Coping with drought:

Options for soil and water management in semi-arid Kenya

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Chapter 1

Introduction

Introduction

1.1 Semi-arid environments

Of Kenya's total land area of 582,646 km², arid and semi-arid lands occupy more than 80%. Semi-arid lands occupy approximately 30% of the total land area and are classified into two agro-climatic zones (ACZ), IV and V (Table 1), on the basis of the ratio of rainfall to open water evaporation (R/E_o). The two agro-climatic zones have a ratio of 25% to 50% and a medium to low potential for plant growth and a high risk (25%-75%) of crop failure (Sombroek et al., 1982). Annual rainfall in the two zones ranges from 900 mm in ACZ IV (transitional zone) to 450 mm in ACZ V (Table 1).

Table 1. Agro-climatic zones of Kenya, excluding areas above 3000 m altitude (Sombroek et al., 1982).

Zone	R/E_o† (%)	Classification	R (mm)	E_o (mm)	Potential for plant growth‡	Risk of crop failure
I	> 80	Humid	1100-2700	1200-2000	Very high	Extremely low (0-1%)
II	65-80	Sub-humid	1000-1600	1300-2100	High	Very low (1-5%)
III	50-65	Semi-humid	800-1400	1450-2200	High to medium	Fairly low (5-10%)
IV	40-50	Semi-humid to semi-arid	600-1100	1500-2200	Medium	Low (10-25%)
V	25-40	Semi-arid	450-900	1650-2300	Medium to low	High (25-75%)
VI	15-25	Arid	300-560	1900-2400	Low	Very high (75-95%)
VII	< 15	Very arid	150-350	2100-2500	Very low	Extremely high (95-100%)

†R - average annual rainfall; E_o - average annual evaporation.
‡Assuming that soil conditions are not limiting

The rainfall patterns in Kenya are governed by the seasonal shifts and intensity of the low pressure Inter-Tropical Convergence Zone (ITCZ). Rainfall occurrence is primarily bimodal with two distinct rainy seasons, the short and long rains. Rainfall peaks in November during the short rains and in April during the long rains. About 90% of the total annual rainfall occurs in the two rainy seasons. In semi-arid Kenya, the short rains (October to December) are more reliable, evenly distributed and adequate for crop production. The long rains (March to May) are associated with most crop failures due to the poor distribution, unreliability and inadequacy for crop production (Biamah et al., 1993).

For cereal crops, rainfall amounts are on average too low for optimal crop yields, and season-to-season rainfall variability is high. Prolonged dry spells during the rainy seasons often lead to food, forage and water shortages. The very high soil moisture deficits experienced in these zones usually result in significant decreases in agricultural production.

The most dominant soils in the Kenyan semi-arid areas are Luvisols, Lixisols, Acrisols, Alisols, Ferralsols, Planosols, Solonchaks, Solonetz, Vertisols and Fluvisols (FAO/UNESCO Classification). The Acrisols, Alisols, Ferralsols and Planosols are predominant in highland areas. Whereas the Luvisols, Lixisols, Solonchaks, Solonetz, Vertisols and Fluvisols are found in lowland areas. These semi-arid soils are considered to be problematic, because their physico-chemical properties limit the uses for agricultural purposes. They generally have low organic matter contents and an unstable structure (Biamah et al., 1994). The main problems associated with these soils are high levels of salinity and sodicity, poor drainage, soil erosion, soil compaction, soil crusting and low soil fertility (Biamah et al., 1994). Surface crusting properties are enhanced by rainfall of high intensity and short duration that is prevalent in semi-arid Kenya. Crust formation is caused by the breakdown in soil aggregates and the dispersion of clay after getting exposed to the beating action of raindrops (Biamah et al., 1993).

The Luvisols, Lixisols, Acrisols, Alisols and Ferralsols are characterized by poor structural stability of the surface soils, which have surface crusting properties and often result in low infiltration rates and high susceptibilities to erosion. The occurrence of hardpans in the subsoils leads to low porosity and reduced water holding capacities. The Solonchaks (saline) and Solonetz (sodic) soils are characterized by poor structure and low infiltration rates. Most of the areas with these soils are severely degraded (Biamah et al., 1994).

Other soils that occur in limited patches in semi-arid Kenya are Fluvisols and Vertisols. They occur mainly in floodplains and depressions. Vertisols due to their heavy clay content are often avoided because they are hard to plough using traditional tillage practices (conventional ox or donkey ploughing). Another constraint to the utilization of Vertisols is their high salinity/sodicity (Biamah et al., 1994).

Most of the problems associated with semi arid soils have in the past been overcome through the traditional shifting cultivation. However, this farming practice is increasingly becoming ineffective and unsustainable as continuous cultivation and associated nutrient depletion become common (Bekunda et al, 1997; Sanchez et al., 1997).

1.2 Agricultural drought

Available soil moisture within the root zone and the actual evapo-transpiration, which responds to the changes in soil moisture content, are the two parameters of the soil water balance that will influence the occurrence of water stress in rainfed agricultural systems. An agricultural drought occurs when extended periods (days) without rainfall are experienced and the crop water requirements (potential evapo-transpiration) exceed the available soil moisture within the crop rooting zone. Seasonal changes in available soil moisture result in agricultural droughts of varying magnitudes. These fluctuations in soil moisture often extend to critical crop growth periods and hence affect crop productivity significantly. Other factors that are critical to crop production and that are affected by the duration of the dry spells are: antecedent soil moisture, the water storage capacity of the soil within the crop rooting zone, and the water requirements of the major crops (e.g. maize, beans, sorghum and millet).

Agricultural droughts that occur in semi-arid Kenya, vary in duration and severity with the prevailing agro-climatic conditions as reflected by seasonal rainfall variability. Rainfall distribution varies with the duration of the short rains and long rains. From an analysis of rainfall data from Iiuni watershed at Machakos, Kenya, the average seasonal rainfall durations are twelve weeks for the short rains and ten weeks for the long rains. The period of cessation of rains starts when a trend of persistent one rain day per week is experienced and the daily rainfall is much less than the expected daily potential evapo-transpiration rate (Biamah, et al., 1998).

According to Biamah (2001), the long-term seasonal drought patterns in semi-arid Kenya show a trend of more deficits (dry spells) than surpluses (wet spells). This trend also varies with the rainy seasons. For instance, there are more dry spells in the long rains (March to May) than in the short rains (October to December). The strong variability of rainfall from year to year and season to season makes it necessary to use long-term data to obtain meaningful drought trends. A period of about 30 years must be considered the absolute minimum for a rainfall event analysis (Nieuwolt, 1978).

1.3 Agricultural crop production

The major staple food crops grown in semi-arid Kenya include maize, beans, sorghum, millet, cassava, pigeon peas, sweet potatoes, cowpeas, pumpkin, and groundnuts. The cash crops include cotton, sisal, and tobacco. Crop performance and yield are significantly influenced by the amount of rainfall and distribution throughout the rainy season. As a result of inherent soil moisture deficits, the period of cropping is limited to the two rainy seasons. The potential length of the growing season differs for the long and short rains, and influences the choice of crops. Most crops are grown during the short rains, since rainfall is more reliable in this period. Inter-cropping of legume cover crops (e.g. beans and peas) with maize is a common farming practice as it minimizes risks of crop failure due to unexpected soil moisture deficits. Extensive mixed cropping (without crop rotation) is practiced as a risk spreading strategy. In the floodplains, where the water table remains high and there is adequate soil moisture, crops like bananas, sugar cane and vegetables are grown (Biamah et al., 1993).

Rainfall effectiveness is a critical factor influencing crop productivity. For example, during the short rains in Katumani, Machakos, an effective rainfall of 230 mm is required to produce a minimum yield of 1.5 ton of maize. The maximum maize yield (7.8 to 8.4 ton per hectare) requires 350-460 mm of effective rainfall. Likewise in the long rains, an effective rainfall of 170-180 mm is required to produce a minimum yield of 1.5 tonnes of maize per hectare. The maximum maize yield (4.8 to 7.2 ton per hectare) requires 280-440 mm of effective rainfall (Stewart and Harsh, 1982).

In semi-arid Kenya, the major constraints for agricultural crop production are accelerated soil erosion, induced soil moisture deficits, soil fertility depletion, and soil crusting and compaction (Biamah et al., 1998). These problems are stratified according to slope, agro-climatic zones, soil types and land use. In upland areas, major problems are soil erosion and low soil fertility. In lowland areas, the main problems are insufficient soil moisture, soil crusting and compaction (Biamah et al., 1998). The soil crusting and compaction problem is attributed to inherent soil properties and poor tillage practices. Tillage using the wrong implements and when done on moist or wet soils is known to cause the development of subsurface plough pans. These hardpans affect root penetration, rainwater infiltration and soil moisture storage capacity (Biamah et al., 1993).

The management options for crop production in semi-arid Kenya vary with soil type and their specific problems (Table 2). An understanding of land management problems on the different soil types is necessary before recommending suitable conservation techniques.

The tillage and residue management practices that are suitable for agricultural drought mitigation in semi-arid Kenya can be broadly grouped under conservation tillage. Conservation tillage creates a suitable environment for growing a crop and conserves soil, water and nutrients. Ideally, conservation tillage per se excludes conventional tillage operations that invert the soil and bury crop residues. However in practice, conservation tillage sometimes is preceded by conventional tillage soon after the crops are harvested. Also, there is a broad spectrum of transitional tillage stages to conservation tillage. These can range from conservation tillage practices like tied ridging, preceded by conventional tillage all the way to zero tillage systems where seeds are spot planted with sticks. Conservation tillage

involves tillage practices that leave plant residues in the field and that create soil surface roughness for controlling soil erosion. Conservation tillage systems include: zero or no tillage; mulch and farmyard manure tillage; and reduced or minimum tillage (Biamah and Rockstrom, 2000).
Residue management practices are often introduced on cropland after primary tillage operations have been carried out along the contour. These practices are complementary to other tillage practices and are expected to improve soil productivity by minimizing soil crusting and compaction, improving soil fertility and soil moisture storage capacity within the plough layer (Biamah and Rockstrom, 2000).

The basic principles of sound conservation tillage practice include: (1) subsoiling to break the plough pan or ripping/chiseling to minimize soil compaction within the plough layer; (2) introduction of effective erosion control measures before tillage; (3) carrying out all tillage practices along the contour; (4) avoiding soil compaction by keeping oxen and machinery off moist/wet soils; (5) avoiding pulverization of the plough layer to prevent soil sealing and crusting; (6) ensuring that soil fertility is optimal before introducing any practices; and (7) recommending residue management practices in marginal rainfall areas with structurally unstable soils (e.g. sodic soils) (Biamah and Rockstrom, 2000).

Table 2. Management options for problems soils in semi-arid Kenya (Biamah, 2001).

Soil type	Management options
Vertisols	Minimize waterlogging through seasonal drainage. Discourage structural conservation measures due to unstable structure. Avoid deep tillage due to subsoil sodicity in some areas. Tillage under optimal soil moisture conditions
Planosols	Minimize waterlogging through deep tillage and artificial drainage. Improve fertility through application of FYM† and inorganic fertilizers. Ideal for shallow rooted crops and pastures for grazing. Tillage under dry conditions when workability is good.
Ferralsols	Apply FYM and chemical fertilizers to improve soil moisture retention in topsoil(s) and ameliorate the fertility problem. Tillage under moist soil conditions when soil compaction is minimal.
Fluvisols	Choose deep-rooted crops that can access fertile subsoils. Apply FYM to improve soil moisture retention in topsoil(s). Tillage under moist soil conditions when workability is good
Luvisols, Lixisols, Acrisols, Alisols	Ripping and subsoiling to improve rainwater infiltration and soil moisture storage. Breaking of soil crusts and subsurface hardpans. Apply FYM to increase infiltration, reduce surface runoff and crusting. Application of chemical fertilizers to ameliorate soil fertility problem. Tillage after harvesting when soil moisture conditions are favourable and draft power requirements are low
Solonchaks	Apply FYM to improve soil aggregation and drainage. Leaching of salts through irrigation. Planting of salt tolerant trees (e.g. Prosopis juliflora and Sesbania sesban). Application of gypsum to neutralize soil reaction.
Solonetz	No disturbance of topsoil through tillage. Diversion of concentrated runoff water flow away from exposed sodic soils. Permanent plant cover. Planting of salt tolerant trees (e.g. Prosopis juliflora and Sesbania sesban). Application of chemicals (e.g. gypsum) to neutralize soil reaction.

†FYM - farm yard manure

1.4 Research problem and aim of the study

In semi-arid Kenya, the demand for agricultural land for the ever-increasing human population has almost invariably pushed farmers into cultivation of structurally unstable soils on steep slopes. Thus, the adoption of intensive exploitative cultivation techniques has led to a rapid decline in soil and crop productivity of steep lands (Biamah and Rockstrom, 2000). This decline in soil and crop productivity has led to the frequent occurrence of agricultural droughts. The severity and duration of those droughts vary with seasonal rainfall variability and associated differential soil moisture deficits. The recurrence of seasonal soil moisture deficits is also attributed to the withdrawal of organic matter in soils and consequent reduction in soil quality.

Over the past 100 years many severe droughts were experienced in East Africa and displaced many people. During this period, it was observed that there was a higher frequency of drought occurrence during the long rains when compared to the short rains (Ininda, 1987). Given the persistence of dry spells in semi-arid Kenya, it is pertinent that an in-depth analysis needs to be done in order to understand the trends and indicators of agricultural drought. Thus, there is the need to predict the stochastic behavior of dry and wet spells so as to provide information for drought preparedness through an early warning system. The mitigation of agricultural drought in semi-arid Kenya requires strategies and technological options that focus on the improvement of soil and crop productivity.

Since most semi-arid areas of Kenya consist of approximately 30% of rainfed agricultural land (major crops are maize, beans, sorghum and millet) and 70% of dry rangeland (degraded pastures), questions arise like:

- How does seasonal rainfall variability and distribution influence the occurrence of seasonal agricultural droughts in semi-arid Kenya?
- What is the stochastic behavior of dry and wet spells in a given study area?
- Which soil types are most vulnerable to drought?
- Under the low, erratic and ineffective rainfall conditions, which tillage and residue management practice conserves the most soil moisture (in terms of available moisture for plant growth) of each soil type?
- How significant are the effects of soil crusting and compaction on the hydrologic responses of dominant soil types in semi-arid Kenya?
- Of what significance are farmers' plots, sub-watersheds and watersheds in the mitigation of agricultural drought in semi-arid Kenya?

At the field scale, tillage and residue management practices should provide adequate ground cover to significantly reduce surface runoff, enhance infiltration and soil moisture availability for crop and fodder production. Thus it is important to evaluate existing tillage practices and their effects on soil and water conservation. The most appropriate practices are those that enhance rainwater infiltration and subsequent soil water storage capacity, improve the effective use of stored water, dissipate raindrop energy of intense rainstorms, and minimize surface runoff, soil losses and evaporation water losses during the initial stages of a crop growing season when the soil is bare and subject to soil erosion. In addition, these interventions should be aimed at reducing the effects of soil surface crusting and compaction whilst maintaining favorable soil moisture conditions during the critical crop growth periods within a rainy season.

At the watershed scale, the different land use types may have a significant impact on watershed hydrology and related erosion problems. Modeling can help to determine the effects of land use and land use changes on hydrology and erosion. Appropriate modeling enables selection of watershed areas, as well as certain land use types that require soil and water conservation. The best soil and water management practices for mitigating problem areas should be chosen on the basis of the extent of the soil erosion, soil crusting and compaction, soil fertility and soil moisture problems. It is important to get an in-depth understanding of agricultural drought and of agro-hydrologic systems responses at the micro, meso and macro scales by examining possible planning and management options for watershed conservation in semi-arid agricultural watersheds in Kenya. The focus in any agricultural drought mitigation effort should be that of improving soil and crop productivity.

The aim of the study described in this thesis was to analyze agricultural drought, and to evaluate soil and water management options and strategies for sustainable crop production in drought-prone semi-arid Kenya.

1.5 Outline of thesis

The agro-hydrologic systems approach used in this study was applied at the micro- and meso-scales. The micro scale agro-hydrologic system study was conducted on one site representative of a farmer's plot with erosion control measures in place. This experimental site was at Katumani, Machakos, and was selected because it represents the micro-scale field conditions experienced by smallholder farmers in Kenya. In this study, different tillage practices, including the use of farmyard manure, were tested on the ability to reduce surface runoff and soil loss (Chapter 4). This information is necessary in mitigating seasonal agricultural drought, which often extends to critical crop growth periods. It is this critical soil moisture occurring within a crop-growing season that significantly affects crop performance and yields. The data collected was expected to provide an understanding of the hydrologic response of crusting and compacting soils to tillage and residue management practices.

The meso-scale agro-hydrologic system study was conducted in one semi-arid watershed with erosion control measures in place. The Iiuni watershed in Machakos was selected to represent a meso-scale conservation-planning unit (Chapters 2, 5 and 6). The experimental watershed has an area of 12 km^2. This watershed is located in a semi-arid area with varying rainfall, soil types, physiographic units, land uses, shapes and slopes. First, this study attempted to understand agricultural drought through an analysis of the stochastic behavior of the longest dry and wet spells and largest rainfall amounts in the watershed (Chapter 2). Then, land use and land management practices were studied, and their effects on watershed hydrology were determined by applying the SCS-CN model (USDA-SCS, 1972) (Chapter 5). This was followed by an overview of possible planning and management options and strategies for watershed conservation in semi-arid agricultural watersheds in Kenya (Chapter 6). The strategies and options proposed were based on a review of tillage methods in East Africa (Chapter 3), the agricultural drought analysis (Chapter 2), the hydrologic soil responses to tillage and residue management practices at the micro-scale level (Chapter 4) and SCS-CN model predictions of watershed runoff volume (Chapter 5). Pertinent strategies explored included: understanding agricultural drought; stratification of production zones; watershed conservation options; planning of watershed conservation and enabling conditions. The enabling conditions that are elaborated upon include agricultural policy, smallholder agriculture and public-community partnerships.

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Chapter 2

Analysis of agricultural drought in Iiuni, Eastern Kenya: Application of a Markov model

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Analysis of agricultural drought in Iiuni, Eastern Kenya: Application of a Markov model

Abstract

In semi-arid Kenya, episodes of agricultural droughts of varying severity and duration occur. The occurrence of these agricultural droughts is associated with seasonal rainfall variability and can be reflected by seasonal soil moisture deficits that significantly affect crop performance and yield. The objective of this study was to stochastically simulate the behavior of dry and wet spells and rainfall amounts in Iiuni watershed, Kenya. The stochastic behavior of the longest dry and wet spells (runs) and largest rainfall amounts were simulated using a Markov (order 1) model. There were eight rain gauge stations within the watershed. The entire analysis was carried out using probability parameters, i.e. mean, variance, simple and conditional probabilities of dry and rain days. An analysis of variance test (ANOVA) was used to establish significant differences in rainfall characteristics between the eight stations. An analysis of the number of rain days and rainfall amount per rain day was done on a monthly basis to establish the distribution and reliability of seasonal rainfall. The graphic comparison of simulated cumulative distribution functions (CDFS) of the longest spells and largest rainfall amounts showed Markovian dependence or persistence. The longest dry spells could extend to 24 days in the long rainy season and 12 in the short rainy season. At 50% (median) probability level, the largest rainfall amounts were 91 mm for the long rainy season and 136 mm for the short rainy season. The short rains were more reliable for crop production than the long rains. The Markov model performed well and gave adequate simulations of the spells and rainfall amounts under semi-arid conditions.

2.1 Introduction

Of Kenya's total land area of 582,646 km^2, semi-arid lands occupy approximately 30% and are a sanctuary for 25% of the human population, 40% of the livestock population, and 50% of the wildlife population (Government of Kenya, 1992). The human population in semi-arid Kenya lives below the poverty line and has no guarantee of household food security due to harsh environmental conditions. Semi-arid lands are prone to periodic and cyclic episodes of droughts and flash floods. These hydrologic phenomena are significantly influenced by the seasonal rainfall patterns experienced in semi-arid Kenya (Government of Kenya, 1992).

The climate of semi-arid Kenya is influenced by the seasonal shifts and intensity of the low pressure Inter-Tropical Convergence Zone (ITCZ). According to Stewart and Harsh (1982), semi-arid areas of Kenya receive average annual rainfall ranging between 500 mm and 900 mm. Rainfall occurrence is primarily bimodal with two distinct rainy seasons. The first rainy season (long rains) runs from March to May, with the peak rainfall in April. The second season (short rains), runs from October to December with most rainfall in November. About 90% of the total annual rainfall occurs in these two rainy seasons. In semi-arid Kenya, the short rainy season (October to December) is associated with long wet spells that are evenly distributed and hence is considered to be more reliable for crop production. Conversely, the long rainy season (March to May) is associated with short wet spells that are sparse and hence the season is unreliable for crop production. In both seasons, the rainfall pattern is characterized as low, erratic and poorly distributed, often resulting in severe and persistent dry spells.

Soils in semi-arid areas have physico-chemical properties that limit their uses for agricultural purposes. Some of the soil problems that limit crop production are: structural instability, low organic matter content, high salinity and sodicity, poor drainage, severe soil erosion, soil crusting and compaction, and low soil fertility. Most of the soils have unstable structures with crusting, slaking and compaction resulting in reduced rainwater infiltration and increased surface runoff and erosion of unstable subsoils. Soil crusting and compaction also inhibit seed germination and root penetration of dryland crops (Biamah et al., 1993).

The climate and soil conditions in semi-arid Kenya result in a medium to low potential for crop growth and a high risk (25-75%) of crop failure (Sombroek et al., 1982). The major staple food crops grown include: maize, beans, sorghum, millet, cassava, pigeon peas, sweet potatoes, cow peas, pumpkin, and groundnuts. The cash crops include: cotton, sisal, and tobacco. Most crops are grown under conventional tillage (ox-drawn moldboard plowing, hand hoeing) systems, which limit the tillage depth to about 10 cm. This limitation in the depth of tillage is due to the occurrence of plough and hard pans. However where conservation tillage practices have been introduced, tillage depths of 20 to 25 cm have been attained. Most farmers prefer early tillage operations and dry planting before the onset of the rains (Biamah et al., 2000).

In Kenya, the major factor that controls agricultural productivity is rainfall. Rainfall variability from year to year causes significant differences in agricultural production with frequent low yields of subsistence food crops such as maize, beans, millet and sorghum, which often results in famine (Nieuwolt, 1978). Over the past 100 years, many severe droughts were experienced in East Africa (including Kenya) and many people displaced. Some of the droughts that persisted for two or more years were 1903-05; 1911-14; 1930-33; 1949-50; 1972-74 and 1981-84. During these periods, it was observed that there was a higher frequency of drought occurrence during the long rains when compared with the short rains (Ininda, 1987).

Droughts are natural phenomena and cannot be prevented. There are however possibilities of predicting them so as to provide the necessary information for drought preparedness through an early warning system (Sharma, 1994). The analysis of drought requires long-term historical rainfall data. The strong variability in rainfall from year to year and season to season makes it necessary to use long periods of observation to obtain meaningful rainfall indices. A period of about 30 years must be considered the absolute minimum for a rainfall event analysis (Nieuwolt, 1978).

Agricultural drought is caused by insufficient rainfall and may be defined as a deficit in soil moisture that affects agricultural production over a large area and an extended period. The duration and severity of a critical agricultural drought is best described by the return period in months and expected soil moisture deficits (in relation to crop water demand). An agricultural drought month occurring at the beginning of the crop-growing season has usually more serious effects on crop response than one occurring towards the end of the crop growth period. The effects of a drought that persist for more than one month are quite severe (Ininda, 1987).

The occurrence of agricultural drought cannot be predicted with certainty and hence must be treated as random variables that can be investigated by the theories of probability and stochastic processes (Sharma, 1994). The stochastic behavior of the longest dry and wet spells can be predicted using the theory of runs (Yevjevich, 1967; 1972), Poisson distribution of the occurrence of spells, geometric distribution of the length of spells and the Weibull distribution of the total rain (rainfall amount) in a wet spell (Sharma, 1996). These theoretical distributions have been used as building blocks for model formulation under Kenyan conditions (Sharma, 1996).

Random and Markov models have been used to simulate the longest dry and wet spells (runs) and largest rainfall amounts (total rain over a wet spell) in semi-arid Kenya (Sharma, 1996). Sharma tested the performance of the two models using theoretical distribution functions (normal, Weibull, log-normal, and gamma distributions). Sharma (1996) developed the theoretical framework for agricultural drought analysis in Kenya by testing the performance of the two models under semi-arid conditions. The results obtained showed Markovian persistence as opposed to the random occurrence of spells. Thus the random model was found to be a poor simulator of runs and rainfall amounts while the Markov model was found to be promising in simulating the length of the longest dry and wet spells (runs) and the largest rainfall amounts during rainy seasons (Sharma, 1996). A Markov chain model is a stochastic process, which develops in time so that the "future" given the "present" is independent of the past. Markov chains constitute a very useful and widely applicable class of models for a range of scientific problems. This study has attempted to apply the Markov model to a specific semi-arid area to validate the research findings obtained by Sharma (1996).

The objective of this study was to stochastically simulate the behavior of dry and wet spells and rainfall amounts in Iiuni watershed, Kenya using a Markov model. The specific objectives were: (1) to determine the characteristics of annual, seasonal and monthly rainfall influencing agricultural drought in Iiuni, Kenya; (2) to estimate the statistical parameters for predicting the cumulative distribution functions (CDFS) of spells and rainfall amounts; and (3) to simulate stochastically the longest dry and wet spells (runs) and largest rainfall amounts using a Markov model.

2.2 Methodology

2.2.1 Description of the study area

The study area of Iiuni watershed (Fig. 1) is located in a semi-arid area that is in the south-eastern part of Machakos District, Kenya. The watershed extends from west to east between longitudes 37°20′E to 37°23′E and from north to south between latitudes 1°39′S to 1°41′S (Thomas et al., 1981). It has relatively concave ridges and watercourses running in a north-westerly direction. The watershed has an area of 12 km^2 and is located in agro-climatic zone IV/V that is a livestock-millet zone. Of this total area, approximately 60% is agricultural land and 40% is rangeland (Biamah et al., 1998).

The mean annual rainfall of Iiuni is 851 mm and is based on 16 years rainfall data from eight rain gauge stations (Fig. 1). Rainfall is bimodal with the long rains due from March to May and the short rains from October to December (Fig. 2). Rainfall in Iiuni is characterized as low, erratic, and poorly distributed. Consequently, seasonal rainfall is ineffective and thus causing some severe soil moisture deficits and persistent dry spells. The mean annual temperatures vary from 22°C to 28°C with no frosts at night. The mean annual potential evaporation ranges from 1650 mm to 2000 mm (Biamah *et al*., 1998).

There are three distinct physiographic units in Iiuni watershed namely: hills or uplands; colluvial footslopes and dissected river valleys or floodplains(Lesslie and Mitchell, 1979; Thomas et al., 1981).

The dominant soil types found in Iiuni include Alisols, Leptosols, Acrisols, Planosols, Cambisols, Gleysols, Arenosols, Vertisols and Fluvisols (FAO/UNESCO Classification, 1990). These soils have low organic matter contents, low cation exchange capacity and are deficient in phosphorus, nitrogen and calcium (Biamah et al., 1998).

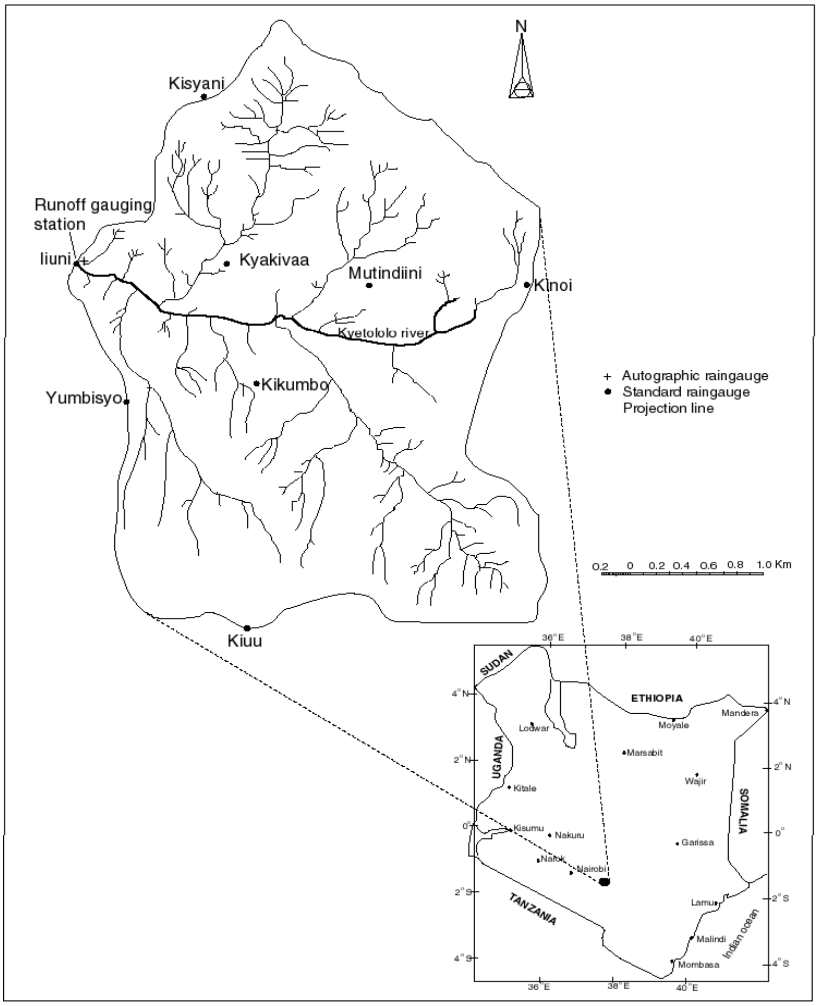


Figure 1. Distribution of rain gauge stations (•) in Iiuni watershed, Machakos District, Kenya

The major food crops grown in Iiuni include maize, beans, sorghum, millet, cassava, pigeon peas, sweet potatoes, cowpeas, and pumpkin. In the floodplains, where the water table remains high and there is adequate soil moisture, crops such as bananas, sugar cane and vegetables are grown (Biamah et al., 1998).

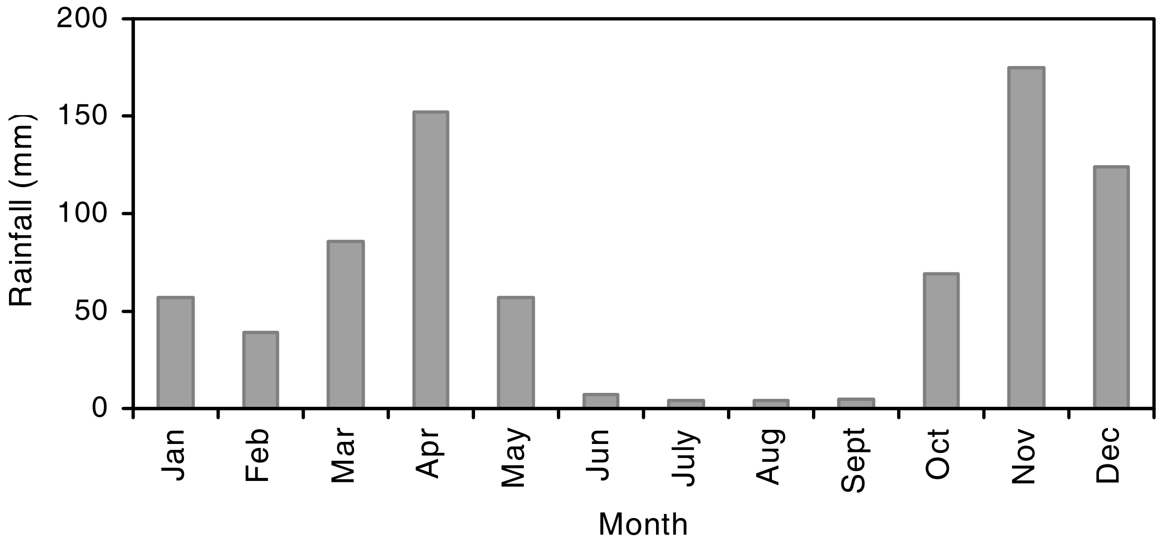


Figure 2. Mean monthly rainfall distribution of Iiuni watershed, Machakos District, Kenya.

