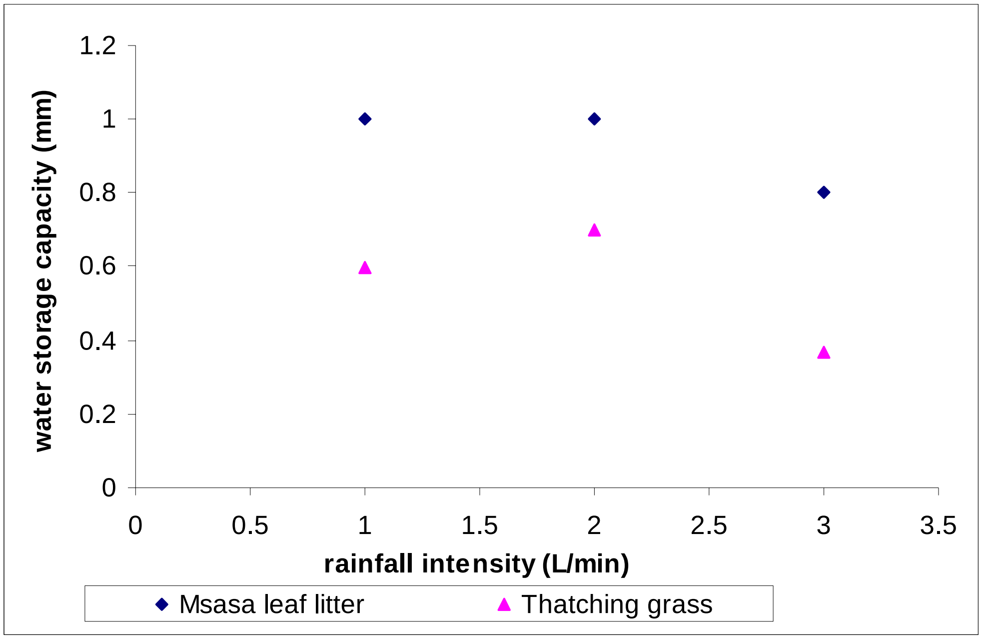

Figure 4.12 Relationship between water storage capacity and rainfall intensity

Figure 4.12 shows that the water storage capacity increases with increasing intensity for both vegetation types until a time when the intensity is too high and water is delivered too quickly for the plants to accommodate then drainage begins. This shows that interception is a threshold process as suggested by Gerrits et al., (2008).

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The study reveals that:

- Interception is a threshold process which is affected by both meteorological factors and vegetation characteristics.
- Vegetation with a higher Leaf Area Index (as with the leaf litter) has a higher storage capacity than that with a lower Leaf Area Index (grass). However, the evaporation loss from a litter layer is less than that from grass which is not as tightly packed as the leaf litter layer allowing wind to flow through it.
- Water storage capacity depends on storm intensity with high intensity storms having less storage capacity and rainfall falling gently having a higher storage capacity.
- Interception is driven by meteorological factors such as evaporation, wind speed and humidity. As shown from statistical analysis, there is a significant ($P<0.05$) relationship between evaporation and canopy interception.
- Interception contributes significantly to the hydrological cycle and should be considered in hydrological modelling and given greater consideration in rainfall – runoff studies. Further, combining canopy and forest floor interception yields a value of approximately half the amount of precipitation received. Disregarding interception is thus a misrepresentation.

5.2 Recommendations

It is recommended that:

- The study is carried out for more rainy seasons so as to determine seasonal effect of rainfall interception and also to create a platform for rainfall partitioning by vegetation in Zimbabwe.
- Stem flow should also be determined as it influences the net rainfall received.
- A hydrological model specific to the study area should be developed so that blanket recommendations of the contributions of hydrological processes to the hydrological cycle are avoided. Future research projects will promote better stewardship of forest and water resources.

5.3 Limitations of the study

One possible source of error is the 'interface effect' as described by Helvey and Patric, (1965) who stated that values of forest floor interception includes the effect of water retained by surface tension between the litter and the strands of the mesh used in the measuring device (in this case the upper basin of the forest floor interception device which was covered with hessian sack). This effect should be subtracted from the measured value to obtain the actual amount of water held by the litter layer. However, in this study, the chicken wire used in the upper basin had large spaces which may have negated this effect.

