EVALUATION OF THE IMPACT OF LAND USE CHANGE ON CATCHMENT HYDROLOGY: THE CASE OF WUNDANYI RIVER CATCHMENT IN TAITA HILLS, KENYA

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A Thesis Submitted to the Graduate School in Partial Fulfilment for the Requirements of the Master of Science Degree in Agricultural Engineering of Egerton University

EGERTON UNIVERSITY

APRIL, 2013

DECLARATION AND RECOMMENDATION

DECLARATION

I declare that this Thesis is my original work and has not been submitted to any other institution known to me for the award of any other Degree.

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RECOMMENDATION

This Thesis has been submitted for examination with our approval as University supervisors.

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ABSTRACT

The conversion of forest land to agricultural land and urban settlement usually increases soil erosion, and volume of storm runoff in a catchment. In Kenya, the rural communities are encroaching into the humid and marginal areas to open up new lands for agricultural production and settlement. These changes have led to environmental degradation, which has negatively altered the hydrologic regimes of many catchments in Kenya. The Wundanyi River catchment is one of the catchments that have undergone rapid land use changes over the last 30 years. It requires intervention to improve and sustain hydrologic processes to prevent further degradation. However, the catchment lacks continuous records for hydrologic data that can be used. Therefore, there was need to apply remote sensing and modelling approach in getting hydrological data for this catchment for analysis and management. The study applied the Soil and Water Assessment Tool (SWAT) model to evaluate the impact of land use change on the catchment hydrology. The input data used included digital elevation model (DEM), land use maps, soil maps and rainfall. Changes of land use in the catchment were characterised and quantified using remote sensing and GIS. The land use evaluation results showed that the agricultural land and built up area increased by 10% and 156% respectively between 1975 and 2004, while the forest land cover reduced by 57%. Simulation of land use change scenes showed that average annual surface runoff and sediment yield increased from 8.74mm to 99.30mm and 0.43t/ha to 20.10t/ha, respectively. These findings can be used by catchment stakeholders and policy makers to address challenges resulting from catchment degradation. This research will further help in making informed decisions in selecting and developing viable catchment management options that will promote sustainable utilization of land and water resources within Wundanyi River Catchment.

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ACRONYMS

AGWA	Automated Geospatial Watershed Assessment Tool
CN	Curve Number
CORINE	Coordination of Information on the Environment
DFID	Department for International Development
DN	Digital Numbers
ERDAS	Earth Resources Data Analysis System
HEC-HMS	Hydrologic Engineering Center-Hydrologic Modelling Systems
HSG	Hydrologic Soil Groups
ILWIS	Integrated Land and Water Information System
KINEROS	Kinematic Runoff and Erosion Model
LCCS	Land Cover Classification System
LUCC	Land Use and Land Cover Classification
MRLC	Multi-Resolution Land Characteristic
MUSLE	Modified Universal Soil Loss Equation
NIR	Near Infrared Band
NS	Nash and Sutcliffe Efficiency
RS	Remote Sensing
RSR	Root Mean Square Error-Observation Deviation Standard Ratio
SCS	Soil Conservation Service
STATSGO	State Soil Geographic Data Base
SUSRGO	Soil Survey Geographic soil data
SWAT	Soil and Water Assessment Tool
T_c	Time of concentration
T_t	Travel time
USLE	Universal Soil Loss Equation
WRMA	Water Resources Management Authority

CHAPTER ONE
INTRODUCTION

1.1 Background

The conversion of forest land to agricultural land and urban settlement has been the main cause of the increase in soil erosion and volume of storm runoff in a catchment. As part of programmes to alleviate these problems, engineers are increasingly assessing the probable effects of urban development, as well as designing and implementing measures that will minimize adverse effects. The need for settlement and agricultural development has increased with increase in population (Chemelil, 1995). As a result of increased population and the need for more land, the natural vegetated areas have been cleared and cultivated (Séguis *et al*., 2004). This has been observed not only in the high potential areas but also in marginal areas which were earlier on predominantly under grazing because of low rainfall (Onyando, 2000).

Increased agricultural and urban development has led to subdivision of land and as a result brought about changes in land use patterns. These changes have led to environmental degradation, which has negatively altered the hydrological regimes of many catchments in Kenya. For instance, deforestation, subdivision of land to small units and urbanisation have significantly altered the seasonality and magnitude of discharge, and annual distribution of stream flows (Karanja *et al*., 1986; Donner, 2004; Mustafa *et al*., 2005). Degradation resulting from intensive agriculture and other activities include: loss of top fertile soil due to erosion, siltation of rivers, high incidence of floods, and eutrophication of surface water bodies. Another effect of catchment degradation is the hypoxia condition resulting in loss of aquatic biodiversity, effluent of agrochemicals and low stream flows during dry periods (Donner, 2004; Araujo and Knight, 2005; Lim *et al*., 2005; Onyando *et al.,* 2005). In addition, the effect of land degradation in most catchments has reduced the infiltration rates and therefore caused increased runoff generation from the catchment.

The Wundanyi River catchment is one of the catchments that have undergone rapid land use changes over the last 30 years. The population of the whole of Taita/Taveta County has grown from 90,146 in 1968 (Republic of Kenya, 1970) to over 285,000 people in 2009 (Republic of Kenya, 2010). The catchment has a population density of about 60 people per km^2 that depends on the scarce natural resources (Pellikka *et al.,* 2004). As a result of high population growth over the years, the forest cover has rapidly been replaced by crop cover and built- up areas, which has led to changes causing the soils to be impervious (Mustafa *et al*., 2005). The Wundanyi River catchment comprises eleven sub-catchments which are in the semi urban stage with approximately 20% impervious area and intensive agriculture as well as a rapid increase in construction activities. This effect has reduced the infiltration rates and caused increased runoff generation from the catchment.Therefore understanding of the effects through catchment modelling allows for monitoring and correlating environmental changes with factors such as socio-economic and health (Troyer, 2002). In addition, it enables planners to formulate policies to minimize the undesirable effects of future land use changes on catchment hydrology (Mustafa *et al*., 2005). Catchment modelling requires hydrologic data such as precipitation, temperature, evaporation, and streamflow. However, the Wundanyi River catchment lacks sufficient and continuous hydrologic data records. Therefore, there was need to develop alternative approaches for getting hydrological data for this catchment, including remote sensing and runoff simulation using the SWAT model. The outcomes of this study could be used by catchment stakeholders and policy makers to address challenges resulting from catchment degradation, and also in making informed decisions in selecting and developing viable catchment management options that would promote sustainable utilization of land and water resources within Wundanyi River Catchment.

1.2 Statement of the Problem

The rapid land use changes caused by conversion of indigenous forest to agricultural land are adversely affecting the hydrology of Wundanyi River catchment. People are migrating to the forested areas and clearing them for agricultural production, subdividing land into smaller units and expanding the built up areas. In most parts of the catchment, deforestation, land fragmentation, cultivation of wetlands and rapid increase in human settlements have had negative impacts on water sources resulting in reduced stream flows, drying of small streams, drying of boreholes and leading to water shortage. The water levels in the Wundanyi River have reduced so much that some sections of its course usually dry up immediately after the short rains seasons. Ground water supply has been declining due to decrease in ground water recharge as observed by the drying of boreholes within the catchment. In addition, lack of continuous data on hydrology, meteorology, and land use in the catchment inhibits proper environmental planning and management.

1.3 Objectives

The broad objective was to evaluate the impact of land use change on catchment hydrology for Wundanyi River catchment for the period between 1975 and 2004.

1.3.1 Specific Objectives

i. To characterize and quantify changes of land use in the catchment using remote sensing and GIS

ii. To evaluate the impact of land use change on catchment hydrology using SWAT model

1.3.2 Research Questions

i. What are the land use changes that have occurred in the catchment between 1975 and 2004?

ii. What impacts have the land use changes had on Wundanyi River catchment?

1.4 Justification

Land use changes in catchments are always due to man-made causes, mainly attributed to the search for resources to meet human needs. As a result, the ecosystem within the catchment gets adversely affected leading to a decline in land productivity, water scarcity, and catchment degradation through deforestation, hence the need to promote sustainable utilization of land and water resources within a catchment. In this regard therefore, an integrated approach in water resource planning, conservation and management is necessary. Research is therefore required with improved methods of data collection, analysis and integration, including remote sensing and GIS which have the advantage of analyzing different synoptic data on catchment variables quickly and efficiently to enable appropriate intervention.

For catchment development, reliable data along with forecasts of changing trends must be available, hence the outcome of this study provided estimates of the land use, and simulated stream discharges from SWAT model for effective management. Wundanyi River represents a system having many features similar to those of other Kenyan rivers and river discharge records are available. Since the application of remote sensing to integrate synoptic data on hydrology and land use within catchments for estimating catchment hydrology in Kenya is yet to be widespread, the results from the study can be extrapolated and used for planning other similar catchments.

1.5 The Scope and Limitations

This study attempted to evaluate the impact of land use change on the catchment hydrology and response for Wundanyi River catchment. The study used only one hydrological model, the SWAT model in the simulation of runoff hydrographs. The model had not been tested in the study area and so its parameters, capability, and sufficiency had to be established first through calibration and validation. The study therefore did not compare simulation results by other models. Hydrologic data such as runoff, sediment yield, evaporation and infiltration rates were also limiting.

CHAPTER TWO

LITERATURE REVIEW

2.1 Land Use and Land Cover Classification

The land cover definition is fundamental, because in many existing classifications and legends, it is confused with land use. Land cover is the observed (bio) physical cover on the earth's surface. When considering land cover in a very pure and strict sense, it should be confined to describe vegetation and man-made features. Consequently, areas where the surface consists of bare rock or bare soil are describing land itself rather than land cover.

Land use is characterized by the arrangements, activities and inputs people undertake in a certain land cover type to produce, change, or maintain it. The definition of land use in this way establishes a direct link between land cover and the actions of people in their environment. The word classification as used in the field is an abstract representation of the situation in the field using well-defined diagnostic criteria where the classifiers are defined as "the ordering or arrangement of objects into groups or sets on the basis of their relationships."

Kundu (2007) describes classification as the systematic framework showing the names of the classes and the criteria used to distinguish them, and the relation between classes. The classification should involve definition of class boundaries that should be clear, precise and based upon objective criteria. A classification should therefore be scale independent, meaning that the classes at all levels of the system should be applicable at any scale or level of detail; source independent, implying that it is independent of the means used to collect information, whether satellite image, aerial photography, field survey or a combination of them is used. Land use classification can be done in two ways, either by a priori or a posteriori system as described in the following sections.

2.1.1 Methods of Land Use and Land Cover Classification

The two methods which are widely used for land use and land cover classification are the Land Cover Classification System (LCCS) and the Co-ordination of Information on the Environment (CORINE).

2.1.2 Land Cover Classification System (LCCS)

The Land cover classification system (LCCS) is standardized a priori classification system which is designed to meet specific user requirements, and created for mapping exercises, independent of the scale or means used to map. By this system, land use which is identified anywhere in the world can be readily accommodated. The classification uses a set of independent diagnostic criteria that allow correlation with existing classifications and legends which are hierarchically arranged to assure a high degree of geographical accuracy. Because of the heterogeneity of land use, the same set of classifiers cannot be used to define all land use types. The hierarchical structure of the classifiers may differ from one land use type to another (Gregorio and Jansen, 2005). Therefore, the classification has two main phases: an initial dichotomous phase, where eight major land use types are distinguished, and a subsequent modular-hierarchical phase where the set of classifiers and their hierarchical arrangement are tailored to the major land use type as shown in Table 1.

Table 1 **: Distinction at the main dichotomous level and the second level**

Classifiers used	Land Cover Class Name and Description
	DICHOTOMOUS PHASE: INITIAL-LEVEL DISTINCTION
Presence of Vegetation: Primarily vegetated	A. Primarily Vegetated Areas: This class applies to areas that have a vegetative cover of at least 4% for at least two months of the year. This cover may consist of the life forms *Woody* (Trees, Shrubs), *Herbaceous* (Forbs, Graminoids), or a combination of them, or consist of Lichens/Mosses (only when other life forms are absent). A separate cover condition exists for Lichens/Mosses that can be only applied if this life form contributes at least 25% to the total vegetative cover (see Glossary).
Presence of Vegetation: Primarily non-vegetated	B. Primarily Non-Vegetated Areas: This class includes areas that have a total vegetative cover of less than 4% for at least 10 months of the year, or an absence of Woody or Herbaceous life forms and with less than 25% cover of Lichens/Mosses
	DICHOTOMOUS PHASE: SECOND-LEVEL DISTINCTION
Primarily vegetated Edaphic Condition: Terrestrial	A1. Terrestrial Primarily Vegetated Areas: The vegetation is influenced by the edaphic substratum.
Primarily non-vegetated Edaphic Condition: Terrestrial	B1. Terrestrial Primarily Non-Vegetated Areas: The cover is influenced by the edaphic substratum.
Primarily vegetated Edaphic Condition: Aquatic or regularly flooded	A2. Aquatic or Regularly Flooded Primarily Vegetated Areas: The environment is significantly influenced by the presence of water over extensive periods of time. The water is the dominant factor determining natural soil development and the type of plant communities living on its surface. Includes marshes, swamps, bogs and all areas where water is present for a substantial period regularly every year. This class includes floating vegetation.
Primarily non-vegetated Edaphic Condition: Aquatic or regularly flooded	B2. Aquatic or Regularly Flooded Primarily Non-Vegetated Areas: The environment is significantly influenced by the presence of water over an extensive period of time each year.