In Iiuni watershed, the short rainy season accounts for 60% of the total annual rainfall and is the most reliable season for crop and fodder production. The long rainy season accounts for 40% of the total annual rainfall and is less reliable for crop and fodder production. The most reliable wet periods are November to mid December for the short rainy season and late March to early May for the long rainy season. Potential evapotranspiration rates during the two rainy seasons average from 5.5 to 5.9 mm day^{-1} over a crop growth period of 90 to 120 days (Stewart and Harsh, 1982). Generally, the dry spells that are experienced in the long rainy season are more severe than those occurring in the short rainy season. During the dry spells, high temperatures above 28^{o}C are expected and often lead to higher potential evapotranspiration rates. Thus these high evapotranspiration rates cause significant soil moisture deficits and crop water stress during crop growing seasons (Biamah et al., 1994).

2.2.2 Analysis of rainfall characteristics

Sixteen years of daily rainfall data were collected from eight rainfall recording stations in Iiuni watershed. The data were analyzed for rainfall characteristics such as: variations in maximum, minimum and mean rainfall; and variations in annual, seasonal and monthly rainfall. An analysis of variance (ANOVA) test was conducted to establish if there were any significant differences in rainfall between the eight stations. The ANOVA was done using annual and seasonal rainfall data. An analysis of the number of rainy days and rainfall amount per rain day was done on a monthly basis to establish the distribution and reliability of rainfall within the short and long rainy seasons.

For the stochastic drought analysis, there was the need to identify a rainfall station with a long-term rainfall record and yet displaying similar characteristics as those of Iiuni watershed. It was found that Kibwezi station, which is in close proximity to Iiuni, has a database of 55 years and could be considered useful for this purpose. First, the similarity in rainfall characteristics between the two stations was determined. This analysis was done by testing the equality of means and variances of the daily rainfall data between the two stations.

Two test statistics, ‘t’ and ‘F’ tests at 5% level of significance, were used to test the equality of means and variances of daily rainfall data from Kibwezi and Iiuni rain gauge stations, respectively (Steel and Torrie, 1981).

2.2.3 Stochastic analysis and modeling of drought

The occurrences and lengths of dry and wet spells (runs) and magnitudes of wet spells (rainfall amount) must be well understood in order to mitigate seasonal agricultural droughts in semi-arid Kenya. A wet spell will occur when there is an uninterrupted sequence of rainy days (Bogardi et al, 1988). Similarly a dry spell will occur when the wet spell is below some threshold crop water demand (critical soil moisture). Therefore a seasonal agricultural drought would occur if there were a number of consecutive dry spells and subsequent cumulative soil moisture deficits. The severity of a critical agricultural drought is best described by the duration in days or months and expected soil moisture deficit in relation to crop water demand.

The occurrence and magnitude of hydrologic phenomena such as dry and wet spells are largely random and hence are described probabilistically. The probability of occurrence of a wet or dry day depends on the climate of a given study area. The sequence of dry or wet days may follow some trend of persistence or may evolve randomly (Sharma, 1996). A Markov process of order one in which today’s state is dependent only up to one day behind best represents the simplest type of persistence or dependence. The process displaying an insignificant level of dependence is termed random or independent process.

The probability of occurrence of spells is often considered on the basis of simple (unconditional) and conditional probabilities. For instance, let a day with rainfall more than zero be designated as a wet day (w) and one with no rainfall be designated as a dry day (d). Thus the simple probability of any day being a wet day is designated as p = P(w) and that of any day being a dry day is designated as q = P(d). Likewise the conditional probability of any day being wet given that the previous day was also wet is designated as pp = P(w/w) and the same connotation applies to a dry day followed by the previous dry day, qq = P(d/d) (Sharma, 1996).

The stochastic analysis of the longest dry and wet spells and largest rainfall amounts requires estimates of unconditional probability parameters q = P(d) and p = P(w); conditional probability parameters qq = P(d/d) and pp = P(w/w); means, μ = E(x); and variances, σ^2 = V(x). These parameters must be estimated from a long-term historical daily rainfall database to be stable and robust (Sharma, 1996). The probability parameter values of q, pp and qq, and statistical mean, variance and standard deviation used to predict the runs and rainfall amounts were obtained from an analysis of long-term rainfall data of Kibwezi (Sharma, 1996). In Iiuni watershed, the Markov (order 1) model was chosen to analyze and simulate the stochastic behavior of the longest dry and wet spells and largest rainfall amounts.

The degree of persistence of agricultural drought is quantified through conditional probability or lag 1 serial correlation coefficient. For Markov (order 1) process, the conditional probability of any day being dry given that the previous day is also dry are not equal [P(d/d)] ≠ [P(d)]. For a random model, the conditional probability, P(d/d) equals the simple probability, P(d), i.e. [P(d/d)] = [P(d)]. For the wet days, the conditional probability of any day being wet given that the previous day is also wet are not equal [P(w/w)] ≠ [P(w)] for the Markov model and are equal [P(w/w)] = [P(w)] for the random model.

Before formulating the Markov model, the stochastic behavior of the spells was tested for Markovian persistence or random independence using the equality of transitional matrices approach and χ-square statistics. This analysis was done for the dry and wet spells and therefore should account for a number of parameters namely: the number of dry (N_d) and wet (N_W) spells; the length of wet (L_w) and dry (L_d) spells; the longest dry and wet spells (L_{dm}, L_{wm}) and largest rainfall amounts (S_m). The stochastic theory (Sharma, 1996) used in this drought modeling exercise is described here below.

The probabilities of rain occurrences obeying a Markov or Random process can be expressed as transitional matrices as follows:

(1) Markov or persistent process (matrix 1)

$$\begin{bmatrix} pp & 1-pp \\ 1-qq & qq \end{bmatrix} \qquad [1]$$

where pp = P(w/w) and qq = P(d/d).

(2) Random or independent process (matrix 2)

$$\begin{bmatrix} p & 1-p \\ 1-q & q \end{bmatrix} \qquad [2]$$

where p = P(w) and q = P(d).

The numerical values of *p, pp, qq* and *q* all lie between 0 and 1, and $p+q = 1$.

A χ-square test can be used to determine if matrix 1 is equivalent to matrix 2. If they are equivalent, then the process in question is random. For a process to be random, the calculated value of χ-square statistic should be less than 3.84 at one degree of freedom and 5% level of significance (Sharma, 1996).

In a time series plot of daily rainfall (X) versus time in days during a rainy season, spells of uninterrupted wet days (X > 0) and spells of uninterrupted dry days (X = 0) will emerge. Thus in a rainy season of n days (n = 92 for the short and long rainy seasons in Iiuni watershed), there will occur spells of wet and dry days. The number of these wet and dry spells are designated as N_W (wet) and N_d (dry) respectively, and are given values 0,1,2,3,.......i. The length of run or spell, L_w (wet) and L_d (dry) take on values 0,1,2,3,.......j. The longest dry and wet spells and largest rainfall amounts are designated as L_{dm}, L_{wm}, and S_m.

The probability distribution of Markovian runs (dry spells) follow Poisson (Gupta and Duckstein, 1975; Şen, 1980) and geometric distributions (Şen, 1980; Kottegoda, 1980; Bogardi et al, 1988) and can be expressed by the following equations (Sharma, 1996):

$$P(N_d = i) = \frac{\exp[-nq(1-qq)][nq(1-qq)]^i}{i!} \qquad [3]$$

$$P(L_d \le j) = 1 - qq^{\,j-1} \; or \; P(L_d > j) = qq^{\,j-1} \qquad [4]$$

where n is the sample size (number of days for the short or the long rainy season).

The longest length of dry spells (L_{dm}) can be determined by the theorem of the extremes of random variables (Torodovic and Woolhiser, 1975) which can be expressed as follows (Şen, 1980):

$$P(L_{dm} \leq j) = P(N_d = 0) + \sum_{i-1}^{\infty} P(L_d \leq j)^{i} \; P(N_d = i) \qquad [5]$$

The mathematical simplification of equation (5) will lead to the following equation:

$$P(L_{dm} \leq j) = \exp[-nq(1-qq)P(L_d > j)] \qquad [6]$$

As

$$P(L_{dm} = j) = P(L_{dm} \leq j+1) - P(L_{dm} \leq j) \qquad [7]$$

Therefore

$$P(L_{dm} = j) = \exp\left[-nq(1-qq)qq^{j-1}\right]\left\{\exp\left[nq(1-qq)^2 qq^{j-1}\right] - 1\right\} \qquad [8]$$

Şen (1977) has derived the following relationships for the expected values of N_d and L_d denoted by E (N_d) and E (L_d) for Markovian runs as:

$$E(N_d) = nq(1-qq) \qquad [9]$$

$$E(L_d) = \frac{1}{1-qq} \qquad [10]$$

Mean (E) and variance (V) of L_{dm} can be obtained from the following relationships:

$$E(L_{dm}) = \sum_{j-1}^{n} jP(L_{dm} = j) \qquad [11]$$

$$V(L_{dm}) = \sum_{j-1}^{n} j^2 P(L_{dm} = j) - E^2(L_{dm}) \qquad [12]$$

Exactly the same analysis above can be carried out for the wet spells except that subscript d is replaced by w and the parameters *qq* by *pp* and *q* by *p*. For the runs following the random process, *qq* = *q* and *pp* = *p*.

In a wet spell analysis, an additional element that appears is the total rain, which is designated as rainfall amounts and is denoted by S. Following the above analysis, the probability distribution of S_m (largest rainfall amount) can be expressed by the following relationship:

$$P(S_m \leq D) = \exp[-n\,p(1-pp)P(S > D)] \qquad \text{for } 0 < D < \infty \qquad [13]$$

where n is the sample size(number of days for the short or the long rainy seasons). P(S ≤ D) is the probability of a rainfall amount being less than or equal to a particular value D (say 20, 200,..........400 mm).

The probability distribution of S follows a Weibull distribution (Benjamin and Cornell, 1970; Miller and Freund, 1985; Bonacci, 1993; Sharma, 1996) and therefore the following relationships (Haan, 1977) hold:

$$P(S \leq D) = 1 - \exp\left[-\left(\frac{D}{B}\right)^{A}\right] \qquad [14]$$

or

$$P(S > D) = \exp\left[-\left(\frac{D}{B}\right)^{A}\right] \qquad [15]$$

The parameters A and B for the Weibull probability distribution function (PDF) can be estimated using the method of moments and are well documented in Haan (1977).

In order to estimate the parameters A and B of the Weibull PDF, the values of the mean, E(S) and variance, V(S) are needed and can be estimated using the following statistical relationships of the daily rainfall sequence (Şen, 1978; 1980; Llamas, 1987):

$$E(S) = kE(x)/\, p \qquad [16]$$

$$V(S) = \left[\frac{pV(x) + qE^{2}(x)}{p^{2}}\right]\left[k + 2r\frac{k(1-r) - (1-r^{k})}{(1-r)^{2}}\right] \qquad [17]$$

$$r = \sin \pi(pp - 0.5) \qquad [18]$$

in which r is the lag 1 serial correlation coefficient between daily rainfalls and k is the mean length of wet spell and can be obtained by the equation:

$$k = E(L_{w}) = \left[\frac{1}{1 - pp}\right] \qquad [19]$$

The mean E (x) and variance V (x) can be calculated using the daily rainfall data for a season.

2.2.4 Simulation of drought

The process of simulating the spells (runs) and rainfall amounts in Iiuni watershed was done using four computer programs written in Quick Basic. The input required to run the programs was daily rainfall data. This computer simulation was done using the historical daily rainfall data of Iiuni and probability parameters of Kibwezi. The four computer programs used were as follows:

1. Program for computing statistical parameters of seasonal daily rainfall data (including zero rains) and based on a sample size of 92 days (3 months) per rainy season (short and long rains)

in Iiuni watershed. This was done using the short and long rainy seasons data and the outputs were the means, variances, standard deviations, and coefficients of variation and skewness.

2. Program for computing drought probabilities and surpluses for the two rainy seasons in Iiuni watershed. The outputs of this computation were unconditional probabilities (*p* and *q*), transitional matrices, chi square statistics, number and values of surpluses. The data obtained from these outputs included the maximum surpluses, number of dry (N_d) and wet (N_w) spells that were determined through a counting procedure from printed data. The occurrences of dry and wet spells were tested for dependence by computing and evaluating transitional probability matrix (1) against matrix (2) for equivalence.
3. Program for computing dry and wet spell length and surplus sum for the two rainy seasons in Iiuni watershed. The outputs of this computation were probability parameters *q, qq* and *pp;* means, E(x) and variances, V(x) of dry and wet spell durations in days and the cumulative probabilities for dry and wet spells during the long and short rainy seasons.
4. Program for computing rainfall amount probabilities using Weibull distribution for the two rainy seasons in Iiuni watershed. The outputs of this Weibull distribution computation were the unconditional (*p*) and conditional (*pp*) probabilities of wet spells, mean - E(S) and variance - V(S) of the largest rainfall amounts, rainfall depths (in mm) and cumulative probabilities for the short and long rainy seasons.

The probability parameter values were estimated on a yearly basis taking into account the long and short rainy seasons. Thereafter, the estimated values of *q, pp* and *qq* were ranked for each season and median values used in equations 1 to 19. Values of E (x) and V (x) were estimated using all 55 years of daily rainfall including zero values (Table 5). The E (x) and V (x) were based on n x 92 data points for the long and short rainy seasons. Iiuni data were used to compute probability parameter values of *q*, *qq* and *pp* by a counting procedure in order to test if the runs and rainfall amount are Markovian or simply random using a chi-square statistic approach. Thus matrices for each season were computed. There were 16 matrices for the short rainy season and 16 for the long rainy season.

Values of $P(S_m < D)$ were computed by assigning D equal to 0 – 400 mm and with a step of 10 mm. The upper limit of D equal to 400 mm was based on the highest seasonal rainfall expected over a long period of time (say 100 years or so) in Iiuni watershed.

During the computer simulation, Kibwezi probability parameters were used with Iiuni daily rainfall data to generate the cumulative probabilities of the runs and rainfall amounts during the short and long rainy seasons and hence were treated as predicted data. The Iiuni probability parameters, that were computed by a counting procedure, however were used to generate cumulative probabilities of the runs and rainfall amounts during the two rainy seasons and hence were treated as observed data. For each season, the length of the longest dry and wet spells and the largest rainfall amounts (i.e. 16 values of the longest runs and largest rainfall amounts) were obtained. These values were ranked by the Weibull method of frequency plotting (i.e. F(x) = [(n+1-z)/(n+1)] where F(x) is the cumulative probability, z is the rank in ascending order, and n is the sample size (16 in this case). The observed CDFS so obtained were graphically plotted along with the predicted CDFS (Fig.s 3, 4 and 5). Thus the observed CDFS were validated against the predicted CDFS through inferences on Markovian dependence.

2.3 Results and discussion

2.3.1 Characteristics of watershed rainfall

The mean annual rainfall in Iiuni watershed (based on 16 years rainfall record) of the eight rainfall recording stations was 851 mm with a station rainfall range from 778 mm (Iiuni Station) to 923 mm (Kinoi Station). During the sixteen years of rainfall record, mean annual rainfall amounts were below the mean in seven years. The coefficients of variation (CV) of station rainfall ranged between 20% to 25%, which shows that the variability in rainfall amounts between the eight stations is low. Table 1 below shows the annual rainfall data (mm) for 16 years from the eight rain gauge stations.

A one-way ANOVA was carried out to establish if the rainfall at these eight stations belongs to the same population. This analysis (Table 2) shows that there are no significant differences in rainfall between the eight rain gauge stations and therefore one station's rainfall could be considered as representative of Iiuni watershed.

In Iiuni watershed, the short rains bring about 453 mm (53%) and the long rains about 320 mm (38%) of the total annual rainfall (851 mm). Hence about 91% of the total annual rainfall occurs in the two rainy seasons. During the two rainfall periods, the coefficients of variation ranged between 30% to 37% (short rains period) and 41% to 53% (long rains period) (Table 1). Owing to this variability of seasonal rainfall, drought periods will occur even when seasonal rainfall averages are high.

Table 1. Annual and seasonal rainfall data (mm) for 16 years (1978-1993) from eight rain gauge stations at Iiuni watershed, Machakos District, Kenya.

Rainfall	Property	Stations								Mean
		Iiuni	Yumbis	Kisyani	Kinoi	Kyakiv	Mutindi	Kikum	Kiu u	
Annual	Max.	1032	1040	1162	1238	1174	1191	1210	120	1118
rainfall	Min.	310	391	324	575	365	330	324	2	382
	Mean	778	798	885	923	820	857	850	433	851
	CV†	0.22	0.22	0.23	0.20	0.25	0.24	0.25	897	0.22
									0.24	
Long	Max.	475	526	584	564	476	548	586	655	517
rains	Min.	42	51	55	75	54	65	53	97	61
	Mean	278	304	327	353	302	311	353	335	320
	CV	0.53	0.48	0.50	0.41	0.47	0.48	0.51	0.47	0.48
	% Ann. mean	36	38	37	37	37	36	41	38	38
Short	Max.	760	721	879	864	673	614	730	751	747
rains	Min.	194	139	203	207	141	145	144	162	167
	Mean	431	411	488	495	434	449	454	465	453
	CV	0.35	0.35	0.37	0.36	0.34	0.30	0.31	0.33	0.34
	% Ann. mean	56	51	56	52	53	52	53	52	53

†CV = Coefficient of variation

Table 2. The ANOVA results for rainfall between eight rainfall stations in Iiuni watershed, Machakos District, Kenya.

Season	Source of variation	Degrees of freedom	Sum of squares	Mean square	F_{cal}	F_{tab}†
Annual rainfall	Stations	7	280698	40100	0.96	2.18
	Error	120	5025003	41875	Null hypothesis of no significant difference is accepted	
Long rains	Stations	7	73207	10458	0.41	2.09
	Error	112	2846807	25418	Null hypothesis of no significant difference is accepted	
Short rains	Stations	7	104341	14906	0.55	2.09
	Error	112	3045024	27188	Null hypothesis of no significant difference is accepted	

†Based on 7, 112 and 120 degrees of freedom at 5% level of significance.

An analysis of variance for the variability of seasonal rainfall within the eight rainfall stations was carried out using the ‘F’ test as was done for the annual rainfall (Table 2). The ‘F’ statistics for the seasonal rainfall provided similar results as those for the annual rainfall.

Thus rainfall within Iiuni watershed can be represented by the data of Iiuni station only. The analysis of dry and wet spells was therefore done using the data of Iiuni station. Moreover, the analysis of rainfall data in Iiuni watershed suggests that for semi-arid environments in Kenya with topographic variations similar to Iiuni, one rain gauge per 12 km^2 can be regarded as satisfactory.

The variability of mean monthly rainfall in Iiuni watershed is significantly high (Table 3). This is so even for the wettest months of November to December (short rains) and March to May (long rains). The variability of mean monthly rainfall during the drier months is significantly higher than the wet months. From this analysis, it is evident that the driest months in Iiuni are January, February, June, July, August and September. In this watershed, the threshold value for distinguishing a rainy day was daily rainfall equal to or less than 5 mm which is equivalent to the mean daily evaporation rate of 5 mm day^{-1} for Iiuni.

An analysis of the number of rainy days and the rainfall amounts received per month was done to establish the distribution and reliability of rainfall within the short and long rainy seasons. This analysis has showed that the average number of rainy days per month during the short rains (Oct. to Dec.) varies between 3 to 11 and during the long rains (March to May) it varies from 4 to 10 days. The average number of seasonal rainy days is 21 for the short rainy season and 16 for the long rainy season (Table 3). These results show some significant monthly variability in rainy days.

Table 3. Mean monthly rainfall, rain days and rainfall depth per rain day at Iiuni watershed, Machakos District, Kenya.

Rainfall	Month												Year
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Mean (mm)	57	39	86	152	57	7	4	4	5	69	175	124	65
CV	1.17	1.31	0.81	0.64	0.64	1.39	1.35	1.07	1.55	0.78	0.40	0.57	0.92
No. of rainy days	3	2	4	8	4	1	0	0	1	4	10	7	4
Rainfall (mm) per rainy day	19	20	22	19	14	2	4	4	5	17	18	18	14

An analysis of rainfall data from Iiuni watershed has shown that the mean coefficient of variation of the short rains (CV = 0.34) is smaller than that of the long rains (CV = 0.48) implying that the short rains are more uniform than the long rains. The lengths of the longest dry and wet spells also confirm that the short rains are more reliable for crop production in Iiuni. The cessation of the rains occurs about the 12th week during the short rainy season and 10th week for the long rainy seasons (Biamah et al., 1998). The end of the rainy season is expected when a trend of persistent one rain day per week is experienced and when the daily rainfall is much less than the expected daily evaporation rate (Biamah et al., 1998).

Table 4. Test of equality values for the means and variances during the long and short rainy seasons in Kibwezi and Iiuni, Kenya.

Season	Station	n	$\bar{x}$	s^2	F_{cal}	F_{tab}†	t_{cal}	t_{tab}‡
Long Rains	Kibwezi	55	2.87	107.73	1.59	2.15	0.11	±1.95
	Iiuni	16	3.17	67.73				
Short Rains	Kibwezi	55	5.00	162.44	1.68	2.15	0.07	±1.95
	Iiuni	16	4.75	96.63				

†'F' test at 5% level of significance, and 54 and 15 degrees of freedom respectively.

‡ 't'-test at 5% level of significance and 69 degrees of freedom.

This analysis of annual, seasonal and monthly rainfall variations in Iiuni watershed has shown that annual rainfall variations are low, seasonal rainfall variations are slightly higher (a bit more for the long rains than for the short rains), while monthly rainfall values have the highest variability.

The test of equality of means and variances of daily rainfall data from Kibwezi (n = 55) and Iiuni (n = 16) stations were done using the 't' and 'F' tests (at 5% level of significance) respectively. The results obtained (Table 4) accepted the null hypotheses of equality of means (H_o: $\mu_1 = \mu_2$) and variances (H_o: $\sigma^2_1 = \sigma^2_2$). These tests confirmed the similarity of rainfall characteristics between the two stations, and justified the use of Kibwezi data for the stochastic drought analysis.

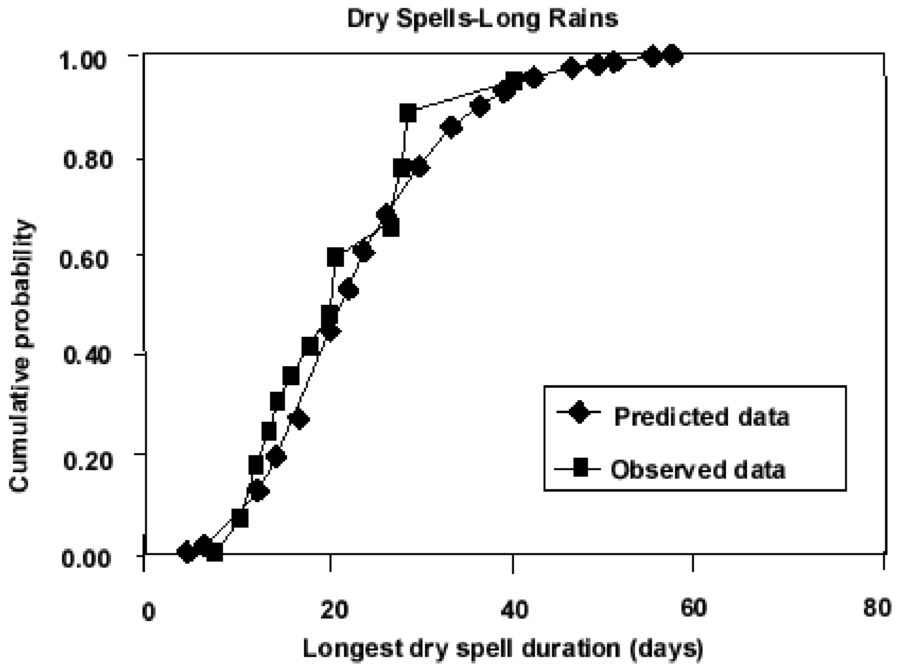
2.3.2 Stochastic behavior of spells and rainfall amounts

The values of the probability parameters, *q, qq, pp*, E(x) and V(x), that were used in simulating the longest dry and wet spells and largest rainfall amounts, were estimated from the daily rainfall data of Kibwezi (n = 55) station. The estimated values of probability parameters were for the long and short rainy seasons (Table 5).

Table 5. Seasonal values of dry and wet spell and rainfall amount parameters of Kibwezi, Makueni District, Kenya.

Parameter	Long rains	Short rains
q	0.83	0.68
pp	0.51	0.64
qq	0.89	0.80
E(x) (mm)	2.86	5.00
V(x) (mm^2)	107.73	162.44
A	0.78	0.78
B	22.96	37.52

The longest dry and wet spells and largest rainfall amounts in Iiuni were analyzed to establish if there was a Markovian dependence. This analysis was done by comparing the CDFS of predicted and observed data. From the results obtained (Fig.s 3, 4 and 5), the spells and rainfall amounts showed a Markovian persistence or dependence. Markovian persistence or dependence is judged by the closeness of observed data points to the predicted data trend line. For example, the dry and wet spells and rainfall amounts during the long rains showed better persistence than the dry and wet spells and rainfall amounts during the short rains (Fig.s 3, 4 and 5). Similar results were obtained when the transitional matrices (1) and (2) were compared. During the analysis, more than 80% of the runs displayed the behavior of being Markovian. Thus, this confirms the reliability of Kibwezi parameters in validating the Markovian persistence of Iiuni rainfall data. The CDFS show that the Markov model is appropriate for predicting the longest dry and wet spells and largest rainfall amounts in semi-arid environments of Kenya.



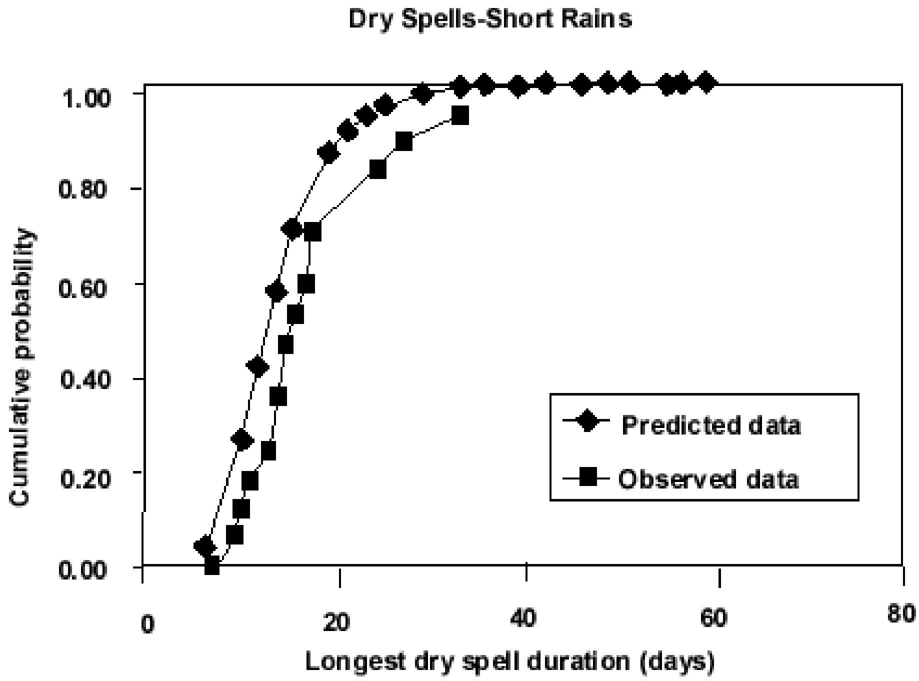


Figure 3. The CDFS of longest dry spells in Iiuni watershed, Machakos District, Kenya.

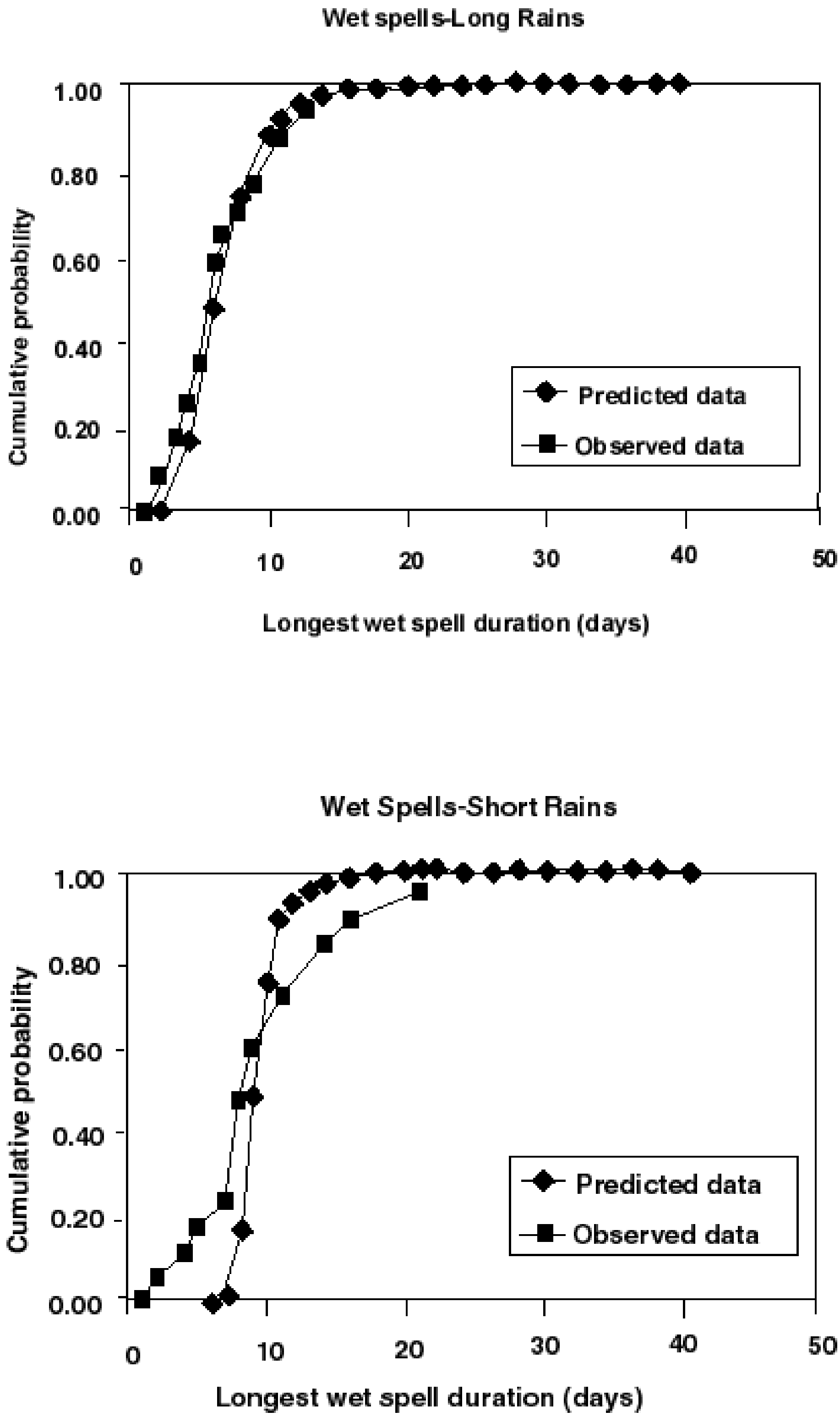
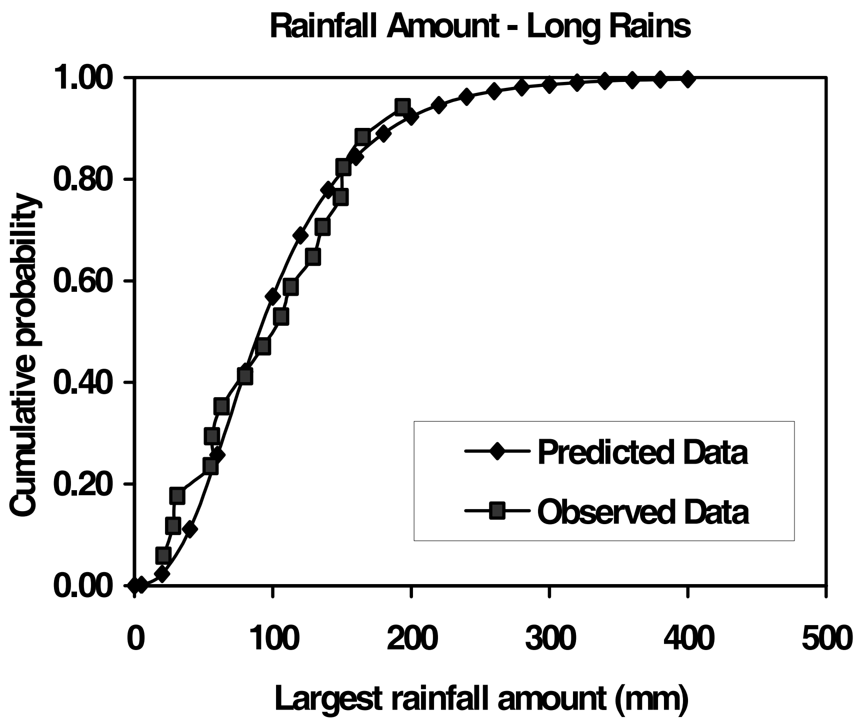


Figure 4. The CDFS of longest wet spells in Iiuni watershed, Machakos District, Kenya.