Due to limited sensors and data loggers only two sets of forest floor interception devices were used.

Initially car batteries were used to power the logger battery. However, the charging of batteries was not consistent so some data gaps exist in the data series. This problem has been rectified and now chargers which convert AC to DC are used.

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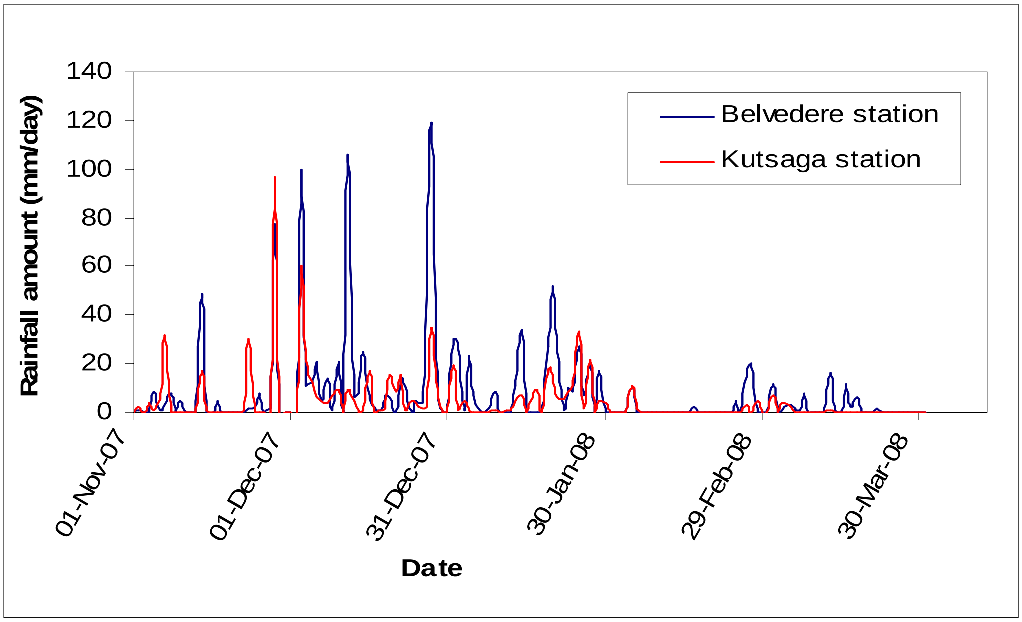
APPENDICES