Source: Gregorio and Jansen (2005)

2.1.3 A Priori Classification System

A priori classification system is used when classes are pre-arranged. However, the use of such a classification assumes that all possible classes any user may derive, independent of scale and tools used, are included in the system. Having all classes pre-defined in the system is the intrinsic rigidity of the system. The advantage of such a system is mainly that it is the most effective way to produce standardization of classification results between user-communities. The disadvantage is that to be able to describe consistently any land cover occurring anywhere in the world, one needs an enormous amount of pre-defined classes. Such a system should be flexible in the sense that any occurring land cover may be accommodated (Gregorio an 2005).

By increasing the number of classes in an *a priori* system, a problem arises of how the users can manage the large number of class names. The wrong, or different, designation of the same land cover feature to different classes affects the standardization process that is one of the chief objectives of the system. The *a priori* classification approach appears to repeat itself when you attempt to create a type of classification as a tool for standardization obliges one to fit the enormous variety of occurring land cover in a limited number of more generic classes, while the endeavour to create more classes increases the danger of having a lack of standardization, the very basic principle used as a starting point.

2.1.4 A Posteriori System

A posteriori classification differs fundamentally by its direct approach and its freedom from preconceived classes. The approach is based upon definition of classes after clustering similarity or dissimilarity of the field samples collected. The advantage of this type of classification is its flexibility and adaptability compared to the implicit rigidity of the a priori classification. The a posteriori approach implies a minimum of generalization (Gregorio and Jansen, 2005). At the same time, however, because an a posteriori classification depends on the specific area described and is adapted to local conditions; it is unable to define standardized classes. Clustering of samples to define the classes can only be done after data collection, and the relevance of certain criteria in a certain area may be limited when used elsewhere or in ecologically quite different regions.

A posteriori is based upon definition of classes before any data collection actually takes place. This means that all possible combinations of diagnostic criteria must be dealt with beforehand in the classification. Basically, in the field, each sample plot is identified and labelled according to the classification adopted. The main advantage is that classes are standardized independent of the area and the means used. The disadvantage, however, is that this method is rigid, as some of the field samples may not be easily assignable to one of the pre-defined classes.

Over the years, several land use and land cover classification systems have been developed. In 1952, the world land use survey (LUS-1) was prepared by a special commission on world land use of the International Geographical Union (Valkenberg *et al.*, 1952). Further, Anderson (1977) developed a method of land use and land cover classification system for use with remotely sensed data. Zonneveld (1988) and Gils *et al*, (1991) developed the International Institute for Aerospace Survey and Earth Science (ITC) system for rural land use and land cover classification (LUCC). These land use and land cover classification systems are summarized in Tables 2, 3 and 4.

Table 2**: The land use survey classification**

Symbol	**Land use/land cover class**
1.	Settlement and associated non-agricultural lands
2.	Horticulture
3.	Tree and other perennial crops
4.	Cropland: a) Continual and rotation cropping
	b) Land rotation
5.	Improved permanent pasture (managed or enclosed)
6.	Unimproved grazing land: a) used
	b) Not used
7.	woodlands: a) dense
	b) open
	c) scrub
	d) Swamp forest
	e) cut-off or burned-over forest areas
	f) Forest with subsidiary cultivation
8.	swamps and marshes (fresh and salt water; non-forested)
9.	unproductive land

Source: Valkenberg *et al*. (1952)

Table 3: LCC, the ITC Land use, and Land cover classification

Class	Land Cover	Related Land Use	Class	Land Use	Related Land Covers
I	Building and artifacts A) Buildings B) Roads C) Canals/ditches, dams, dikes D) Dikes/dams E) Fences/hedgerows F) Wells/boreholes G) Terraces	1,2,3,4,5	1	Settlement and infrastructure a)Residential b) Industrial, quarrying, mining (above ground) c) Transport and communications d) Recreational e) Agricultural	I,II, V
II	Fields/crop plantations A) Fallow B) Herbaceouis crops C) Wetland rice D) Shrub/vine crops		2	Agriculture a)semi-permanent cultivation b) Permanent rain fed cultivation c) Pastoralism	II
III	Open natural vegetation A) Grass B) Savanna C) Scrub	3,4,5,6,7	3	Grazing a) intensive grazing b) ranching c) pastoralism	III (IV)
IV	Forest A) Forest plantation B) (semi) natural forest	2c,3,4,5,6	4	Forestry a) Timber b) Pulp-wood c) Firewood, charcoal, pole wood and other domestic use d) Other: eg bark, turpentine, tannin, cork	II, IV, III
V	Water body: snow/ice cover	5,6,7 (1b), (1d) (1c), (2), (3)	5	Conservation a) Natural reserve b) Game reserve c) Watershed management d) Dune stabilization e) Other	III, IV, V,(VI)
VI	Burned over land		6	Hunting, fishing and gathering a) Hunting b) Fishing c) Food gathering d) Fiber gathering e) Firewood collection	III,IV,V,(II)
VII	Barren land	7 (5)	7	Not used	

Source: (Zonneveld, 1988; Gils *et al*, 1991)

Table 4: LUS-2, land use, and land cover classification system

Level I	Level II
1. Urban Built–up land	11 Residential
	12 Commercial and Services
	13 Industrial
	14 Transportation, Communications and utilities
	15 Industrial and Commercial Complexes
	16 Mixed urban and Built-up land
	17 other urban and Built-up land
2. Agricultural land	21 cropland and pasture
	22 Orchards, groves, vineyards, nurseries and ornamental horticulture areas
	23 Confined feeding operations
	24 Other agricultural land
3. Rangeland	31 Herbaceous range
	32 shrub and brush rangeland
	33 Mixed rangeland
	41 deciduous forest land
4. Forest land	42 Evergreen forest land
	43 mixed forest land
	51 streams and canals
5. Water	52 Lakes
	53 Reservoirs
	54 Boys and Estuaries
	55 Other
	61 Forested wetland
6. Wetland	62 Non-forested wetland
	71 Salt flats
7. Barren Land	72 Beaches and mudflats
	73 Sandy area other than beaches
	74 bare exposed rock
	75 Strip mines, quarries and gravel pits
	76 Transitional areas
	77 Mixed barren land
	81 Shrub and brush tundra
8. Tundra	82 Herbaceous tundra
	83 Bare ground tundra
	84 Wet tundra
	85 Mixed tundra
	91 permanent snowfields
9. Permanent snow and Ice	92 Glacier

Source: Anderson (1977)

2.1.5 The CORINE Method

The CORINE Land Cover project is executed in Central and Eastern Europe as part of the Regional Environmental Programme. The CORINE Land Cover project is used in mapping the land cover at scale 1:100.000 in accordance with a standard European nomenclature of 44 categories. The main parameters of the map are the size of the minimum mapping unit (25 hectare) and the minimum width of linear elements (100 meter) (Kundu, 2007). The methodology relies on interpretation of satellite images (Landsat Thematic Mapper) and storing the results in GIS. A computer assisted verification procedure is applied to improve reliability. The database represents a basic tool for studies on the environment, impact assessment and regional planning. This database is used by the Image2000 team in performing the selection, acquisition and ortho-rectification of the satellite data (Landsat-7 ETM+) assisted by the national project team.

Based on interpretation of satellite images, the Corine Land Cover, (CLC) provides comparable digital maps of land cover for each country for much of Europe. It is useful for environmental analysis and comparisons as well as for policy making and assessment. No other land cover information programme in the world covers such a wide geographical area in such detail. This inventory provides a quantitative dataset of land use changes during this period of unprecedented economic growth. The CLC 2000 data is intended primarily for non-commercial use; however, the national competent authorities are entitled to make it available for commercial usage under licence terms and conditions

2.2 Catchment Hydrology

Marloes (2009) describes the changes in hydrological regime due to land use changes as related to two dividing points on the catchment hydrology as shown Figure 1. The first dividing point determines the effective rainfall, which equals the rainfall (P) minus the evaporation from interception (EI) and divides it into direct surface runoff (Ks*)* and infiltration (F*)*. The governing processes on catchment hydrology are the infiltration rate and interception, depending on vegetation cover and soil surface roughness. The second dividing point separates the infiltrated water into transpiration (ET), evaporation from the soil (Es) and recharge to the groundwater (R). Water stored in the unsaturated zone can also come to runoff through the unsaturated zone (Ku). Vegetation cover and crop stage influence the divide at this dividing point in the catchment. Transpiration rates are different for different vegetation covers, whereby forests generally transpire at higher rates than shrubs or agricultural lands. Miller *et al*. (2002) showed that for a deforested catchment, in general, the total annual surface runoff increases as a result of decreasing transpiration. Therefore the water balance on catchment hydrology can be shown by the Equation 2.1:

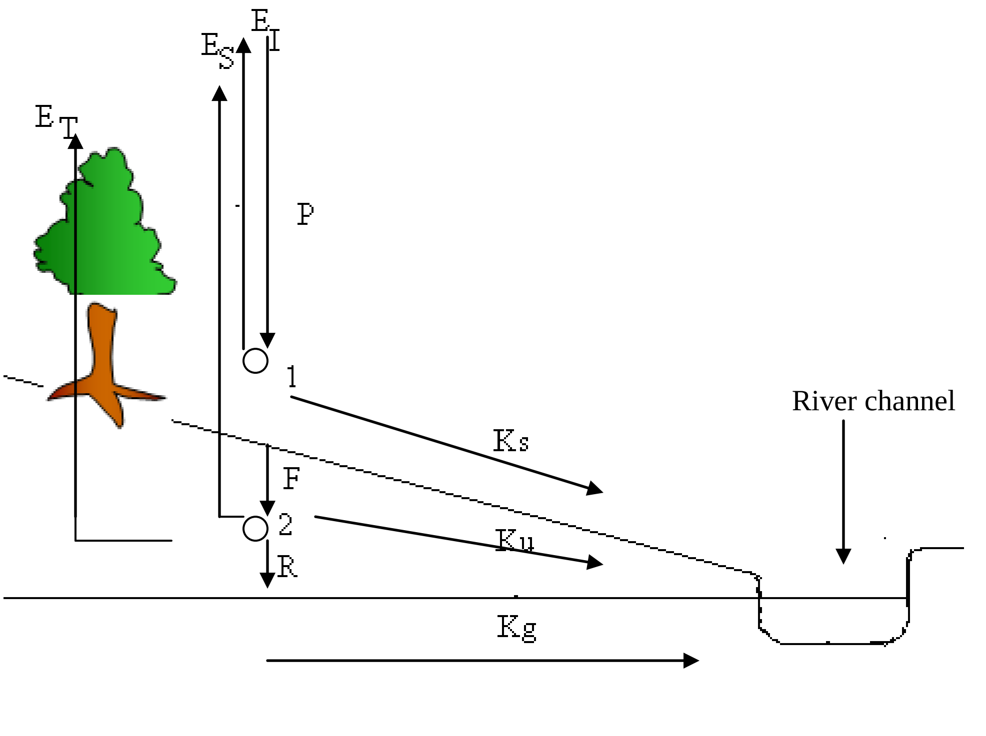


Figure 1: The two dividing points on the catchment hydrology

$$I - O = \frac{ds}{dt} \tag{2.1}$$

where *I* are inputs (precipitation ,P + occult water, OW), *O* are outputs (evapotranspiration ,ET + runoff ,R), and $\frac{ds}{dt}$ is the change in catchment storage over time. Neglecting the minor inputs of occult water, the water balance can be revised to be:

$$P - R - ET = \frac{ds}{dt} \tag{2.2}$$

Finally, considering a catchment on a long time scale, typically a year or more, removes the storage component in equation (2.2) and the new equation becomes:

$$P - R = ET \tag{2.3}$$

The annual water balance may be the same after a change in land use but it does not necessarily mean that at a smaller time scale there is no change. Figure 2 shows a conceptual representation for a single hydrograph. It shows a forested and deforested catchment, the deforested catchment has a smaller time of concentration (A) and peak flows are larger (B) compared to the forested catchment (Marloes, 2009). Base flow on the other hand is smaller (C); reduced infiltration rates decrease the replenishment of the groundwater aquifer and subsequently the base flow. In addition, the peak of the flow may increase, which could have severe consequences downstream. However, the volume under the hydrograph may change in either direction, indicating an increase or decrease of the total runoff. Land use change can direct the runoff response of a catchment in different ways, depending on the rainfall divide on catchment. The processes governing rainfall divide on catchment hydrology have a time scale ranging from one day (interception) to a couple of weeks (transpiration) after the actual rainfall took place (Maidment, 1993), depending on rainfall intensity, soil conditions and cover. However, the implications for the hydrological regime of the catchment have a longer time scale depending on the spatial scale. For example, the difference in residence time of a particle that infiltrates and recharges the groundwater compared to a particle that becomes surface runoff is from a day to up to years. That means that if the path of a particle is changed it will affect the residence time and hence the runoff. Not only can the changes in rainfall divide affect the total annual surface runoff, it, more so, affect the inter-annual distribution of the surface runoff. The actual impact of the land use change is dependent on the catchment conditions, from local climate to hydrological processes on the catchment.