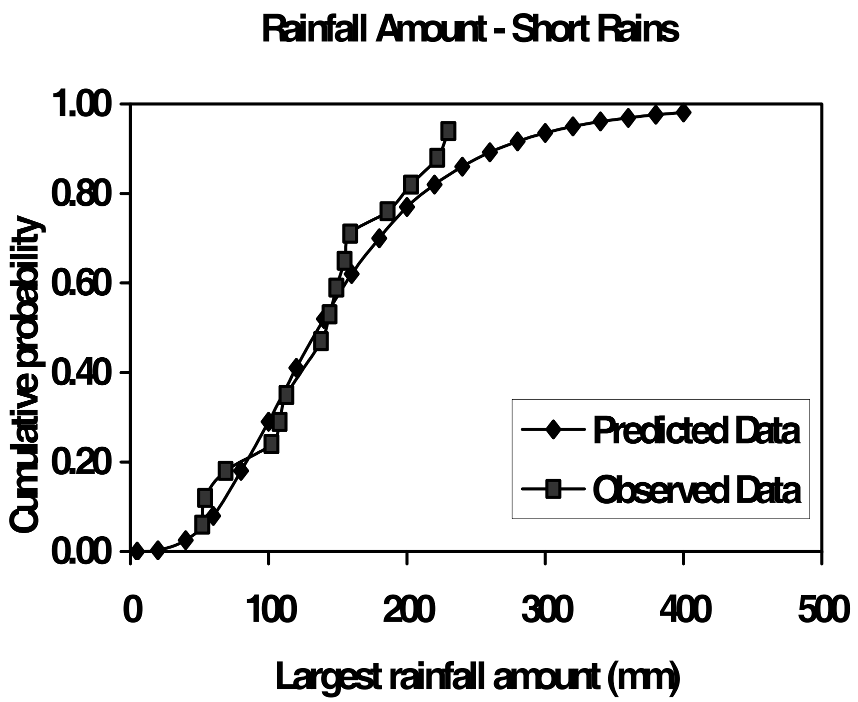


Figure 5. The CDFS of largest rainfall amounts in Iiuni watershed, Machakos District, Kenya.

Table 6. Probabilities of exceedence of dry spells during the long and short rainy seasons in Iiuni watershed, Machakos District, Kenya.

Duration	Probability of exceedence (%)	
(days)	Dry spells – long rains	Dry spells – short rains
60	1	0
50	2	0
40	8	0
30	22	1
20	56	13
10	93	74
6	98	96

Table 7. Probabilities of exceedence of rainfall amounts during the long and short rainy seasons in Iiuni watershed, Machakos District, Kenya.

Rainfall amount	Probability of exceedence (%)	
(mm)	Long rains	Short rains
400	0	2
380	0	2
360	0	3
340	1	4
320	1	5
300	1	6
280	2	8
260	3	11
240	4	14
220	5	18
200	8	23
180	11	30
160	16	38
140	22	48
120	31	59
100	43	71
80	59	82
60	74	92
40	89	97
20	98	100

The seasonal probabilities of exceedence derived from the CDFS of Iiuni watershed are presented in Tables 6 and 7. Generally, during the long rainy season, there is a higher probability of occurrence of longer dry spells and smaller rainfall amounts when compared with the short rainy season (Table 6). For example, the duration of a dry spell with an exceedence level of 80% is 14 days during the long rains and 9 days during the short rains. Similarly, the probability of occurrence of rainfall amounts with an exceedence level of 59% is 80 mm for the long rains and

120 mm for the short rains (Table 7). The mean and variance values of dry and wet spells and rainfall amounts

Table 8. Statistics for the longest dry and wet spells and largest rainfall amounts based on predicted data in Iiuni watershed, Machakos District, Kenya.

Parameter	Long rains		Short rains	
	Dry spell (days)	Wet spell (days)	Dry spell (days)	Wet spell (days)
Mean	24	5	12	6
Variance	120	4	33	9
	Largest rainfall amount (mm)			
Rainfall amount at 50% exceedence probability		91		136
Rainfall amount at 80% exceedence probability		53		85

are shown in Table 8. Based on the mean values of observed data of Iiuni watershed, the longest dry spells are expected to last for 24 days (about 3.5 weeks) during the long rains and 12 days (about 2 weeks) during the short rains. The largest rainfall amounts at 50% exceedence probability (median) are 136 mm for the short rains and 91mm for the long rains. This analysis has confirmed that the short rains are more reliable for crop production than the long rains in Iiuni watershed.

2.4 Conclusions

An analysis of variance (ANOVA) carried out on Iiuni rainfall data established that annual and seasonal rainfall variability between the stations in Iiuni watershed is not significant and hence Iiuni station's daily rainfall data was used to represent the rainfall features of the entire watershed in this study. ANOVA has also shown that for semi-arid environments with topographic variations similar to Iiuni, one rain gauge per 12 km^2 can be regarded as satisfactory. An ANOVA established the equality of means and variances implying that Kibwezi and Iiuni stations have similar rainfall characteristics. Therefore, the probability parameters obtained from the long-term rainfall data of Kibwezi were used in this drought analysis for Iiuni watershed.

The monthly rainfall analysis of the two rainy seasons showed high variability of monthly rainfall and that the six driest months in Iiuni are January to February and June to September. There was also significant monthly variability in rainy days. On a monthly basis, the analysis showed that approximately 91% of the expected seasonal rainfall amount occurred in the first two months after the onset of the rains. Thus any tillage practices recommended must ensure the effectiveness of rainfall in this critical period of two months.

The Markov model performed well in simulating the longest spells (runs) and largest rainfall amounts during the short and long rainy seasons in Iiuni watershed. The graphical comparison of predicted and observed CDFS of spells and rainfall amounts provide the best means of establishing if there is a Markovian dependence in line with the findings of Sharma (1996). The median values of probability parameters based on the daily rainfall data from Kibwezi station were used in these predictions.

The dry and wet spell analysis based on the probability parameters from Kibwezi rainfall data has shown that dry spells last for 24 days during the long rains and 12 days during the short rains. For the wet spells, their duration may vary from 5 days during the long rains to 6 days during the short rains. Also total rainfall amount expected during the extended wet spell periods are 91 mm for the long rains and 136 mm for the short rains.

The longest dry spell analysis is of practical relevance to the selection of the best conservation practices (including conservation tillage) for the management of Iiuni watershed. The largest rainfall amount analysis can be used to determine the watershed runoff volume and discharges that would assist in the design of flood and erosion control structures, and the design of runoff water catchment systems (RWCS), which are essential for supplementary irrigation in semi-arid Kenya.

If a runoff water catchment system is to be designed for a probability of exceedence level of 50%, then the design values of rainfall amount are 91 mm for the long rains and 136 mm for the short rains. Thus the best conservation practices and RWCS should be designed according to the longest dry spell and the largest rainfall amount respectively.

The statistics from this analysis have shown that the short rains (October to December) are evenly distributed, reliable and adequate for crop production. On the contrary, the long rains (March to May) are poorly distributed, unreliable and inadequate for crop production. Also severe drought episodes are less likely to occur during the short rains.

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Chapter 3

Tillage methods and soil and water conservation in Eastern Africa

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Tillage methods and soil and water conservation in Eastern Africa

Abstract

This paper reviews some research studies on tillage methods influencing soil and moisture conservation in the eastern African countries of Kenya, Tanzania, Malawi and Ethiopia during the past four decades (1950-1990). Most of these studies were conducted in marginal rainfall (semi-arid) areas and on shallow soils of various textures (sandy clay loam, sandy clay, clay and loam). The studies were meant to establish the effects of tillage and residue management practices on physico-chemical soil properties (i.e. structure, bulk density, soil moisture and organic matter contents), runoff and infiltration. This review emphasizes the importance of appropriate tillage and residue management methods (contour bunds and terraces, minimum tillage, tied ridging, mulching and conventional tillage) in providing soil conditions favorable for soil moisture conservation and subsequent crop performance and yield on smallholder farms.

3.1 Introduction

3.1.1 General background

The primary objective of any tillage operation should be to optimize soil conditions such as bulk density, pore size distribution, temperature, consistency, soil water intake rate and moisture retention capacity for increased crop production through appropriate and timely seedbed preparation and weed control.

Most smallholder farmers in eastern Africa use traditional methods of seedbed preparation and weed control (i.e. hand hoeing, slash and burn). In practice, timely seedbed preparation using these methods is difficult to achieve especially where ground-breaking operations require high energy inputs. The occurrence of soil surface hardpans has often delayed tillage operations up to the onset of the rains when soil moisture conditions would be favorable. High labor demands during this peak period have delayed seedbed preparation operations and consequently affected soil productivity. Furthermore, soil productivity is threatened by shallow digging (causing subsurface hardpans) and soil erosion hazards (owing to tillage operations on steep slopes and highly erodible soils) that are quite evident on fragmented smallholder farms.

In marginal rainfall areas of eastern Africa, recurrent low soil moisture conditions have been attributed to low infiltration of rainwater (owing to soil surface sealing and crusting properties) and organic matter content of the soils. Rainfall impact causes surface sealing and crusting of bare soils resulting in very high runoff water losses. It is this runoff water that must be harnessed and conserved in the soil to sustain crop growth. This calls for appropriate tillage practices that not only improve rain penetration but also conserve adequate soil moisture for plant growth. Current conservation tillage practices used in these areas include contour bunds and terraces, minimum tillage, conventional tillage, residue mulching and tied ridging.

Conservation tillage research studies in eastern Africa have focused on the effects of these tillage practices on soil and moisture conservation for increased crop production. These studies have attempted to develop appropriate and sustainable tillage and residue management methods that would maintain favorable soil conditions for good plant growth on small-scale farms. To be successfully adopted by smallholder farmers, conservation tillage methods must offer tangible benefits through increased crop yields, fuel wood and fodder production. These tillage methods, whilst adapted to area specific soils conditions, should also be well designed to cope with the high rainfall intensities, high erodibility of soils and high temperatures prevailing in the region. The new conservation farming techniques must be closely knit within the existing fabric of traditional farming practices like mulching, ridging, mixed cropping, crop rotation and shifting cultivation and should be socio-economically acceptable to smallholder farmers.

3.1.2 Environmental aspects

Climate

The seasonal rainfall patterns are governed by the seasonal shifts and intensity of the low pressure Inter Tropical Convergence Zone (ITCZ). In eastern Africa, rainfall occurrence is primarily bimodal with two distinct rainy seasons (short and long rains). Semi-arid areas receive average annual rainfall of 800-1000 mm. The short rains account for about 65% of the total annual rainfall. Potential evaporation ranges from 1450 to 2200 mm y^{-1}. The rainfall though low and erratic, occurs in high intensities of short duration and is highly erosive. High amounts of runoff are often generated from these storms owing to inherent low infiltration rates of the soils. Concentrated runoff flows are responsible for the severe erosion that occurs in these marginal rainfall areas.

Soils

The most dominant soils in marginal rainfall areas of eastern Africa are Luvisols, Acrisols and Vertisols. Except for the Vertisols, the other two soils are characterized as shallow soils with inherent low organic matter, water retention capacity, salt and sodium content and strong surface sealing and crusting properties. The dominant clays of Luvisols/Acrisols are usually of the 1:1 ratio (kaolinite). Water infiltration in the soils is rather low, especially in the B-horizons which generally have a heavy texture. The management of these soils requires deep plowing (to break the crust and subsoil hardpans) and addition of organic matter content from residue mulch or organic manure. Luvisols/Acrisols are often cropped during the rainy season. Vertisols are characterized as deep soils having moderate to high salt and sodium content, montmorillonitic (2:1) clay mineralogy, and low infiltration rates (owing to swelling when wet). Structural tillage practices are not feasible on Vertisols owing to their unstable structure (2:1 clays). Vertisols are usually cropped after the rainy season.

Overall, tillage management requirements of these three soils would depend on clay mineralogy, workability, moisture holding capacity and other soil characteristics. Luvisols/Acrisols have a compact subsoil layer (argillic horizon) owing to an increase in clay content from A to B. These soil problems (especially the sealing and crusting) are known to affect seedling emergence, decrease rain infiltration and consequently result in high surface runoff rates (with minimal soil loss unless the soils are disturbed and have a cloddy top soil structure). Vertisols, owing to their swelling and shrinking properties, affect crop root development when dry and infiltration when wet. These soils are workable immediately after the rainy season (under optimum soil moisture conditions) when the soils are loose and crumbly and hence requiring low draught per unit area.

Cropping systems

The major crops grown in semi-arid areas of eastern Africa include maize, beans, sorghum, millet, cassava, pigeon peas, sweet potatoes, cowpeas, groundnuts and cotton. Crop performance and yield are significantly influenced by the amount of rainfall and distribution throughout the rainy season. As a result of inherent soil moisture deficits, the period of cropping is limited to the rainy season. The potential length of growing season as determined by the long and short rains influences the choice of crops in these areas. Most crops are grown during the short rains since more rainfall occurs within this period. Intercropping is a very common farming practice as it minimizes the risks of crop failure owing to unexpected soil moisture deficits. Usually combinations of two or three crops are evident in most of these areas.

Socio-economic aspects

During the past two to three decades, human and livestock population in semi-arid areas of eastern Africa has significantly increased and consequently led to an over exploitation of the limited land and water resources. Soil and vegetative degradation have become widespread owing to overgrazing, deforestation, burning and over-cultivation. Accompanying this unprecedented population increase is the fragmentation of landholdings and sedentarization of pastoralists, which has destabilized the very fragile ecology of the areas. This has adversely affected food and fodder production and left the entire population vulnerable to food and fiber shortages. Unpredictable weather conditions have exacerbated the problems and further decreased the production potential of the resource base.

3.1.3 Tillage methods

Traditional tillage and residue management methods that are widely practiced in this region include slash and burn, residue mulching, ridging, mixed cropping, conventional tillage (hand hoeing), crop rotation and shifting cultivation. Additionally, new conservation tillage methods like minimum tillage (no till), terracing, cover cropping, intercropping, contour buffer stripping, tied ridging, contour bunding and plowing have been introduced to optimize soil conditions for improved crop performance and yield. Most of these traditional and new tillage operations involve high-energy inputs (labor intensive, use of hand tools) both in construction and maintenance.

The applicability of tillage practices depends on soil properties, climatic conditions, types of crops to be grown and socio-economic conditions of the beneficiaries (smallholder farmers). For instance, contour bunds and ridges have proven to be very effective in marginal rainfall areas where rainfall intensities and runoff rates are high. These structures are recommended for stable soils with surface sealing and crusting properties and low water intake rates. Contour bunds and ridges are expected to impound the runoff and increase the infiltration opportunity time of the soil.

In conventional tillage, farmers use hand hoes to break the land up to a depth of 20 cm often leaving large soil clods at the surface. Where the clods are too large and the weeds have grown, harrowing to break the clods and remove the weeds is recommended. Often conventional tillage involves primary tillage operation with no secondary tillage until weed control.

Minimum tillage operations often involve strip tillage (narrow strips of 20 cm width of cut along the planting rows) or spot tillage (where planting holes of size 10 cm x 10 cm are made using hand hoes). Minimum tillage is also practiced using the traditional slash and burn techniques.

Contour buffer strips of widths of 1 to 2 m are often combined with contour ridges to check runoff and soils loss. Tied ridging at 2-3 m spacing along the furrows is usually done before the onset of the rains to avoid any breakages of ridges as a result of concentrated runoff flows.

Crop residues are either placed on the soil surface (to dissipate rain energy and reduce surface sealing effects) or incorporated into the soil (ridges and furrows) as a means of supplementing organic matter deficiencies and improving the water holding capacities of soils.

3.2 Tillage research

3.2.1 Kenya

Tillage research in Kenya has been conducted over the last four decades with the focus of the studies being on tillage methods such as mulching, tied ridging, minimum tillage, conventional tillage and contour furrows. Most of these studies were conducted in marginal rainfall areas where the soils were characterized as having inherent low organic matter content and surface sealing and crusting properties. Rainfall in these areas is quite intense, of short duration and highly erosive.

Within the semi-arid area of Makaveti, Machakos, Pereira and Beckley (1952), conducted a pasture improvement study and found that the infiltration rate of a Luvisol (FAO/UNESCO Classification) improved when its soil surface crust was broken through contour plowing, ridging and ripping. The best pastures were obtained by contour plowing and ridging with incorporation of a small dressing of cattle manure. Plowing and ridging conserved moisture, but deep ripping did not assist in grass establishment under the low rainfall conditions of the experimental site.

In the same area, Pereira et al. (1954) conducted a crop rotation study in which infiltration rates were comparatively low after 1 year of uniform cropping. The rotation of grasses, cover crops and cultivated crops over a 3 year period had some short term improvements on soil structure.

In an experiment in a drier area of Kenya, Pereira et al. (1954) found that a 10 cm mulch of elephant grass in a coffee plantation produced after 2 years an infiltration rate equal to that of 5 years under elephant grass.

Pereira et al. (1958) in a water conservation study in a semi-arid area established that tied ridges do not improve the resistance of soil to surface sealing, but may impede surface flow of water within the furrow, thus allowing more time for water to infiltrate.

Pereira and Jones (1965) found that clean weeding caused an average of 15% reduction in infiltration during very heavy storms compared with minimum weeding or the incorporation of grass mulch into the soil during cultivation.

Robinson et al. (1965) found that mulching increased total pore space, free drainage and rainfall acceptance by 8%, 9% and 53%, respectively on a latosol in a coffee growing area of Kenya.

Pereira et al. (1967) studied soil and water conservation systems for high rainfall areas of Kenya. The study established that contour plowing (using Nichols terraces) and tied ridging of a Kikuyu red loam soil (Nitisol, FAO/UNESCO Classification) on slopes of 10%, effectively controlled soil and runoff water losses. Runoff was heaviest from well-established grass leys (*Cynodon dactylon*) immediately after intensive grazing and subsequent trampling by livestock and when exposed to rainfall intensities exceeding 50 mm h^{-1}. The trampling effects at the site were transient with variable runoff rates. Soil surface profiles at the experimental site showed remarkable slope stability under intensive tillage. Furthermore, some benching effect was noted on fields under contour cultivation. High soil loss and runoff rates were observed where ridging and tying operations were undertaken at different times. Where both operations were done at the same time, the tied ridges effectively controlled runoff and reduced soil loss. At the same site, soil moisture measurements (using gypsum blocks) were taken at 0.6, 1.2, 1.8, 2.4 and 3 m depths for two terrace spacings (1.5 and 6 m vertical intervals) on 10% slopes. There were no significant differences in the availability of soil moisture between the two treatments. Soil moisture extraction patterns of star grass (*Cynodon dactylon*) showed extensive root development to 3 m depths 9 months after planting. Over the 2 year period of soil moisture measurements, moisture deficits occurred when rainfall was less than the consumptive use of *Cynodon dactylon* (Table 1).

Table 1. Water consumption by star grass (*Cynodon dactylon*) (after Pereira et al., 1967).

Days after planting	Rainfall (mm)	ET_o† (mm)	SMC‡ (mm)	ET_c† (mm)	ET_c/ET_o ratio
91	80	493	-54	153	0.31
178	231	536	+67	163	0.30
319	263	537	-32	295	0.55
412	33	272	-110	143	0.53
493	298	434	+51	248	0.57
567	320	386	+130	191	0.49
608	37	148	-65	102	0.69
733	75	484	-91	166	0.34

†ET_o - Reference crop evapotranspiration; ET_c - Actual crop evapotranspiration.
‡SMC - Soil moisture change.

In a tillage study at Katumani, Machakos, Marimi (1978) found that minimum tillage, conventional tillage and tied ridging operations on a sandy clay soil (chromic Luvisol, FAO- UNESCO Classification) broke the soil surface crust and improved infiltrability and moisture storage of the soil. Higher soil moisture contents were obtained under tied ridges when compared with the other tillage methods (Table 2). Minimum tillage stored the least amount of soil moisture. Significantly higher dry matter and grain yields of maize and beans were obtained in tied ridged plots as compared to the other plots (Table 3). Minimum tillage gave the lowest crop yields. During the study period, runoff occurred on two occasions from minimum and conventional tillage when rainfall exceeded 15 mm. This confirmed that soil surface sealing occurred rapidly even with light rains.

Table 2. Effect of tillage methods on soil moisture content at end of short rains period, 1976/1977 (after Marimi, 1978).

Soil depth	Soil moisture content (% volume)				
(cm)	Minimum tillage	Conventional tillage	Tied ridging	SE†	PWP‡
0-30	15.7	16.1	17.9	0.52	19.0
30-60	19.7	19.4	21.9	0.55	20.3
60-100	19.6	19.0	21.1	0.36	20.6
100-150	16.3	16.5	16.7	0.21	19.9

†SE - Standard error.
‡PWP - Permanent wilting point.

Table 3. Effect of tillage methods on crop yield (after Marimi, 1978).

Period	Crop	Crop yield (kg ha^{-1})			
		Minimum tillage	Conventional tillage	Tied ridging	SE†
Long rains	Maize (dry matter)	1068	1047	1105	63
Short rains	Maize (dry matter)	2040	1920	1760	0.09
	Maize (grain yield)	337	221	513	51

†SE - Standard error.

Onchere (1977), in an infiltration study at Kitale, found that bare fallow, minimum tillage and conventional tillage operations on an orthic Luvisol (FAO/UNESCO Classification) at a slope of 3%, significantly improved infiltration and other soil properties. It was observed that the method of seedbed preparation significantly influenced the pore size distribution and density, moisture holding capacity, bulk density and surface sealing and crusting properties of the soil. Whereas the coarse seedbed had no crusted soil surface, the other seedbeds showed some crusting. Bare fallow had the least crusted soil surface. From the moisture characteristic curve (Fig. 1), a coarse seedbed absorbed more water than the other treatments and hence had the highest moisture holding capacity (9.1% by volume). Njihia (1979) at Katumani, Machakos monitored the effects of tied ridges, conventional tillage, crop residue mulch and farmyard manure on soil and moisture conservation. These tillage practices were tested on red sandy clay soil (chromic Luvisol, FAO/UNESCO Classification) at a slope of 12%. The soils had strong surface sealing and crusting properties and an average bulk density of 1.25 g cm^{-3}. Maize stover mulch was sufficiently effective in controlling runoff through increased surface water storage.

The storage increased the time available for infiltration. Maize stover also helped minimize evaporation and surface sealing and crusting. Tied ridges effectively controlled runoff even from a maximum storm of 70 mm per day (with a return period of 3 years). Conventional tillage with or without farmyard manure lost about 40% of the storm rainfall (Table 4). A grain yield of maize was realized from the tied ridged and stover mulch plots for a seasonal rainfall of 171 mm. No grain was harvested from conventional tillage with or without farmyard manure.

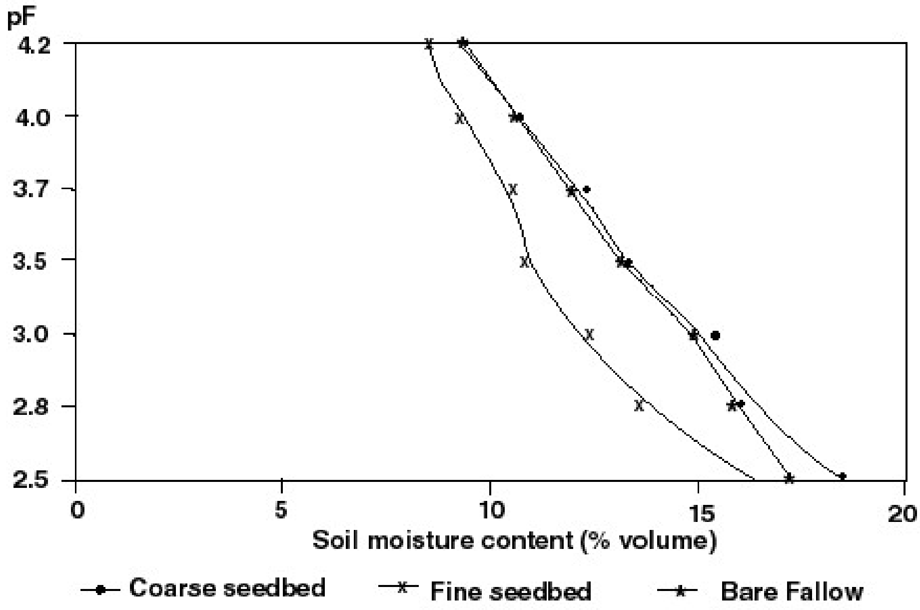

Figure 1. Topsoil moisture characteristic curves of selected tillage practices (after Onchere, 1977).

Table 4. Soil moisture and runoff arising from 122.1 mm rainfall (after Njihia, 1979).

Treatment	Soil moisture storage (mm)	Runoff (%)
Stover mulching	122.1	-
Tied ridging	86.0	13.7
Farmyard manure	69.0	38.0
Conventional tillage	65.8	42.7

Othieno (1980) at Kericho found that mulching effectively controlled water vapor losses from the soil. The application of straw mulch with a thickness of 5 cm reduced evaporation significantly from 0 to 35 cm soil depth during a hot, rainless 10 days period.

Muchiri and Gichuki (1982) at Katumani found that contour furrows were effective in controlling surface runoff and subsequently conserving soil moisture in a semi-arid area. The desi-plow used in making contour furrows was reported to produce a much rougher seedbed and a draft requirement, depth of tillage and rate of work comparable with the moldboard plow.

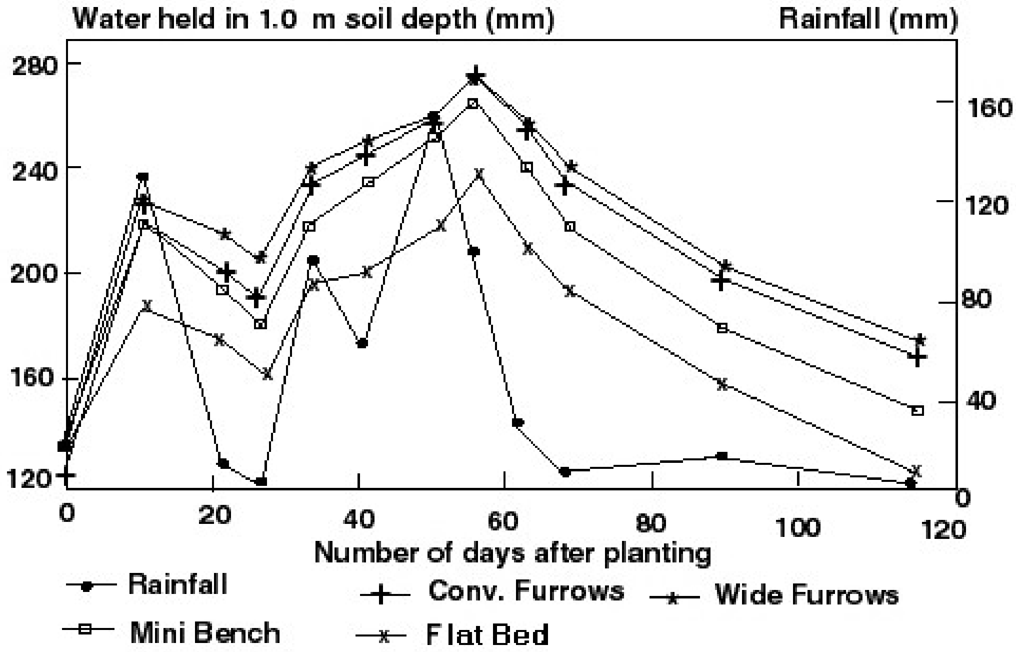

Figure 2. Rainfall distribution and variation of soil moisture content with tillage method during the short rains period (after Kilewe and Ulsaker, 1983).

Table 5. Effect of tillage method on maize yield (after Kilewe and Ulsaker, 1983).

	Maize yield (kg ha^{-1})	
Tillage method	Short rains	Long rains
Flat	3722	256
Conventional furrow	5242	725
Wide furrow	5458	844
Mini bench	4680	643

Kilewe and Ulsaker (1983) at Katumani, found that contour furrows, bench terracing and conventional tillage operations on a sandy clay loam (ferral-chromic Luvisols, FAO/UNESCO Classification) effectively controlled runoff and conserved soil moisture. The study showed that conventional furrows, wide furrows and mini benches retained all the runoff within the furrows and increased infiltration opportunity time after the rainfall. Wide furrows (1 m wide) had the highest soil moisture content followed by conventional tillage during both the short and long rains (Fig. 2 and Fig. 3). These furrows had significantly higher maize grain yield than all the other tillage methods (Table 5).

In a tillage study at Embu, Ngugi and Michieka (1986) monitored the effects of conventional tillage and two minimum tillage operations (strip and spot tillage) on brown clays (eutric Nitisols, FAO/UNESCO Classification). The soils had a low organic matter content (1.66%) and were located in a medium rainfall area (1081 mm). The study showed that conventional tillage had the best crop performance and yield (Table 6) when compared with the other tillage methods during both rainy seasons (short and long rains).