Appendix 1: Rainfall data



Appendix 2: Canopy interception values at Belvedere station

Date	Gross rainfall mm	Cumulated gross rainfall mm	Net rainfall mm	Cumulated net rainfall mm	Canopy Interception mm	Cumulated canopy interception mm
14-Nov-07	48.6	48.6	37		11.6	11.6
15-Nov-07	0.3	48.9	0	37	0.3	11.9
16-Nov-07	0	48.9	0	37	0	11.9
17-Nov-07	4.8	53.7	2	39	2.8	14.7
18-Nov-07	0	53.7	0	39	0	14.7
19-Nov-07	0	53.7	0	39	0	14.7
20-Nov-07	0	53.7	0	39	0	14.7
21-Nov-07	0	53.7	0	39	0	14.7
22-Nov-07	0	53.7	0	39	0	14.7
23-Nov-07	1.2	54.9	0	39	1.2	15.9
24-Nov-07	2.4	57.3	0.8	39.8	1.6	17.5
25-Nov-07	7.6	64.9	5	44.8	2.6	20.1
26-Nov-07	0	64.9	0	44.8	0	20.1
27-Nov-07	3.3	68.2	1.8	46.6	1.5	21.6
28-Nov-07	77.6	145.8	62	108.6	15.6	37.2
29-Nov-07	0	145.8	0	108.6	0	37.2
30-Nov-07	0	145.8	0	108.6	0	37.2
1-Dec-07	0	145.8	0	108.6	0	37.2
2-Dec-07	0	145.8	0	108.6	0	37.2
3-Dec-07	100	245.8	91	199.6	9	46.2
4-Dec-07	11	256.8	6	205.6	5	51.2
5-Dec-07	13.1	269.9	8.4	214	4.7	55.9
6-Dec-07	20.9	290.8	17.3	231.3	3.6	59.5
7-Dec-07	4.3	295.1	2.3	233.6	2	61.5
8-Dec-07	13.7	308.8	10	243.6	3.7	65.2
9-Dec-07	1.1	309.9	0	243.6	1.1	66.3
10-Dec-07	21	330.9	16	259.6	5	71.3
11-Dec-07	1.3	332.2	0	259.6	1.3	72.6
12-Dec-07	106.3	438.5	95	354.6	11.3	83.9
13-Dec-07	6.4	444.9	3.4	358	3	86.9
14-Dec-07	8.8	453.7	5.4	363.4	3.4	90.3
15-Dec-07	25	478.7	19	382.4	6	96.3
16-Dec-07	5.7	484.4	2.1	384.5	3.6	99.9
17-Dec-07	2.6	487	0.6	385.1	2	101.9
18-Dec-07	0.6	487.6	0	385.1	0.6	102.5
19-Dec-07	6.7	494.3	2.1	387.2	4.6	107.1
20-Dec-07	6.2	500.5	1.3	388.5	4.9	112
21-Dec-07	0	500.5	0	388.5	0	112
22-Dec-07	14.8	515.3	9.3	397.8	5.5	117.5
23-Dec-07	10.6	525.9	7	404.8	3.6	121.1
24-Dec-07	0	525.9	0	404.8	0	121.1
25-Dec-07	4.3	530.2	2.1	406.9	2.2	123.3
26-Dec-07	3.8	534	1	407.9	2.8	126.1
27-Dec-07	65.4	599.4	48.6	456.5	16.8	142.9
28-Dec-07	117.2	716.6	96	552.5	21.2	164.1
29-Dec-07	5.7	722.3	1.7	554.2	4	168.1
30-Dec-07	0	722.3	0	554.2	0	168.1
31-Dec-07	0	722.3	0	554.2	0	168.1
1-Jan-08	30.4	752.7	26	580.2	4.4	172.5
2-Jan-08	28.5	781.2	23.3	603.5	5.2	177.7
3-Jan-08	0.7	781.9	0	603.5	0.7	178.4
4-Jan-08	23.1	805	19.7	623.2	3.4	181.8
5-Jan-08	6.7	811.7	3.6	626.8	3.1	184.9
6-Jan-08	0.4	812.1	0	626.8	0.4	185.3
7-Jan-08	0	812.1	0	626.8	0	185.3
8-Jan-08	1.9	814	0.5	627.3	1.4	186.7

Appendix 3: Regression analysis for Canopy interception and evaporation

Regression Statistics	
Multiple R	0.526873651
R Square	0.277595844
Adjusted R Square	0.272322821
Standard Error	2.7384944

	Coefficients	*P-value*
Intercept	5.979735865	3.55654E-18
Evaporation	-0.964879713	2.68993E-11

Appendix 4: Litter interception at Belvedere station (14 November to 31 January 2008)