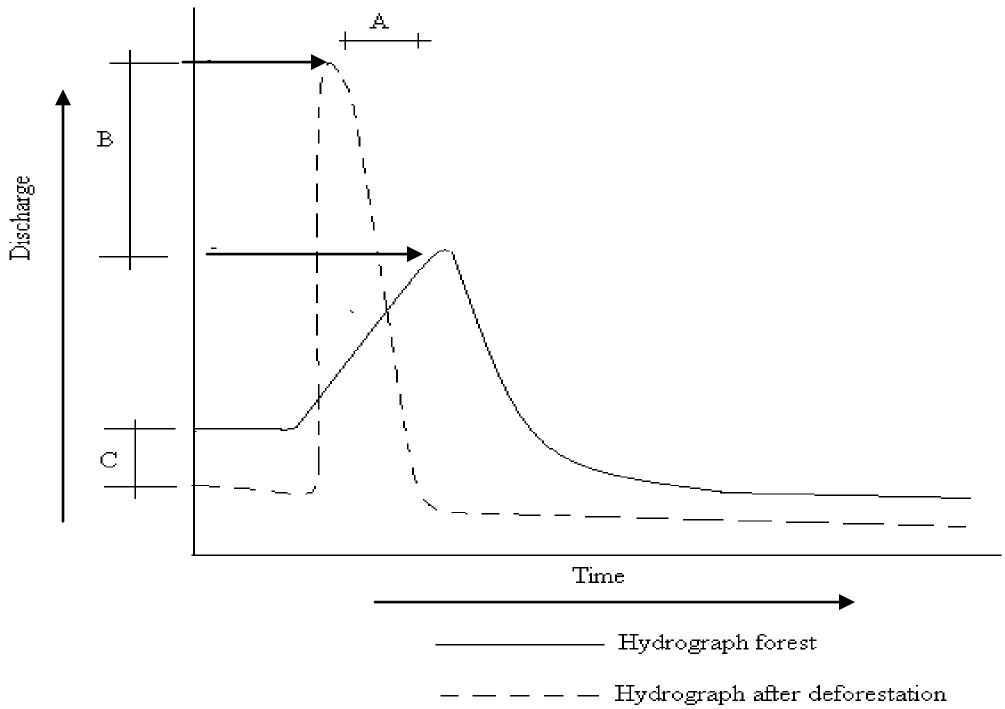


Figure 2: Conceptual representation of changes in hydrograph on catchment hydrology

2.2.1 Hydrologic Cycle

Water is regarded as the source of all life on earth. However, its distribution is quite varied with some catchments having plenty of it while others have very little. The earth water exists in three states as ice in solid form, liquid and water vapour. Therefore, water in oceans, rivers, clouds, and rain is in a frequent state of change where surface water evaporates, cloud water precipitates, rainfall infiltrates into the ground. However, the total amount of the earth's water does not change. The circulation and conservation of earth's water is called the hydrological cycle

The hydrological cycle therefore refers to the occurrence and interaction between water in the atmosphere, on the earth’s surface, and that in the underground. The process involves precipitation, of which part is intercepted by vegetation while some infiltrates into the soil to replenish groundwater reserves. The rest flows as surface runoff, lateral and return flows to streams, swamps and lakes where it again evaporates to the atmosphere to continue the cycle. The influence of land use change on rainfall within a single catchment is likely to be very minimal over forest land use. Consequently, no significant effect on total rainfall is likely to occur (Shaw, 1994). The total evaporation from a given land use is influenced by aerodynamic resistance to transportation of vapour between the evaporating surface and the atmosphere.

The balance between the atmospheric vapour demand and radiation leads to the occurrence of water at the evaporating surface. Land use change is likely to affect the free surface area in the lakes and swamps. This depending on the rate of abstraction the extent of the free water surface in the lake and the swamps will be reduced. Also altered will be the availability of soil water to the plants in the case of deep rooted plants that replace short rooted grass and decrease in the availability of water during the dry season. These changes in the availability of water at the evaporating surface cause changes in the evaporation rate leading to changes in the near surface atmospheric conditions and considering the extent of the land use, this leads to a catchment hydrology scale change in water balance (Kundu, 2007). For instance, replacing the short grasses with taller vegetation increases the aerodynamic roughness and lowers aerodynamic transport resistance. The overall effect of altering the surface fluxes of heat and water vapour is an increase in the total evaporation thus altering the mass balance of catchment hydrology.

2.2.2 Precipitation

Precipitation is the circulation of water from the atmosphere to the land. Precipitation can be in the form of rain, snow, hail and sleet and it is the most important part of hydrological cycle (Subramanya, 1984). The Precipitation in the form of rain is the driving force of the land phase of hydrologic cycle. Precipitation is characterized by both high spatial and temporal variability and is random or probabilistic in nature. Part of the precipitation is intercepted by natural vegetation cover and is either redistributed through runoff or evaporates back to the atmosphere. Precipitation also moves into the soil through the process of infiltration. Some of this infiltrated water percolates deep down into the ground to recharge the ground water reservoir.

Precipitation can be estimated by using recording or non-recording gauges. The recording gauges produce a continuous plot of rainfall against time and provide valuable data of intensity and duration of rainfall for hydrological analysis. These gauges automatically record the depth of rainfall in intervals ranging from as little as one minute in duration while non-recording gauges are read manually at longer time interval usually at 9 am and 3 pm. Recording gauges include the weighing-bucket type, float type and the tipping bucket type. Non-recording gauges are the standard and the storage type.

2.2.3 Precipitation Analysis

Precipitation data needs to be checked for quality, especially continuity and consistency before being used. The continuity of the records may be broken with missing data due to reasons such as a damaged instrument or a faulty rain gauge in a given period. The missing data can be estimated using the data of the neighbouring stations. There are several methods that can be used to estimate the missing data. The methods that are normally applied include; the simple arithmetic method and normal ratio method. The latter is used if the normal precipitation varies considerably. The normal rainfall is the average value of rainfall at a particular date, month or year over a specified 30 year period. The spatial rainfall is usually used in hydrology for various applications. Several procedures have been developed to convert point rainfall data into spatial format. The various methods used are discussed under the following sub headings:

2.2.4 The Arithmetic Mean

The arithmetic mean method is usually applied when the rainfall measured for various stations show little variation about the mean. It gives a very satisfactory measure of the areal rainfall under following conditions:

(i) The catchment area is sampled by many uniformly spaced rain gauges.

(ii) The area has no marked diversity in topography, so that the range in altitude is small and hence variation in rainfall amounts is minimal. The arithmetic mean is readily used when short-duration rainfall events spread over the whole area under study and for monthly and annual rainfall totals which is not usually the case of Wundanyi River catchment.

2.2.5 The Isohyetal Method

Isohyetal method, the catchment area is drawn to scale and the rain gauge stations are marked. The isohyets, which are lines joining points of equal rainfall magnitude are then drawn. The area between two adjacent isohyets is computed and the average rainfall indicated by the two isohyets is assumed to be acting over the inter-isohyetal area. The Isohyetal method is superior especially when the rain gauge stations are many. The areal rainfall is calculated from the product of the inter-isohyetal areas (a_i) and the corresponding mean rainfall between the isohyets (r_i) dividing by the total catchment area (A). The areal rainfall is then given as:

$$\overline{R} = \sum_{i=1}^{n} \frac{a_i r_i}{A} \tag{2.4}$$

Where $\overline{R}$ is the areal rainfall over the catchment, $a_1, a_2 \ldots a_n$ are inter-isohyetal area, $r_1, r_{2 \ldots} r_n$ *are* the mean rainfall between the isohyets and A is the total catchment area.

2.2.6 The Thiessen Polygon Method

For Thiessen Polygon method, the rainfall recorded at each station is assigned a weighting factor on the basis of the area closest to the station. The catchment area is drawn to scale and the stations are marked on it. The rain gauge stations are joined to form a network of triangles and perpendicular bisectors for each of the sides of the triangles are drawn. These bisectors form a polygon around each station. The area of each polygon is determined and used to calculate the average weighted rainfall using the equation given as:

$$\overline{R} = \frac{\sum_{i}^{n} R_i a_i}{a_i} \qquad (2.5)$$

where $\overline{R}$ is the average rainfall over the catchment, $R_1, R_{2 \ldots} R_n$ *are* the rainfall amounts recorded by each station and $a_1, a_2 \ldots a_n$ are the polygon areas.

Thiessen polygon method is more superior to the arithmetic method because it applies some weighting factor. This weightage is given to the rainfall station on a rational basis.

2.2.7 Evapotranspiration

Evapotranspiration (ET) which is an important part of the hydrologic cycle is a term used to describe the sum of evaporation and plant transpiration from the earth's land surface to the atmosphere. Evaporation accounts for the movement of water to the air from sources such as the soil, canopy interception and water bodies (Sintondji, 2005). Transpiration accounts for the movement of water within a plant and the subsequent loss of water as vapour through stomata in its leaves. Types of vegetation and land use significantly affect evapotranspiration, and therefore the amount of water leaving catchment. Because water transpired through leaves comes from the roots, plants with deep reaching roots can more constantly transpire water. Herbaceous plants generally transpire less than woody plants because they usually have less extensive foliage. Conifer forests tend to have higher rates of evapotranspiration than deciduous forests, particularly in the dormant and early spring seasons. This is primarily due to the enhanced amount of precipitation intercepted and evaporated by conifer foliage during these periods. Factors that affect evapotranspiration include the plant's growth stage or level of maturity, percentage of soil cover, solar radiation, humidity, temperature, and wind.

Evapotranspiration may be estimated by creating an equation of the water balance of a catchment hydrology. The equation balances the change in water stored within the catchment (S) with inputs and exports:

$$\Delta S = P - ET - Q - G \qquad (2.6)$$

The input is precipitation (P), and the exports are evapotranspiration (which is to be estimated), streamflow (Q), and groundwater recharge (G). If the change in storage, precipitation, streamflow, and groundwater recharge are all estimated, the missing flux, ET, can be estimated by rearranging the above equation as follows:

$$ET = P - \Delta S - Q - G \qquad (2.7)$$

Potential evapotranspiration (PET) is a representation of the environmental demand for evapotranspiration and represents the evapotranspiration rate of a short green crop, completely shading the ground, of uniform height and with adequate water status in the soil profile. It is a reflection of the energy available to evaporate water, and of the wind available to transport the water vapour from the ground up into the lower atmosphere (Gimeno-García *et al*., 2007). Actual evapotranspiration is said to equal potential evapotranspiration when there is ample water. The actual evapotranspiration is very important especially in the design and operation of hydraulic structures and systems within water catchments.