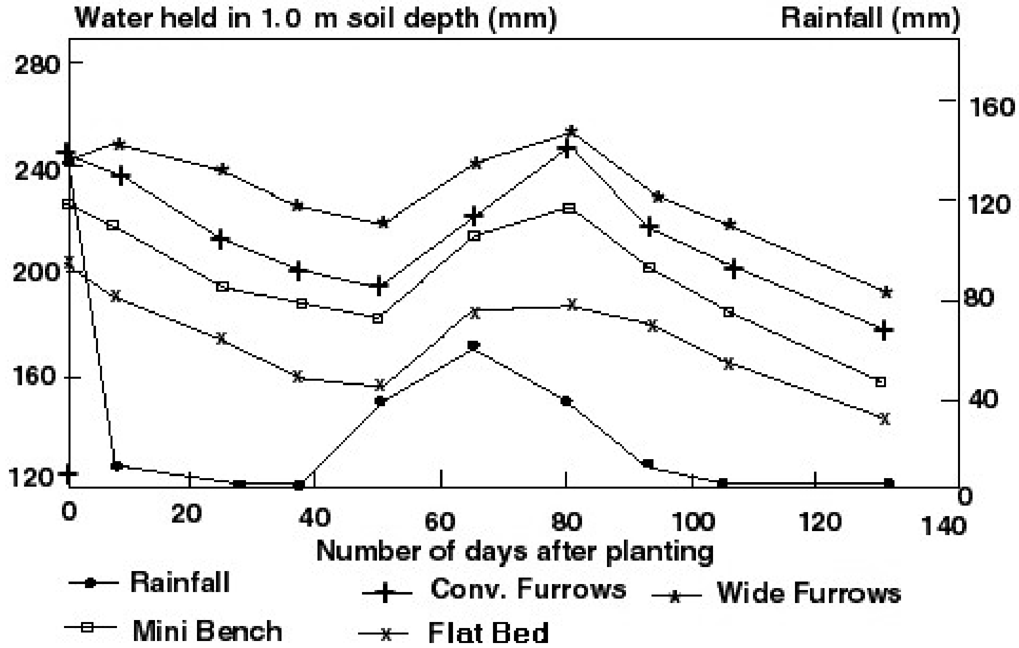

Figure 3. Rainfall distribution and variation of soil moisture content with tillage method during the long rains period (after Kilewe and Ulsaker, 1983).

Table 6. Effect of tillage methods on maize grain yield (after Ngugi and Michieka, 1986).

Tillage method	Maize grain yield (kg ha^{-1})			
	Short rains	LSD† (0.05)	Long rains	LSD† (0.05)
Conventional tillage	3380	1.00	6060	1.09
Strip tillage	3330	1.00	5790	1.09
Spot tillage	3340	1.00	4650	1.09
SE† (treatment means)	0.118		0.114	

†LSD - Least significant difference; SE – Standard error.

Liniger (1989) observed that the reduction of runoff and evaporation loss was a significant factor in mulched plots. Consequently the maximum storage of plant available water was between 45 and 110% higher in the mulched plots than under conventional tillage. Mulching was also reported to have increased maize yields by 4.5 times when compared with similar yields under conventional tillage.

In Kalalu, Laikipia, Gicheru (1990) monitored the effect of conventional tillage, tied ridging and crop residue mulching on soil moisture conservation under marginal rainfall (750 mm) conditions. The experiment was carried on a clay soil (ferric Acrisols, FAO/UNESCO Classification; Table 7) at a slope of 2%. This study showed that crop residue mulching (despite lagging behind in seedling emergence) did conserve more moisture and had the best crop (maize and beans) performance and yield when compared with the other two tillage practices (Tables 8, 9, 10). The tied ridged plots had the lowest amount of soil moisture (Tables 8 and 9) and hence the poorest crop performance and yield (owing to no runoff to impound and high evaporation water losses from increased soil surface area) (Table 10).

Table 7. Soil profile characteristics of a ferric Acrisol, Kalalu, Laikipia (after Gicheru, 1990).

Soil depth (cm)	Bulk density ($g\ cm^{-3}$)	Soil texture†	Organic matter (%)	Field capacity (% volume)	Permanent wilting point (% volume)	Available moisture (% volume)
0-30	1.3	C	2.0	43.6	35.7	7.9
30-60	1.2	C	1.7	45.2	27.9	16.3
60-90	1.3	C	0.7	39.2	31.3	7.9
90-120	1.4	C	0.7	36.1	32.1	4.0

†C - Clay.

Table 8: Cumulative soil moisture for beans, short rains period, Kalalu, Laikipia (after Gicheru, 1990).

Crop stage	Cumulative soil moisture content (% volume)		
	Residue mulch	Conventional tillage	Tied ridging
Emergence	27.6	30.6	27.4
Budding	25.6	25.6	25.6
Flowering	21.3	21.2	15.3
Maturity	10.0	13.9	6.0
Harvesting	5.5	8.9	0.7

Table 9. Cumulative soil moisture for maize, long rains period, Kalalu, Laikipia (after Gicheru, 1990).

Period after planting (weeks)	Cumulative soil moisture content (% volume)		
	Residue mulch	Conventional tillage	Tied ridging
3	10.3	14.3	0.2
7	19.6	0.8	4.4
11	147.6	148.8	131.4
14	2.3	6.1	3.8

Table 10. Average grain yields of maize and beans, Kalalu, Laikipia (after Gicheru, 1990).

Crop	Average grain yield ($kg\ ha^{-1}$)		
	Residue mulch	Conventional tillage	Tied ridging
Maize	1083.3	850.0	833.3
Beans	936.1	922.2	683.3

3.2.2 Tanzania

Research on tillage methods in Tanzania has been conducted over the past three decades or so. The studies have concentrated on the effects of tied ridging, mulching, zero tillage and conventional tillage operations on soil moisture conservation, crop performance and yield. The experimental sites were located in low rainfall areas with significant soil moisture deficits.

Peat and Brown (1960) while conducting an experiment in the Lake Province of Tanzania found higher crop yields of cotton and sorghum from tied ridges than from conventional tillage in most years, and sometimes the yield doubled. However, in high rainfall seasons there were no significant yield differences recorded.

Dagg and Macartney (1968) in an experiment within Jaro Valley, showed that tied ridging was quite effective in conserving water and enhancing the soil moisture holding capacity. Macartney et al. (1971) at Kongwa, Central Tanzania, reported better crop yield from tied ridging as well.

Huxley (1979), at Morogoro, monitored the effects of zero (minimum) tillage, mulching and conventional tillage on crop production. The results showed that maize yields obtained from zero tillage were about 65-75% of those from conventional tillage. The incorporation of mulch increased maize yields by 18-54%. Generally grass mulch was more effective in conserving soil moisture and increasing crop yields than woody mulch (Table 11).

Table 11. Effects of tillage and mulching on crop yields (after Huxley, 1979)

Crop	Crop yield (kg ha^{-1})					
	Zero tillage	Conventional tillage	LSD† (0.05)	Grass mulch	Woody mulch	LSD† (0.05)
Maize	1080	1600	0.137	1600	1420	0.238
Cowpea	471	591	0.040	570	520	0.054

†LSD - Least significant difference.

Other investigations on zero tillage by Khatibu and Huxley (1979) at Morogoro, showed some significant cowpea yield increases in tilled systems (1069 kg ha^{-1}) when compared with no till systems (869 kg ha^{-1}).

Masseri and Jana (1979) at Morogoro found that conventional tillage, zero tillage, strip tillage and grass mulching (4 t $ha\text{-}^{1}$) operations on a sandy clay loam soil (Ferralsol, FAO/UNESCO Classification) with an organic matter content of 3.5% and a top soil bulk density of 1.4 g cm^{-3}, resulted in varying average soil moisture contents for 0-90 cm soil depths. At 68 days after planting, soil moisture was highest in conventional tillage plus mulch and decreased in the order of strip tillage, zero tillage and conventional tillage (Table 12). The soil moisture content at 109 days was in the order of strip tillage, conventional tillage plus mulch, conventional tillage and zero tillage.

Jones and Mitawa (1986) established that cereal crops on tied ridges with crop residue mulch performed better than those on open ridges without residue mulch. This good crop performance was attributed to adequate soil moisture conservation in the mulched plots.

Table 12. Effect of tillage on soil moisture and crop grain yields (after Masseri and Jana., 1979).

	Soil moisture content (% volume)				Grain yield (kg ha^{-1})			
	Growing days				Crops			
	68	109	118	144	Maize	LSD† (0.05)	Soy bean	LSD† (0.05)
Conventional tillage	24.4	18.0	16.6	16.7	4215	1238	716	524
Conventional tillage + mulch	26.2	18.7	18.4	17.0	4625	1238	936	524
Strip tillage	25.5	19.5	19.1	16.2	4155	1238	678	524
Zero tillage	25.1	17.9	18.1	16.6	4715	1238	750	524

†LSD, Least significant difference.

3.2.3 Malawi

Biamah (1988) conducted a diagnostic study of existing conservation tillage practices in the Machinga Area of south eastern Malawi. The study involved contour ridges, contour buffer strips, graded terraces, diversion ditches and crop residue mulching operations on medium textured slightly acidic brown to reddish brown sandy clay loams to sandy clays. These soils are predominantly Latosols with a few patches of Vertisols within the dambos (swamplands). The study area receives a mean annual rainfall of 559 mm (unimodal) with a 6-7 months dry season. The entire area has fairly shallow soils with an effective topsoil depth of 10-20 cm and a low organic matter content (0.7-1.5%).

Conservation tillage practices consist of boxed (tied) or plain ridges aligned on the contour with the aid of contour marker ridges and contour buffer strips planted to a variety of productive perennial crops and trees. Box ridging of 2-3 m spacing along the furrows is often done before the onset of the rains. Planting of pigeon peas (*Cajanus cajan*) and pastures (*Rhodes* grass) along the contour marker ridges is used to improve the structure and nutrient status of the soil and also provide the fodder. Contour buffer strips of *Rhodes* grass at widths of 1-2 m are combined with contour ridges to check runoff and soil loss. Crop residue is incorporated into the soil (ridges and furrows) as a means of supplementing deficiencies in organic matter and also improving the water retention capacities of the soil.

Field observations on the effectiveness of these structures, showed that when boxed ridges break during severe storms, runoff-flow down-slope will be intercepted by the buffer strips, its velocity slowed by the perennial vegetation allowing more infiltration opportunity time before finally being checked by the marker ridge. Soil washed out of the cropped area and deposited by the buffer strips, over a period of years would develop into a bench terrace.

The introduction of contour ridges, buffer strips and residue mulching has proven to be a feasible and sustainable conservation alternative to labor intensive and costly physical conservation structures (i.e. diversion ditches and graded terraces). Significant increases in soil moisture and subsequently in grain yields have been obtained from these conservation tillage practices.

Mitchell (1986), in the Lower Shire Valley of Malawi monitored the effects of tied ridges, conventional tillage (on natural slope) and contour bunds (on leveled land) on crop production. The dominant soils in the study area were chromic and pelitic Vertisols (FAO/UNESCO Classification). The annual rainfall in the area was 750 mm, 90% of which fell between November and April.

Field observations showed that traditional cultivation techniques (hand hoeing and planting on flat beds) did not prevent runoff. On newly opened lands, tilled soils maintained coarse crumb structure in the top soil, but which deteriorated to smaller aggregates with some soil capping after 4 years. The smaller aggregates were more prone to erosion by runoff (owing to high surface runoff rates).

Results from this study showed that all the tillage practices (except flat seedbed) on leveled land effectively retained rainwater in the soil. There was a reduction in yields in tied ridged and contour bunded plots owing to excessive water storage and consequent water logging (which reduced the nitrogen supply to the crop) (Table 13).

An examination of traditional planting techniques of cotton showed that the method of spot tillage (scooping a ditch of 0.3 m long, 0.25 m wide and 0.1 m deep with a hoe and planting seed uncovered) enabled the crop to germinate successfully after only 12-15 mm of rain when compared with at least 50 mm for conventional planting. It was also observed that floods destroyed cotton sown on ridges whereas the cotton planted on the flat bed was undamaged.

Table 13. Effect of tillage practices on cotton yields (after Mitchell, 1986).

Location	Rainfall (mm)		Treatment	Cotton yield (kg ha^{-1})	
	Year 1	Year 2		Year 1	Year 2
Nsangwe	802	484	Conventional tillage on natural slope	1869	1584
			Tied ridges	1607	1206
			Ridges on leveled land	1404	1308
Mphonde	695	537	Conventional tillage on natural slope	1733	941
			Tied ridges	1484	1085
			Conventional tillage on leveled land	1507	1101
			Ridges on leveled land	1560	1135

3.2.4 Ethiopia

Tillage research in Ethiopia that has been reviewed in this paper was conducted over the past decade. The studies monitored the effects of conventional tillage, contour furrows, tied ridging, sub-soiling and zero tillage operations on crop production, runoff, soil and organic matter losses. The experimental sites were located in medium and low rainfall areas with variable soil conditions.

Alem (1986) at Mekele, conducted trials on seedbed preparation methods (conventional tillage, open furrows and tied ridging). Significant maize yield differences were obtained among the treatments with the highest yields (1800 kg ha^{-1}) observed on tied ridges followed by plain ridges (1040 kg ha^{-1}). The lowest yields were obtained from conventional tillage (431 kg ha^{-1}). These results showed that improved seedbed preparation methods were effective in conserving soil moisture and in increasing yields in drought affected areas of Ethiopia.

Zugec et al. (1991) at Horro Aleltu, Nekemte, Wollega, monitored the effect of conventional tillage (20-25 cm), subsoiling (30-35 cm deep) disc harrowing (8-10 cm deep), zero tillage and ridging operations on maize and soya bean production. The experiment was conducted over a 2 year period on a rhodic Ferralsol (FAO/UNESCO Classification) with 4-5% organic matter content. Mean annual rainfall over the 2 year period ranged from 1007 to 1346 mm. The results obtained showed that there were no significant maize yield differences between the treatments in the first year (1007 mm rainfall). This year, zero tillage performed better than conventional tillage. In the second year (1346 mm rainfall), significant maize yields were obtained. The yields were higher on plowed plots than in the other tillage treatments. This year, ridging had better crop performance than the other tillage practices. Soy bean yields showed significant differences between conventional tillage and subsoiling and also between zero tillage and the other tillage methods.

In the same area, Basic et al. (1991) monitored the effects of conventional tillage (disc plowing and harrowing) operations on soil erosion. The experiment was on an acric Ferralsol (FAO/UNESCO Classification) with a slope of 5%. Results obtained showed that surface runoff, soil and organic matter losses varied with tillage practices (Table 14).

Table 14. Effect of tillage method on runoff, soil and organic matter losses (after Basic et al., 1991).

Tillage method	Runoff (% volume)	Soil loss (t ha^{-1})	Organic matter loss (kg ha^{-1})
No tillage	39	7.6	370
Up and down slope	40	27.0	1267
Across slope	14	1.1	51

3.3 Conclusions

The semi-arid areas of eastern Africa are characterized by low, erratic and poorly distributed rainfall and problem soils (with strong surface sealing and crusting and low organic matter content). Hence these soils require early seedbed preparation in order to conserve adequate soil moisture for good crop growth. Timely seedbed preparation would facilitate early planting, which subsequently enables crops to get established before the rains subside.

Tillage research work done in this region was conducted in medium to marginal rainfall areas and on shallow soils of various textures (sandy clay loam, sandy clay, clay and loam). The studies showed that both timeliness in planting and the amount of antecedent soil moisture conserved in the soil before planting have a major effect on crop yields. Field observations on tillage and residue management practices showed that conventional tillage practices did not prevent runoff whereas conservation tillage practices effectively controlled runoff and soil loss.

Significant increases in soil moisture and grain yields were observed under conservation tillage practices introduced where terracing was in place. Tied ridges performed poorly under excessive or no runoff conditions. Zero tillage performed poorly under these soil conditions because of high soil crusting and compaction, low rainwater infiltration and subsequent increases in surface runoff generation. Smallholder farmers are primarily interested in tillage practices that improve soil moisture conditions, do not involve high energy inputs and that increase crop production.

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Chapter 4

Tillage and farmyard manure effects on crusting and compacting soils at Katumani, semi-arid Kenya

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Tillage and farmyard manure effects on crusting and compacting soils at Katumani, semi-arid Kenya

Abstract

In semi-arid Kenya, the most dominant soil types are of limited agricultural productivity due to crusting and compaction. The occurrence of soil crusting and compaction is attributed to seasonal rainfall characteristics, physical soil properties and bad tillage practices. Soil crusting and compaction decrease rainwater infiltration and increase surface runoff. Seasonal rainwater losses through increased runoff volumes reduce soil moisture and hence result in agricultural drought. The objective of this study was to examine the hydrological effects of two tillage practices with and without farmyard manure on surface runoff and soil loss of crusting and compacting soils under field conditions at Katumani in semi-arid Kenya. Field investigations on rainfall characteristics, surface runoff, soil loss, soil bulk density and soil shear strength covered two rainy seasons (short and long rains) and were done on a Chromic Luvisol. The field treatments were zero tillage and conventional tillage, and two farmyard manure applications (5 and 10 Mg ha^{-1}). The results obtained showed significant effects of conventional and zero tillage and farmyard manure on infiltration and soil moisture, surface runoff and soil loss. Soil crusting and compaction significantly influenced the hydrological response of all treatments. These responses were attributed to seasonal rainfall events of varying amounts, intensities and duration, and treatment differences in soil surface conditions and aggregation. Farmyard manure (FYM) application enhanced infiltration and reduced soil crusting, compaction, and surface runoff during the initial stages of the rainy season. But in the mid-stages of the rainy season, the effects of FYM on soil aggregation diminished. Conventional tillage without farmyard manure led to high surface runoff and soil loss in this structurally unstable soil. Zero tillage performed poorly under these soil conditions because of high soil crusting and compaction, low rainwater infiltration and subsequent increase in surface runoff generation.

4.1 Introduction

Semi-arid environments in Kenya occupy approximately one third of the country's total land area. Land use in semi-arid Kenya consists of approximately 30% rainfed agriculture and 70% rangeland. Soils are considered as problem soils because their physico-chemical properties limit their uses for agricultural production. The most important problems are crusting and compaction (Hoogmoed, 1999). Over the past three to four decades, semi-arid environments in Kenya have experienced some unprecedented soil degradation due to an ever-increasing human and livestock population (Government of Kenya, 1992). This population increase is due to continuing migration of people with their livestock from the humid highlands to the semi-arid lowlands in search of more productive land. The establishment of settlements and subsequent fragmentation of land and cultivation of fragile semi-arid ecosystems has resulted in a rapid decline in agricultural productivity (Biamah et al., 1994). This decline in soil productivity is specifically attributed to the overgrazing and over-cultivation that has caused severe soil erosion, soil crusting and compaction, soil moisture and soil fertility problems (Biamah et al., 2000).

Soil crusting and compaction through human activities and natural forces has reduced productivity of semi-arid soils and destabilized fragile ecosystems (Le Houerou, 1996; Thurow, 1991). Soil crusting and compaction can result from accelerated soil erosion, loss of vegetative cover, oxidation of soil organic matter, and impairment of other soil physical, chemical, and biological properties (Romkens et al., 1995; Unger, 1996; USDA-ARS, 2001). For structurally unstable soils, the occurrence of soil surface sealing and crusting leads to the development of a top soil layer with a higher bulk density, lower porosity and lower conductivity than underlying soil (Moore, 1981). In semi-arid Kenya, soil crusting and compaction is an increasing problem that has reduced rainwater infiltration and soil moisture storage in cultivated lands. Soil crusting and compaction also inhibit seed germination and root penetration of dryland crops (Biamah et al., 1993).

Soil compaction is regarded as the most serious environmental problem caused by conventional agriculture and is a reversible form of soil degradation (Arshad, 1999; Balasdent et al., 2000; Biot et al., 1995; Koolen, 1994; McGarry, 1990; Oldeman et al., 1991; Soane and van Ouwerkerk, 1994). Soil compaction may be a naturally occurring condition especially with heavy clay soils (e.g. Vertisols) and sometimes referred to as hardsetting (McGarry, 1993; Mullins et al., 1990; Mullins and Ley, 1995) or soils known to have subsurface hardpans (e.g. Luvisols) and at times referred to as soil structure degradation (Douglas et al., 1999; McGarry, 1993). Soil compaction may also arise due to bad soil tillage practices (Robertson and Erickson, 1980). Some of the causes of compact soil conditions include: (1) naturally compact subsoil; (2) inadequate surface and subsurface drainage due to field operations done when soils are wet; (3) excessive tillage which weakens soil aggregate stability; (4) inadequate replenishment of soil organic matter through application of crop residues and farmyard manure; (5) cropping systems involving more tillage operations; (6) untimely field operations (ploughing, harrowing, planting and harvesting); and (7) inadequate design of some farm implements (Allmaras et al., 1993; Coder, 2000; Petersen and Ayers, 2001). Effects of soil compaction on physical soil properties are characterized by a decrease in soil porosity, increase in draft power requirements for tillage, a breakdown of soil aggregates and restriction of root penetration in soils. Depending on the degree of soil compaction, its effects on soil physical properties may or may not be harmful to plants. For instance, an air filled pore space of less than 10% when soil moisture is at field capacity can be expected to restrict root growth and subsequent crop development (Vomocil and Flocker, 1961).

Soil crusting is yet another soil degradation problem that significantly influences the hydrologic response of soils (Thurow and Taylor, 1999). Soil crusting is common where there are unfavourable tillage practices and a low soil organic matter content. Crust-prone soils are characterized by a poor stability of the surface layer (Hoogmoed, 1995; 1999). Excessive tillage results in soil pulverization and burning of organic matter. When pulverized soils are exposed to raindrop impact, detached particles clog soil pores and seal them completely (Lynch and Bragg, 1985). Soil crusting causes the destruction of soil structural units within the top few millimetres of the soil profile and consequently results in the loss of voids within and between structural aggregates and soil particles (FAO, 1995). In crusting soils, surface sealing under rainfall markedly affects infiltration (Edwards and Larson, 1969; Freebairn et al., 1991; Moore, 1981). Edwards and Larson (1969) observed that there was a 50% reduction in infiltration after a two hour period of rainfall and attributed it to soil crusting. A "washed in" layer of clay particles that clogs soil pores and forms a crust may reduce infiltration rates by up to 90% (Boyle et al., 1989). As a site becomes increasingly vulnerable to soil crusting and compaction, the difficulty in maintaining soil moisture storage and soil aggregation increases and the site becomes more vulnerable to accelerated soil erosion, which consequently reduces the production potential of the soil (Le Houerou, 1996; Mannering, 1981; Thurow, 1991).

The most common tillage practice in semi-arid Kenya is conventional tillage using ox-drawn mouldboard ploughs or hand hoes. This tillage is done with and without farmyard manure application and to a maximum depth of about 10 to 15 cm. Conventional tillage of structurally unstable soils is a major contributor to the soil crusting and compaction problem and related increases in surface runoff and soil loss (Biamah et al., 1994). Moreover, the conventional tillage may result in sub-surface plough pans that negatively affect soil hydrology (Biamah et al., 1993). With traditional tillage practices, timeliness of seedbed preparation is difficult to achieve especially where ground-breaking operations require more draft power. High labour demands during the period before the onset of the rains, often delay seedbed preparation operations and thus affect soil productivity. Furthermore, soil productivity is threatened by the shallow digging that is quite evident on cultivated lands in semi-arid Kenya (Gitau and Biamah, 2000). The occurrence of subsurface hardpans has often delayed tillage operations up to the onset of the rains when soil moisture conditions would be favourable and draft power requirements are low.

Farmyard manure applications are occasionally used in areas where crusting soils are dominant to improve soil moisture storage and seedling emergence (i.e. by reducing crust formation), and to improve soil aggregation and permeability (Biamah et al., 1993). Farmyard manure applications are done at 3 to 5 Mg ha^{-1}. However, at the onset of seasonal rains, the loosening of soil due to manure application could reduce the resistance of a soil to rainfall erosivity and hence result in more surface runoff and soil loss (Biamah, et al., 1994). This risk of erosion due to farmyard manure application is critical when the soils are still bare with no ground cover and with good aggregate stability and infiltrability. The farmyard manure that is used by farmers is a mixture of cow dung and crop residues or grass straws. Its chemical composition varies with mix ratios and quality of the residues used.

Given the decline in soil productivity and associated increase in soil crusting and compaction on cultivated lands in semi-arid Kenya, it is important that farmers understand the hydrologic responses of crusting and compacting soils to tillage and residue management techniques. The suitability of these techniques should be seen in terms of improved infiltrability and soil structure stability, and thus reducing surface runoff and soil loss. The objective of this study was to examine the physical effects of different tillage practices, with and without farmyard manure, on surface runoff and soil loss of crusting and compacting soils under field conditions in semi-arid Kenya.

4.2 Materials and methods

4.2.1 The study area

The experimental site selected for this study was the National Dryland Farming Research Centre, at Katumani. The Katumani Research Centre ($37^0 14$'E; $01^0 35$'S) is located in the dry lowlands of Machakos, Eastern Kenya. It is situated in the transitional agro-climatic zone IV/V, a livestock-millet zone, with a semi-arid climate. The ratio of rainfall to potential evaporation (R/E_o) is the criterion for classifying agro-climatic zones in Kenya (Sombroek et al., 1982). Semi-arid agro-climatic zones have an R/E_o ratio range of 25% to 50%, and have medium to low potential for plant growth and a high risk (25%-75%) of crop failure (Sombroek et al., 1982).

The site has a bimodal rainfall pattern that is common in most of semi-arid Kenya. The long rains occur from March to May and the short rains occur from October to December (Fig. 1). The mean annual rainfall during the last 27 years was 702 mm. The most reliable rains are the short rains as is the case in most of semi-arid Kenya. The dates of onset of the rains are mid-March for the long rains and mid-October for the short rains. Rainfall is usually of high intensity and short duration (Stewart and Faught, 1984).

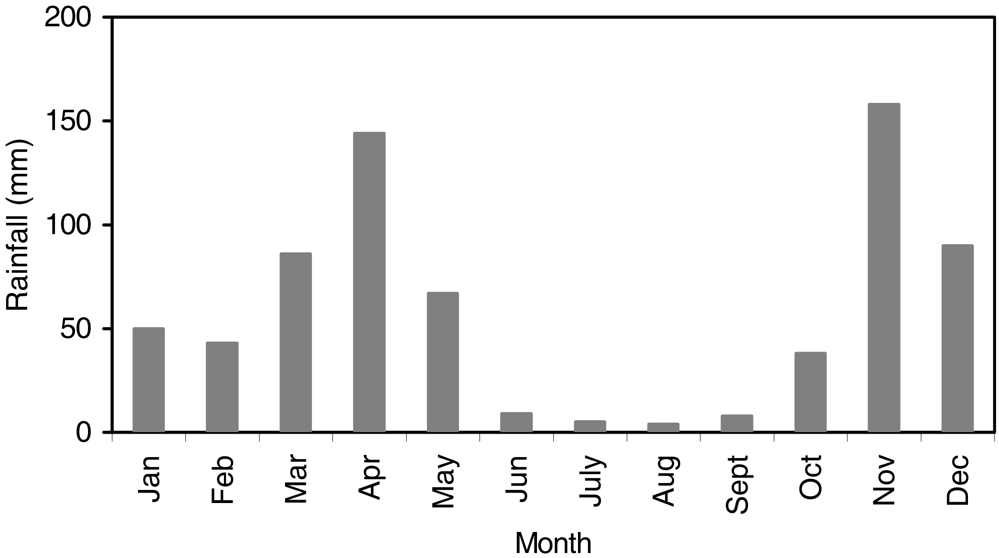

Figure 1. Long-term mean monthly rainfall distribution at Katumani, Machakos, Kenya.

The soils at Katumani are characterized as structurally unstable and crusting sandy clay loams, which are classified as Chromic Luvisols (FAO/UNESCO Classification). This soil type is structurally unstable as depicted by a rapid breakdown in soil aggregation when exposed to intense rainstorm events. This instability is attributed to the inherent low organic matter content of the soils (Table 1). The most prevalent soil problems are soil crusting and compaction, soil erosion, seasonal soil moisture deficits, and low soil fertility.

Table 1. Properties of a Chromic Luvisol at the Katumani experimental site, Machakos, Kenya.

Soil profile depth (cm)	Bulk density ($Mg\ m^{-3}$)	Soil texture Sand (%)	Silt (%)	Clay (%)	Organic matter (%)	Textural class†	Field capacity (%vol)	Wilting point (%vol)	Available moisture (%vol)
0-15	1.42	67	5	28	1.6	SCL	26	9	17
15-35	1.40	64	7	29	1.4	SCL	27	13	14
35-60	1.37	57	8	35	0.7	SCL	22	11	11
60-100	1.34	51	8	41	0.6	SC	24	15	9

† SCL – Sandy Clay Loam; SC – Sandy Clay

The management of Katumani soils requires minimum disturbance of subsoil horizons and improved rainwater infiltration. Feasible interventions for minimizing surface runoff include maintaining ground cover (e.g. cover cropping and mulching), modification of soil surface conditions (using minimum, conventional and conservation tillage) and increasing surface water storage (e.g. tied ridges and micro catchments). The application of farmyard manure is expected to reduce inherent surface crusting properties of these soils and hence improve rainwater infiltration and increase soil moisture storage.

4.2.2 Experimental procedure and analysis

The physical effects of tillage and farmyard manure on surface runoff and soil loss were measured under bare soil conditions during one short rainy season (1992/93) and one long rainy season (1993). This experiment was based on a completely randomized block design of three blocks of four plots. The size of the plots was 2 m^2. Each block consisted of four treatments: (1) conventional tillage without manure (CT); (2) zero or no tillage without manure (ZT); (3) conventional tillage with 5 Mg ha^{-1} of farmyard manure (5 FYM); and (4) conventional tillage with 10 Mg ha^{-1} of farmyard manure (10 FYM). Conventional tillage was done with a forked hoe, before the onset of the short and long rains. Farmyard manure was also applied twice, at the onset of the short rains and at the onset of the long rains. The farmyard manure was a mixture of cow dung and crop residues or grass straws and was prepared through composting. For the mixture to decompose well, it was preserved for several months before application on the experimental plots.

Several soil parameters were measured in the topsoil (0-15 cm) of the experimental plots. Measured parameters related to soil structural stability were organic matter content and soil aggregate stability. Soil samples from each treatment were taken for organic matter content determination using the Walkley-Black Method (Nelson and Sommers, 1982). This method was used to determine the organic carbon content of each sample. To get the percentage organic matter content, organic carbon was multiplied by a conversion factor of 1.73. The determination of soil organic matter content was done at the beginning and at the end of each rainy season. Soil aggregate stability was determined using the wet sieving method (Kemper and Rosenau, 1986; Burke et al., 1986). This method determines the percentage of water stable aggregates after 10 minutes of wet sieving a soil aggregates sample of 25g. After sieving, the percentage stable aggregates are determined as follows: % of stable aggregates = 100 x (weight of aggregates retained)-(weight of sand)/(total sample weight) – (weight of sand). Soil crusting and compaction was monitored using bulk density and soil shear strength measurements. Bulk density was measured using 100 cm^3 ring samples that were oven dried for 24 hours at 105°C. Bulk densities were determined at the beginning and at the end of every rainy season. Soil shear strength was measured on a weekly basis using a shear vane apparatus.