Date	Gross Rainfall	cum. GR	Net Rainfall	cum NR	dSu+dSl	cum U+L	FFI
11/14/2007		0		0		0	
11/14/2007	48.6	48.6	37	37	25.24	25.24	11.76
11/15/2007	0.3	48.9	0	37	0	25.24	0
11/16/2007	0	48.9	0	37	0	25.24	0
11/17/2007	4.8	53.7	2	39	0	25.24	2
11/18/2007	0	53.7	0	39	0	25.24	0
11/19/2007	0	53.7	0	39	0	25.24	0
11/20/2007	0	53.7	0	39	0	25.24	0
11/21/2007	0	53.7	0	39	0	25.24	0
11/22/2007	0	53.7	0	39	0	25.24	0
11/23/2007	1.2	54.9	0	39	0	25.24	0
11/24/2007	2.4	57.3	0.8	39.8	0	25.24	0.8
11/25/2007	7.6	64.9	5	44.8	4.61	29.85	0.39
11/26/2007	0	64.9	0	44.8	0	29.85	0
11/27/2007	3.3	68.2	1.8	46.6	0	29.85	1.8
11/28/2007	77.6	145.8	62	108.6	42.41	72.26	19.59
11/29/2007	0	145.8	0	108.6	0	72.26	0
11/30/2007	0	145.8	0	108.6	0	72.26	0
12/1/2007	0	145.8	0	108.6	0	72.26	0
12/2/2007	0	145.8	0	108.6	0	72.26	0
12/3/2007	100	245.8	91	199.6	75.74	148	15.26
12/4/2007	11	256.8	6	205.6	5.86	153.86	0.14
12/5/2007	13.1	269.9	8.4	214	6.11	159.97	2.29
12/6/2007	20.9	290.8	17.3	231.3	14.57	174.54	2.73
12/7/2007	4.3	295.1	2.3	233.6	2.1	176.64	0.2
12/8/2007	13.7	308.8	10	243.6	7.91	184.55	2.09
12/9/2007	1.1	309.9	0	243.6	0	184.55	0
12/10/2007	21	330.9	16	259.6	12.85	197.4	3.15
12/11/2007	1.3	332.2	0	259.6	0	197.4	0
12/12/2007	106.3	438.5	95	354.6	91.21	288.61	3.79
12/13/2007	6.4	444.9	3.4	358	3.1	291.71	0.3
12/14/2007	8.8	453.7	5.4	363.4	4.8	296.51	0.6
12/15/2007	25	478.7	19	382.4	17.59	314.1	1.41
12/16/2007	5.7	484.4	2.1	384.5	0	314.1	2.1
12/17/2007	2.6	487	0.6	385.1	0	314.1	0.6
12/18/2007	0.6	487.6	0	385.1	0	314.1	0
12/19/2007	6.7	494.3	2.1	387.2	0	314.1	2.1
12/20/2007	6.2	500.5	1.3	388.5	0	314.1	1.3
12/21/2007	0	500.5	0	388.5	0	314.1	0
12/22/2007	14.8	515.3	9.3	397.8	8.4	322.5	0.9
12/23/2007	10.6	525.9	7	404.8	6.17	328.67	0.83
12/24/2007	0	525.9	0	404.8	0	328.67	0
12/25/2007	4.3	530.2	2.1	406.9	0	328.67	2.1
12/26/2007	3.8	534	1	407.9	0	328.67	1
12/27/2007	65.4	599.4	48.6	456.5	42.71	371.38	5.89
12/28/2007	117.2	716.6	96	552.5	84.79	456.17	11.21
12/29/2007	5.7	722.3	1.7	554.2	0	456.17	1.7
12/30/2007	0	722.3	0	554.2	0	456.17	0
12/31/2007	0	722.3	0	554.2	0	456.17	0
1/1/2008	30.4	752.7	26	580.2	23.5	479.67	2.5
1/2/2008	28.5	781.2	23.3	603.5	11.6	491.27	11.7
1/3/2008	0.7	781.9	0	603.5	0	491.27	0
1/4/2008	23.1	805	19.7	623.2	18.87	510.14	0.83
1/5/2008	6.7	811.7	3.6	626.8	2.82	512.96	0.78
1/6/2008	0.4	812.1	0	626.8	0	512.96	0
1/7/2008	0	812.1	0	626.8	0	512.96	0
1/8/2008	1.9	814	0.5	627.3	0	512.96	0.5
1/9/2008	8.8	822.8	4.6	631.9	3.51	516.47	1.09
1/10/2008	0	822.8	0	631.9	0	516.47	0
1/11/2008	0.3	823.1	0	631.9	0	516.47	0
1/12/2008	0	823.1	0	631.9	0	516.47	0
1/13/2008	10.5	833.6	8.4	640.3	8.14	524.61	0.26
1/14/2008	34.2	867.8	27.2	667.5	20.86	545.47	6.34
1/15/2008	0.3	868.1	0	667.5	0	545.47	0
1/16/2008	0.3	868.4	0	667.5	0	545.47	0
1/17/2008	0	868.4	0	667.5	0	545.47	0
1/18/2008	0	868.4	0	667.5	0	545.47	0
1/19/2008	26.8	895.2	19.8	687.3	17.42	562.89	2.38
1/20/2008	52.2	947.4	46.2	733.5	33.82	596.71	12.38
1/21/2008	27.7	975.1	22	755.5	20.01	616.72	1.99
1/22/2008	1.2	976.3	0	755.5	0	616.72	0
1/23/2008	10.2	986.5	7.3	762.8	5.32	622.04	1.98
1/24/2008	8.2	994.7	5	767.8	4.1	626.14	0.9
1/25/2008	27.4	1022.1	19.4	787.2	17.87	644.01	1.53
1/26/2008	6.8	1028.9	2.3	789.5	0	644.01	2.3
1/27/2008	19.1	1048	14.4	803.9	13.4	657.41	0
1/28/2008	0	1048	0	803.9	0	657.41	0
1/29/2008	17.3	1065.3	13.8	817.7	12.24	669.65	1.56
1/30/2008	9	1074.3	4.3	822	3.94	673.59	0.36
1/31/2008	0	1074.3	0	822	0	673.59	0