Thus potential evapotranspiration is calculated on hourly basis and converted to daily and monthly values, coinciding with the manual observations at 9 am and at 3 pm, using the Penman and Penman-Monteith equations (Monteith, 1965; Penman, 1948). Penman's open water equation, for potential evapotranspiration can be given by,

$$E_{pot} = \frac{1}{\lambda\rho}\left[\frac{s(R_n - G) + C_p\rho_a\left(\frac{e_a - e_d}{r_a}\right)}{s + \gamma}\right]\left[LT^{-1}\right] \qquad (2.8)$$

where λ is latent heat flux, 2,450,000 J kg^{-1}, ρ is density of water, 1,000 kg m^{-3}, ρ_a is density of moist air, J d^{-1} m^{-2}, G is heat flux density into the water body, J d^{-1}m^{-2}, *cp* is specific heat of dry air at constant pressure, 1004.6 J kg^{-1} K^{-1} and γ is psychrometric constant 0.067 kPa °C. Pressure, *ea* [kPa] is given:

$$e_a = 0.611\exp\left(\frac{17.3\mathrm{T}_a}{237.3 + T_a}\right) \tag{2.9}$$

at temperature *Ta*, (in °C)

Actual vapour pressure, e_d [kPa] is given:

$$e_d = e_a h \tag{2.10}$$

Aerodynamic diffusion resistance r_a [hr m^{-1}] is given:

$$r_a = \frac{208}{u_2}\frac{1}{3600} \tag{2.11}$$

Energy flux density of the net incoming radiation, R_n [J hr^{-1} m^{-2}] is given:

$$R_n = R_{ns} - R_{nl} \tag{2.12}$$

where r is albedo (0.06 for open water and 0.23 for short grass (Allen *et al*., 1998)) and R_{ns} is observed in W m^{-2}, this is converted to J hr^{-1}m^{-2} by dividing the observed by 3600 to change inio hours. Net outgoing long wave radiation, R_{nl} [J hr^{-1} m^{-2}] is given:

$$R_{nl=\sigma(273.3+T_a)}{}^4\left(\alpha\frac{n}{N} + \beta\right)\left(C + d\sqrt{e_d}\right) \tag{2.13}$$

where α, β, c and d are climatic dependent factors. $\frac{n}{N}$ is calculated with the measured solar radiation (n) over the maximum observed solar radiation of that specific hour in that month (based on the first three years of data). It is assumed that this value is equal to the potential solar radiation at that time within that month. The potential transpiration through the Penman-Monteith's equation then becomes:

$$E_{t,pot} = \frac{1}{\lambda\rho}\left[\frac{S(R_{n-G}) + C_p\rho_a\frac{(e_a - e_d)}{r_a}}{S + \gamma\left(1 + \frac{r_s}{r_a}\right)}\right]\left[mhr^{-1}\right] \tag{2.14}$$

where r_s is canopy diffusion resistance, for short grass this is 0.019 hr m^{-1}. Very high potential transpiration is calculated during the dry period in January and February, even exceeding 9 mm d^{-1}. During the colder dry period from May to August the potential evaporation is reduced to 2-5 mm d^{-1}.

2.2.8 Infiltration

Infiltration is the passage of water through macro pores from the surface to the subsurface. It is the downward movement of water from the land surface into soil or porous rock. This process is directly or indirectly influenced by the vegetation cover and land use practices. The other factors that affect infiltration rate include the intensity and duration of precipitation, soil characteristics, soil saturation and the slope of the land. The initial infiltration rate depends on the antecedent soil moisture content prior to the introduction of water on the soil surface. As infiltration continues, the soil becomes increasingly wet, causing the rate of infiltration to decrease with time until it reaches a steady value referred to as the infiltration capacity. The final rate of infiltration is equivalent to the saturated hydraulic conductivity of the soil in question. In order to calculate or determine the infiltration rate, a number of methods have been proposed. These methods include; the Horton's infiltration model, Green and Ampt infiltration method and Philip equation.

The Green and Ampt infiltration method was developed to predict infiltration assuming that there will be excess water at the surface at all times (Chow *et al*., 1988). The equation assumes that the soil profile is homogenous and the antecedent moisture content is uniformly distributed in the soil profile. As water infiltrates into the soil, the model assumes that the soil above the wetting front is completely saturated and there is a sharp break in moisture content at the wetting front. The Green and Ampt infiltration method is given as:

$$f = K\left[1 + \frac{(\phi - \theta_i)Sf}{F}\right] \tag{2.15}$$

where f is the infiltration rate, K is the effective hydraulic conductivity, Sf is the effective suction in the wetting front, ϕ is the soil porosity, θ_i is the water content and F is the accumulated infiltration.

The amount of water entering the soil profile is calculated as the difference between the amount of rainfall and the amount of surface runoff. The Green and Ampt infiltration method directly models infiltration, though it requires precipitation data in smaller time steps such as hours.

Horton's equation is another viable option when measuring ground infiltration rates or volumes. It is an empirical formula that says that infiltration starts at a constant rate f_o, and is decreasing exponentially with time, t (Horton, 1940).

After some time when the soil saturation level reaches a certain value, the rate of infiltration will level off to the rate f_c.

$$f_t = f_c + (f_o - f_c)e^{-kt} \quad (2.16)$$

where f_t is the infiltration rate at time *t*, f_o is the initial infiltration rate or maximum infiltration rate, f_c is the constant or equilibrium infiltration rate after the soil has been saturated or minimum infiltration rate, k is the decay constant specific to the soil.

The other method of using Horton's equation is as below. It can be used to find the total volume of infiltration, *F*, after time *t*.

$$F_t = f_c + \frac{(f_o - f_c)}{k}(1 - e^{-kt}) \quad (2.17)$$

Another method of determining the infiltration rate is the Philip's method (Philip, 1954). However, this method was derived from the theory for one dimensional infiltration and equations were developed which described the infiltration on both a short term and long term scale, with the revelation that when ponded infiltration in uniform soils occurs, the flow will approach the saturated hydraulic conductivity:

$$I = S\sqrt{t} + At \quad (2.18)$$

where S is sorptivity and A is the steady-state infiltration rate

2.2.9 Runoff

Runoff is that portion of precipitation that does not evaporate or infiltrate but makes its way towards stream channels, lakes and oceans as surface or subsurface flow and baseflow. It is the essential factor in determining the catchment hydrology in a catchment that is affected by land use changes (Barkhordari, 2003). Land use change is an important factor in the runoff process that affects infiltration, erosion and evapotranspiration (Croke *et al*., 2004). Due to rapid land development and subdivision, land use is subjected to changes causing soils to become impervious surfaces. This leads to decrease in the soil permeability, and consequently increase the amount and rate of runoff. For instance, Kute and Stuart (2007) concluded that an increase of 11% in impervious area increased the peak discharge in their study area in East London by 35% and decreased the time to reach the peak flow by one hour. However, they assumed 100% runoff due to the size of the catchment which is not the case for most of the catchments. Mustafa *et al.* (2005) found out that it is possible to describe the catchment characteristics when determining runoff response to rainfall input.

Several methods have been developed for estimating runoff from a given catchment. One of these methods is the Soil Conservation Service (SCS) curve number (CN) method. The curve number model is given as:

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \qquad (2.19)$$

where Q (mm) is the runoff, P (mm) is the rainfall, I_a (mm) is the initial abstraction and S (mm) is the potential maximum retention after the runoff begins in mm. The retention parameter varies spatially due to changes in soils, land use, management, and slope, and temporally due to changes in soil water content. The retention parameter is given as:

$$S = \frac{25400}{CN} - 254 \qquad (2.20)$$

where CN is the curve number

The initial abstraction I_a represents all losses before runoff begins. It includes water retained on the surface depression, water intercepted by vegetation, evaporation and infiltration. The initial abstraction I_a is highly variable; however, it is commonly approximated as *0.2S*. By substituting this approximate variable into Equation 2.19, the equation reduces to:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}, \qquad \text{For } P > 0.2S \qquad (2.21)$$

In this case, runoff will only occur when, $P > I_a$.

The major factors that determine the *CN* value are the Hydrologic Soil Group (HSG), land cover type, treatment and antecedent soil condition. In hydrology, the curve numbers are stated for average soil moisture levels and they can either be single or several depending on the heterogeneity of the catchment. For soil moisture conditions other than the average one, value of soil moisture is used to adjust the mean curve number to reflect the soil moisture status of the catchment at the time under consideration. In the classical curve number procedure, only two soil moisture levels apart from the mean one is used to represent the antecedent catchment wetness and subsequently to adjust the mean curve number. These two conditions represent dryness and wetness of a catchment.

The adjustments for dry and wet conditions proceed as in Equation (2.22 and 2.23).

$$CN(I) = \frac{4.2 * CN(II)}{10 - 0.058 * CN(II)} \tag{2.22}$$

$$CN(III) = \frac{23 * CN(II)}{10 + 0.13 * CN(II)} \tag{2.23}$$

where CN(I) is curve number of dry condition, CN(II) is curve number of normal condition, CN(III) is curve number of wet condition.

Another model of estimating surface runoff is Nash-Cascade-Diskin-Infiltration model as describe by Onyando (2000). The Nash-Cascade-Diskin-Infiltration model is a two component rainfall-runoff model consisting of surface runoff generation and runoff routing components. Although the model is lumped, the runoff generation component has been applied based on spatial distribution of soil storage capacity derived from similar areas of land use and soil units. This tends to improve the performance of the model since the effects of different types of land use and soils are taken into account by generating direct runoff in every soil and land use unit.

The other model which can be used to generate surface runoff is the linear reservoir infiltration model of Diskin and Nazimov (1995). In their study on a finite area using artificial data, the authors obtained results using this model which showed expected infiltration trends. It was also demonstrated later by Diskin and Nazimov (1995) that the model can be used in determining ponding time and infiltration capacity variation during steady rainfall. In the same study, the authors tested the model under varying rainfall conditions and found results which showed the expected infiltration trends. These potentials of the model make it suitable for test on catchment hydrology scale. The previous study upon which this model is based was presented by Bauer 1974 and Onyando, 2000. By modifying Horton's equation, the authors presented an infiltration rate equation as a function of soil moisture storage. In this case also, infiltration during intermittent rainfall could be evaluated under varying initial soil moisture conditions. Similar modification of Horton equation to adapt it to variable rainfall situations but only for part of the time when rainfall rate is less than the potential infiltration rate has also been presented by (Verma, 1982). This version was found to be suitable for small catchments which respond quickly to storm input, unlike Wundanyi River catchment which is medium catchment.

The surface runoff routing component of this is based on Nash cascade. Combining this with Diskin infiltration model, results in a conceptual rainfall-runoff model for surface runoff modelling. It also provides the opportunity to test Diskin infiltration model on a catchment hydrology scale.

The generation of surface runoff in Nash-Cascade-Diskin-infiltration model is achieved using Diskin infiltration model. The mathematical expression for accomplishing this are adapted from (Onyando, 2000). In formulating these equations, one of the assumptions made is that the storage element is a linear reservoir which produces an output proportional to the volume in storage. The value of this output $g(t)$ at time t is expressed as:

$$g(t) = K * S(t) \tag{2.24}$$

where K is model parameter

Another assumption made in this model is that the state variables of the inlet regulating elements $f(t)$ is determined by the value of $S(t)$ transmitted by the feedback loop to the inlet regulating element. The two state variables are related by a decreasing linear relation as given in Equation 2.25.

$$f(t) = X - Y * S(t) \tag{2.25}$$

where X and Y are model parameters

The outputs q (t) and y (t) from the inlet regulating element depend on the state variable $f(t)$ and on the input $p(t)$. The relationships are stated in the following equations.

$$q(t) = \begin{cases} p(t) & \text{for} \quad p(t) < f(t) \\ f(t) & \text{for} \quad p(t) > f(t) \end{cases} \tag{2.26}$$

$$y(t) = \begin{cases} 0 & \text{for} \quad p(t) < f(t) \\ p(t) - f(t) & \text{for} \quad p(t) > f(t) \end{cases} \tag{2.27}$$

The time value of the state variable $S(t)$ of the storage element is dependent on the input $q(t)$ and the output $g(t)$. Based on the principles of conservation of mass, the relationship between these three variables can be expressed as;

$$\frac{ds}{dt} = q(t) - g(t) \tag{2.28}$$

2.2.10 Stream Flow Generation

Stream flow is the flow of water in streams, rivers, and other channels, and is a major element of the water cycle. Water flowing in channels comes from surface runoff from adjacent hillslopes, from water discharged from storm or other drains. Runoff becomes part of total stream flow when it joins the stream. It is possible to measure the amount of water in this phase of the cycle as it leaves the catchment (Linsley and Franzini, 1989).

The streamflow data is an important indicator of biophysical changes in the catchment. For instance, the streamflow rate at a particular point in time and location on a drainage system, integrates all the hydrologic processes and storages upstream of that location. Maidment (1993) found out that the rate of streamflow depends on several factors such as rainfall events, the seasonal distribution, type and transpiration of the vegetation. These factors when altered through land development significantly affect the seasonal and annual distribution of stream flow. Among these factors, vegetation cover has been recognised as a key factor in runoff production and protection against erosion (Gimeno-García *et al*., 2007).