At each plot, rainfall, surface runoff and soil loss measurements were made for every rainfall event. Rainfall was recorded on a storm-by-storm basis using two rain gauges (recording and non-recording) installed at the site. Rainfall intensity and distribution was obtained from the recording or autographic rain gauge. Kinetic energy of each rainstorm event was computed. Surface runoff and soil loss were measured using a collecting trough, a PVC pipe to convey the surface runoff and suspended sediment into the collector, a collector unit with a 200 liter metallic drum and a 20 liter plastic container (used for low runoff and sediment collection). Soil moisture was determined gravimetrically on a weekly basis in every plot. Surface runoff and soil losses were monitored on a storm basis.

The effects of single storms on the hydrologic response of Katumani soils were monitored during the experimental period. The analysis focused on temporal changes in infiltration, surface runoff and soil loss of the crusting Luvisol when subjected to conventional tillage, zero tillage, and farmyard manure application (5 and 10 Mg ha^{-1}). Differences in treatment responses were then described in terms of hydrologic processes and associated characteristics (amount, intensity and duration) of rainfall events. This analysis was based on a selected sample size of one rainy season, the short rains of 1992/93.This selection was due to the good rainfall received in the short rains as opposed to the long rains. A one-way analysis of variance (ANOVA) at 5% level of significance was used to determine the differences between treatments.

4.3 Results and discussion

Rainfall amounts received during the 1992 short rains were unusually high (767 mm compared to a 27 year seasonal mean of 379 mm), and unusually low during the 1993 long rains (108 mm compared to a 27 year seasonal mean of 297 mm) (Fig. 2). Other extreme rainfall amounts recorded during the short rains season were 155 mm in 1981 and 925 mm in 1961, while during the long rains season these extremes were 133 mm in 1973 and 660 mm in 1979 (Stewart and Faught, 1984; Stewart, 1988). When comparing the number of rainy days during the two seasons, there were 69 rainy days over a 151 days period during the short rains season and 11 rainy days stretched over a 61 days period during the long rains season.

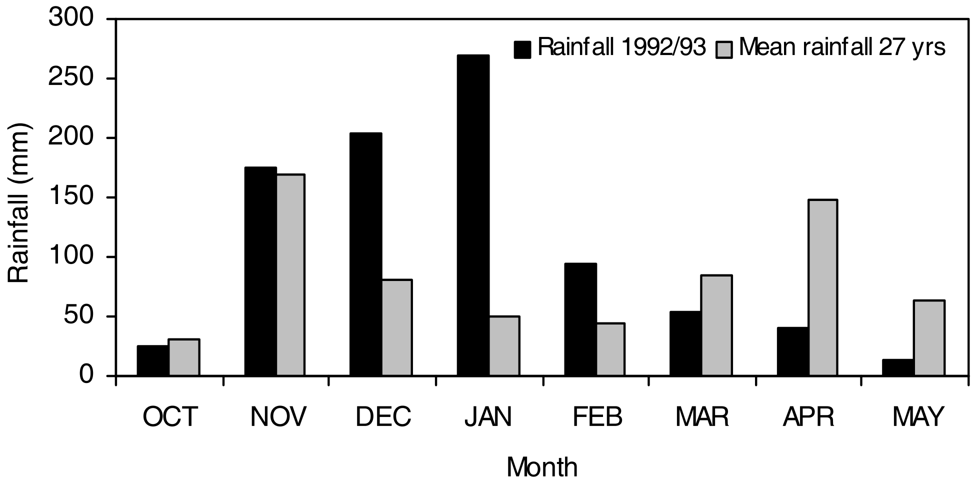

Figure 2. Seasonal rainfall distribution at Katumani, Machakos, Kenya.

Rainfall duration varied with individual rainstorms. The maximum storm duration recorded was 10 hours and 48 minutes with a rainfall amount of 24 mm, while the minimum storm duration was 6 minutes with a rainfall amount of 1 mm. The mean storm duration was 2 hours and 30 minutes. Rainfall intensity varied from 46 mm hr^{-1} to 0.5 mm hr^{-1} with a mean of 8 mm hr^{-1}.

Application of farmyard manure resulted in an initially much higher organic matter content and aggregate stability at the beginning of the short rainy season, but these soil properties significantly decreased at the end of the long rainy season (Table 2). The lowest values of organic matter content of 10 FYM and 5 FYM were only slightly higher than the values in the non-fertilized plot treatments of conventional tillage (CT) and zero tillage (ZT). This result indicates the difficulty of increasing the organic matter contents in semi-arid soils, where burning of organic matter is generally high (Thomas et al., 1981). However, despite the rapid decrease in organic matter contents, the application of organic matter still resulted in a better soil structure, as reflected by the percentage stable aggregates (Table 2). This was not only true at the beginning of the experiment, but also at the end, when the FYM plots still had 5 to 7% more stable aggregates.

Table 2. Treatment effects on organic matter content and stable aggregates in the topsoil (0-15 cm) of a Chromic Luvisol during the short and long rainy seasons at Katumani, Machakos, Kenya.

Treatment	Highest† organic matter content (%)	Lowest‡ organic matter content (%)	Highest† stable aggregates (%)	Lowest‡ stable aggregates (%)
10 FYM	2.5	1.6	26	17
5 FYM	2.1	1.5	20	15
CT	1.6	1.4	12	10
ZT	1.5	1.4	11	10

† Highest values were obtained at the beginning of the short rainy season.
‡ Lowest values were obtained at the end of the long rainy season

Soil crusting and compaction changes during the experimental period were based on treatment differences in soil bulk densities for compaction and differences in soil shear strengths for crusting (Table 3). Soil bulk density and shear strength varied with seasonal soil moisture contents and were lowest at the beginning and increased during the two rainy seasons. The highest bulk densities and soil shear strengths were observed at the end of the short rains season. Soil bulk density and shear strength were highest under ZT and CT, and lowest under 5 and 10 FYM treatments.

The increase in soil bulk densities and shear strengths in the topsoil horizons, which may have affected root penetration of the crops grown in the area, were attributed to soil crusting and compaction due to raindrop impact, decrease in organic matter content (Table 2) and high evaporation rates from the bare soil surface during dry spells. A high bulk density of 1.65 Mg m^{-3} for sandy clay loam and 1.5 Mg m^{-3} for clay loam soils is known to limit root growth leading to poor water and nutrient extraction from deep soil horizons (Coder, 2000). This also leads to inadequate aeration and subsequently to poor crop productivity.

The highest bulk densities and shear strengths were observed in the plots with zero tillage treatments. Because no tillage was applied in those plots, the initial values were higher than those in the other treatment plots. But the strong increase in bulk density during the short rains (from 1.28 to 1.58 Mg m^{-3}) is not fully understood. The most likely explanation is the combination of a low amount of stable aggregates (Table 2), low infiltration rates, and high evaporation rates from the bare soil surface.

Table 3. Treatment effects on bulk density and shear strength in the topsoil (0-15 cm) of a Chromic Luvisol at Katumani, Machakos, Kenya.

Treatment	Lowest† bulk density ($Mg\ m^{-3}$)	Highest‡ bulk density ($Mg\ m^{-3}$)	Lowest† soil shear strength (kPa)	Highest‡ soil shear strength (kPa)
10 FYM	1.21	1.45	8.0	10.0
5 FYM	1.25	1.45	9.1	10.2
CT	1.26	1.49	10.7	14.8
ZT	1.28	1.58	17.2	17.8

† Lowest values were obtained at the beginning of the short rainy season.
‡ Highest values were obtained at the end of the long rainy season.

The generation of surface runoff varied with antecedent soil moisture and seasonal rainfall characteristics. After the onset of the rains, there was rain falling every day for the first ten days of the short rains season. The first nine storms with a total rainfall amount of 70 mm never caused surface runoff or soil loss. Thus the first surface runoff was generated ten days after the onset of the short rains. Throughout the two rainy seasons, 23 out of 75 rainfall events caused surface runoff. Rainstorms of small amounts, low intensities and long duration never caused surface runoff. These storms occurred at the onset of the short rains when the soil was dry following the long dry season. Generally, there were neither significant differences in surface runoff between ZT and CT, nor between 5 and 10 FYM. But ZT and CT produced significantly ($P<0.05$) more surface runoff when compared to 5 and 10 FYM (Table 4). There was much more treatment runoff observed in the short rains season than in the long rains season due to the higher rainfall amount that occurred during this season.

Table 4. Treatment effects on surface runoff and soil loss from a Chromic Luvisol at Katumani, Machakos, Kenya.

Season	Rainfall	Treatment							
		ZT		CT		5 FYM		10 FYM	
	(mm)	Surface runoff (mm)	Soil loss ($kg\ m^{-2}$)	Surface runoff (mm)	Soil loss ($kg\ m^{-2}$)	Surface runoff (mm)	Soil loss ($kg\ m^{-2}$)	Surface runoff (mm)	Soil loss ($kg\ m^{-2}$)
Short rains, 92/93	767	327[a†]	9.52[c]	286[a]	14.77[d]	221[b]	10.00[c]	207[b]	9.35[c]
Long rains, 1993	108	52[e]	4.4[h]	40[f]	3.87[i]	34[g]	2.37[j]	31[g]	2.16[j]

†Values along the row with the same letter in superscript were not significantly different.

Soil aggregation, rainfall characteristics, and soil crusting and compaction significantly influenced soil loss. Rainfall that occurred during the short rains was of low intensity and long duration when compared to the high intensity and short duration rainfall that occurred in the long rains. An increase in soil aggregation enhanced depression storage of surface runoff, increased rainwater infiltration and decreased soil loss. There were no significant differences in soil loss between ZT, 5 and 10 FYM during the short rains season (Table 4). But, CT showed a significantly ($P<0.05$) higher soil loss when compared with the other three treatments due to the loosening of soils and consequent breakdown of soil aggregates.

The low soil loss values during the short rains for ZT were most likely the result of the initially crusted and compacted condition of the topsoil. The rainfall kinetic energy was too low in this season to cause serious soil losses. During the long rains, however, when kinetic energy of rainfall was much higher, the rainfall erosivity apparently was sufficient to cause a breakdown of soil stability, and soil losses were relatively high. Moreover, the seasonal decrease in organic matter content due to erosion and oxidation (due to high soil temperatures) contributed to the high soil losses in the long rains season.

In the long rains season, 5 and 10 FYM treatments had significantly ($P<0.05$) less soil loss when compared to ZT and CT tillage treatments (Table 4) because of the rainfall of low amounts, low intensity and long duration that occurred. There was more soil loss in the short rains season when compared with the long rains season due to more seasonal rainfall events that generated runoff. However, when soil losses between the two rainy seasons were compared in relation to surface runoff generated, more soil loss per unit runoff was observed in the long rains than during the short rains. This high unit soil loss observed in the long rains was attributed to rain storm events of high intensity, high kinetic energy and short duration that occurred. One example of such a rainstorm event was a highly erosive storm of 46 mm with a total kinetic energy of 1236 J m^{-2} and duration of one hour that occurred in the long rains. The soil losses due to this erosive storm were: 2.72 kg m^{-2} (CT), 2.21 kg m^{-2} (ZT), 1.54 kg m^{-2} (5 FYM), and 1.50 kg m^{-2} (10 FYM); and the runoff was 40 mm (ZT), 31 mm (CT), 26 mm (5 FYM), and 22 mm (10 FYM). During the same season, the additional soil losses occurred during two rainstorms, one of 12 mm on 1/4/93 with an intensity of 9.5 mm hr^{-1} and kinetic energy of 95 J m^{-2}, and one storm of 20 mm on 17/4/93 with an intensity of 5 mm hr^{-1} and kinetic energy of 182 J m^{-2}. The rest of the rainfall that occurred in the long rains season was of low intensity, low kinetic energy and long duration. For instance, the only significant rainstorm that occurred on 6/5/93 of 9 mm had an intensity of 2.6 mm hr^{-1}, kinetic energy of 51 J m^{-2} and duration of 3.5 hours.

The storm responses during the 1992/1993 short rains season varied with treatments and time of the season. At the onset of the short rains season (November, ‘92), when the unstable soil had been tilled (i.e. under CT and FYM treatments) and was cloddy, there were differences in storm runoff between tillage treatments (ZT and CT) and farmyard manure treatments (5 and 10 FYM) (Fig. 3). Zero tillage (ZT) resulted in the highest surface runoff amounts throughout the entire short rains season, but the difference with the CT treatment became less later in the season. These two treatments without farmyard manure had significantly ($P<0.05$) more surface runoff than the two FYM treatments. Farmyard manure application improved soil aggregation and thus also improved the infiltrability of the soil. However, the effect of the farmyard manure application was only significant in the first month of the rainy season. During subsequent events in the following two months of the same rainy season, there were hardly any differences between the four treatments.

Towards the end of the short rains season (February 1993), there was a significant ($P<0.05$) decrease in both single and cumulative storm surface runoff and soil loss (Fig. 3) because the rainfall was less erosive than in the previous month of January. For example, a storm of 38 mm that occurred on 20/1/93 and had a kinetic energy of 594 J m^{-2} caused a mean (of all plots) surface runoff amount of 22 mm and a mean soil loss of 1.52 kg m^{-2} whereas a storm of 50 mm that occurred on 9/2/93 and had a kinetic energy of 450 J m^{-2} caused a mean surface runoff amount of only 13 mm and a mean soil loss of 0.65 kg m^{-2}. The intensities of these rainstorms were 10 mm hr^{-1} for the 38 mm rainstorm and 5 mm hr^{-1} for the 50 mm rainstorm.

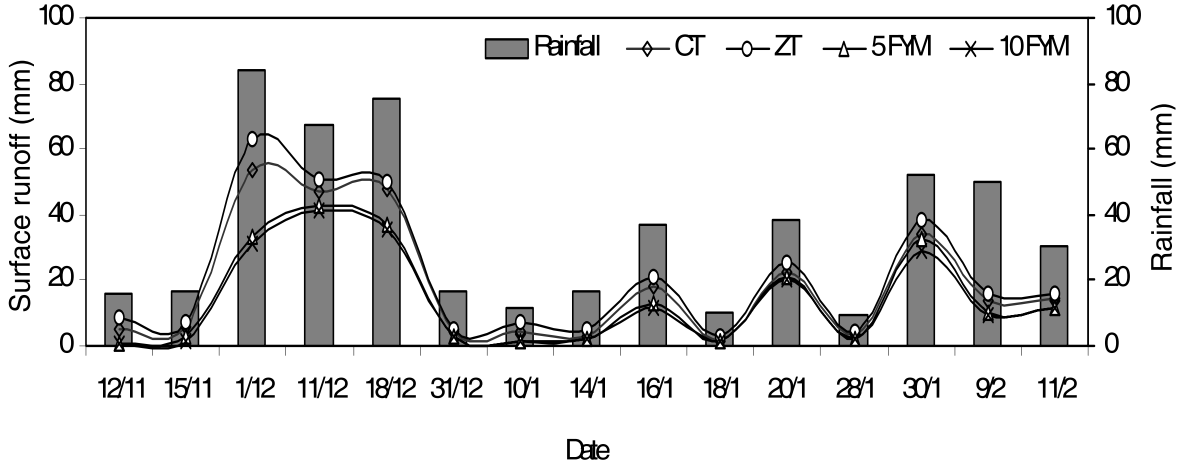

Figure 3. Hydrologic responses of a Chromic Luvisol to single rainstorm events during the 1992/1993 short rains season at Katumani. Machakos. Kenva.

During this short rainy season, the effect of farmyard manure application was more pronounced in the first two months after the onset of rains than in later stages of the rainy season (Fig. 3). This was attributed to the seasonal decrease in soil aggregation due to the decrease in soil organic matter content (Table 2) and the related increase in soil bulk density and shear strength (Table 3). An increase in soil bulk density was indicative of an increase in compaction while an increase in shear strength showed increased soil crusting.

4.4 Conclusions

Soil physical properties and their effects on soil crusting and compaction varied with time during the experimental period. Soil aggregation improved with the application of farmyard manure. However, there was a decrease in soil aggregation for all FYM treatments at the end of each rainy season. The strongest decrease in soil aggregation was in 5 and 10 FYM. This decrease was attributed to a reduction in soil organic matter content due to oxidation and soil losses. Soil bulk density and shear strength gave indications for soil crusting and compaction. They varied with treatment and both properties increased during the rainy seasons. Soil shear strength and bulk density were highest under ZT and CT, and least under FYM treatments. They reached the highest values at the end of the short rains season.

Farmyard manure application enhanced infiltration, reduced soil crusting and compaction and decreased surface runoff during the initial stages of the rainy season. Towards the end of the rainy season when soil crusting and compaction had occurred, some significant decrease in soil loss with FYM treatments was observed. Conventional tillage without farmyard manure led to high surface runoff and soil loss for this structurally unstable Chromic Luvisol. Zero tillage performed poorly under these soil conditions because of the significantly high soil crusting and compaction and subsequent high surface runoff and low rainwater infiltration.

In conclusion, zero tillage (no-tillage) was not appropriate for the soils of Katumani, Machakos, Kenya, because it leads to increased surface runoff due to crusting and compaction. Also the high bulk densities observed under zero tillage may impede root development and result in poor crop productivity. Conventional tillage without farmyard manure leads to low rainwater infiltration, high surface runoff and soil loss, especially at the onset of the rains when highly erosive rainstorms occur in semi-arid Kenya. Thus, conventional tillage without farmyard manure is not effective in reducing surface runoff and soil loss for the unstable crusting and compacting Chromic Luvisols of Katumani. Farmyard manure application significantly decreases soil crusting and compaction and hence improved hydrological conditions of soils for crop productivity. Also farmyard manure application can reduce surface runoff only where rainfall events of low amounts and intensity, and duration are expected. Otherwise farmyard manure application under rainstorms of high amounts, high intensity and short duration, would still generate significant amounts of surface runoff.

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Chapter 5

Influence of land use changes on watershed runoff volume: Application of AGNPS model in Iiuni watershed, Kenya

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Influence of land use changes on watershed runoff volume: Application of AGNPS model in Iiuni watershed, Kenya

Abstract

Watershed modeling offers a good approach for simulating an agro-hydrologic system's response to different land use changes like conservation tillage and terracing. Thus a watershed's hydrologic response can be predicted by incorporating system variables, and validating the model for a given location. The objective of this study was to use a semi analytical model, the Agricultural Non-point Source Pollution (AGNPS) model to predict the effects of land use changes on surface runoff volume from selected rainstorm events in Iiuni watershed, Machakos, Kenya. This model was applied using input parameters derived from watershed characteristics that included slope, soil type, vegetative cover, land use, storm rainfall and stream flow data. These watershed characteristics were obtained from rain gauges, a stream gauging station, a resource survey and subsequent interpretations of topographical map, aerial photographs and a remote sensing image of the study area. The results obtained showed that the AGNPS model gave good predictions of surface runoff volumes under the wet antecedent moisture condition, due to the shallow ploughed soil layer that was prone to soil surface sealing. The crusting of the soils is known to generate high amounts of surface runoff. Model evaluation using statistics of comparison showed acceptable results. The coefficients of efficiency, R^2 were above 70% for the model, indicating good model prediction of runoff volume. This study has shown that for Iiuni watershed, storm runoff is distributed 66% as direct runoff and 34% as base flow. However, direct runoff makes 10% and base flow 5.6% of the total rainfall. Thus the rest of received rainfall (84%) is retained within the watershed as expected due to effective soil conservation practices in place. The generation of runoff in Iiuni watershed was influenced by land use changes that included terracing and conservation tillage. Despite the significant changes in land use changes between 1978 and 1996, their effects on *CN* values and runoff prediction values were insignificant. Land use changes and antecedent soil moisture conditions explained the variability of curve numbers and hence the generation of surface runoff within the watershed.

5.1 Introduction

Agricultural watersheds in semi-arid Kenya are prone to episodic seasonal agricultural droughts of varying severity and duration (Sharma, 1996; 1997). The occurrence of agricultural droughts is attributed to low, erratic and ineffective rainfall of high intensity and short duration, and consequent surface runoff generation. Depending on hydrologic and soil conditions, up to 70% of the total rainfall may be lost as surface runoff and hence reducing significantly effective rainfall (Biamah et al., 1998). The ineffectiveness of rainfall is responsible for the soil moisture deficits and associated crop failures that are characteristic of semi-arid agricultural watersheds. The recurrence of soil moisture deficits has been attributed to low infiltration of rainwater (due to soil crusting and compaction) and low organic matter content of the soils (Biamah et al., 1993).

In semi-arid Kenya, population pressure has contributed to agricultural drought through bad land use changes such as overgrazing, deforestation, and continuous cultivation for dryland crop production (Biamah, 1988; Tiffen et al., 1994; Biamah et al., 1998). The very high demand for agricultural land has almost invariably pushed farmers into cultivation of very steep lands using intensive and exploitive cultivation techniques that have led to the withdrawal of soil organic matter and associated reductions in soil quality (Biamah and Rockstrom, 2000; Hoogmoed et al., 2000). Hence, there is a strong need for conservation practices in these semi-arid areas.

The scientific basis for determining the best conservation practices for soil and water management in a watershed is that of modeling a system's response to selected practices (Anderson and Howes, 1986). Mathematical modeling provides a reasonable approach for simulating a real system by incorporating system variables such that once the model has been validated for a given location, it can be used in another location by replacing some of the system variables by appropriate values valid for the new location (Sarkar and Bhattacharya, 1988). Mathematical models could be empirical or process-based and are widely used to predict watershed runoff. An appropriate model for predicting watershed runoff should be simple given the complexity of watershed hydrologic processes and the limitations on data availability (Anderson and Howes, 1986). The degree of accuracy of predicted runoff values is established by the closeness of the predicted values to the measured values (Chanasyk et al., 2003).

Approaches to watershed hydrology prediction are twofold: those oriented towards scientific research objectives using the distributed parameter approach and those oriented towards practical applications using the lumped parameter approach. Scientific research objectives are achieved through the application of distributed models like the Agricultural Non-Point Source Pollution (AGNPS) model that requires detailed and accurate spatially distributed input data. Where there are data limitations and the emphasis is on practical application objectives, simple and empirically derived lumped models like the Soil Conservation Service-Curve Number (SCS-*CN*) are used for forecasting and prediction of hydrologic processes (Anderson and Howes, 1986).

The potential areas of mathematical model applications in watersheds include: prediction of the effects of changes in land use on spatial patterns of surface runoff and sediment yields in small watersheds; prediction of discharge from un-gauged watersheds or watersheds with limited hydrologic data; and prediction of effective rainfall at the elemental area (farmer's plot) scale where soil and climatic conditions are homogeneous (Biamah et al, 1998; Nielsen and Panda, 1988). Thus modeling of surface runoff and effective rainfall is of practical significance to the farmer and in the mitigation against seasonal agricultural drought, since the model should be able to respond to changes in conservation practices and land cover. The information provided by models would support watershed management and the selection of the best conservation practices for control of surface runoff and erosion.

The objectives of this study were: (1) to test the performance of the AGNPS model in predicting surface runoff volume from a semi-arid watershed in Kenya, and (2) to evaluate the effect of land use changes on the hydrologic response of the watershed.

5.2 Materials and methods

5.2.1 The study watershed

The area where the study was conducted is Iiuni watershed, which is located in the semi-arid south-eastern part of Machakos, Kenya. The watershed extends from west to east between longitudes 37°20′E to 37°23′E, and from north to south between latitudes 1°39′S to 1°41′S (Thomas et al., 1981). It has relatively concave ridges and watercourses running in a north-westerly direction (Fig. 1). The watershed has an area of 12 km^2 and is located in agro-climatic zone IV/V that is a livestock-millet zone (Sombroek et al., 1982). Of this total area, approximately 60% is agricultural

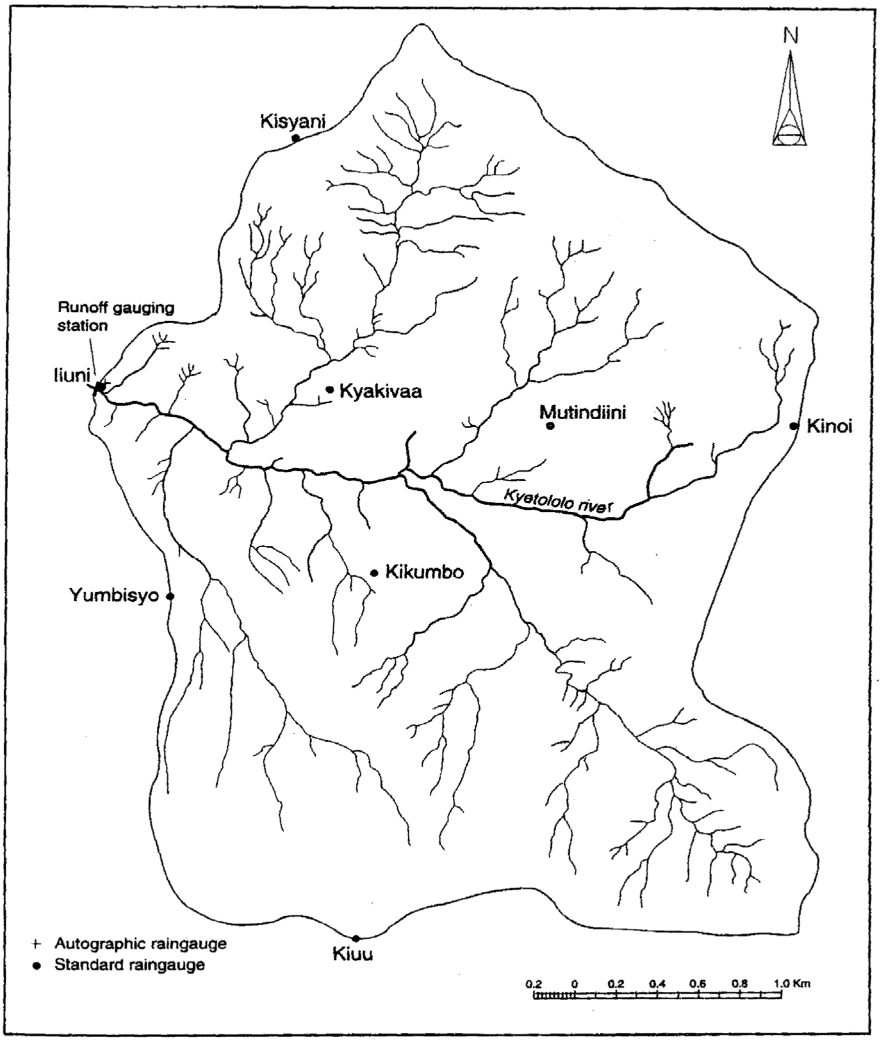

Figure 1. Drainage pattern and distribution of rain gauge stations at Iiuni watershed, Machakos, Kenya.

land and 40% is rangeland (Biamah et al., 1998). The mean annual rainfall of Iiuni is 851 mm (based on 16 years rainfall data) and is bimodal with the long rains due from March to May and the short rains from October to December. The mean annual temperatures vary from 22°C to 28°C with no frosts at night. The mean annual potential evaporation ranges from 1650 mm to 2000 mm (Biamah et al., 1998). Iiuni watershed was identified for this study because of its hydrologic, soil and morphological characteristics that are representative of other semi-arid environments.

A watershed resource survey, which involved soil and land use surveys was conducted at a semi-detailed scale of 1:20,000. The soil survey was done using 120 auger hole observations (one observation per every 9 ha) and 20 profile pit descriptions combined with aerial photo (scale of 1:10,000) interpretations. The soil sampling sites were selected randomly according to physiographic units identified within the watershed. The base map used in this resource survey was prepared from available topographic maps (scale of 1:50,000) of the watershed. Land use survey was based on aerial photo and satellite imagery (SPOT imagery at a scale of 1:50,000) interpretations. This resource survey provided information on physiography, soils and land use. The land use survey was done twice: in 1978 (Lesslie and Mitchell, 1979) and in 1996 (Biamah et al., 1998).

There are four distinct physiographic units namely: hills, uplands, colluvial foot slopes, and dissected river valleys and floodplains. The hills or foot slopes (e.g. surrounding Kalama and Iiuni hills) have slopes of 35% to 47% with some areas increasing to more than 60%. The colluvial foot slopes have slopes ranging from 5% to 35% and extend downslope to the valley slope breaks. The river valley sides and floodplains have slopes ranging from 2% to 5%. The majority of slopes are convex in shape and vary from 5% to 47%. These slopes are suitable for conservation bench terraces. The slopes above 47% are steep, dissected and unsuitable for agriculture (Lesslie and Mitchell, 1979; Thomas et al., 1981).

The dominant soil types found in Iiuni watershed include: Lixisols, Alisols, Leptosols, Acrisols, Planosols, Cambisols, Gleysols, Arenosols, Vertisols and Fluvisols (FAO/UNESCO Classification, 1990). Some of these soils are unstable and are highly susceptible to surface crusting and erosion. The soils generally have low organic matter contents, low cation exchange capacity and are deficient in phosphorus, nitrogen and calcium (Biamah et al., 1998).

Land use in Iiuni watershed is mainly agriculture. Smallholder mixed farming (crop production and grazing) is widely practiced within the watershed. The subsistence crops that are grown in this area include maize, beans, pigeon peas and millet. Most of the rangelands are used for grazing by cattle and goats. The common natural vegetation occurs as scrublands and bushlands. The most dominant tree species are *Acacia*, *Euphorbia*, *Aloe Vera* and *Combretum* species, which are found in degraded grazing lands.

5.2.2 Model selection

The AGNPS model (Young et al., 1987; 1989) was selected for simulating hydrology in Iiuni watershed for selected rainstorm events. AGNPS is an event-based, distributed parameter erosion model, which utilizes directly the spatial variations of key land characteristics (e.g. soil type, vegetation and topography) in determining surface runoff, erosion and watershed discharge (Young et al., 1987; 1989). It simulates surface runoff volume, peak flow rate, sediment yield, and nutrient yield from medium to large sized agricultural watersheds by using empirical and quasi-physically based algorithms (Grunwald and Norton, 1999). Basic model components include: hydrology, erosion, sediment transport and nutrient transport. The model requires information about rainfall, soil characteristics, relief and land use at elemental area or cell basis. Surface runoff is routed through cells from the watershed divide to the outlet in a stepwise manner so that flow at any point between cells may be examined. The direction of surface runoff is based on the drainage direction determined from topography information (Young et al., 1989). For watersheds exceeding 800 ha (8 km^2), cell sizes of 16 ha are recommended (Young et al., 1989). Reducing the cell size can increase accuracy of results, but this increases the time and labor required to run the model.

AGNPS permits simulation of hydrological processes that change both spatially and temporally throughout the watershed. In this study, the model was only used to calculate the surface runoff volume for each cell on a storm basis. After establishing if a watershed has a potential surface runoff problem, conservation practices can be recommended by assessment of their effects on hydrology and erosion. It is possible to vary input data consistent with alternative conservation practices and analyzing the resulting watershed response (Young et al., 1989). Also, effects of land use changes on hydrology can be analyzed by adjusting input to the new land use conditions.