Appendix 5: Litter interception at Kutsaga station (14 November to 31 January 2008)

Date	Gross Rainfall	cum. GR	dSu+dSl	cum U+ L	FFI
11/14/2007		0		0	
11/14/2007	16.8	16.8	13.73	13.73	3.07
11/15/2007	0.4	17.2	0	13.73	0.4
11/16/2007	0	17.2	0	13.73	0
11/17/2007	0	17.2	0	13.73	0
11/18/2007	0	17.2	0	13.73	0
11/19/2007	0	17.2	0	13.73	0
11/20/2007	0	17.2	0	13.73	0
11/21/2007	0	17.2	0	13.73	0
11/22/2007	0	17.2	0	13.73	0
11/23/2007	30.5	47.7	24.25	37.98	6.25
11/24/2007	0	47.7	0	37.98	0
11/25/2007	0	47.7	0	37.98	0
11/26/2007	0	47.7	0	37.98	0
11/27/2007	0.3	48	0	37.98	0.3
11/28/2007	96.8	144.8	87.56	125.54	9.24
11/29/2007	0	144.8	0	125.54	0
11/30/2007	0	144.8	0	125.54	0
12/1/2007	0	144.8	0	125.54	0
12/2/2007	0	144.8	0	125.54	0
12/3/2007	60.5	205.3	44.12	169.66	16.38
12/4/2007	21.5	226.8	19.5	189.16	2
12/5/2007	12	238.8	10.34	199.5	1.66
12/6/2007	6.5	245.3	5.32	204.82	1.18
12/7/2007	4.5	249.8	4.3	209.12	0.2
12/8/2007	3.5	253.3	2.8	211.92	0.7
12/9/2007	7	260.3	5.58	217.5	1.42
12/10/2007	9	269.3	7.44	224.94	1.56
12/11/2007	0	269.3	0	224.94	0
12/12/2007	9.5	278.8	7	231.94	2.5
12/13/2007	4.8	283.6	4.15	236.09	0.65
12/14/2007	0	283.6	0	236.09	0
12/15/2007	1	284.6	0	236.09	1
12/16/2007	17	301.6	12.97	249.06	4.03
12/17/2007	0	301.6	0	249.06	0
12/18/2007	0.5	302.1	0	249.06	0.5
12/19/2007	1.5	303.6	0	249.06	1.5
12/20/2007	15.5	319.1	13.8	262.86	1.7
12/21/2007	8.5	327.6	7.92	270.78	0.58
12/22/2007	15.5	343.1	12.46	283.24	3.04
12/23/2007	0.4	343.5	0	283.24	0.4
12/24/2007	4.7	348.2	3.53	286.77	1.17
12/25/2007	3.8	352	3.4	290.17	0.4
12/26/2007	1.5	353.5	0	290.17	1.5
12/27/2007	2.3	355.8	1	291.17	1.3
12/28/2007	35	390.8	24.8	315.97	10.2
12/29/2007	5.9	396.7	4.74	320.71	1.16
12/30/2007	0	396.7	0	320.71	0
12/31/2007	0	396.7	0	320.71	0
1/1/2008	19.4	416.1	18.1	338.81	1.3
1/2/2008	1.5	417.6	0	338.81	1.5
1/3/2008	4.7	422.3	4.1	342.91	0.6
1/4/2008	0.4	422.7	0	342.91	0.4
1/5/2008	0.2	422.9	0	342.91	0.2
1/6/2008	0	422.9	0	342.91	0
1/7/2008	0	422.9	0	342.91	0
1/8/2008	0	422.9	0	342.91	0
1/9/2008	0.4	423.3	0	342.91	0.4
1/10/2008	0	423.3	0	342.91	0
1/11/2008	0.5	423.8	0	342.91	0.5
1/12/2008	0.5	424.3	0	342.91	0.5
1/13/2008	4.3	428.6	3.96	346.87	0.34
1/14/2008	7	435.6	5.67	352.54	1.33
1/15/2008	0.1	435.7	0	352.54	0.1
1/16/2008	4.5	440.2	4.01	356.55	0.49
1/17/2008	9	449.2	7.6	364.15	1.4
1/18/2008	0	449.2	0	364.15	0
1/19/2008	17.5	466.7	14.56	378.71	2.94
1/20/2008	14.3	481	12.07	390.78	2.23
1/21/2008	5.9	486.9	3.64	394.42	2.26
1/22/2008	5.5	492.4	3.5	397.92	2
1/23/2008	8.6	501	6.4	404.32	2.2
1/24/2008	11	512	10.42	414.74	0.58
1/25/2008	33	545	27.5	442.24	5.5
1/26/2008	1.5	546.5	0	442.24	1.5
1/27/2008	21.5	568	19.72	461.96	1.78
1/28/2008	0.1	568.1	0	461.96	0.1
1/29/2008	4.4	572.5	4.03	465.99	0.37
1/30/2008	3.5	576	1.23	467.22	2.27
1/31/2008	0	576	0	467.22	0