Vegetation cover increases infiltration and surface roughness, and hence reduces the kinetic impact of raindrops on the land surface. For instance Gimeno-García *et al.* (2007) concluded in their study that after the clearing of vegetation by fire, there was a significant change in catchment hydrology in their study area. In another study carried out by Li *et al.* (2007), it was concluded that total deforestation increased the simulated runoff ratio from 0.15 to 0.44 and the annual stream flow by 35-36%, depending on the location of the catchment. Likewise, some studies in Mississippi indicated that there was a reduction in discharge due to increase in vegetation density (Donner, 2004). The understanding of how these activities influence stream flow aids planners in formulating policies towards minimizing undesirable effects on stream flow patterns.

Kirui (2008) in the study carried out in the Upper Molo catchment of Kenya concluded that land cover change of less than 48% had insignificant effect on catchment hydrologic response. The author pointed out that the simulation results and parameters both physical and conceptual were unique for each catchment.

2.2.11 Time of Concentration and Travel time

The travel time (T_t) is a component of time of concentration (T_c) which is the time for runoff to travel from the hydraulically most distant point of the catchment to a point of interest within the catchment. The time of concentration (T_c) is computed by summing all the travel times for consecutive components of the drainage conveyance system. The time of concentration (T_c) influences the shape and peak of the runoff hydrograph. While urbanization usually decreases (T_c) by increasing the peak discharge, the time of concentration can be increased as a result of; ponding behind small or inadequate drainage systems, including storm drain inlets and road culverts, or reduction of land slope through grading (Donner, 2004).

Water moves through a catchment as sheet flow, open channel flow, or some combination of the two. The flow that occurs is a function of the conveyance system and is best determined by field inspection (Kute and Stuart, 2007).

The travel time T_t is the ratio of flow length to flow velocity given as:

$$T_t = \frac{L}{3600V} \tag{2.29}$$

where T_t is the travel time (hr), L is the flow length (m), V is the average velocity (m/s), and 3600 is the conversion factor from seconds to hours.

The time of concentration T_c is the sum of T_t values for the various consecutive flow segments and is given as:

$$T_c = T_{t1} + T_{t2} + ... + T_n \tag{2.30}$$

where T_c is time of concentration (hr), n is the number of flow segments.

To compute time of concentration, another equation referred to as Kirpich's equation (Kirpich, 1940) was also developed for small, agricultural catchments. It was derived by examining the required time for the stream to rise from low to maximum stage during a storm. The time of concentration was then assumed equal to that time.

$$T_c = \frac{0.00013L^{0.77}}{S^{0.385}} \tag{2.31}$$

where T_c is time of concentration in hours, L - length of the overland flow in metre and S is average overland slope in m/m.

This equation given below was developed for overland flow on bare earth. For overland flow on grassy earth, T_c should be multiplied by 2.0. On concrete and asphalt surface it should be multiplied by 0.4. An adjustment is made for catchments with a CN number less than 80 using the following equation:

$$T_c = T_C * (1 + (80 - CN) * 0.04) \tag{2.32}$$

The CN value must be defined for the given model (HEC-1, TR-20, etc.), otherwise a default CN of 50 is used.

Kerby (1959) also developed an equation for computing the time of concentration for overland flow distances of less than 150 m and greater than 90 m.

$$T_c = \left(\frac{0.67 * n * Lo}{\sqrt{S}} \right)^{0.467} \quad (2.33)$$

where T_c is time of concentration in minutes, S is overland slope in m/m, n is roughness coefficient and Lo is length of overland flow in metre. A table of recommended values for n are as given below:

Table 5: Roughness coefficient (n)

Recommended surface roughness values	
Surface Description	**n**
Smooth, impervious surface	0.02
Smooth, packed bare soil	0.1
Poor grass, cultivated row crops of moderately rough bare soil	0.2
Pasture or average grass	0.4
Deciduous timberland	0.6
Timberland with deep forest litter or dense grass	0.8

Ramser (1927) developed equation for computing the time of concentration in well-defined channels. The equation is based on the length and slope of the channel.

$$T_C = 0.008 L_c^{0.77} S_c^{-0.385} \quad (2.34)$$

where T_c is the time of concentration in minutes, L_c is the length of channel reach in metre and S_c is the average channel slope in m/m. For flow in concrete channels, T_c should be multiplied by 0.2.

2.2.9 Factors affecting Time of Concentration and Travel time

The main factors that affect the time of concentration and travel time include surface roughness, channel shape, flow patterns and slope. Undeveloped areas usually have very slow and shallow overland flow through vegetation. The flow in built up areas is usually delivered to streets, footpath, gutters, and storm sewers that transport runoff downstream more rapidly. Thus there is decrease in travel time through the catchment under built up areas, showing that surface roughness affects time of concentration and travel time.

Typically, urbanization reduces overland flow lengths by conveying storm runoff into a channel immediately after the rain storm. Since channel designs have efficient hydraulic characteristics, runoff flow velocity increases and travel time decreases in urban development (Croke *et al*., 2004).

2.3 Channel Routing

Flow routing in channels is a process of computing outflow hydrograph at the downstream end of a channel, given the inflow hydrograph to the channel at the upstream end. Generally speaking, channel routing techniques can be broadly classified into hydrologic and hydraulic routing. The hydrologic routing is also referred to as storage routing, because a continuity equation in conjunction with the relationship between storage and discharge are used. On the other hand, the hydraulic routing involves simultaneously computing both stage and discharge as a function of location and time (Wurbs and James, 2001).

The flow at the sub-catchment outlets, due to overland flow, is routed to their downstream sub-catchment outlets using either the Pure Lag method or Muskingum routing technique. The choice of the technique to be employed is based on the channel flow time and analysis time step. If the channel flow time is less than the analysis time step, then the channel routing is conducted using the Pure Lag method; otherwise the routing is done using the Muskingum method (Corps of Engineers, 1960).

2. 3.1 Pure Lag Method

This is a simple channel routing method which is used for channels whose flow time is less than the analysis time step, in which the inflow hydrograph is lagged in time so as to obtain the outflow hydrograph (Olivera *et al.*, 1999). In other words, the inflow hydrograph is shifted along the time axis, by an amount equal to the lag time. The lag time is the same as average flow time (K) in a channel. This method assumes only pure translation to take place, but does not consider storage effects in channels. Due to this reason, the shape of the hydrograph is conserved.

Mathematically the model can be represented as:

$$Q(t + t_{lag}) = I_{(t)} \tag{2.35}$$

where Q (t) is the outflow hydrograph, $I_{(t)}$ is the inflow hydrograph, t_{lag} *is* the lag time.

2. 3.2 Muskingum Method

This is an approximate hydrological method of flood routing through a reach of river, based on the equation of continuity and a storage equation expressing the linear dependence of the water volume in the reach on the weighted inflow and outflow. Therefore the flow from sub-catchments is routed to the catchment outlet using Muskingum method, which computes the outflow from a reach using Equations 2.36, 2.37 and 2.38 (Corps of Engineers, 1960). For the purpose of calibration and validation, the daily mean discharge (m^3/s) from the outlet station is used to calibrate the model and routing parameters to fit the simulated hydrograph to the observed one as given by Equation 2.36.

$$S = f_1(O) + f_2(I - O) \tag{2.36}$$

From equation (2.36) $f_1(0)$ and $f_2(I - O)$ are considered to be both straight line functions that is. $f_1(O) = K.O$ and $f_2(I - O) = b(I - O)$. Thus:

$$S = bI + (K - b)O$$

$$= K\left[\frac{b}{K} I + \left(1 - \frac{b}{K}\right) O\right] \tag{2.37}$$

And writing $x = \dfrac{b}{K}$, Equation (2.37) becomes:

$$S = K[xI + (I - x)O] \tag{2.38}$$

Thus x is a dimensionless weighting factor indicating the relative importance of I and O in determining the storage in the reach. The value of x has limits of zero and 0.5, with typical values in the range 0.2 and 0.4. K has the dimension of time. From the continuity equation:

$$S_2 - S_1 = \frac{1}{2}(I_1 + I_2)\Delta T - \frac{1}{2}(O_1 + O_2)\Delta T = K[xI_2 + (1 - x)O_2] - K[xI_1 + (1 - x)O_1] \tag{2.39}$$

To get O_2 , the unknown outflow Equation (2.39) is arranged as follows.

$$O_2(-0.5\Delta T - K + Kx) = I_1(-Kx - 0.5\Delta T) + I_2(Kx - 0.5\Delta T) +$$
$$O_1(-K + Kx + 0.5\Delta T) \tag{2.40}$$

Then:

$$O_2 = c_1 I_1 + c_2 I_2 + c_3 O_1 \tag{2.41}$$

where:

$$\left.\begin{aligned} c_1 &= \frac{\Delta T + 2Kx}{\Delta T + 2K - 2Kx} \\ c_2 &= \frac{\Delta T - 2Kx}{\Delta T + 2K - 2Kx} \\ c_3 &= \frac{-\Delta T + 2K - 2Kx}{\Delta T + 2K - 2Kx} \end{aligned}\right\} \tag{2.42}$$

where I_1 is the inflow to the routing reach in m^3/s, O_2 is the outflow from the routing reach in m^3/s, K is the travel time through the reach in hours, x is Muskingum weight factor, ΔT is the analysis time step. Thus the out-flow at the end of a time step is the weighted sum of the starting inflow and outflow and the ending inflow as in equation (2.39).

Though these equations can be directly applied to all channels, for channels that are long, numerical instability may arise. Here long channels refer to those that fail the condition given in the form, $K/3 < \Delta_t > K$. Once a channel is determined to be long, it is sub-divided into sub-channels based on the following equation (Olivera *et al.*, 1999):

$$n = Int\left[\frac{L}{3\Delta_t V}\right] + 1 \tag{2.43}$$

where n is the number of sub-channels, L is the length of the channel, Δ_t is the analysis time step, V is the average flow velocity in the channel.

2.4 Impact of Land Use Changes on Catchment Hydrology

Human activities such as agriculture and urban development affect the land surface. Land cover is the biophysical state of the earth's surface and immediate subsurface, which include: biota, soil, topography, surface and underground water, and human structures (Hartemink *et al*., 2006). The land use involves the manner in which the biophysical attributes of the land are manipulated and the intent underlying that manipulation for which the land is used (Hartemink *et al*., 2006).

Land use changes are significant in catchment studies especially in assessing environmental impact. The environmental impacts at local, regional, and global levels significantly affect the hydrology of a catchment. Alterations in the earth's surface have major implications on the radiation balance, water quality and quantity, surface runoff dynamics and lowering of groundwater tables (Mungai *et al*., 2004). Furthermore, vegetation modification, whether resulting from harvesting or planting, alters the water balance of the site. This may eventually alter the hydrologic regime of the catchment. If vegetation is significantly reduced, the flow path of precipitation can be altered and significant surface flow can take place causing increase in surface runoff, erosion and sedimentation of water bodies.

Cultivation of land exerts a major influence on the relationship between surface and subsurface flow. For instance, the annual surface runoff from loam soil increases by four times in a cultivated catchment, according to data from long-term observations done in paired catchments in the forest zone of Central Russia (Golosov and Panin, 2006). Studies have shown that surface runoff is extremely limited under grass or forest vegetation compared with agricultural land.

Effects of land use changes are manifested in many ways and at different spatial and temporal scales. The most obvious ones are the immediate and direct effects on the quantity and quality of the catchment's runoff. For instance, land use changes are the most significant factors driving hydrological changes such as runoff volume, timing, and variability (Donner, 2004). The simplest method to assess these effects on catchment hydrology is by comparing stream flow and runoff generated from catchment areas with contrasting land use types (Barkhordari, 2003).

The need for fertile land to meet the ever increasing demand for food has led the rural population into clearing the natural and exotic forest for agricultural development and settlement (Maingi and Marsh, 2001). As the landscape in a catchment is altered both spatially and temporally, the factors that influence catchment hydrology also change (Barkhordari, 2003). The evaluation of the relationship between the land uses and catchment hydrology is important for the efficient catchment management. This evaluation has normally been done using several types of models that vary from strictly empirical to physically based distributed models (Barkhordari, 2003). Physically distributed models in particular need specific data on land use and soil types and their locations within a catchment (Chakraborty *et al*., 2005).