The hydrology component of the model includes estimates of surface runoff volume and peak runoff rate for each cell. Surface runoff volume estimates are based on the SCS-Curve Number (SCS-*CN*) model (USDA-SCS, 1972). The relationship between storm rainfall and runoff is given by:

$$Q = \frac{(R - 0.2s)^2}{(R + 0.8s)} \qquad R > 0.2s \qquad [1]$$

where Q is the storm runoff (mm), R is the storm rainfall (mm), and s is the retention parameter or potential maximum storage (mm). The retention parameter varies with watershed characteristics (soils, land use, slope, soil management practices and soil moisture content). It is related to the curve number (*CN*) by (USDA-SCS, 1972):

$$s = 254\left(\frac{100}{CN} - 1\right) \qquad [2]$$

The constant 254 is used to convert s from inches into mm. The key parameter is the *CN*, a dimensionless parameter that varies from 0 to 100 and is dependent on rainwater infiltration capacity, land use or cover; soil management practice, hydrologic soil group and the moisture condition of the soil (Grunwald and Norton, 1999). The USDA Soil Conservation Service (USDA-SCS, 1972) divided all soil groups into four hydrologic groups A, B, C, and D on the basis of final infiltration rates. These hydrologic soil groups have final infiltration rates of 8-12 mm h^{-1} for A, 4-8 mm h^{-1} for B, 1-4 mm h^{-1} for C and 0-1 mm h^{-1} for D.

The storage capacity of the soil is influenced by the rainfall in the preceding period, which is accounted for by taking the total rainfall amount in the preceding five days as an Antecedent Moisture Condition (AMC). There are three antecedent moisture conditions (AMC I, II, and III). AMC I is for dry soil conditions, with low surface runoff potential. AMC III is for wet soil conditions prior to the rainstorm. AMC II is for median soil conditions and is often used for computing the average *CN*, which can be obtained easily for any area using the SCS Hydrology Handbook (USDA-SCS, 1972) or other hydrology literature (Chow et al., 1988). *CN*'s for AMC I and III can be computed with equations which are related to the *CN* for AMC II, or can be obtained from standard tables (USDA-SCS, 1972).

Within a cell, various physiographic units, hydrologic soil groups and land use types may occur and affect the *CN* value. Hence, a single *CN* value for each cell was derived by weighting the *CN*s according to the proportion of the area within the cell occupied by each land use type, conservation practice and hydrologic soil group using the equation:

$$Weighted \quad CN = \frac{A_1 CN_1 + A_2 CN_2 + \ldots + A_n CN_n}{A_1 + A_2 + \ldots + A_n} \qquad [3]$$

where A_1, A_2, …, A_n are the respective areas of the land use, conservation practice and hydrologic soil groups within the cell, and CN_1, CN_2, …, CN_n are the corresponding curve numbers. The derived weighted *CN* value represented the median soil moisture condition (AMC II).

According to Williams (1995), the standard *CN* values need to be adjusted according to the average slope percentage of the watershed. The tabulated *CN* values for AMC II are assumed to represent an average slope of 5%. The following equations was developed to adjust for other slopes (Williams, 1995):

$$CN_s = \frac{1}{3}\left(CN_{AMCIII} - CN_{AMCII}\right)\left[1 - 2\exp\left(-13.86\varphi\right)\right] + CN_{AMCII} \qquad [4]$$

where CN_s is the adjusted *CN* value, and φ is the average slope (%) of the watershed. This equation was used to adjust *CN* values for the different grid cells, using the average slope of the cell.

Finally, the obtained *CN* values were adjusted according to the previous 5-day rainfall to either a dry (AMC I) or wet (AMC III) condition using the standard tables from the USDA-SCS (1972).

5.2.3 Model application

Surface runoff volumes corresponding to specific rainstorm events were predicted using the AGNPS model. When the model was subjected to three runs using cell sizes of 16 ha for 76 cells, 10 ha for 134 cells and 4 ha for 294 cells, it was observed that cell size had no significant effect on predicted surface runoff volume within the watershed. Boerboom (1992) also observed similar results while performing a sensitivity analysis of this model. Thus final model runs were done using one cell size of 16 ha for 76 cells**.**

Field data collected from the watershed on a storm basis included: rainfall amount, rainfall intensity, and storm runoff volume. On a periodic or seasonal basis the data collected was on surface runoff flow directions, land use types (crop management and conservation practices), channel width, channel roughness characteristics, channel and land slope, canopy and ground cover, infiltration capacity, soil texture, soil bulk density, and antecedent soil moisture content.

Rainfall of each event was observed from one recording and eight non-recording rain gauge stations placed in strategic locations within the watershed (Fig. 1). Stream flow data was obtained from a gauging station (compound rectangular weir) with an automatic water level recorder installed at the outlet of the watershed at the Iiuni Site (Fig. 1). Measured data were collected from October, 1979 till November, 1982. The storm hyetograph-hydrograph relationships were based on an analysis of rainfall (at one hour interval) and stream flow data. The direct runoff (i.e. surface runoff) hydrograph for each event was determined by separating base flow from the total runoff hydrograph. The standard procedure for base flow separation used in this study was that of the variable slope method (Chow et al., 1988).

Model input for each cell were storm rainfall (mm), weighted *CN* value, percent land slope, direction of runoff flow, soil texture, impoundment (terrace) factor, channel indicator and cell area. The rainfall input data was obtained from the rain gauges in Iiuni watershed (Fig. 1), and was interpolated using the Thiessen Polygon Method. On the basis of established watershed hydrologic conditions, *CN* values were assigned by superimposing land use/ground cover and management practices on the identified hydrologic soil groups. All required data, including those on land use/cover and conservation practices were derived from the resource survey, aerial photographs and SPOT imagery interpretation. This information together with other watershed characteristics obtained from SCS tables (USDA-SCS, 1972) was used to estimate *CN*s for each cell within the watershed. This was done twice; for 1978 and 1996. In order to apply the AGNPS model to specific storm events, derived *CN* values for AMC II were first adjusted for land slope and then for the previous 5-day rainfall to either a dry (AMC I) or wet (AMC III) condition (Anderson and Howes, 1986).

The calibration of AGNPS was done using half of the measured rainfall-runoff events in the period 1979-82. The other half of measured events was used for model validation. Calibration involved adjustment of *CN* values for individual cells, such that predicted surface runoff volume was as close as possible to observed runoff volume.

Model validation was performed by using statistical methods to test the suitability of the model for predicting surface runoff volume under Iiuni watershed conditions. The statistical method used to evaluate observed and predicted runoff volume data were the coefficient of efficiency (R^2) as defined by Nash and Sutcliffe (1970). The equation representing this statistical relationship is as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(Q_{oi} - Q_{pi}\right)^2}{\sum_{i=1}^{n}\left(Q_{oi} - Q_{m}\right)^2} \qquad [5]$$

where R^2 is the coefficient of efficiency, Q_{oi} is the observed runoff of event i; Q_{pi} is the predicted runoff of event i; Q_m is the mean observed runoff of all the events; and n is the number of events. Coefficients of efficiency (R^2) values in the range of 0.70 to 1.00 are indicative of good model prediction (Nash and Sutcliffe, 1970). When the value of R^2 becomes negative, this indicates a poor model performance.

After successful validation of the model, it finally was applied to predict surface runoff volumes for the 1996 land use condition. For this purpose, the same rainstorms as used in the model validation were used. Predicted surface runoff volumes for the 1996 land use were compared with the surface runoff volumes predicted for 1978.

5.3 Results and discussion

5.3.1 Land use changes and hydrological characteristics

Land use in Iiuni can be broadly categorized into four major groups, namely (1) bushland/woodland; (2) grassland/pasture; (3) cultivated/non-terraced; and (4) cultivated/terraced. It varies from smallholder cultivation in the hills and upland areas to grazing on rangelands in the lower parts of the watershed. The watershed resource surveys revealed significant changes in land use changes between 1978 and 1996. In 1978, approximately 45% of the watershed area was cultivated land while the rest was grazing land (35%) and roads, paths and settlements (20%). By 1996, cultivated land had increased to 75% and grazing land decreased to 10% and roads, paths and settlements to 15%. In 1978, cultivated lands with conservation (mainly bench terracing) comprised 43% of the total cultivated area. But, by 1996 cultivated lands with conservation measures covered

70% of the cultivated area. All the terrace embankments had been stabilized with grasses, mainly Napier grass (*Panicum coloratum*).

The observed changes in land use from 1978 to 1996 have been mainly caused by population increase and subsequent opening up of more grazing land for crop production. The area under roads and paths decreased due to fragmentation of land that reduced access roads. The increased crop production has been achieved through horizontal expansion - opening up of more land for crop production, or vertical expansion - increasing productivity per unit land through intensification. But for resource poor farmers, vertical expansion (intensification) is difficult to achieve due to the high input requirements. Land use intensification puts heavy pressure on the soil resources particularly in this area with bimodal rainfall and two crops being grown per year. The very high demand for agricultural land has invariably pushed farmers into cultivation of very steep lands using terracing and conservation tillage practices. These practices have improved the retention of surface runoff water within the watershed (Biamah and Nhlabathi, 2003).

Landforms and associated watershed characteristics (e.g. soil types, drainage, vegetation, land use and topography) that influence surface runoff were distinguished, classified, mapped and described. Iiuni watershed was divided into four hydrological soil groups – A, B, C, and D and four physiographic units, namely hills, uplands, foot slopes and valleys (Table 1).

5.3.2 Watershed rainfall and runoff

During the measurement period in Iiuni watershed, intense rainfall events of short duration generated significant runoff volumes. The total runoff percentage of the watershed ranged between 3% and 70% of the total rainfall, with a mean of 16% and standard deviation of 15% (Table 2). This shows that on average 84% of the total rainfall received was conserved in the watershed or lost through evapo-transpiration. Direct runoff (surface runoff) accounted for 10% of the total rainfall. Thus in Iiuni watershed, direct runoff and particularly surface runoff is dominant (Table 2). The base flow contribution to total runoff was about 5.6% of total rainfall.

The rainfall hyetograph-runoff hydrograph relationships were used to establish which component of total runoff was quickly released out of Iiuni watershed as discharge (Fig. 2). This is clearly illustrated by the runoff hydrographs developed for different rainstorms. From the runoff components separation data presented in Table 2, the rainstorm of 8/5/80 produced 9.2% of direct runoff and 1.2% of base flow; the rainstorm of 3/4/81 produced 27.8% of direct runoff and 5.4% of base flow; the rainstorm of 19/4/82 produced 12.6% of direct runoff and 4.1% of base flow; and the rainstorm of 18/10/82 produced 13.5% of direct runoff and 7.6% of base flow. These results confirm that the dominant component of runoff in Iiuni watershed is surface runoff. In hydrological literature, it is reported that hydrographs with sharp rising limbs (short time to peak flow) and a short time of the recession limb indicate a large contribution of surface runoff to the total outflow Moreover, sharp crested runoff hydrographs show that the watershed has a good drainage network, is concave in shape and of fairly steep to moderate slopes (Meijerink, 1985; Mutreja, 1986).

Table 1. Watershed characteristics and associated hydrologic soil groups in Iiuni watershed, Machakos, Kenya.

Landform	Soil type	Texture†		Internal drainage	Slope class	Area	Hydrologic
		Topsoil	Subsoil			(km^2)	soil group‡
Hills	Haplic Acrisols	CL	SiCL	Well drained	Mountaineous (> 40%)	0.33	B
	Chromo Humic Acrisols	SC	SC-C	Well drained	Mountaineous (> 40%)	0.12	B
	Dystric Leptosols	CL	SC-C	Excessively to well drained	Hilly to mountaineous (20-40%)	0.92	B
	Chromic Cambisols	CL	C	Well drained	Hilly to mountaineous (20-40%)	1.34	B
Uplands	Haplic Arenosols	SL-SCL	SL-SC	Excessively drained	Hilly to mountaineous (20-50%)	0.49	B
	Ferric Alisols	SC	SC-C	Well drained	Rolling to hilly (10-30%)	1.66	B
	Dystric Leptosols	SC	SC-C	Well drained	Hilly to mountaineous (30-40%)	0.55	B
Footslopes	Ferric Alisols	SCL-SC	SC-C	Excessively drained to well drained	Rolling to hilly (15-40%)	0.59	A
	Dystric Cambisols	SCL	SC	Well drained	Rolling to hilly (15-30%)	1.02	B
	Eutric Gleysols	SCL	C	Poor to moderately drained	Undulating to rolling (8-15%)	0.54	B
	Rhodi Haplic Acrisols	SC-C	C	Well drained	Flat to undulating (1-8%)	0.24	B
	Haplic Acrisols	SCL-SC	SC-C	Well drained	Undulating to rolling (8-16%)	0.43	C
	Areni Eutric Planosols	LS-SL	SL-SC	Poor to well drained	Gently undulating to undulating (4-8%)	0.04	D
	Chromo Haplic Lixisols	SC-C	SC-C	Well drained	Undulating to hilly (10-30%)	0.78	C
	Lepto Eutric Cambisols	SC	SC	Well drained	Hilly (20-30%)	0.59	D
Valleys and floodplains	Eutric Cambisols	SC	SC	Well to excessively drained	Various	0.50	B
	Eutric Cambisols	SC-C	SC	Well to excessively drained	Various	1.45	B
	Eutric Fluvisols	Stratified LS to C		Poor to well drained	Flat (0-4%)	0.02	D

†CL - Clay Loam; SC - Sandy Clay; C – Clay; SL - Sandy Loam; LS - Loamy Sand; SCL - Sandy Clay Loam; SiCL - Silty Clay Loam.
‡A – high infiltration rate; B - moderate infiltration rate; C – low infiltration rate; D – very low infiltration rate.

Table 2. Measured rainfall and runoff data for selected events in Iiuni watershed, Machakos, Kenya†.

Date	AMC	R (mm)	Dr (mm)	Bf (mm)	Tr (mm)	Dr (%)	Bf (%)	Tr (%)
23/10/79	I	7.5	0.3	0	0.3	4.5	0	4.5
25/10/79	II	15.0	0.8	0	0.8	5.1	0	5.1
05/11/79	II	28.0	1.5	0	1.5	5.3	0	5.3
06/11/79	III	13.5	0.7	0	0.7	5.4	0	5.4
19/4/80	III	18.0	2.5	0.3	2.7	13.8	1.4	15.2
08/5/80	I	24.5	2.2	0.3	2.6	9.2	1.2	10.4
09/5/80	II	15.0	0.8	0.2	0.9	5.3	1.0	6.3
29/3/81	III	11.5	0.5	0.2	0.6	4.3	1.3	5.6
30/3/81	III	15.3	2.0	0.5	2.4	12.9	3.1	16.0
03/4/81	III	13.6	3.8	0.7	4.5	27.9	5.4	33.2
05/4/81	III	7.4	3.7	1.5	5.2	50.5	19.7	70.3
14/4/81	III	6.0	0.7	1.4	2.0	10.8	23.0	33.8
15/4/81	III	9.4	0.6	1.5	2.0	6.1	15.6	21.7
03/4/82	III	8.0	0.1	0.6	0.7	1.5	7.3	8.8
04/4/82	III	1.5	0.0	0.0	0.1	0.7	2.7	3.3
19/4/82	II	26.4	3.3	1.1	4.4	12.6	4.1	16.7
27/4/82	I	12.4	0.2	0.5	0.8	1.8	4.4	6.1
06/5/82	I	15.5	2.0	0.1	2.2	13.1	0.8	13.9
08/5/82	I	8.5	0.5	0.2	0.6	5.5	1.8	7.3
14/5/82	I	7.0	0.3	0.1	0.4	3.9	1.6	5.4
18/10/82	III	17.5	2.4	1.3	3.7	13.5	7.6	21.1
21/10/82	III	12.1	2.3	1.4	3.7	19.3	11.6	30.8
29/10/82	I	9.0	0.5	0.8	1.2	5.0	8.8	13.8
01/11/82	I	2.6	0.0	0.3	0.4	1.5	13.1	14.6
Mean		12.7	1.3	0.5	1.9	10.0	5.6	15.6
Sd‡		6.8	1.2	0.5	1.5	10.8	6.6	14.8

†AMC – Antecedent moisture condition: R – Rainfall; Dr – Direct runoff; Bf – Base flow; Tr – Total runoff.
‡Sd – Standard deviation.

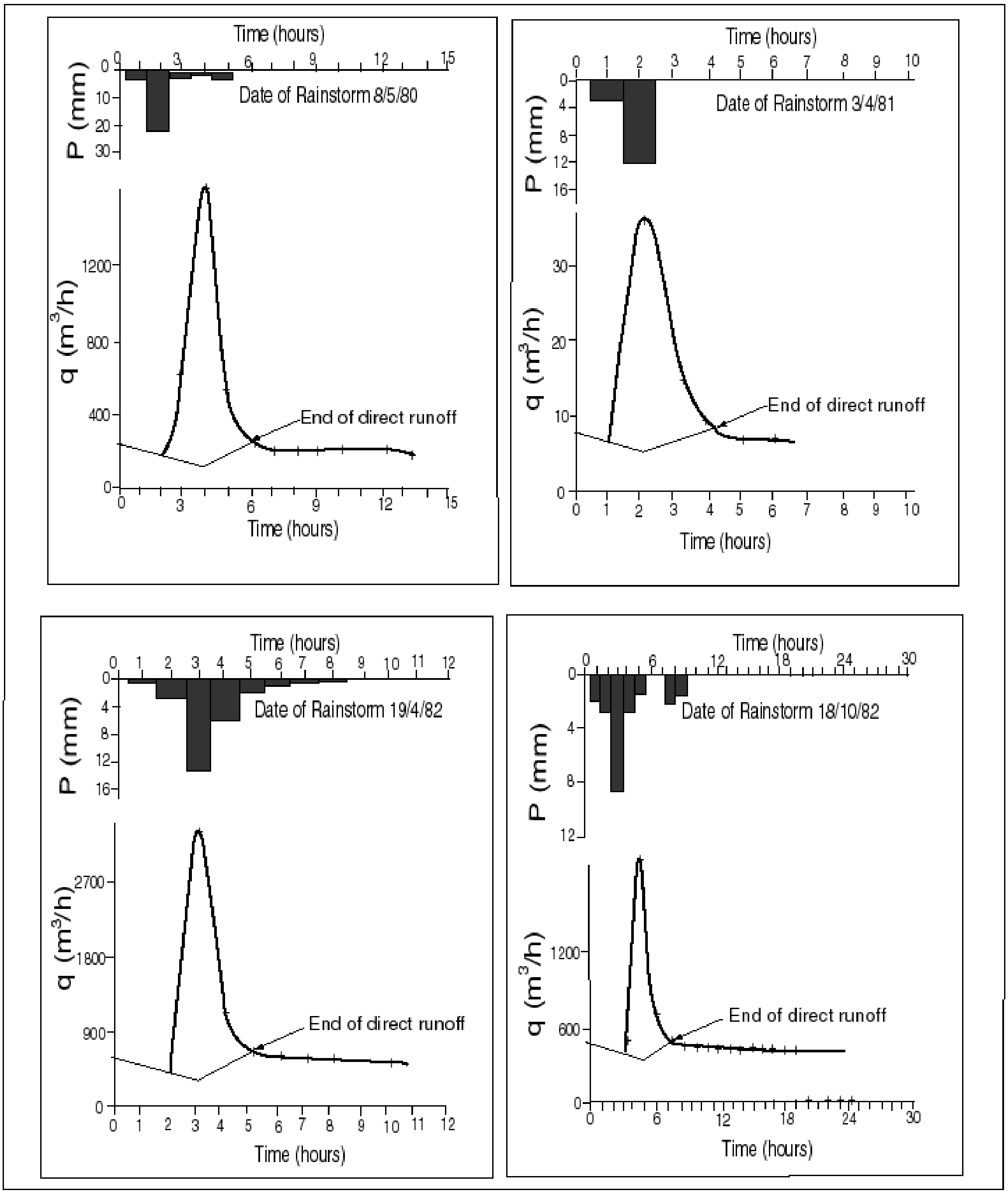

Figure 2. Four selected rainfall (P) – runoff (q) relationships for Iiuni watershed, Machakos, Kenya.

5.3.3 AGNPS model calibration and validation

The curve numbers that were determined from physical watershed characteristics are presented in Table 3. These curve numbers were derived for the four land use types in 1978 and 1996. The factors that were considered in assigning *CN*s for Iiuni watershed were: land use type, hydrologic soil group, vegetative cover, and soil and water management practices such as terracing, conservation tillage, row cropping. Differences in *CN* values for the same land use type and hydrologic soil group can be explained by changes in the vegetation cover, and/or the introduction of conservation measures between 1978 and 1996.

Table 3. Effect of land use types and hydrologic soil groups on curve numbers under the three antecedent moisture conditions for 1978 and 1996 in Iiuni watershed, Machakos, Kenya.

Land use type	Hydrologic soil group	*CN* values assigned for three antecedent soil moisture conditions					
		1978			1996		
		AMC I	AMC II	AMC III	AMC I	AMC II	AMC III
Bush land/woodland and cultivated/terraced land	A	37	57	76	41	61	79
Grassland /pasture land	B	54	73	87	54	73	87
and cultivated/un-terraced land	C	65	82	92	63	80	92
Pasture/grassland	D	68	84	94	63	80	92

The AGNPS model calibration was done using half of the measured rainfall-runoff events in the period 1979-82 (Table 2). It involved assigning appropriate *CN* values for each of the 76 cells (each cell of size 16 ha) in the watershed using equations 3 and 4. This calibration involved predictions of runoff volume using *CN* values for the appropriate antecedent moisture conditions (AMC I, AMC II, and AMC III), and comparing the predicted surface runoff volumes with the observed runoff volumes of individual rainstorms. The runoff volume that was predicted under AMC I and II gave surface runoff volumes that were generally lower than the measured runoff volumes. However, predicted runoff volume under AMC III gave runoff volumes that were closer to the observed runoff volumes. This closeness in surface runoff values (predicted and observed) led to the application of AMC III (wet condition) to predict runoff volumes in Iiuni watershed for all rainstorms. It is interesting to note that the hydrologic response of Iiuni watershed is biased to that of AMC III (wet condition) and not AMC I (dry condition) as expected for semi-arid environments.

The selection of the wet antecedent moisture condition (AMC III) for predicting watershed runoff volume in Iiuni watershed can be justified because of prevailing soil conditions in Iiuni watershed. These soil conditions are: (a) the ploughed layer is shallow (about 10 cm depth), and underneath is a compacted layer. Thus exposure of the ploughed soil layer to the frequent intense rainstorms often results in quick saturation of the ploughed soil and hence quick runoff generation; (b) due to the structural instability of the soils in this area, the top soil layer when exposed to intense rainstorms of high kinetic energy, would easily disaggregate and start forming surface seals and thus generating surface runoff quickly; and (c) after tillage operations, exposure of bare soils to several rainstorms result in the development of soil surface crusts. When these crusted soils are rained on, they generate runoff quickly. Put it the other way, the role of the crusting behavior of the soils is of great significance towards enhancing runoff despite the crusts being deficient in moisture content and thus elevating the *CN*s. These intuitive reasons lend support to the experimental findings of AMC III conditions in semi-arid environments, even though the semi-arid climate points more towards AMC I or II conditions to a casual observer. Similar behaviour was noticed in a micro catchment study in the arid and semi-arid lands (ASAL) region of West Pokot District, Kenya and hydrologic behavior tended to be highly biased to AMC III conditions (Katana, 1998).

AGNPS model validation was done using 12 out of 24 of the measured rainfall-runoff events in the period 1979-82. It was based on comparing predicted and measured runoff data under wet antecedent moisture condition (AMC III). Under this condition, the predicted runoff volumes by the model compared very well with the observed values (Fig. 3). The obtained coefficient of efficiency (R^2) was 0.86, which means a good model performance (Nash and Sutcliffe, 1970).

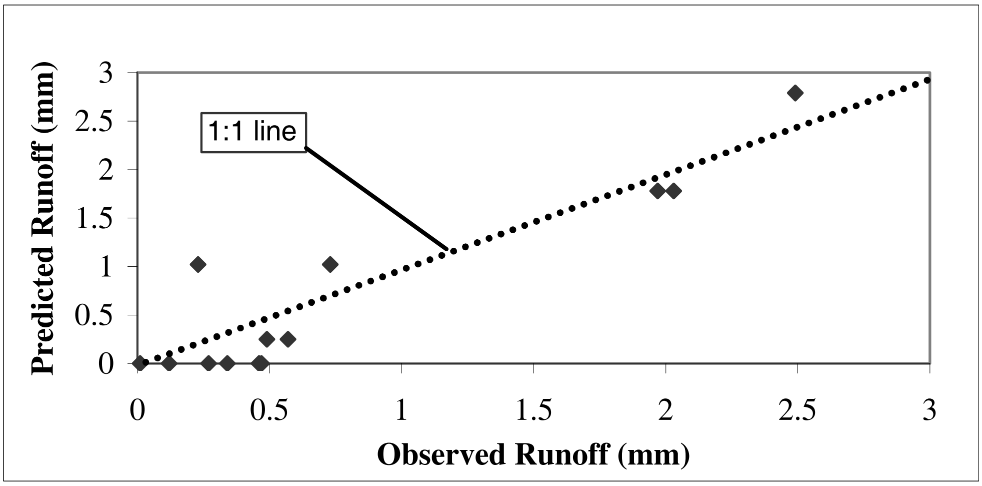

Figure 3. Comparison of observed and predicted surface runoff volumes for rainstorms in Iiuni watershed, Machakos, Kenya, in the period 1979-1982.

5.3.4 Effects of land use changes on hydrological response

The effects of changes in land use between 1978 and 1996 on the hydrological response of the watershed are best represented by the comparison of changes in curve numbers under AMC III (Table 3). According to the results presented in this table, there was a slight increase in *CN* values from 1978 to 1996 under bush land/woodland and cultivated/terraced land and a slight reduction under pasture land. The other two land use types representing hydrological soil groups B and C had the same curve numbers in both years.

These changes in *CN*'s were considered in the computation of weighted *CN* values for the cells of the watershed. Then, the same rainstorms as used for model validation were used for prediction of surface runoff volume using 1996 land use conditions. The slight changes in *CN* values translated into insignificant differences in runoff predictions between 1978 and 1996 (Table 4). Thus the model runoff prediction values of the two years were quite close.

The generation of surface runoff in Iiuni watershed was influenced by changes in land use type and particularly conservation measures such as terracing and conservation tillage. As more grazing land was converted into cultivated land, farmers put in place effective conservation tillage practices and terracing that significantly reduced the amount of surface runoff generated. On grazing lands, attempts have been made to reduce runoff and stop sheet erosion through diversion ditches and check dams. These structures have reduced the generation of runoff from degraded areas and along

Table 4. Comparison of predicted runoff volumes in 1978 and 1996 for the same rainfall events in Iiuni watershed, Machakos, Kenya.

Rainstorm	Predicted runoff volume (mm)	
	1978	1996
1	1.02	1.12
2	0.0	0.0
3	0.0	0.0
4	0.0	0.51
5	0.0	0.0
6	1.78	1.72
7	0.0	0.0
8	0.0	0.0
9	0.25	1.02
10	0.25	0.51
11	1.78	1.83
12	2.79	2.71

the stock routes. Where gullies have formed, structural and agronomic measures have been applied to heal and stabilize the gullies. Nearly all cultivated lands are well terraced, with bench terraces or narrow based terraces being the most dominant and effective conservation practices. Most of the terrace embankments are stabilized with Napier grass (*Panicum coloratum).* These conservation measures have significantly reduced the amount of surface runoff generated.

Farmer preferences of conservation practices vary depending on the costs of construction and maintenance. Labour availability and soil stability are major constraints to the adoption of structural technologies in upland and lowland areas. In the steep lands (hills and upland areas), farmers prefer bench terraces. In the foot slopes, river valleys and floodplains (lowland areas), farmers prefer grass strips and un-ploughed strips. Sugar cane and bananas are grown in river valleys and floodplains where they act as filters. Thus there is the build up of sandy alluvium within the crops with depths of up to 30 to 45 cm having been recorded (Lesslie and Mitchell, 1979; Thomas et al., 1981). The two crops have proven to be effective in controlling soil erosion on cropped lowlands.

Despite using the elemental/cell area approach, the AGNPS model's prediction of runoff volume assumes that the watershed's elemental areas have uniform hydrologic soil groups, a condition that does not exist in most natural watersheds including Iiuni. Although the model gave good prediction of runoff volume, there are lumped parameter assumptions with the curve numbers that could be sources of error. For instance, in the model, the initial abstraction is assumed to be 0.2*s*, which means physically that for a given storm, 20% of the potential maximum retention becomes the initial abstraction before runoff begins. This assumption is based on US conditions, where the SCS-CN method was developed, and could be a source of error for the semi-arid conditions of Iiuni. Other difficulties observed with the application of curve number based models (Boszany, 1989; Rallison and Miller, 1982) arise from the omission of the effect of time distribution of rainfall on retention parameter(s) and thus *CN* values.

In this study, the hydrologic response of cells depended on the *CN* values derived from watershed characteristics. Cells with high *CN* values generated high runoff volumes while those with low *CN* values had low runoff volumes. It was not possible in this study to pin point the relative influence of the various factors on runoff response due to the use of the integrated *CN* parameter to represent heterogeneous watershed conditions. In Iiuni watershed, the dominant factors that influenced runoff response were slope, hydrologic soil group, management practice and vegetative cover.

5.4 Conclusion

The success or failure of prediction of hydrologic response of a watershed in terms of adequacy and reliability largely depends on the model used and the determination of input parameters such as the watershed causative and conditioning factors. It also depends upon the accuracy of prediction as well as the application of predicted data. The simpler the model, the better in terms of ease of application, computational economy, determination of model parameters and saving of time and costs.

The runoff response of Iiuni watershed was investigated through determination of the distribution of runoff (direct runoff and base flow) within the watershed through an analysis of discharge data. The results showed that a small fraction 10% (mean) of the total storm rainfall constituted direct runoff (rainfall excess, the portion which makes surface runoff hydrographs). This direct runoff was a large fraction 66% (mean) of the total runoff hydrograph. Base flow comprised 5.6% of the total storm rainfall and 34% of the total runoff hydrograph. Consequently, most of the rainfall is retained within the watershed. Therefore, it is possible to determine the proportion of storm runoff outflow (of large rainstorms) that could be conserved for dryland crop production within the watershed through water conservation measures such as check dams, terraces and conservation tillage.

The application of the AGNPS model in Iiuni watershed showed good agreement between observed and predicted surface runoff volumes under the wet antecedent moisture condition (AMC III). It must be highlighted that the crusting behavior of the soils is tantamount to the high soil moisture conditions prompting the generation of runoff. So, the AGNPS model, when applied under AMC III is a reasonable tool that could be used to predict runoff volume from similar semi-arid watersheds where hydrological data from river gauging stations are not available. In this study it was applied to predict the effect of land use changes on the generation of surface runoff volumes. Despite significant changes in the land use pattern, the predicted runoff remained more or less the same. This was explained by the terracing, conservation tillage practices and other soil and water conservation measures that had been adopted in the watershed.

From the good correlation of predicted and observed data, the AGNPS model has potential areas of application such as: prediction of the effects of changes in land use changes on spatial runoff yields in small semi-arid watersheds; prediction of runoff from un-gauged watersheds or watersheds with limited hydrologic data; and prediction of effective rainfall at the elemental area (farmer's plot) scale where soil and climatic conditions are homogenous. The AGNPS model is of practical significance to the farmer and in mitigating seasonal agricultural drought - since the model responds well to changes in land use types and ground cover. Thus the information provided by this model would support watershed management and the selection of the best conservation practices for runoff and erosion control.

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Chapter 6

Watershed conservation in semi-arid Kenya

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Watershed conservation in semi-arid Kenya

Abstract

Over the past three decades, agricultural watersheds in semi-arid Kenya have experienced some rapid decline in soil and crop productivity due to severe soil erosion, low soil water, low soil fertility and high soil crusting and compaction. Thus, the management of these watersheds requires some good understanding of agricultural drought, stratification of production zones according to slope, and suitable conservation options that include in-situ water conservation and runoff utilization. The planning of watershed conservation requires the application of runoff models in the selection of interventions that reduce upstream flood magnitude and downstream sedimentation. Successful interventions can be introduced under enabling conditions to farmers at various hierarchical policy levels. A few of these enabling conditions that are elaborated upon include: agricultural policy; focus on smallholder agriculture; and public-community partnerships.