Appendix 6: Litter interception at Belvedere station (19 February to 31 March 2008)

Date	Gross Rainfall	cum. GR	Net Rainfall	cum NR	dSu+dSl	cum U+L	FFI
2/19/2008	0	0	0	0	0	0	0
2/20/2008	0	0	0	0	0	0	0
2/21/2008	0	0	0	0	0	0	0
2/22/2008	0	0	0	0	0	0	0
2/23/2008	0	0	0	0	0	0	0
2/24/2008	5	5	3	3	3.68	3.68	1.32
2/25/2008	0	5	0	3	0	3.68	0
2/26/2008	15.9	20.9	13	16	11.91	15.59	1.09
2/27/2008	20	40.9	17.2	33.2	14.34	29.93	2.86
2/28/2008	0	40.9	0	33.2	0	29.93	0
2/29/2008	0	40.9	0	33.2	0	29.93	0
3/1/2008	0	40.9	0	33.2	0	29.93	0
3/2/2008	11.9	52.8	10	43.2	8.29	38.22	1.71
3/3/2008	0	52.8	0	43.2	0	38.22	0
3/4/2008	0.8	53.6	0	43.2	0	38.22	0
3/5/2008	3	56.6	1.3	44.5	0	38.22	1.3
3/6/2008	2.7	59.3	0	44.5	0	38.22	0
3/7/2008	0.7	60	0	44.5	0	38.22	0
3/8/2008	7.4	67.4	5.2	49.7	4.31	42.53	0.89
3/9/2008	0	67.4	0	49.7	0	42.53	0
3/10/2008	0	67.4	0	49.7	0	42.53	0
3/11/2008	0	67.4	0	49.7	0	42.53	0
3/12/2008	0	67.4	0	49.7	0	42.53	0
3/13/2008	15.9	83.3	13	62.7	11.46	53.99	1.54
3/14/2008	0.4	83.7	0	62.7	0	53.99	0
3/15/2008	0	83.7	0	62.7	0	53.99	0
3/16/2008	11.8	95.5	9	71.7	7.02	61.01	1.98
3/17/2008	2.6	98.1	1.2	72.9	0	61.01	1.2
3/18/2008	6.1	104.2	3.7	76.6	2.16	63.17	1.54
3/19/2008	0	104.2	0	76.6	0	63.17	0
3/20/2008	0	104.2	0	76.6	0	63.17	0
3/21/2008	0	104.2	0	76.6	0	63.17	0
3/22/2008	1.3	105.5	0	76.6	0	63.17	0
3/23/2008	0	105.5	0	76.6	0	63.17	0
3/24/2008	0	105.5	0	76.6	0	63.17	0
3/25/2008	0	105.5	0	76.6	0	63.17	0
3/26/2008	0	105.5	0	76.6	0	63.17	0
3/27/2008	0	105.5	0	76.6	0	63.17	0
3/28/2008	0	105.5	0	76.6	0	63.17	0
3/29/2008	0	105.5	0	76.6	0	63.17	0
3/30/2008	0	105.5	0	76.6	0	63.17	0
3/31/2008	0	105.5	0	76.6	0	63.17	0