A number of methods are currently being used to assess the impacts of different land use on catchment hydrological regimes. Some of these methods include the modelling approach and use of paired catchments. The paired catchment approach applies the comparison of the hydrologic response of a catchment consisting of degraded lands where catchment management is to be introduced with catchments that already have the desired land use characteristics anticipated to be achieved. Bosch and Hewlett (1982) reviewed the results of 94 catchments throughout the world and concluded that removal of forest almost invariably leads to higher streamflow and that reforestation of open lands generally leads to a decline in the overall streamflow.

By using modelling approach, several researchers have assessed the effect of land use changes on catchment hydrology. Chemelil (1995) applied the HYDRROM model for stream flows in river Njoro catchment, Kenya. The author used secondary data for land use and land cover for 1979 obtained from the Department of Remote Sensing and Resources Survey (DRSRS) and from subsequent studies by Karanja *et al*. (1986).

For large scale catchments, effects of changes in land use on the hydrological regimes may be difficult to distinguish since they have a variety of land use classes, and vegetation in various stages of regeneration (Pearee *et al*., 2003). Wilk *et al*. (2001) studied the catchment hydrology for a 12,100 km^2 Nam Pong catchment in northeast Thailand, where the area classified as forest decreased from 80 to 27% between 1957 and 1995. At the end of the rainy season, the researchers could not detect changes in the rainfall totals and patterns, or in the dynamics of the recession of the hydrograph. However, detectable changes in streamflow were expected where large tracts of forest have been replaced by annual cropping rather than leaving the forest to regenerate.

In Kenya, results from studies done on the effects of land use conversions on the catchment hydrology for very large catchments (50,000 km^2) are scarce (Onyando, 2000). The few large-scale catchment studies reviewed have not found a consistent pattern of hydrological response to large-scale changes in land use (Kundu, 2007). The lack of studies for very large and persistent land use conversions suggests that if appropriate land use maps, precipitation, and discharge data were available, it would be possible to determine whether the impact of land use change across very large catchments is the same as to that observed in smaller catchments.

2.5 Catchment Discretization

Catchment discretization refers to the process of sub-dividing of catchment into small homogeneous areas within the sub-catchments. This is therefore used by distributed hydrological models to derive distributed estimation of water balance components or to study the impact of land-use or climate change on water resources and water quality. In these models, the choice of an appropriate spatial discretization is a crucial issue. It is obviously linked to the available data, their spatial resolution and the dominant hydrological processes. For a given catchment and a given data set, the "optimal" spatial discretization should be adapted to the modelling objectives, as the latter determine the dominant hydrological processes considered in the modelling (Goodrich *et al*., 2003). For small catchments, landscape heterogeneity can be represented explicitly, whereas for large catchments such fine representation is not feasible and simplification is needed. The question is thus: is it possible to design a flexible methodology to represent landscape heterogeneity efficiently, according to the problem to be solved? This methodology should allow a controlled and objective trade-off between available data, the scale of the dominant water cycle components and the modelling objectives. This methodology therefore requires catchment discretization.

For this catchment discretization, the study used the principles borrowed from land use classification. These principles are independent of the catchment size. They allow retaining suitable features required in the catchment description in order to fulfil a specific modelling objective. The method leads to unstructured and homogeneous areas within the sub-catchments, which can be used to derive modelling parameters. It avoids map smoothing by suppressing the smallest units, the role of which can be very important in hydrology, and provides a confidence map (the distance map) for the classification (Ma *et al*., 2008). The confidence map can be used for further uncertainty analysis of modelling results. The final discretization remains consistent with the resolution of input data and that of the source maps (Mao *et al*., 2008). The interest of the method for an efficient representation of land use heterogeneity is illustrated by a comparison with more traditional mapping approaches (Barnaby and Pellikka, 2000). Examples of possible models, which can be built on this spatial discretization, are finally given as perspectives for the study.

2.6 Catchment Modelling

A well conducted modelling study requires detailed knowledge of the system being modelled and the strengths and weaknesses of the model under consideration (Chemelil and Smout, 2000). The factors to be considered when modelling are the model's complexity, data requirements and transferability of the model to other sites and conditions. In addition, the model's potential to predict specific effects for specific changes and implicit uncertainties in the model predictions are of great importance (Singh, 1996). A model has to contain parameters that are sensitive to the catchment changes taking place such as land use changes (ASCE, 1993).

Some of the models employed on a catchment scale for simulating impact of land use changes on catchment hydrology include Precipitation-Runoff modelling system (PRMS), Top model, Automated geospatial Watershed Assessment tool (AGWA) Kinematic Runoff and Erosion model, HEC-HMS(Hydrologic Modeling System) and Soil Water Assessment Tool (SWAT).

2.6.1 Precipitation-Runoff Modelling System (PRMS)

The Precipitation-Runoff modelling system (PRMS) was developed to simulate catchment response over long periods of time. The PRMS is a modular designed, physically based distributed model system simulating water fluxes and storages at the catchment scale. It evaluates the effects of various combinations of precipitation, climate and land use on catchment response (Maidment, 1993). It is simulates discharge by routing the flow down the sub reaches to the outlet. The model is event based, hence cannot be used for continuous stream flow simulation.

The PRMS is used to derive flood hydrographs from storm rainfall, where one of the most important hydrographs derived using this model is the unit hydrograph. The unit hydrographs are computed from recorded rainfall and runoff data from gauged catchments. For ungauged catchments, the unit hydrograph is computed from the catchment characteristics as described by (Onyando, 2000) in the study of Rainfall-runoff models for ungauged catchments in Kenya. To compute a flood hydrograph, the particulars of storm rainfall must be selected and assessment of losses carried out. The PRMS provides simulations on both daily and storm time scale by using variable time step, hence could not be used in this study.

2.6.2 Topmodel

The Topmodel (Beven *et al*., 1995) is a distributed model designed to simulate runoff from Hill slopes and source areas of ungauged catchment of up to 500 km^2. It routes the runoff from different sub-catchments down to the outlet producing a final catchment discharge. The model requires the computation of the frequency or spatial distribution of topographic index from topographic data, such as a Digital Elevation Model (Wolock and Price, 1994). It is flexible and incorporates the contributing area concept. In addition, it is suitable for continuous simulation, but not single event isolated storms as was evident in the work done by Onyando (2000) in the study of Rainfall-runoff models for ungauged catchments in Kenya. The Topmodel is not suitable for Hortonian runoff and hence not suitable for the Wundanyi River catchment which experiences both Hortonian and saturation excess flow.

2.6.3 Automated Geospatial Watershed Assessment Tool (AGWA)

The Automated Geospatial Watershed Assessment Tool (AGWA) is a multipurpose hydrologic analysis system that can be used in catchment scale studies (Semmens *et al*., 2002). The AGWA model has three components namely; the catchment delineation component, parameterisation component, component that writes the parameter files and that allows visualisation of simulation results. It provides the functionality to conduct all phases of catchment assessment for the two widely used models, the Soil and Water Assessment Tool (SWAT), and Kinematic Runoff and Erosion Model (KINEROS2) (Miller *et al*., 2002). The models provide insight into the response of the catchment hydrology to land use changes and management change. It also delineates the catchment boundaries through a process referred to catchment delineation. They operate at different temporal and spatial scales, and can be applied in a range of environmental conditions to evaluate the impact of land use changes on catchment hydrology and erosion response (Miller *et al*., 2002).

The data that AGWA model requires include Digital Elevation Model (DEM), soils information, land use and precipitation. These data are used by the model in preparing input files for any of the models it supports. The SWAT model in addition requires rainfall station coverage data for rainfall weighting, where data from several gauging station is used. The AGWA model is an extension of the Arc View which is a geographical information system (GIS) software package. The GIS frame work is ideally suited for catchment based analysis, which relies heavily on landscape information for both deriving model input parameters and presenting the results. Previously, the model supported only the State Soil Geographic Database (STATSGO) and Soil Survey Geographic (SUSRGO) soil data. However, the new version can accommodate the Food and Agricultural Organisation (FAO) soil data. Therefore, for any given case study, there is no need to convert the FAO soil data into the US Soil Taxonomy as was the case before. Baldyga (2005) used the model in Njoro River catchment to simulate hydrologic response due to change in land use. In this case, techniques of converting the FAO soil data to the US taxonomy for it to be compatible with the model had to be applied. The results as per the Nash and Sutcliffe Efficiency were found to be between 0.7 and 0.9, therefore indicating that the simulated stream flow was approximating the observed stream flow.

2.6.4 Kinematic Runoff and Erosion Model (KINEROS)

The Kinematic Runoff and Erosion Model (KINEROS) (Smith *et al*., 1995) is a physically based model designed to simulate runoff and erosion for single storm events in small catchment of less than 100 km^2 (Semmens *et al*., 2002). It utilizes a network of planes to represent a catchment and kinematic wave method to route water off the catchment. Although the model is restricted to cover about 100 km^2 and is used for single event storms, it is usually applied for critical areas that require immediate attention. In this model, catchments are represented by subdividing contributing areas into a cascade of one-dimensional overland flow and channel elements using topographic information (Van der Weert, 1994). The infiltration component is based on the simplification of the Richard's Equation.

$$f_c = K_s \frac{e^{F/B}}{\left(e^{F/B} - 1\right)} \tag{2.44}$$

$$B = G.\varepsilon.\left(S_{\max} - SI\right) \tag{2.45}$$

where f_c is the infiltration capacity (m/s), Ks is the saturated hydraulic conductivity (m/s), F is the infiltrated water (m), B is the saturation deficit (m), G is the effective net capillary drive (m), ε is the porosity, Smax is the maximum relative fillable porosity, and SI is the initial relative soil saturation. Runoff generated by infiltration excess is routed interactively using the kinematic wave equations for the overland flow and channel flow, respectively stated as:

$$\frac{\partial h}{\partial t} + \frac{\partial \alpha . h^m}{\partial x} = r_i(t) - f_i(x,t) \tag{2.46}$$

$$\frac{\partial A}{\partial t} + \frac{\partial Q(A)}{\partial x} = q_I(t) - f_{c1}(x,t) \tag{2.47}$$

where h is the mean overland flow depth (m), t is the time (s), x is the distance along the slope (m), α is the $1.49\frac{S}{2 \times n}$, S is the slope, n is the Manning's roughness coefficient, m is 5/3, $r_i(t)$ is the rainfall rate (m/s), $f_i(x,t)$ is the overland infiltration rate (m/s), A is the channel cross-sectional area of flow (m^2), Q(A) is the channel discharge as a function of area (m^3/s), $q_I(t)$ is the net lateral inflow per unit length of channel (m^2/s), and $f_{c1}(x,t)$ is the net channel infiltration per unit length of channel (m^2/s).

2.6.5 HEC-HMS (Hydrologic Modeling System)

The HMS is a comprehensive hydrologic model developed by Hydrologic Engineering Center (HEC) of United States Army Corps of Engineers (USACE). It is an event based overall lumped model (HEC, 2000). The HMS offers several options to model various physical processes occurring in a catchment system. One such process is the direct runoff computations. Most of the runoff models available with the HMS are lumped in nature except for two which are distributed. Most of the lumped runoff models derive their roots from the Unit Hydrograph (UH) concept. This model provides a lumped model option called the Clark's UH. To overcome its lumped character, a modified version called ModClark method was developed for HMS (Daniel and Arlen, 1998).

The ModClark's method requires that the catchment be further divided into sub-catchments by intersecting it with a grid. Each of these sub-catchments is assigned individual lag time, instead of one value for the whole catchment, as in the case of Clark's UH. The precipitation excess at each sub-catchment is transported to the catchment outlet using the corresponding lag time. Thus, the inflow contributions due to all the sub-catchments to linear reservoir are computed. These flows are then routed through a linear reservoir (only a single value for storage coefficient being defined for all the sub-catchments) to obtain the hydrograph at the outlet, which is later routed through the channels. The ModClark's technique though tries to overcome the lumped character of Clark's Unit Hydrograph (UH), it has certain limitations. The limitations that have been recognized are that; the model is not a physically based model and does not capture the dispersion effects that occur along the flow path since the model assumes one single linear reservoir for the whole catchment.

2.6.6 Soil Water Assessment Tool (SWAT)

The Soil Water Assessment Tool (SWAT) (Arnold *et al*., 1994; Neitsch *et al*., 2002 and Schuol et al., 2008) was developed to predict the effect of alternative decisions on water, sediment and chemical yields for ungauged catchments. It is a physical and empirical based distributed model operating on a daily time step (Miller *et al*., 2002; Sintondji, 2005; Bekele and Nicklow, 2007).