6.1 Introduction

6.1.1 Status of agricultural watersheds

Over the past three decades, there has been a general decline in soil and crop productivity of agricultural watersheds in sub-Saharan Africa (Stoorvogel and Smaling, 1990). This decline has been attributed to demographic pressure on land and poverty (Levia, 1999), climatic variations and human activities (UNCED, 1992) inappropriate and ineffective technologies (Hopper, 1995), upstream erosion due to land use changes and to downstream flooding and sedimentation (Doolette and Magrath, 1990).

In semi-arid Kenya, population pressure on unstable agricultural watersheds has contributed to land degradation through overgrazing, deforestation, and continuous cultivation for dryland crop production (Biamah et al., 1998). The very high demand for agricultural land has almost invariably pushed farmers into cultivation of very steep lands using intensive exploitive cultivation techniques that have led to the withdrawal of soil organic matter and associated reductions in soil quality (Hoogmoed et al., 2000).

Resulting negative effects on agricultural watersheds include seasonal episodes of agricultural drought, seasonal flooding and sedimentation and the drudgery of poverty. With time, agricultural droughts will become more persistent and when combined with ecological degradation can contribute to desertification (Biamah, 1988; UNEP, 1992; Lal, 1993).

The rapid decline in soil and crop productivity in Kenya has resulted from severe soil erosion, low soil water, low soil fertility and high soil crusting and compaction (Biamah, 1988; Biamah et al., 1998). These causes are attributed to factors such as climate (rainfall characteristics), slope (steepness of cultivated/grazing land), soil type (physico-chemical properties) and land use (vegetation cover and erosion control measures).

The rainfall factor significantly influences soil erosion and subsequent availability of soil water. In semi-arid Kenya, rainfall is low, erratic, intense, highly erosive and of short duration. It has been observed that about 60% of the intense and erosive rainstorms occur immediately after the onset of the seasonal rains when there is no vegetative cover (Biamah et al., 1998). During the rainy seasons, high amounts of surface runoff occur when there is no more surface storage capacity and the rainfall intensity exceeds the infiltration rate of the soil. With time, the recurrence of soil water deficits due to this generation of high surface runoff may decrease the availability of soil water to plants and hence affect crop productivity.

6.1.2 Challenges in dryland agriculture

Dryland agriculture has been defined as land husbandry under conditions of moderate to severe soil water stress during a substantial portion of the year, which require special cultural techniques, adapted crops and sustainable production systems (Oram, 1980). Dryland agriculture is practised where there is water stress and seasonal agricultural drought due to low water supply (low rainfall, high runoff water losses and high evaporation) and lack of opportunities for (supplemental) irrigation.

The major challenge in dryland agriculture is to establish ways to minimize deficiencies in agricultural production factors through efficient soil, water, nutrient and crop management practices (Sen and Sinha Ray, 1997), or through the management of soil erosion, management of soil water, and the management of fertilization (Oram, 1980; Li Shengxiu, 1994). In dryland agriculture, the prerequisite to the conservation of water and nutrients in an agricultural watershed is erosion control. After managing soil erosion, the need for soil water and fertilization to sustain crop productivity becomes crucial. The effectiveness of soil, water and nutrient management (SWNM) interventions in dryland agriculture could be objectively assessed in terms of enhanced infiltration of rainwater, increased soil water storage capacity, improvement of effective use of stored water, minimization of evaporation from the soil and improved soil fertility (Li Shengxiu, 1994).

Table 1. Land management matrix for dryland agriculture in semi-arid agricultural watersheds in Kenya.

SWNM†			Verifiable	Impact/
Problems	Objectives	Practices	Indicators	Output
1. Soil Erosion 2. Soil Water 3. Soil Fertility 4. Soil crusting & compaction 5. Soil drainage	1. Enhance rainwater infiltration. 2. Increase soil water storage capacity. 3. Improve effective use of stored water. 4. Minimize evaporation from the soil. 5. Minimize soil loss. 7. Improve fertilizer use efficiency. 8. Improve excess water drainage.	Conservation tillage, diversion ditches, check dams, gully head dams, conservation bench terraces, runoff catchment systems, application of organic manure and residue mulching, agroforestry, legume cover cropping.	Increased PWUE, CWUE and FUE‡. Improved drainage. Decreased soil loss.	Improvement in crop yields, incomes and farm inputs.

†SWNM – Soil water and nutrient management.
‡PWUE - Precipitation water use efficiency; CWUE - Crop water use efficiency; FUE - Fertilizer use efficiency.

A land management matrix (Table 1) provides an objective oriented approach in recommending soil water and nutrient management techniques in semi-arid agricultural watersheds in Kenya. In order to enhance soil and crop productivity under dryland agriculture, there is need to increase precipitation water use (Stroosnijder, 2003), crop water use and fertilizer use efficiency (Stroosnijder et al., 2001). These are verifiable indicators of effective soil and water management in dryland areas (Table 1).

Precipitation water use efficiency could be improved through: runoff water harvesting and water conservation; crop rotation with deep rooted plants that can use water in deeper soil horizons; surface residue mulching and cover cropping to decrease surface evaporation; enhancement of infiltration and reduction of surface runoff; and ultimately an increase in crop water use efficiency. An increase in crop water use efficiency could be realized through enhanced transpiration, application of fertilizer and organic manure, and enhancement of drought tolerance by crops. Likewise, a high fertilizer use efficiency can be attained when there is some good crop response due to the balanced availability of nitrogen, phosphorus and potassium.

6.1.3 The watershed management approach

A watershed management approach is a strategy for effectively conserving and restoring ecosystems and protecting the environment (US-EPA, 1996). This strategy has its premise that many ecosystems degradation problems are best solved at the watershed level rather than at the individual farm or discharge level. Thus watershed management is a holistic approach aimed at optimising the use of land, water and vegetation in a hydrologically defined geographic area and therefore could help alleviate agricultural drought, moderate floods, prevent soil erosion, improve water availability and increase agricultural production on a sustained basis (Druva Narayana et al., 1987; US-EPA, 1996). The levels of watershed management should be hierarchical and must consider all factors influencing hydrologic processes such as infiltration, surface runoff, and soil and nutrient loss that have a bearing on soil productivity (Biamah et al., 1998). Causative and conditioning factors of runoff significantly influence the hydrologic, soil, and crop responses of agricultural watersheds. Thus when delineating geographic management units, boundaries should be constructed to accommodate hydrologic connections and processes by accounting for both inflow and outflow, and address the priority watershed problems at all levels (Doolette and Magrath, 1990).

This study provides an overview of planning and management options for watershed conservation in semi-arid agricultural watersheds in Kenya. The presented results are based on findings obtained from an agricultural drought analysis in semi-arid Kenya (Chapter 2) a review of tillage methods in East Africa (Chapter 3), hydrologic soil responses to tillage and residue management practices at the micro-scale level (Chapter 4), SCS-CN model predictions of watershed runoff volume (Chapter 5), and an assessment of suitable conservation techniques in an agricultural watershed (Biamah et al., 1999).

6.2 Understanding agricultural drought

The risk of agricultural drought is a product of both the exposure to the hazard (climatology) and the vulnerability of cropping practices to drought conditions (Wilhite, 2000). Exposure to drought is assessed through year to year climatic variations. Vulnerability, which is dynamic, is the result of land use and management, farm policies, and many other factors. Many efforts to date have focussed at understanding drought hazard rather than drought vulnerability (Downing and Bakker, 2000) which largely depends on climatology, land use (e.g crop composition) and soil water holding capacity (Wilhemi and Wilhite, 2002).

Effects of agricultural droughts vary according to the time of occurrence, frequency (probability), severity (persistence), and duration. Recurrence of agricultural droughts can be established where long term weather data is available. The severity of these droughts depends on the number of dry spells within a crop growing season. The temporal fluctuations in seasonal and mean annual rainfall are indicative of the persistence of agricultural drought. A good definition of agricultural drought should be able to account for the variable susceptibility of crops during different stages of crop development, from emergence to maturity.

The pertinent indicators of agricultural drought include: occurrence, frequency (probability), severity (persistence), sequence and truncation level. The occurrence of a drought can be reflected by the deficiency of the rainfall sequence below the long-term mean annual/seasonal value. This mean value is the truncation level for identifying rainwater deficits and hence the intensity of drought. The severity of drought (expressed in mm or mm y^{-1}) is the cumulative period of occurrence of a drought. It is equivalent to the deficit sum at the given crop water demand level. The longest duration and largest severity for a desired return period are often used to design reservoirs to store water to meet supplemental irrigation water demand during drought periods. The watershed runoff volume predicted using semi-analytical models (e.g. the AGNPS and SCS-CN models) would be used to design water storage reservoirs that meet the crop water demand for a selected drought period.

The frequency of an agricultural drought is the number of times that a short-term dry spell occurs over a crop growing season. The number of such occurrences will vary from year to year or season to season. The mean value of such occurrences is the frequency of drought. Drought frequency may follow normal, log-normal or gamma distribution and may evolve randomly or in a Markovian fashion (Sharma, 1997). Knowledge of the severity and duration of an agricultural drought event will significantly influence the choice of conservation agriculture practices. The most appropriate and effective conservation techniques will be those that can conserve adequate soil water to sustain crop growth during a long dry spell.

The nature of the probability distribution function (pdf) of a drought sequence and its dependence structure may influence the extreme severity and duration. The truncation level is the reference level for identification of droughts or for quantifying severity. The truncation level is a measure of the sufficiency or deficiency in rainfall. It is also a measure of crop water demand and therefore varies from crop to crop and season to season. The best truncation level is the long-term mean value in a time series. Drought duration is dependent upon the truncation level (demand), the time span of analysis, and the simple probability at the truncation level.

According to Biamah (2001), the long-term annual/seasonal drought patterns in semi-arid Kenya show a trend of more deficits (dry spells) than surpluses (wet spells). This trend varies with the rainy seasons. For instance, there are more dry spells than wet spells in the long rainy season (March to May) than in the short rainy season (October to December). The strong variability of rainfall from year to year and season to season makes it necessary to use long-term data to obtain meaningful drought trends. A period of about 30 years must be considered the absolute minimum for a rainfall

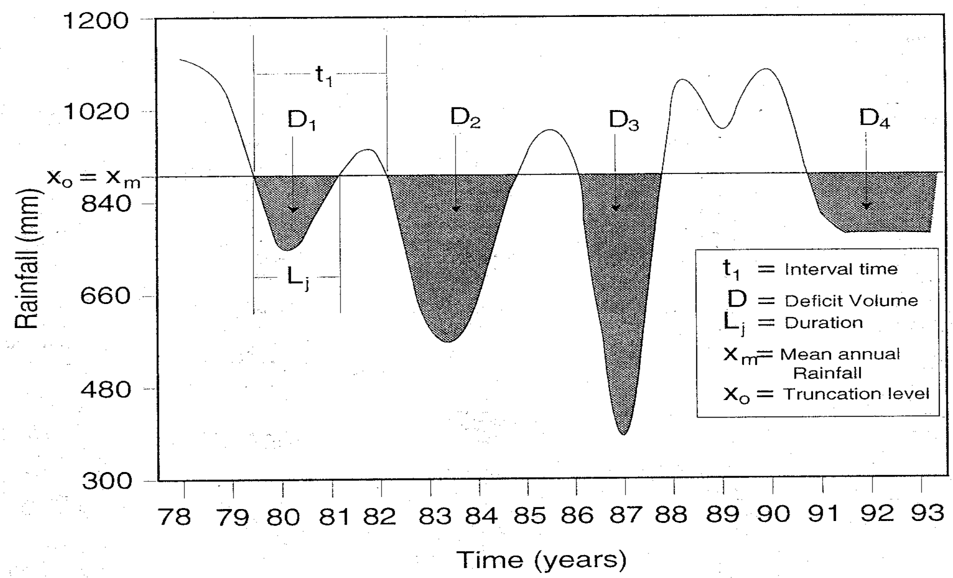

Figure 1. Schematic illustration of annual drought events experienced in Iiuni watershed, Machakos, Kenya (Biamah, 2001).

event analysis (Nieuwolt, 1978). Thus, a seasonal agricultural drought is expected when the annual/monthly rainfall received is less than 50 % of the long-term mean value.

In Iiuni Watershed, semi-arid Kenya, long-term drought events of varying durations and severities have been observed over a sixteen year period (1978-1993) (Fig. 1). There were four drought events with a total duration of seven years observed during this period (Biamah, 2001). The longest period of dry spells and corresponding largest deficit volume was during 1983-84. This drought did affect crop yields during several crop growing seasons. Extended drought durations (e.g 1983-84; 1991-93) significantly influenced the choice of tillage practices in Iiuni (Biamah, 2001). On the basis of time series data, drought events can be categorized as mild, moderate and severe using a standardized index (Gibbs, 1975; Rossi, *et al.*, 1992; Sharma, 1997). According to Sharma (1997), a mild drought corresponds to 90 to 100 % of the mean annual rainfall and may extend from 2 to 6 years over a time span of 10 to 200 years. A moderate drought corresponds to 80 to 90 % of the mean annual rainfall and may persist for 2 to 4 years over the same time span. A severe drought corresponds with 60 to 80 % of the mean annual rainfall and may persist for 1 to 3 years over the aforementioned time span. Critical severity of agricultural drought ranges from 2 to 5 units of the standardized annual rainfall over a time span of 10 to 100 years. Drought severity in units of mm or mm y^{-1} is equivalent to $[X_m (1 + E (C_v)]$ where X_m is the mean annual rainfall, E is the standardized index and C_v is the coefficient of variation.

The process of planning for drought has three elements namely: drought monitoring, risk assessment and mitigation. Monitoring drought involves identification of indicators of drought that can be tracked in the process. Risk assessment involves understanding of the impacts of drought severity, duration and spatial extent and societies vulnerability to drought. Mitigating drought is taking actions in advance of drought to reduce its long-term risk. This requires policies, activities, plans, and programs aimed at reducing drought vulnerability. A drought forecast is part of a drought monitoring and has four elements namely: duration, severity, distribution, and occurrence. Thus in an agricultural drought forecast, it is important to study the duration and severity aspects of critical droughts using annual and seasonal rainfall time series data.

6.3 Stratification of production zones

The demarcation of watershed management units in semi-arid Kenya should be based on hydrological and bio-physical considerations and an agrohydrologic system approach. For instance a watershed could be divided into three categories: macro scale agro-hydrologic system - watershed (100-200 km^2); meso scale agro-hydrologic system or sub-watershed (5-15 km^2) and micro scale agro-hydrologic system or micro-watershed (0.5-2.5 km^2) (Fig. 2). Experience has showed that the sub-watershed is a convenient unit for watershed planning using information collected from constituent micro-watersheds (Doolette and Magrath, 1990). At the watershed and sub-watershed levels, agricultural production zones could be stratified according slope and associated soil and water management problems (Fig. 3).

The management of agricultural watersheds in Kenya requires some clear understanding of the spatial occurrence of the four major soil and water management problems influencing agricultural productivity namely: severe soil erosion, low soil water, low soil fertility and high soil crusting and compaction (Fig. 3). The occurrence of these problems on croplands and rangelands is significantly influenced by factors such as climate, soil type, land use (especially tillage practices), erosion control measures and slope. Slope is the single most important factor for stratifying soil and water management problems at the watershed and sub-watershed levels. Slope based differences in watershed management can be broadly categorized into three distinct production zones (Biamah et al., 1998) namely: uplands slopes (hilly and gully area); midlands slopes (gully-plateau area); and lowland slopes (plain-flat area) (Fig. 3).

Upland Slopes (> 47%)

This area represents the forest zone and often has steep slopes and is well drained. In the past, this area was under forest and permanent vegetation and showed little erosion. However due to expansion of cultivated lands, this area is now prone to severe soil erosion and this zone often has no erosion control measures in place yet. Depending on the soil type and extent of vegetation degradation, this area generates very high amounts of surface runoff. The low rainwater infiltration and high crop evapo-transpiration rate limit the availability of soil water within the crop rooting zone. Erosion of the fertile topsoil lowers the fertility of the soil.

Recommended conservation practices for this zone include construction of gully head dams in valley bottoms, construction of terraces especially excavated bench terraces and contour ditches depending on soil depth and slope. Agronomic practices such as grass, unplowed, and sisal strips could be applied where appropriate and effective.

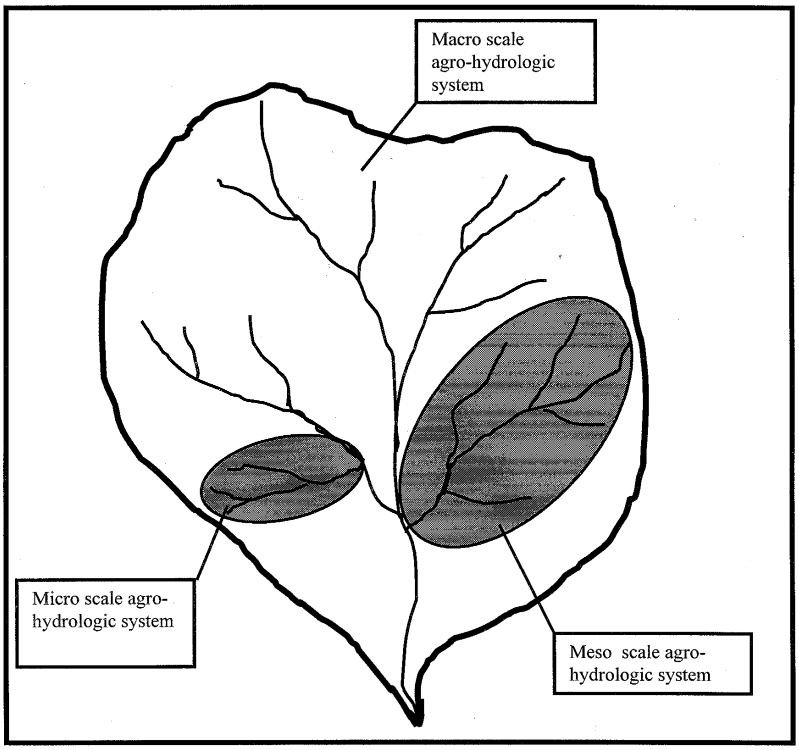

Figure 2. An illustration of the three levels of watershed management based on an agro-hydrologic system approach.

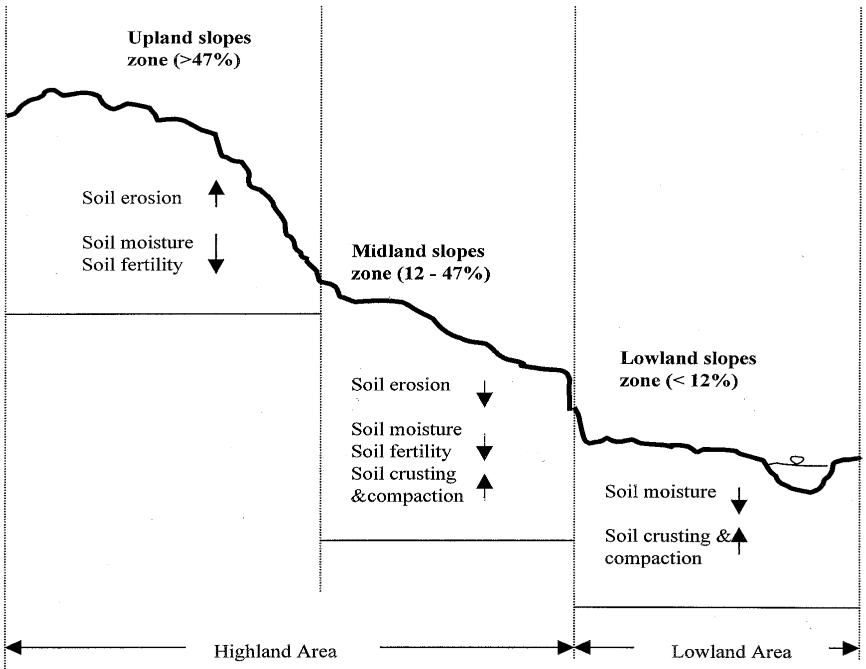

Figure 3. Slope-based stratification of soil, water and nutrient problems in agricultural watersheds.

Midland Slopes (12%-47%)

This area represents a zone of high potential erosion and is characterized by lands under full cultivation. However, where crop cultivation is common and erosion control measures are in place, there is minimal soil erosion. But surface runoff will continue to be generated and safe disposal through waterways is a must. So soil erosion, soil crusting and compaction and soil water are problems. Soil water is low but soil productivity is high. The low soil water problem is accentuated by the very high evapo-transpiration rate experienced in this zone.

Recommended conservation practices for this zone include tied ridging, residue mulching, farmyard manure application, contour bunds, bench terraces, and retention ditches depending on soil depth and slope.

Lowland Slopes (<12%)

This area represents the zone of sedimentation. This zone is characterized by the occurrence of alluvial sediment deposits (Fluvisols) and spatial inconsistencies in profile characteristics. In many places, the fertile fine topsoil transported from upland areas is deposited in deep horizons

Low infiltration rates can be expected in some areas due to soil crusting and compaction and hence soil water availability is a problem. Soil fertility is also a problem and significantly affects the shallow rooted crops. Otherwise the deep-rooted tree crops that can access the fertile subsoil horizons would be exposed to abundant soil nutrients.

Recommended conservation practices for this zone include runoff water harvesting and conservation techniques such as contour bunds/ridges, soil saving dams, water spreading bunds, micro-basins (trapezoidal, semi circular and rectangular bunds); and conservation bench terraces. Applications of these techniques involve in-situ water conservation and runoff utilization (e.g. reservoir water conservation and runoff water spreading).

6.4 Conservation options

6.4.1 Soil types and problems

An understanding of the dominant soil types and associated problems in semi-arid Kenya is necessary for the recommendation of appropriate and effective watershed conservation options. The most dominant soil types in these watersheds include: Vertisols, Luvisols, Lixisols, Planosols, Ferralsols, Fluvisols, Solonchaks and Solonetz. The problems associated with these soil types are poor drainage, workability, salinity, sodicity, soil crusting and compaction, low fertility and susceptibility to erosion (Table 2).

6.4.2 Suitable conservation techniques

The conservation technologies that are widely practised in Kenya include agronomic and structural practices. Agronomic practices include residue mulching, green manuring, application of farmyard manure, cover cropping, rotational systems of cropping and controlled grazing management techniques. Structural conservation measures include diversion ditches, tied ridges, check dams, terraces and grassed waterways; and selective methods of tillage with emphasis on conventional and/or conservation tillage.

Table 2. Soil types and associated problems in semi-arid Kenya (Biamah, 2001).

Soil type	Characteristic	Associated Problems
Vertisols	Dark colored clay soils	Poor drainage, high sodicity, poor workability, soil compaction, gully erosion
Planosols	Plain area soils	Poor drainage, soil compaction (subsurface hard pans), low fertility.
Ferralsols	Deeply weathered soils rich in iron and aluminum	Low organic matter content and chemically poor. High surface runoff.. Prone to soil crusting and compaction
Fluvisols	Young alluvial soils	Variable fertility, low water retention.
Luvisols and Lixisols	Argic B-horizon soils (more clay in B than A horizon)	Soil erosion, low water, and subsurface hardpans in B-horizon.
Solochaks	Saline soils	High salinity and poor drainage
Solonetz	Sodic soils	High sodicity and poor drainage

Farmer preferences of these conservation techniques vary depending on the costs of construction and maintenance. Labor availability and structural soil stability are major constraints to the adoption of structural technologies in both upland and lowland areas. Generally, farmer preferences vary in upland and lowland areas. For instance in upland areas, farmers prefer grass strips, bench terraces, stone lines and unplowed strips. In lowland areas, farmers prefer grass strips, sisal strips, plain ridges, and unplowed strips.

6.4.3 Water conservation techniques

Given that approximately 90% of the expected annual rainfall occurs during the long and short rains seasons in semi-arid agricultural watersheds in Kenya, it is imperative that as much rainwater be conserved during these periods to sustain crop growth. Thus soil and water management techniques used during these periods should increase soil water storage in the soil by enhancing infiltration and minimizing surface runoff water, and decrease evaporation from bare soil. The two broad categories of water conservation techniques used in semi-arid Kenya include in-situ water conservation and runoff utilization through reservoir water conservation and runoff water spreading.

In-situ water conservation

This is necessary where rainwater is in excess of direct infiltration and surface retention and the objective is to prevent surface flow of excess rainwater and prolong the time available for infiltration. In semi-arid Kenya, in-situ water conservation is applied through micro-basins and tillage and residue management practices such as crop residue mulching, farmyard manure application, conventional tillage, tied ridging, terracing and contour cultivation. These technologies have been most effective in sustaining crop, tree and pasture growth during prolonged dry periods. The use of micro basins has proven to be the most appropriate water conservation technique for the establishment of trees and pastures.

There are water saving tillage techniques that have been developed through applied research and are now recommended for Kenya (Gitau and Biamah, 2000; Biamah, 2001). These conservation tillage options include early deep tillage operations (i.e. sub-soiling and ripping) to maximize on soil water conservation during the short rains period and shallow tillage operations to minimize soil water losses during the long rains period. What is most critical to crop productivity is the timing of tillage operations especially during the long rainy season.

Other measures that conserve water are the application of farmyard manure to enhance soil water storage (Biamah et al., 2003); use of residue mulching (Mando and Stroosnijder, 1999) to improve the availability of soil water to plants; and use of drought resistant/high yielding crops to improve water and fertilizer use efficiencies (Zougmoré et al, 2003).

Runoff utilization

Reservoir water conservation is increasingly becoming a common practice in dryland conservation agriculture. In semi-arid Kenya, road drainage water is harnessed and stored in underground water tanks and micro dams (Rockstrom et al., 2001). The water stored is then pumped out or extracted for supplemental irrigation of dryland crops.

Runoff water spreading (Tesfai and Stroosnijder, 2001) is a specialized form of surface runoff irrigation accompanied by diverting floodwater from natural channels or watercourses and spreading the flow over relatively level areas. It is an efficient system for increasing the production of fodder (grasses and legume cover crops) and cereal crops on suitable land areas that can make effective use of additional water to supplement in situ rainwater penetration. Runoff water spreading is often done on soils with moderate to high water holding capacity (deep soil profile to hold sufficient water within the crop rooting zone) and slow infiltration rates to facilitate the spreading. The soils should not exhibit any salinity or sodicity properties. Exposure of saline or sodic soils to excess water often results in soil slaking. Deep medium to moderately permeable subsoils are ideally suited to runoff water spreading. Runoff water spreading requires good water quality (in terms of salt and sodium content and amount of sediment transported) and gentle, broad and smooth slopes free from rills and channels. Rills and channels concentrate water flow and thus causing soil erosion.

In semi-arid Kenya, runoff water is diverted by means of dams, stone spillways, contour terraces or bunds and diversion ditches, and each system delivers a set proportion of the surface runoff to the spreading area. The design of a runoff spreading system must compromise between the size and slope of the spreading area and the water infiltration rate of the soil (Biamah, 1988).

6.5 Planning of watershed conservation

Upland slope zones of semi-arid agricultural watersheds in Kenya have in the past been sparsely populated. However, the population pressure in the midland slopes zone has led to the encroachment into steep upland areas and therefore results in increased surface runoff and erosion. The principal emphasis therefore in upland watershed conservation must be on interventions that reduce upstream flood magnitude (a reservoir flood routing process). Given the limited resources for the implementation of such conservation, prioritisation of measures and targeting on hot spots is needed (Stroosnijder, 2000). Of much help are runoff models that respond well to changes in conservation practices and land cover (Biamah et al., 1998).

6.5.1 Watershed runoff prediction

Approaches to watershed runoff prediction are two-fold: those oriented towards scientific research objectives using the elemental value approach and those toward practical applications using the mean or the distributed value approach (Fig. 4). Scientific research objectives are achieved through the application of physically based, distributed models like Agricultural non-point source pollution model (AGNPS)(Biamah et al., 1998) and a physically based model like the Morgan-Morgan-Finney model (Vigiak and Sterk, 2001). These models are complex and require detailed and accurate spatially distributed input data. Where there are data limitations and operation logistics, and emphasis is on practical application objectives, simpler structures of statistical, empirical and conceptual models (e.g. USDA-SCS CN and Rational Formula Methods) are used.

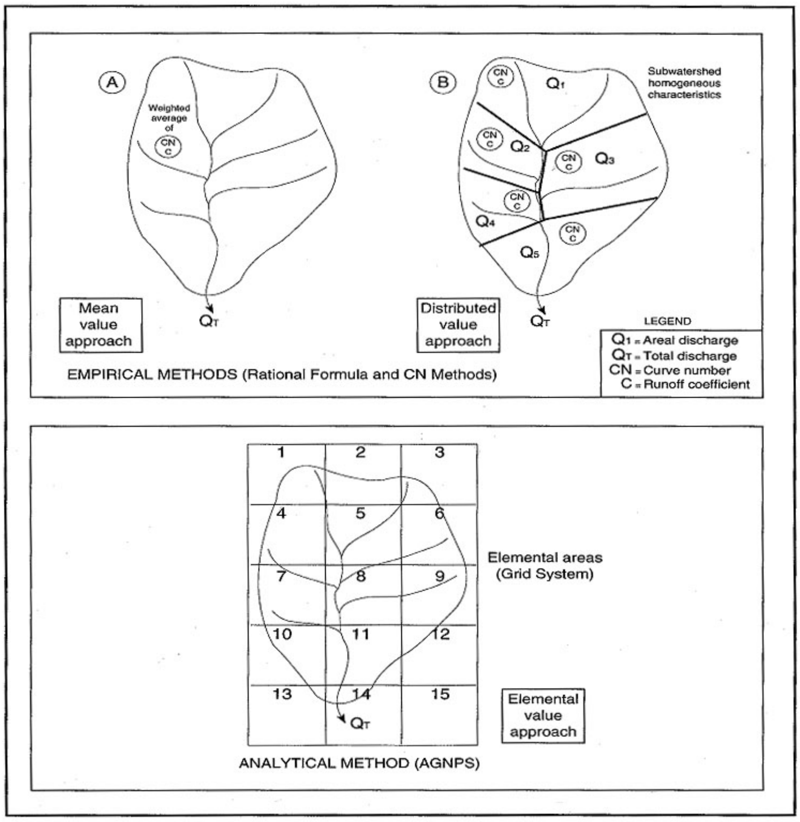

Figure 4. Empirical and analytical approaches to watershed runoff prediction.

These models are designed for forecasting and prediction and provide no insight into the dynamics of hydrologic processes (Anderson and Howes, 1986). The application of simulation models like AGNPS, Rational Formula Method, USDA Soil Conservation Service Curve Number (USDA SCS-CN) (Biamah et al., 1998) and Nash Model (Biamah et al., 2002), that are semi-analytical, to semi-arid agricultural watersheds in Kenya and subsequent good correlation of observed with predicted surface runoff values, has showed that these models could be used to predict runoff volume and peak flow rates from ungauged agricultural watersheds (where hydrological data from river gauging stations is not available). AGNPS, Rational Formula and SCS-CN models have potential areas of application such as: prediction of the effects of changes in land use on spatial runoff and sediment yields in small agricultural watersheds; prediction of runoff from ungauged watersheds or watersheds with limited hydrologic data; and prediction of effective rainfall at the elemental area (farmer's plot) scale where soil and climatic conditions are homogenous. Similar observations were made in agricultural watersheds of India using a different model (Nielsen and Panda, 1988). The prediction of surface runoff using AGNPS is of practical significance to the farmer and in the mitigation against seasonal agricultural drought - since the model responds well to changes in conservation practices and land cover (Biamah et al., 1998). Thus the information provided by simulation models would support watershed management by determining erosion hotspots and the selection of the best conservation practices (BCPs) for runoff and erosion control.