Appendix 7: Interception by grass at Belvedere station (19 February to 31 March 2008)

Date	Gross Rainfall	cum. GR	dSu+dSl	cum U+ L	FFI
2/19/2008	0	0	0	0	0
2/20/2008	0	0	0	0	0
2/21/2008	0	0	0	0	0
2/22/2008	0	0	0	0	0
2/23/2008	0	0	0	0	0
2/24/2008	5	5	4.21	4.21	0.79
2/25/2008	0	5	0	4.21	0
2/26/2008	15.9	20.9	12.87	17.08	3.03
2/27/2008	20	40.9	18.18	35.26	1.82
2/28/2008	0	40.9	0	35.26	0
2/29/2008	0	40.9	0	35.26	0
3/1/2008	0	40.9	0	35.26	0
3/2/2008	11.9	52.8	8.04	43.3	3.86
3/3/2008	0	52.8	0	43.3	0
3/4/2008	0.8	53.6	0	43.3	0.8
3/5/2008	3	56.6	1.6	44.9	1.4
3/6/2008	2.7	59.3	1.4	46.3	1.3
3/7/2008	0.7	60	0	46.3	0.7
3/8/2008	7.4	67.4	5.82	52.12	1.58
3/9/2008	0	67.4	0	52.12	0
3/10/2008	0	67.4	0	52.12	0
3/11/2008	0	67.4	0	52.12	0
3/12/2008	0	67.4	0	52.12	0
3/13/2008	15.9	83.3	12.33	64.45	3.57
3/14/2008	0.4	83.7	0	64.45	0.4
3/15/2008	0	83.7	0	64.45	0
3/16/2008	11.8	95.5	8.57	73.02	3.23
3/17/2008	2.6	98.1	0	73.02	2.6
3/18/2008	6.1	104.2	4.71	77.73	1.39
3/19/2008	0	104.2	0	77.73	0
3/20/2008	0	104.2	0	77.73	0
3/21/2008	0	104.2	0	77.73	0
3/22/2008	1.3	105.5	0	77.73	1.3
3/23/2008	0	105.5	0	77.73	0
3/24/2008	0	105.5	0	77.73	0
3/25/2008	0	105.5	0	77.73	0
3/26/2008	0	105.5	0	77.73	0
3/27/2008	0	105.5	0	77.73	0
3/28/2008	0	105.5	0	77.73	0
3/29/2008	0	105.5	0	77.73	0
3/30/2008	0	105.5	0	77.73	0
3/31/2008	0	105.5	0	77.73	0