The hydrology model is based on the water balance equation given as:

$$SW_t = SW + \sum_{i=1}^{t}\left(R_i - Q_i - ET_i - P_i - QR_i\right) \quad (2.48)$$

where *SW* is the soil water content minus the 15-bar water content, *t* is the time in days, and R_i, Q_i , ET_i, P_i, and QR_i are the daily amounts of precipitation, runoff, evapotranspiration, percolation, and return flow, respectively; all the units are in mm. Since the model maintains a continuous water balance, complex catchments are subdivided to reflect differences in *ET* for various crops and soils. It is capable of simulating spatial heterogeneity within a catchment and can provide spatially distributed outputs (Bekele and Nicklow, 2007). It is suitable for assessing land use change impacts on catchment hydrology (Baldyga *et al*., 2004). It also allows the catchment to be divided into sub-catchments based on unique land use and vegetation changes (Guo *et al*., 2008). This makes it possible to describe spatial heterogeneity in land use and soil types within the catchment. The SWAT model uses the modified curve number approach, which is a core mechanism for determining excess rainfall (Miller *et al*., 2002; Bekele and Nicklow, 2007). The modified SCS curve number method (USDA, 1986) used to estimate Surface runoff as shown;

$$Q = \frac{(R - 0.2S)^2}{R + 0.8S} \qquad R > 0.2S \tag{2.49}$$

$$Q = 0 \qquad R <= 0.2S$$

where Q is the daily surface runoff (mm), R is the daily rainfall (mm), and S is the retention parameter. The retention parameter, S, varies (1) among watersheds because of changes in soils, land-use, and slope and (2) with time because of changes in soil water content. The parameter S is related to curve number (CN) by the SCS Equation (2.50).

$$S = 254\left(\frac{100}{CN} - 1\right) \tag{2.50}$$

The constant 254 in Equation [2.50] gives S in mm. The curve number varies non-linearly from 1, dry condition at wilting point, to the wet condition at field capacity and approaches 100 at saturation. Also to estimate sediment yield, the Modified Universal Soil Loss Equation (MUSLE) is used (Williams and Berndt, 1972). The MUSLE is intended to estimate sediment yield for a single event. The MUSLE combined with the runoff models was tested on 26 watersheds in Texas. The equation is expressed as:

$$S = \alpha(QXq_p)^{\beta} KLSCP \tag{2.51}$$

where *Y* is the sediment yield from an individual storm in metric tons, *Q* is the storm runoff volume in m3, q_p is the peak runoff rate in m3/sec, *K* is soil-erodibility factor, *LS* is the slope length and gradient factor, C is the crop management factor, P is the erosion control practice factor, α and β are location specific parameters. Values of α =11.8 and β = 0.56 were obtained for United States upon calibration and validation using 778 storm events on catchments near Reisel, Texas, Hastings and Nebraska.

In this present study the MUSLE model was preferred mainly because of its simplicity, ease of deriving the geocharacteristics parameters and integration in GIS for analysis (Mekonnen, 2005). It is also a single event based model applied at a catchment scale. Using GIS enables easier derivation of difficult-to-obtain key data for large areas which, when used with the MUSLE model, can provide estimates of sediment yield for a storm. The model can be used in ungauged catchments and hence allows evaluation of hydrological changes resulting from land use changes in ungauged areas (Baldyga *et al*., 2004).

The SWAT model, unlike other models, was used in this study because it can model large complex catchments with limited monitoring data, and can also handle both Hortonian and saturation excess flow experienced in Wundanyi River catchment.

2.7 Geographical Information System (GIS)

The Geographical Information System (GIS) can be defined as a computer based system designed specifically to manage large values of geocoded data derived from various sources (ESRI, 1995). GIS is used in hydrologic modelling to facilitate the processing, managing and interpretation of hydrological data. It is capable of performing sophisticated manipulations and provides a framework within which spatially distributed data are captured. The spatially distributed data are used to prepare model files and evaluate model results. Its capabilities are to accept, overlay, store, and generate buffer around points (Lim *et al*., 2005; Mustafa *et al*., 2005).

One of the most useful capabilities of GIS is its ability to describe the topography of a region (Singh and Fiorentino, 1996). This capability is used to develop a Digital Elevation Model (DEM) which is a digital representation of the elevation of a land surface. The DEM is required to automate catchment delineation to generate streamlines, flow direction, flow accumulation, flow length, slope steepness, and catchment boundary among other catchment attributes (Lim *et al*., 2005). They have intrinsic geomorphologic features for simulation of important water flow processes such as runoff and infiltration (Vazquez and Feyen, 2007). This allows the models to account for spatial heterogeneity of hydrologic variables within the catchment. GIS based systems have greatly enhanced the capacity for researchers to develop and apply models due to their improved data management and advanced computing facilities.

2.8 Application of Remote Sensing in Land Use and Land Cover Mapping

Remote Sensing (RS) is the science and art of obtaining information about an object, area or phenomena through analysis of data acquired by a sensor that is not in direct contact with the target of investigation (Ritchie and Rango, 1996). Remote sensing also refers to those methods and processes used for detecting, capturing and recording data from a distance. The science of remote sensing started early in the 19th century with the invention of photography. The first aerial photographs were taken from captive balloons. In the 20th century, technological advances in a number of areas such as the development of colour and infrared sensitive films, airborne and space based platforms and powerful computers widened the scope for remote sensing (Singh, 1996). It is now used for a wide range of applications which include: mapping, land use analysis, geological exploration, meteorology and oceanography.

The current practice of remote sensing began with two major advances in technology namely; the launch of high resolution digital imaging systems of the landsat series in 1972 and the development of microcomputers and image-display terminals in the 1970s. The evolution of remote sensing continued in the 1980s with increased range of processing functions, faster processors, higher resolution displays and user-friendly menu interfaces. More data is now obtainable from new sensors such as landsat TM, SPOT, Radars, and airborne multi-spectral scanners. The remote sensing from aerial photography to satellite image constitutes a powerful tool for improving accuracy and precision in earth observation, making it possible to investigate previously unknown phenomena (Rouse *et al*., 1974). Remotely sensed spectral-reflectance data can be used to estimate plant-canopy attributes such as green-leaf area, green phytomass, and photosynthetic capacity based on the principles of the electromagnetic radiation as shown in Figure 3.

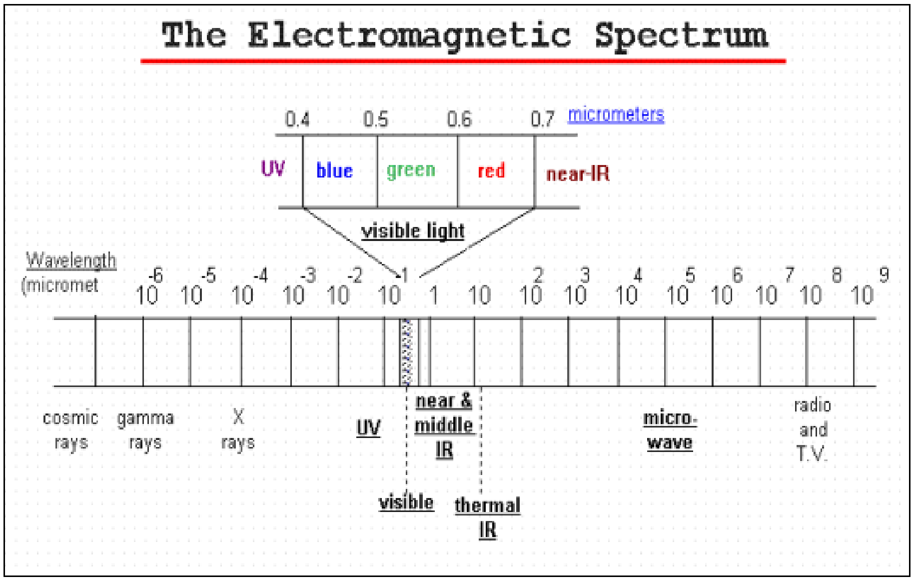


Figure 3: The electromagnetic spectrum

Band 1: 0.45-0.52 micrometre (blue)

It provides increased penetration of water bodies as well as supporting analyses of; land use, soil, and vegetation characteristics. Shorter-wavelength cutoff is just below the peak transmittance of clear water, while upper-wavelength cutoff is the limit of blue chlorophyll absorption for healthy green vegetation. Wavelengths below 0.43 micrometres are substantially influenced by atmospheric scattering and absorption.

Band 2: 0.52-0.60 micrometre (green)

This band ranges region between blue and red chlorophyll absorption bands and therefore corresponds to green reflectance of healthy vegetation. Bands 1 and 2 combined provide the same spectral sensitivity as Kodak's Water Penetration Aerial Color Film (SO-224).

Band 3: 0.63-0.69 micrometre (red)

This is the red chlorophyll absorption band of healthy green vegetation and represents one of the most important bands for vegetation discrimination. It is also useful for soil-boundary and geological boundary delineations. This band may exhibit more contrast than bands 1 and 2 because of the reduced effect of atmospheric attenuation. The 0.69 micrometre cutoff is significant because it represents beginning of a spectral region from 0.65 to 0.75 micrometres, where vegetation reflectance crossovers take place that can reduce the accuracy of vegetation investigations.

Band 4: 0.63-0.69 micrometre (reflective-infrared)

For reasons discussed above, the lower cutoff for this band was placed above 0.75 pm. This band is especially responsive to the amount of vegetation biomass present in a scene. It is useful for crop identification and emphasizes soil-crop and land-water contrasts.

Band 5: 1.55-1.75 micrometre (mid-infrared)

This band is sensitive to the turgidity or amount of water in plants. Such information is useful in crop drought studies and in plant vigor investigations. In addition, this is one of the few bands that can be used to discriminate between clouds, snow, and ice, so important in hydrologic research.

Band 6: 2.08-2.35 micrometre (mid-infrared)

This is an important band for the discrimination of geologic rock formations. It has been shown to be particularly effective in identifying zones of hydrothermal alteration in rocks.

Band 7: 10.4-12.5 micrometre (thermal infrared)

This band measures the amount of infrared radiant flux emitted from surfaces. The apparent temperature is a function of emissivities and true or kinetic temperature of the surface. It is useful for locating geothermal activity, thermal inertia mapping for geologic investigations, vegetation classification, vegetation stress analysis, and soil moisture studies.

Remote sensing and GIS are increasingly becoming important tools in hydrology and water resources management (Lillesand and Kiefer, 1994). This is because data required in hydrological evaluation can easily be obtained by using these tools. With the development of these techniques, hydrological catchment models have become more physically based and distributed to enumerate various interactive hydrologic processes considering spatial heterogeneity (Linsley *et al*., 1982). In this study, the satellite images were used to determine land use changes in Wundanyi River catchment, which was required to determine catchment hydrology, in particular surface runoff.

2.9 Concluding Remarks

To address the existing gaps, there was need for a new approach in land use mapping and classification. The methods being employed are not suitable for small catchments like Wundanyi River catchment which are densely populated and have small heterogeneous land use types. Often, the land use classes are inappropriate for a particular classification, or scale may be unrelated to a specific purpose and the information may most likely be obsolete by time it is made available. Furthermore, many factors are often used in classifications which result in undesirable mixtures of potential and actual land use.

Therefore, the GIS technology has made it possible to perform direct integration with data sources of different origin and use them simultaneously. Planning for sustainable resources exploitation and management within river catchments requires datasets on land use, climate, physiography, and socio-economic aspects. The remote sensing and GIS have the capacity to link and analyse such dataset especially for detection, extrapolation and interpretation, area calculation and monitoring. GIS uses georeferenced databases, making it a powerful tool for decision making for sustainable development.

In the catchment, data on environmental factors were incomplete where they existed. Due to steep terrain and remoteness, field data from Taita hills are often scarce or lacking. Remote sensing and GIS tools were therefore found to play an important role in extrapolating existing data and filling the missing gaps, for better planning of the catchment. Integration of remote sensing and GIS should therefore be adopted at all levels in order to enhance and sustain development in Wundanyi River catchment.

CHAPTER THREE
MATERIALS AND METHODS

3.1 The Study Area

The Wundanyi River catchment shown in Figure 4 is the study area. It is part of the larger Taita Hills catchment and covers approximately 356 km^2, lying to the west of Voi town. It is located within Latitude $03^0 20'40''$ S and Longitude $38^0 20'32''$E. The elevation ranges from 700 to 2208m above mean sea level (a.m.s.l) and is drained by Wundanyi/Voi River that joins Galana/Sabaki River in Tsavo East National Park (Pellikka *et al.*, 2004).