6.5.2 Production zone conservation techniques

Techniques to minimize the occurrence of excessive runoff and that can conserve soil water and nutrients in upland areas include structural and agronomic measures. The adoption of structural measures has generally been poor due to: high labour requirements of construction and maintenance, inappropriate designs for specific soil types, and exposure of shallow and unstable sub-soils to erosion. However, agronomic measures are acceptable because of: low labour requirements, high adaptability, soil fertility improvement and greater farmer control. Conservation tillage has proven to be very beneficial to farmers in improving soil water and soil fertility, decreasing soil crusting and compaction and thus increasing soil and crop productivity.

Table 4 presents recommended conservation measures for the three production zones in semi-arid watershed in Kenya. Recommendations were derived from the use of the AGNPS model (Biamah et al., 1998) and on findings obtained from an agricultural drought analysis in semi-arid Kenya (Biamah et al., 2004), an assessment of suitable conservation techniques in an agricultural watershed (Biamah, 1999), hydrologic soil responses to tillage and residue management practices at the micro-scale level (Biamah et al., 2003), SCS-CN model predictions of watershed runoff volume (Chapter 5), and a review of tillage studies in eastern Africa (Biamah et al., 1993).

Table 4. Recommended conservation measures per production zone for semi-arid watersheds in Kenya

Production zone	Priority conservation measures
Upland slopes	diversion ditches, bench terraces, and stone lines.
Midland slopes	diversion ditches, terraces, tied ridging, residue mulching and farmyard manure application
Lowland slopes	unploughed strips, grass strips, sisal strips and residue mulching.

Upland Slopes (> 47%)

The priority problems in this zone are soil erosion and soil fertility. In upland areas, farmers prefer using structural conservation techniques such as diversion ditches, bench terraces, and stone lines. These techniques are effective in controlling runoff and erosion on cultivated steeplands.

Midland Slopes (12%-47%)

The priority problems in this zone are soil erosion, soil moisture, soil fertility and soil crusting and compaction. In midland areas, farmers prefer using structural and agronomic conservation techniques such as diversion ditches, terraces, tied ridging, residue mulching and farmyard manure application. These techniques are effective in reducing runoff and erosion and conserving soil moisture and nutrients on cultivated lands.

Lowland Slopes (<12%)

The priority problems are soil water, soil moisture and soil crusting and compaction. In lowland areas, farmers prefer using agronomic techniques such as unploughed strips, grass strips, sisal strips and residue mulching. In waterlogged areas, structural techniques like drainage ditches and ridges are common. Agronomic techniques are effective in controlling runoff and erosion on cultivated flatlands. In these areas, farmers are hesitant in using structural conservation techniques because of frequent seasonal repairs due to damage from animal trampling during grazing periods.

6.6 Enabling conditions

Successful watershed conservation requires a number of enabling conditions that lead to 'good governance' with respect to land and farmers at the various hierarchical policy levels. Given their importance a few of these conditions will be elaborated upon here.

6.6.1 Agricultural policy

In Kenya today, there is no land use planning policy. The Agricultural Act (CAP 318) provides rules for maintaining stable agriculture, conservation of soil and its fertility, and stimulating the development of Agricultural Law. The Act defines Agriculture as inclusive of dairy farming, livestock breeding and keeping and the use of land. Under section 48, the Act provides "The Agriculture (Basic Land Usage) Rules". These rules are specific to the cultivation of land according to slope and to the protection of watercourses (riverbanks). Land use changes that have occurred since independence in 1963 were done without due consideration of appropriate land use. Hence areas that were hitherto earmarked for forest and grazing have been converted into cultivation due to an increasing demand for agricultural land.

Upland areas of agricultural watersheds have undergone increasing land use change due to population pressure and subsequent fragmentation of landholdings. Considerable forestlands have been opened up for cultivation or grazing. Within farmlands, land use changes have been influenced by farm size. The majority of smallholder agricultural lands have a size of 2 ha and below. As the population increases, land subdivision and intensification of farming will continue due to the increasing demand for agricultural land.

Given that land is a finite resource, the process of subdivision cannot continue indefinitely. Already the negative impacts of fragmentation of land have been felt within many agricultural watersheds. Thus there is a strong need for a firm policy framework on land use.

The search for an appropriate land use planning policy must begin by identifying the factors influencing the relationships between soil degradation and land use. The major factors include land suitability, cropping pattern and cropland conservation techniques. Land suitability should be assessed in terms of capability, soil stability and erosion risk. Cropping patterns should consider the benefits of rotating perennial and annual crops in order to optimize on soil and crop productivity.

Cropland conservation techniques should be selected on the basis of appropriateness, effectiveness and sustainability according to slope, agro-climatic zone, soil types and farmer preferences.

6.6.2 Focus on smallholder agriculture

In many parts of semi-arid Kenya, communal land ownership is no more and most parcels of land have been adjudicated and allocated to individuals. This individualization of land tenure and subsequent subdivision among family members is compelling farmers to intensify their farming systems for subsistence and improved incomes. On small landholdings, traditional conservation techniques such as fallowing and shifting cultivation are no longer feasible. Instead, cover cropping, strip cropping and crop rotation are viable conservation options for smallholder farming. Where agro-silvopastoral systems (crops, trees and livestock) are practiced through zero grazing, inter-cropping, poultry production and agro-forestry, farmers have been able to improve household incomes as well as provide organic manure for crop and fodder production. From these small scale farmer experiences, it is evidently clear that the intensification of farming systems through smallholder agriculture significantly reduces soil erosion and improves soil productivity.

The focus in watershed conservation in upland areas should be to improve the productivity soils through smallholder agriculture in upland areas and thus reduce degradation. Surface runoff and erosion in upland areas reduce soil water and soil fertility. Undertaking soil and water conservation practices on farms will increase food output and incomes and reduce downstream sedimentation.

6.6.3 Public-community partnerships

There are traditional and modern agro-techniques that have been recognized and accepted by farmers and are suitable to upland and lowland areas of agricultural watersheds in semi-arid Kenya. The choice of appropriate, effective and sustainable agro-techniques for specific areas would depend on slope, soil type, land use type, climate and availability of labor for construction and maintenance. The extension of proven agro-techniques can be done through several ways that include direct farmer to farmer contact at the grassroots level, demonstrations through selected (innovative) farmers, and organized excursion tours. Under this extension structure, extension messages to be passed on to the farmers are done in the form of action plans prepared by watershed planning teams. The current extension approach in Kenya (The Catchment Approach) is presently being improved as part of the African Highlands Initiative (AHI) and financed by the ecoregional fund (Sterk and Van de Bosch, 1999). The two main improvements introduced include a methodology of quantifying erosion and sedimentation, and a cost-benefit tool for determining the investment cost and benefits of soil conservation.

There is a need to promote the concept of dryland conservation agriculture in homesteads and villages within semi-arid agricultural watersheds. This is a sustainable method of integrating farming by emphasizing on crops, trees and animal production (agro-silvo pastoral system) in households and focusing on villages as operational areas. In each household, there should be chicken, pigs, cows, a silage pit (where maize silage is kept for stall feeding cows), a biogas plant, an orchard and a vegetable garden. After the waste from the animals has been utilized to produce biogas, the slurry manure should be applied to the crops and fodder grass. This is an excellent example of organic farming in practice. With good management, deficiencies of phosphorus and nitrogen in the soil could be offset with organic manure (especially from chicken) applications in appropriate quantities in orchards and vegetable gardens. Already demonstration trials on such comprehensive conservation techniques have been conducted in selected watersheds and farmers have started to adopt the new techniques on their farm plots.

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Chapter 7

Summary and conclusions

Summary and conclusions

In semi-arid Kenya, episodes of agricultural droughts of varying severity and duration occur. The occurrence of agricultural droughts is attributed to erratic and ineffective rainfall of high intensity and short duration and consequent generation of high amounts of surface runoff. Depending on hydrologic and soil conditions, up to 70% of expected rainfall may be lost as surface runoff and hence reducing significantly effective rainfall. The ineffectiveness of rainfall is responsible for the persistent soil moisture deficits and associated crop failure that are characteristic of the agricultural droughts in semi-arid Kenya.

Since most areas in semi-arid Kenya consist of approximately 30% of dryland agriculture (major crops are maize and beans) and 70% of dry rangeland (degraded pastures), pertinent research questions arise like: Under the low, erratic and ineffective rainfall conditions of semi-arid Kenya, which tillage and residue management practice conserves the most soil moisture?; How does seasonal rainfall variability and distribution influence the occurrence of seasonal agricultural droughts in semi-arid Kenya?; How does seasonal rainfall variability and distribution influence the occurrence of seasonal agricultural droughts in semi-arid Kenya?; What is the stochastic behavior of dry and wet spells in a given study area?; Which soil types are most vulnerable to drought?; Under the low, erratic and ineffective rainfall conditions, which tillage and residue management practice conserves the most soil moisture (in terms of available moisture for plant growth) of each soil type?; How significant are the effects of soil crusting and compaction on the hydrologic responses of dominant soil types in semi-arid Kenya?; and Of what significance are farmers' plots, sub-watersheds and watersheds in the mitigation of agricultural drought in semi-arid Kenya? To address these questions, this study was initiated with the following broad research objective: to analyze agricultural drought and evaluate options for soil and water management in drought-prone semi-arid Kenya. The specific research objectives were: (1) To stochastically simulate the behavior of dry and wet spells and rainfall amounts in Iiuni watershed, Kenya using a Markov (order 1) model; (2) To review research studies on tillage methods influencing soil and moisture conservation in the eastern African countries of Kenya, Tanzania, Malawi and Ethiopia during the past four decades (1950-1990); (3) To examine the hydrological effects of two tillage practices with and without farmyard manure on surface runoff and soil loss of crusting and compacting soils under field conditions at Katumani in semi-arid Kenya; (4) To use a semi analytical model, the Agricultural Non-point Source Pollution (AGNPS) model to predict the effects of land use changes on surface runoff volume from selected rainstorm events in Iiuni watershed, Machakos, Kenya; and To apply all of the above objectives in identifying pertinent strategies for watershed conservation in semi-arid Kenya. The scientific focus of this research was on improvement of soil and water management to mitigate agricultural drought in semi-arid Kenya.

The research framework for this study was expected to provide insights into the hydrologic soil moisture responses due to tillage (conventional, zero and tied ridging) and residue management (residue mulching and farmyard manure) practices in semi-arid Kenya. It adopted an agro-hydrologic systems approach to the mitigation of agricultural drought at micro, meso and macro scale levels. This approach had its premise that many agricultural drought problems in unstable ecosystems are best solved through farmers interventions at the micro scale level, conservation planning at the meso scale level and resource management at the macro scale level. Thus, the adopted agro-hydrologic systems approach is holistic and aimed at optimizing soil and water management in hydrologically defined geographic areas. The three levels of agricultural drought mitigation should be hierarchical and must consider all factors influencing the hydrologic and hydraulic properties of dominant soils in semi-arid Kenya.

At the meso scale level, the stochastic behavior of the longest dry and wet spells (runs) and largest rainfall amounts were simulated using a Markov (order 1) model. There were eight rain gauge stations within the watershed. The entire analysis was carried out using probability parameters, i.e. mean, variance, simple and conditional probabilities of dry and rain days. An analysis of variance test (ANOVA) was used to establish significant differences in rainfall characteristics between the eight stations. An analysis of the number of rain days and rainfall amount per rain day was done on a monthly basis to establish the distribution and reliability of seasonal rainfall. The graphic comparison of simulated cumulative distribution functions (CDFS) of the longest spells and largest rainfall amounts showed Markovian dependence or persistence. The longest dry spells could extend to 24 days in the long rainy season and 12 in the short rainy season. At 50% (median) probability level, the largest rainfall amounts were 91 mm for the long rainy season and 136 mm for the short rainy season. The short rains were more reliable for crop production than the long rains. The Markov model performed well and gave adequate simulations of the spells and rainfall amounts under semi-arid conditions.

At the regional level, a review of research studies on tillage methods influencing soil and moisture conservation in eastern Africa, showed that most tillage studies were conducted in marginal rainfall (semi-arid) areas and on shallow soils of various textures (sandy clay loam, sandy clay, clay and loam). The studies were meant to establish the effects of tillage and residue management practices on physico-chemical soil properties (i.e. structure, bulk density, soil moisture and organic matter contents), runoff and infiltration. This review emphasized the importance of appropriate tillage and residue management methods (contour bunds and terraces, minimum tillage, tied ridging, mulching and conventional tillage) in providing soil conditions favorable for soil moisture conservation and subsequent crop performance and yield on smallholder farms.

At the micro scale level, field investigations on rainfall characteristics, surface runoff, soil loss, soil bulk density and soil shear strength covering two rainy seasons (short and long rains) were done on a Chromic Luvisol. The field treatments were zero tillage and conventional tillage, and two farmyard manure applications (5 and 10 Mg ha^{-1}). The results obtained showed significant effects of conventional and zero tillage and farmyard manure on infiltration and soil moisture, surface runoff and soil loss. Soil crusting and compaction significantly influenced the hydrological response of all treatments. These responses were attributed to seasonal rainfall events of varying amounts, intensities and duration, and treatment differences in soil surface conditions and aggregation. Farmyard manure (FYM) application enhanced infiltration and reduced soil crusting, compaction, and surface runoff during the initial stages of the rainy season. But in the mid-stages of the rainy season, the effects of FYM on soil aggregation diminished. Conventional tillage without farmyard manure led to high surface runoff and soil loss in this structurally unstable soil. Zero tillage performed poorly under these soil conditions because of high soil crusting and compaction, low rainwater infiltration and subsequent increase in surface runoff generation.

Modeling of runoff volume was done at the meso scale level, in Iiuni watershed at Machakos. The AGNPS model was applied using input parameters derived from watershed characteristics that included slope, soil type, vegetative cover, land use, storm rainfall and stream flow data. These watershed characteristics were obtained from rain gauges, a stream gauging station, a resource survey and subsequent interpretations of topographical map, aerial photographs and a remote sensing image of the study area. The results obtained showed that the AGNPS model gave good predictions of surface runoff volumes under the wet antecedent moisture condition, due to the shallow ploughed soil layer that was prone to soil surface sealing. The crusting of the soils is known to generate high amounts of surface runoff. Model evaluation using statistics of comparison showed acceptable results. The coefficients of efficiency, R^2 were above 70% for the model, indicating good model prediction of runoff volume. This study has shown that for Iiuni watershed, storm runoff is distributed 66% as direct runoff and 34% as base flow. However, direct runoff makes 10% and base flow 5.6% of the total rainfall. Thus the rest of received rainfall (84%) is retained within the watershed as expected due to effective soil conservation practices in place. The generation of runoff in Iiuni watershed was influenced by land use changes that included terracing and conservation tillage. Despite the significant changes in land use changes between 1978 and 1996, their effects on *CN* values and runoff prediction values were insignificant. Land use changes and antecedent soil moisture conditions explained the variability of curve numbers and hence the generation of surface runoff within the watershed.

At the macro scale level, options and strategies for soil and water management were explored based on the experiences gained at the micro and meso scale levels. This analysis was based on the concerns that over the past three decades, agricultural watersheds in semi-arid Kenya have experienced some rapid decline in soil and crop productivity due to severe soil erosion, low soil water, low soil fertility and high soil crusting and compaction. Thus, the management of watersheds in semi-arid Kenya requires some good understanding of agricultural drought, stratification of production zones according to slope, and suitable conservation options that include in-situ water conservation and runoff utilization. The planning of watershed conservation requires the application of runoff models in the selection of interventions that reduce upstream flood magnitude and downstream sedimentation. Successful interventions can be introduced under enabling conditions to farmers at various hierarchical policy levels. A few of these enabling conditions that are elaborated upon in this study include: agricultural policy; focus on smallholder agriculture; and public-community partnerships.

In conclusion, this study has identified effective tillage and residue management practices for mitigating seasonal agricultural drought in the three study areas of semi-arid Kenya. It has also given the trends and indicators of agricultural drought that would help with forecasting and future early warning systems in Kenya. Besides, an attempt was made to develop criteria to be used in prioritizing the best conservation practices for semi-arid conditions. At the watershed scale, planning and management options for watershed conservation are presented that could be useful for policy makers and farmers.

Samenvatting en Conclusies

In semi-aride Kenia komen periodes van (landbouw)droogte voor; deze periodes verschillen in ernst en in duur. Het optreden van deze droogtes wordt toegeschreven aan onregelmatige en inefficiënte regenval (neerslag van korte duur en met een hoge intensiteit) waardoor er een hoge runoff wordt gegenereerd. Afhankelijk van hydrologische condities en de bodemgesteldheid kan tot 70% van de neerslag verloren gaan door runoff, waardoor de efficiëntie van de neerslag aanzienlijk wordt verminderd. Het gevolg van inefficiënte neerslag is een persistent bodemvochttekort en daaraan gelieerd het mislukken van gewasoogsten. Beiden zijn karakteristiek voor (landbouw)droogte in de semi-aride gebieden van Kenia.

Aangezien semi-aride Kenia bestaat uit ongeveer 30% regenafhankelijke landbouwgebieden (met gewassen als maïs en bonen) en 70% extensieve veeteeltgebieden (gedegradeerd graasland) komen pertinente onderzoeksvragen op: welke ploegtechnieken en managementpraktijken kunnen onder de gegeven omstandigheden het beste worden toegepast, opdat het meeste bodemvocht vastgehouden wordt?; hoe wordt het voorkomen van seizoensdroogte in semi-aride Kenia beïnvloedt door seizoensneerslagvariabiliteit en -verdeling?; kan het gedrag van droge en natte perioden in een gegeven studiegebied worden beschreven volgens een stochastisch model?; welke bodemtypen zijn onder droogte het kwetsbaarst?; hoe significant zijn de effecten van (bodem)korstvorming en compactie voor de hydrologische reactie van dominante bodemtypen in semi-aride Kenia?; en hoe belangrijk zijn boerenvelden, sub-stroomgebieden en stroomgebieden in het bestrijden van (landbouw)droogte in semi-aride Kenia? Om deze vragen te kunnen beantwoorden is dit onderzoek opgezet met een breed onderzoeksdoel: het analyseren van (landbouw)droogte en het evalueren van opties voor bodem- en waterbeheer in droogte gevoelig semi-aride Kenia. De specifieke onderzoeksdoelen waren: (1) met behulp van een eerste order Markov model stochastisch simuleren van het gedrag van droge en natte perioden en neerslag hoeveelheden in het Iiuni stroomgebied, Kenia, (2) het uitvoeren van een literatuurstudie naar ploegtechnieken die invloed hebben op bodem- en waterconservering in de Oost-Afrikaanse landen Kenia, Tanzania, Malawi en Ethiopië (literatuur van 1950 – 1990); (3) het onder veldcondities onderzoeken van het hydrologische effect van twee ploegtechnieken met en zonder mesttoediening op runoff en bodemverlies op kompacterende bodems in Katumani, Kenia; (4) het voor geselecteerde regenbuien (in het Iiuni stroomgebied) voorspellen van de effecten van landgebruikveranderingen op runoff hoeveelheden met behulp van een semi-analytisch model, het Agricultural Non-point Source Pollution (AGNPS); en (5) de hiervoor genoemde doelstellingen toepassen bij het identificeren van strategieën voor stroomgebiedconservering in semi-aride Kenia. De wetenschappelijke focus van dit onderzoek was gericht op de verbetering van bodem- en waterbeheer om (landbouw)droogte te verminderen in semi-aride Kenia.

Het onderzoek moet inzicht verschaffen in de reacties van het hydroligische bodemvocht op ploegtechnieken (conventioneel, zero en tied ridges) en residu management praktijken (bodembedekking en het gebruik van organische mest). Het onderzoek is gebaseerd op een agro-hydrologische benadering op een micro-, meso- en macroschaalniveau. Er is uitgegaan van de veronderstelling dat veel (landbouw)droogteproblemen in onstabiele ecosystemen het beste opgelost kunnen worden door middel van boeren interventies op het microschaalniveau, conserveringsplanning op het mesoschaalniveau en het beheer van de natuurlijke hulpbronnen op het macroschaalniveau. De toegepaste agro-hydroligische benadering is daarom holistisch en gericht op het optimaliseren van bodem- en waterbeheer in geografische gebieden die zich onderscheiden op hydrologische eigenschappen. De drie niveaus van (landbouw)droogte zijn hiërarchisch en daardoor moeten ze de kenmerken dragen van alle factoren die de hydrolische- en hydraulische eigenschappen van de meest voorkomende bodems in semi-aride Kenia.

Op het mesoschaalniveau is met behulp van een eerste order Markov model het stochastische gedrag van droge en natte perioden en de grootste neerslag hoeveelheden gesimuleerd. Gebruikt is gemaakt van acht regenstations die zich in het gebied bevonden. De gehele analyse is uitgevoerd met waarschijnlijkheidparameters van droge dagen en dagen met neerslag (gemiddelde, variantie, enkelvoudige en conditionele waarschijnlijkheden). ANOVA werd gebruikt om de significante verschillen in regenvalkarakteristieken tussen de acht stations te bepalen. Om de distributie en betrouwbaarheid van de neerslag te kunnen bepalen is een analyse van het aantal dagen met neerslag en de hoeveelheid neerslag per bui gedaan per periode van een maand. Uit de grafische vergelijking van de gesimuleerde cumulatieve distributiefuncties (CDFS) van de langste droge en natte periodes en de meest volumineuze buien volgde een Markov-afhankelijkheid of Markov-persistentie. Droogte periodes kunnen een periode van 24 dagen beslaan in het lange regenseizoen en 12 dagen in het korte regenseizoen. Op een 50% (mediaan) waarschijnlijkheidsniveau is de hoogste neerslag hoeveelheid 91 mm voor het lange en 136 mm voor het korte regenseizoen. Korte buien zijn betrouwbaarder voor gewasproductie dan lange buien. Onder de gegeven semi-aride condities geeft het gebruikte Markov model een adequate simulatie van droge en natte periodes en neerslaghoeveelheden.

In het verleden werd het meeste onderzoek naar ploegtechnieken uitgevoerd in de marginale regengebieden (semi-aride) en op ondiepe bodems van verschillende textuur (zandige kleileem, zandige klei, klei en leem). Binnen dit PhD onderzoek werd een literatuurstudie naar ploegtechnieken en hun invloed op bodem en water conservering in Oost-Afrika uitgevoerd. Deze studie had tot doel om het effect aan te tonen van ploegtechnieken en residu-management praktijken op de fysisch-chemische bodemeigenschappen, te weten: structuur, dichtheid, bodemvocht en organische stofgehalte, runoff en infiltratie. De literatuurstudie toonde het belang van de juiste ploegtechniek en residu-management methode (ruggen en terrassen langs de hoogtelijnen, minimaal ploegen, tied-ridges, bodembedekkers en conventioneel ploegen) voor het creëren van bodemcondities welke bodemvochtconservering bevorderen en als gevolg daarvan zorgen voor een betere gewasgroei en oogst.

Op het microschaalniveau werd gedurende twee regenseizoenen veldonderzoek naar regenvalkarakteristieken, runoff, bodemdichtheid en afschuifweerstand uitgevoerd op een Chromische Luvisol. De velden waren ofwel behandeld volgens zero- ofwel conventioneel ploegen, en er waren twee behandelingen met toediening van dierlijke mest (FYM) (5 en 10Mg ha^{-1}). De verkregen resultaten toonden een significant effect van conventioneel- en zeroploegen en van mest op infiltratie en het bodemvochtgehalte, alsmede op de runoff en het bodemverlies. Korstvorming en compactie beïnvloedden de hydrologische reactie van alle behandelingen. Deze beïnvloeding kan worden toegeschreven aan seizoensneerslag van variërend volume, intensiteit en duur en behandelingsverschillen in de bodemoppervlakte en aggregaten. FYM toediening bevorderde infiltratie en reduceerde korstvorming, compactie en runoff gedurende de beginstadia van het regenseizoen. Echter, in het midden van het regenseizoen waren de effecten van FYM op aggregaatvorming afgenomen. Conventioneel ploegen zonder FYM resulteerde in hoge runoff en bodemverliezen in deze structureel onstabiele bodem. Zeroploegen had zwakke resultaten op dit bodemtype als gevolg van een hoge korstvormingsgraad en hoge compactie, lage infiltratie en als gevolg hiervan een hoge runoff.

Runoff is op het meso schaalniveau, in het Iiuni stroomgebied in Machakos, gemodelleerd met behulp van het AGNPS model, met input parameters die verkregen zijn door bepalingen in het stroomgebeid (helling, bodemtype, vegetatiebedekking, landgebruik, regenval en aftromingsdata). Deze eigenschappen van het stroomgebied werden verkregen door middel van regenmeters, een afvoermeter en door interpretatie van kaartmateriaal, luchtfoto's en remote- sensingbeelden van het studiegebied. Het AGNPS model bleek een goede voorspeller te zijn van runoff volumes onder natte bodemcondities; dit was het gevolg van de ondiep geploegde laag welke gevoelig was voor korstvorming, welke erom bekend staat tot een hoge runoff te leiden. De evaluatie van het model door middel van statistische vergelijking toonde acceptabele resultaten. De efficiëntie coëfficiënten, R^2, waren hoger dan 70% voor het model, wat een goede modelvoorspelling van de runoff aantoont. Voor het Iiuni stroomgebied bestaat de neerslag runoff voor 66% uit directe runoff en voor 34% uit een 'base flow'. Directe runoff is 10% en 'base flow' is 5.6% van de regenval. De overige neerslag (84%) wordt vastgehouden in het stroomgebied als gevolg van effectieve bodemconserveringsmaatregelen. De runoff in het Iiuni stroomgebied werd beïnvloed door landgebruikveranderingen zoals terrassering en ploegtechnieken. Landgebruikverandering en de als gevolg daarvan veranderde bodemvochtcondities zijn een verklaring van de variabiliteit van de *Curve Numbers* en dus van het ontstaan van runoff in het stroomgebied. Alhoewel er grote veranderingen in het stroomgebied zijn waargenomen van 1978 tot 1996, zijn de effecten van deze veranderingen op de *CN*-waarden en runoff voorspellingswaarden niet significant.

Op het macro schaalniveau werden de opties voor bodem- en waterconservering bestudeerd, gebaseerd op de ervaringen op micro- en mesoschaalniveau. Deze analyse was gebaseerd op de zorg dat over de laatste 30 jaar de agrarische productie in de stroomgebieden in semi-aride Kenia snel afneemt als gevolg van ernstige bodemerosie, lage bodemvochtgehalten en bodemvruchtbaarheid en een hoge mate van korstvorming en compactie. Het beheer van de stroomgebieden in semi-aride Kenia vereist een goed begrip van agrarische droogte, stratificatie van productiezones als functie van de helling, aangepaste conserveringstechnieken zoals in-situ waterconservering en runoffgebruik. De planning van stroomgebiedsconservering vereist de toepassing van runoff modellen bij de selectie van interventies om de bovenstroomse afstroming en de benedenstroomse sedimentatie te verminderen. Op verschillende hierarchische politieke niveau's kunnen interventies succesvol worden geïntroduceerd, indien tegelijkertijd maatregelen voor de boeren worden genomen die de interventies vergemakkelijken. Enkele van deze ondersteunende maatregelen waren onderwerp van dit onderzoek: landbouw politiek, focus op kleine boerenbedrijven en samenwerking tussen overheid en boerengemeenschap.

Concluderend; deze studie heeft effectieve ploegtechnieken, alsmede residu management praktijken geïdentificeerd welke een bijdrage leveren aan het verminderen van seizoens (landbouw) droogte in drie studiegebieden in semi-aride Kenia. De studie geeft ook trends en indicatoren aan die wijzen op (landbouw)droogte; deze trends en indicatoren kunnen bijdragen aan het voorspellen van droogte en aan vroege waarschuwingssytemen in Kenia. Ook is gepoogd criteria te ontwikkelen die kunnen worden gebruikt bij het kiezen van de beste conserveringmaatregelen in semi-aride condities. Op stroomgebiedsniveau worden opties voor planning en management gepresenteerd voor stroomgebiedsconservering die nuttig kunnen blijken voor zowel beleidsmakers als boeren.

Curriculum Vitae

Elijah K. Biamah was born on 9th April 1952 in Kapsengere, Nandi District (now South Nandi District), Kenya. He studied at Kapsengere Primary School from 1961 to 1967 and Kapsabet Boys High School, Nandi, Kenya from 1968 to 1971. He received a Diploma in Agricultural Engineering from Egerton Agricultural College (now Egerton University), Njoro, Kenya in March 1975. He went to the US for further studies on a USAID Scholarship in January, 1980 where he joined Oklahoma State University, Stillwater, Oklahoma and obtained a BSc degree in Agricultural Engineering (1982) and an MSc degree in Soil and Water Engineering (1983). He registered for a sandwich PhD degree program at Wageningen University in 1993. As of the time of obtaining his PhD degree, he is an accomplished agricultural and environmental engineer with 29 years of academic and practical experience in technical and environmental aspects of land and water management. He has held various professional positions that include: Deputy Officer in Charge, Soil Conservation Service, Nakuru, Kenya (1975-79); National Coordinator, Soil and Water Conservation Extension and Training, Ministry of Agriculture, Kenya (1984-85); and Lecturer/Senior Lecturer, University of Nairobi, Kenya (1986 to date). He has provided professional expertise in soil and water management, agricultural project planning and management, pastoral land tenure and resource management, watershed resource management, smallholder irrigation system design, dams and dam design, strategic planning and environmental impact assessment to many organizations that include Commonwealth Secretariat, World Bank, FAO, WFP, IFAD, UNEP, UNDP and NOVIB (OXFAM The Netherlands). He has been actively involved in donor, community and environment oriented project planning and management in Kenya and China.

He has made many international, regional and national contributions that include: Preparation of a background paper on " Sustainable development and management of land and water resources " that was presented by FAO at the UNCED Conference in Rio de Janeiro, Brazil (paper prepared in cooperation with Professor Dr. Rattan Lal of Ohio State University, USA); Provision of three years (1994-96) of technical expertise in soil and water management for dryland agriculture in the arid and semi-arid Northwest part of China; Assisted FAO to formulate soil conservation strategies and land management strategies for Africa; Prepared report on suitable conservation techniques for the Nyando Catchment Area, Lake Victoria Basin, Kenya; Conducted an environmental impact assessment on the arid lands of Kenya (report written jointly with Prof. Dr. Wilson Yabann of Moi University, Kenya); Undertook a land tenure and natural resource management study of the arid lands of Kenya; Conducted community oriented project planning on drought recovery and management activities in the arid lands of Kenya; Involvement in project formulation missions with IFAD; Involvement in the setting up of the Kenya Conservation Tillage Initiative and representing the International Soil Tillage Research Organization as Branch Chairman in Kenya.

In his academic career, he has conducted research work on watershed resource management, agricultural drought analysis, and conservation tillage with specific interest in arid and semi-arid environments and has published more than 50 papers in International Conference Proceedings and Journals. He is happily married to his dear wife Gladys J. Biamah and has three sons Stephen (16), Michael (14) and Brian (10).