Appendix 8: Sprinker experiment test data

Leaf litter				Grass		
time (mins)	Exp 1 0.4 L	Exp 2 0.8 L/min	Exp 3 1.5L/min	Exp 1 0.4 L/min	Exp 2 0.6 L/min	Exp 3 1.4L/min
0	0	0	0	0	0	0
1	0.05754573	0.352220373	1.023447416	0.28396922	0.494649991	0.428089573
2	0.56800556	0.882267437	1.399705004	0.558866787	0.856258912	0.775487339
3	0.7853484	1.197212515	1.563981247	0.659139879	0.963119449	1.009344193
4	0.96668522	1.269008321	1.568440966	0.783711272	1.129357925	1.158392396
5	1.05854853	1.314645203	1.694171189	0.85228468	1.253901518	1.220632192
6	1.1871238	1.317172475	1.627958083	0.866200845	1.331023165	1.244669797
7	1.26571146	1.442086379	1.500901848	0.953272796	1.418145445	1.27363433
8	1.34631619	1.500423052	1.596317	1.005691488	1.397940273	1.317576835
9	1.42613005	1.516531524	1.618453749	1.018683519	1.354489017	1.247174356
10	1.53844708	1.559685525	1.648946379	1.064705201	1.407723949	1.206569604
11	1.62015564	1.613365354	1.666817741	1.028215637	1.452492812	1.212976938
12	1.67094429	1.620419143	1.620035578	1.053765385	1.468679205	1.10434498
13	1.68079686	1.594107951	1.722684842	1.063719215	1.44942516	1.14415607
14	1.63563391	1.602492961	1.681581675	1.083766067	1.473897674	1.139177668
15	1.68131196	1.632669329	1.773512976	1.048039354	1.53256158	1.187767987
16	1.71411931	1.688918911	1.697588159	1.085422613	1.454970931	1.164371685
17	1.68765607	1.66267626	1.698703916	1.108528484	1.461798424	1.246793791
18	1.60382231	1.648112899	1.582101496	1.091703788	1.444828153	1.20196854
19	1.66648473	1.605496786	1.564972241	1.118367161	1.297895288	1.082281267
20	1.68158469	1.655603478	1.262949632	1.116364087	1.144750985	0.873148066
21	1.56906213	1.688227217	1.134764376	0.953710355	1.062308525	0.785730428
22	1.45433307	1.634437079	1.065676068	0.875772664	1.042215292	0.700012388
23	1.37866581	1.383717778	1.007666566	0.833038557	1.005914402	0.65300269
24	1.36797497	1.296545663	0.96789859	0.784137884	0.945829734	0.605816342
25	1.35642771	1.258286808	0.925998643	0.753353775	0.948331359	0.573164775
26	1.33427819	1.200888002	0.907960092	0.72285775	0.906743874	0.536335042
27	1.30533531	1.168526765	0.883639537	0.703097614	0.873973392	0.510742057
28	1.27637314	1.142268988	0.870949375	0.68645998	0.854159378	0.487554056
29	1.25486168	1.118767686	0.853099668	0.670660049	0.85588039	0.481881191
30	1.25225358	1.092221304	0.841861379	0.655789364	0.838370641	0.473389672
31	1.27020622	1.084459651	0.836927732	0.65393977	0.815389439	0.451481168
32	1.25195005	1.063495427	0.825842649	0.642107683	0.801875599	0.450383623
33	1.20549205	1.052637761	0.829908116	0.630293012	0.785705154	0.449851099
34	1.19799153	1.039837129	0.815034114	0.628876318	0.757846778	0.437633078
35	1.19024269	1.029102016	0.811268167	0.614692955	0.733086988	0.398639476
36	1.17535765	1.020725485	0.813808274	0.611155196	0.705050542	0.380246867
37	1.15607822	1.011239887	0.807750852	0.611320287	0.665352111	0.384737721
38	1.14993929	0.999121426	0.808824088	0.601749782	0.704425069	0.385115372
39	1.15015976	0.993712846	0.801686682	0.597521938	0.673750275	0.378826702
40	1.11964366	0.987670074	0.802359088	0.58707061	0.667903812	0.370611398