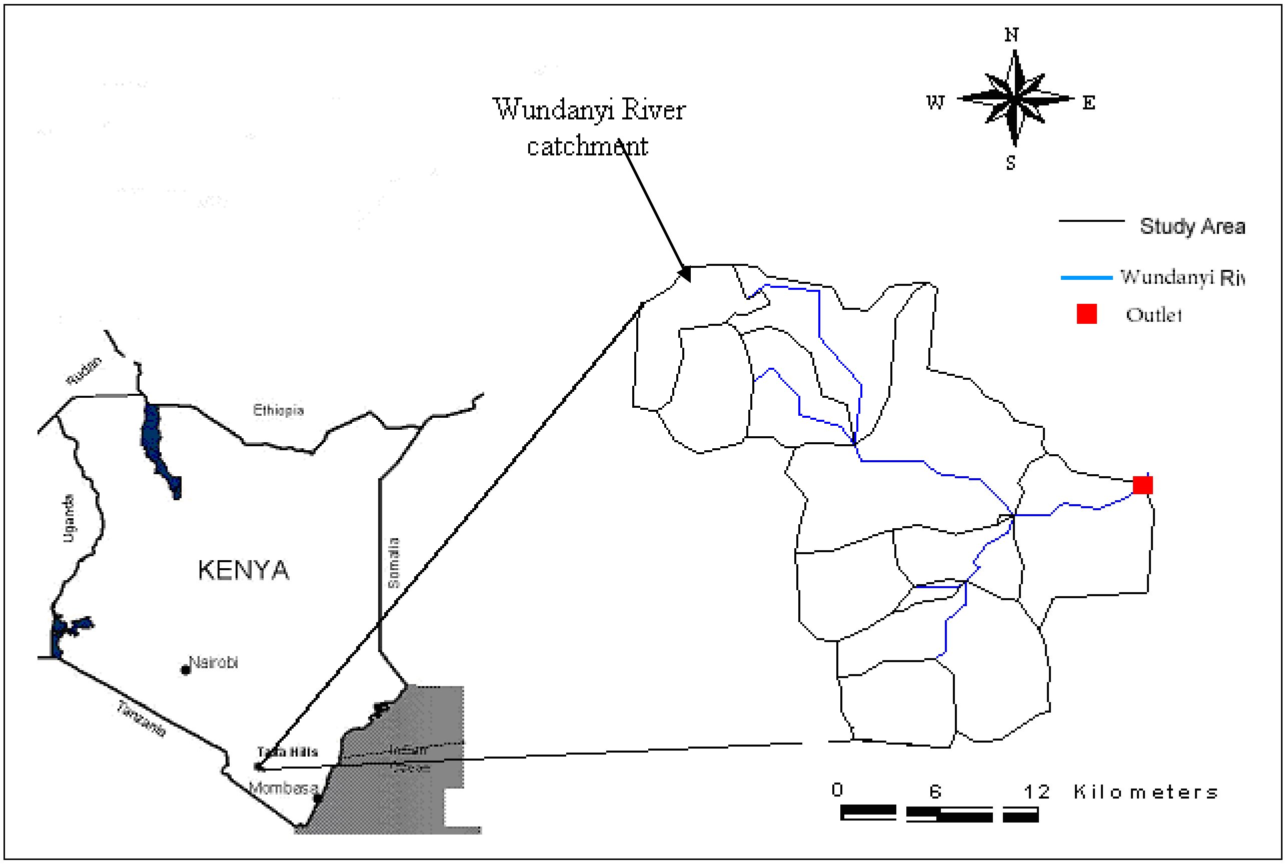


Figure 4: The study area

3.1.1 Soil Data

The major soils in the study area were of volcanic origin. Soils found on the hills and major rocks of the catchment were developed on undifferentiated basement system rocks, predominantly gneisses (Jaetzold and Schmidt, 1983). They were generally well drained, moderately deep, reddish brown to brown, friable, stony sandy clay loam with humic topsoil (1.2-1.8 m). They vary from dark reddish brown to dark brown, clay loam to loamy soils with thick acid humic topsoil in shallow to moderately deep and rocky places (Bauernhofer *et al.*, 2008). They were generally classified as humic cambisols.

3.1.2 Climate

The climatic conditions in the study area were quite diverse due to considerable differences in altitude and relief. The annual temperatures range from 14 to 30^{0}C. The rainfall regime within the catchment is influenced by local relief, with two rainy seasons being experienced in the catchment. Long and short rains occur in the months of March to May and between October and November respectively. The plains experience an average annual rainfall of 500 mm, and the wettest slopes of Taita hills receive as much as 1400 mm per annum (Pellikka *et al.*, 2004).

3.1.3 Rainfall Data

The daily rainfall data records from weather stations within the catchment were obtained from Kenya Meteorological Department, Nairobi. The locations of the stations were obtained using the Global Positioning System (GPS) after which a map showing their spatial distribution was prepared. Unweighted rainfall data was used with the map to obtain uniform rainfall data distribution of the catchment. Uniform rainfall was utilized in writing the precipitation files as input for SWAT model simulation.

3.1.4 Rainfall Analysis

The average monthly rainfall and standard deviations were calculated from the DC's office meteorological station data, located at the high potential area of the catchment as given in Appendix 3 and 4. Also a correlation analyses between the two meteorological stations data in catchment were done as given in Appendix 5 and 6. The daily data from the DC's office rainfall station (assumed to be representative of the Wundanyi River catchment) was used as input for SWAT model simulation.

3.1.5 Stream Flow Data

The stream flow data from gauging station number 3LA7 at the outlet of Wundanyi River catchment was acquired from the WRMA regional office in Mombasa Town. The period of the data was from 1975 to 2005. The location of the gauging station 3LA7 was 0btained using the Global Positioning System (GPS) after which a map showing the location was prepared. Then the river gauging station point map was utilized to locate the outlet point (3LA7) of the catchment.

For this study, the quality of the stream flow data was checked using the annual stream flow trend from 1975 to 2005. Also to ascertain stream flow data reliability, quality control was undertaken. This involved consistency test using the single mass curve method as given in Appendix 1.

3.1.6 Derivation of Contour Map

In this study, a topographic map of scale 1:50,000 was used to derive the digital contour map for Wundanyi River Catchment. The topographic map was obtained from Survey Department of Kenya. In deriving the digital contour map, a number of steps were followed. The first step involved scanning the topographic map. Scanned topographic map was then imported to ArcGIS. The map was georeferenced and an onscreen digitization was carried out to trace the contours.

3.1.7 Generation of Digital Elevation Model (DEM)

A DEM may be a raster map or arrays of numbers or shaded relief showing the elevation of each point in the catchment. The main input in the DEM generation was the digital contour map. A digitised contour map of the catchment was exported as a shape file into Arc View GIS platform. The generation of the DEM was done by first creating a Triangulated Irregular Network (TIN) for the contour map. The TIN is an object used to represent the surface and is a specific storage structure of the surface data. It partitions the surface into a set of non overlapping triangles, and here a height value is recorded for each triangle node. The TINs can accommodate irregularly distributed as well as selective data sets. In this study, the TIN was converted into a Grid (Raster) format in which each cell stored a numeric data value.

3.1.8 Soil Map for Wundanyi River Catchment

A soil map of scale 1:100,000 for this study was obtained from Soil Survey Department of Kenya. The map was clipped using the geoprocessing wizard tool in Arc View GIS. Soil classification data for this study was based on the Food Agricultural Organization of the United Nation Version 3.6 (FAO/ UNESCO, 2003) data as given in Appendix 8. The soil types in this case were already in the standard format that is supported by the model. The soil texture for various soil types was derived.

3.1.9 Land Use Maps

Aerial photographs and Landsat images were used to produce land use maps of the study area. Landsat MSS image for 1975 (P179R062), Landsat TM image for 1987 (P167r062) and Landsat ETM+ image for 2001(P167R062) were obtained from Global Land Cover Facility (GLCF). A topographic map sheet for Taita Hills was obtained from the Survey Department of Kenya. The catchment delineation dialog from the AGWA tools menu was used to establish the catchment boundary and also divide the catchment into series of sub-catchments. Polygons on the landsat image were then digitized using the GeoVis software under "Drawing by Arcs and Points Tree" which was ideal for on-screen digitizing of linear features directly from the landsat images. The digitized maps and polygons were then exported to ArcView 3.3 software which was preferred because of its versatility given that its language was well integrated with related mapping technologies. A fuzzy tolerance too small was not able to close polygons, to intersect arcs, and to clean polygon slivers. On the other hand, a too large fuzzy tolerance created a problem with the shifting and merging of arcs causing polygons to collapse or cause arcs to move. A fuzzy tolerance was therefore defined to provide the minimum distance to separate all arc coordinates in the data layer.

3.1.10 Delineation and Discretization of Wundanyi River Catchment

The AGWA model has a catchment delineating component, parameterisation component and result visualisation component. The data required by this model were Digital Elevation Model (DEM), Land use/cover data, Soils Data and Precipitation.

In this study, AGWA model was used to prepare input files for SWAT model. The model required a DEM, which encompassed the drainage basin for the streamlines which were required to delineate and discretize the catchment. The AGWA model also provided a database for Land Cover data, Soils Data and Precipitation. It also contained tables used by the interface to set default input values and define the upper and lower limits for variable values. The land use/cover and soils data were parameterised to fit to the situation in the study area.

3.1.11 Catchment Delineation

The catchment delineation was the first step which was used to creating a new catchment outline by using the area of interest to locate the outlet of the catchment. From the outlet the raster surfaces to be utilized to delineate catchment outline were specified. These surfaces included a digital elevation model (DEM), a flow direction grid (FDG) and a flow accumulation grid (FACG). An additional surface, a stream map was generated following the selection of these inputs to facilitate outlet location. When the outlet was located then AGWA model generated a grid that delineated the outline of the catchment which was contributing surface runoff to the outlet. The AGWA model is usually used to determine the outlet based on the intersection of the specified point and the stream map and the available outlet locations within a given radius. The outlet locations that were not intersecting the stream map were moved to a suitable location on the stream map before catchment discretization process occurred. Some of the required gird layers which were generated are discussed below.

3.1.12 Flow Direction

In this study, the Flow direction which is a raster map/surface showing the direction of runoff at every point throughout the landscape was derived using an eight direction approach, the direction of flow is determined by finding the steepest descent from the cell of interest to each cell. If the descent to all adjacent cells is the same, the neighbourhood is enlarged until the steepest descent is found. The output cell is coded with the value representing that direction..

3.1.13 Flow Accumulation

The Flow accumulation is the raster map/surface that represents accumulation of runoff throughout the study area. Using the flow direction, the flow accumulation at a given location was determined by following two rules. If the pixel had no neighbouring pixels, it was assigned the value of one and if the pixel was draining from the neighbouring pixels, it was assigned the value of one plus the sum of flow accumulation draining from each of the neighbouring pixels.

3.1.14 Stream Lines

The Stream lines map is a model containing all the streams for a given DEM (Maune, 2001). It represents all the cells in the DEM that receive runoff from a certain number of cells.

In order to create the stream lines map, the threshold number of cells which refers to minimum number of cells contributing runoff to a given cell before it can be considered to be a stream was set to 2,500. This threshold is recommended for DEMs with a resolution of 30m (Maune, 2001). After setting the threshold the streamlines map appears automatically in window.

3.1.15 Catchment Discretization

The AGWA model was used to subdivide the catchment into hydrologic elements based on the contributing source area (CSA) approach, where the channels were defined as a function of the contributing area, or the total area required for channelised flow to occur. Smaller contributing source area (CSA) values resulted in a more complex catchment. Therefore default contributing source area (CSA) was set to 2.5% of the catchment. Then it was change to 2900 and the units were changed to hectares. The default relationship for hydraulic relationship was selected Walnut Gulch. This was the AGWA model default hydraulic geometry relationship. The AGWA model was then clicked to discretize the catchment, thus creating the individual planes and channels for the simulation. This generated the sub-catchments for the study area. The maximum flow length, area, and slope were also determined for each sub-catchment.

3.2 Characterize and Quantify changes of Land Use for Wundanyi River Catchment

Classification refers to the process of extracting information from remotely sensed images, which can then be developed into interpreted maps of various land use and land cover types. This information computed for different images taken over different time periods is subsequently used for change analysis. In this study, therefore the procedure used in image classification was based on Earth Resources Data Analysis System (ERDAS Imagine 9.1) Field guide. The first stage in image classification was to characterize land use types of this study area. This was accomplished through conducting field survey, use Land Cover Classification System and use of topographic maps. The land use types represented by various classes were identified. This involved the identification of the elements, for example agricultural land, shrubland, thicket, woodland, needle leaved closed canopy forest, broadleaved closed canopy forest, bare soils, built-up areas, water body, and bare rock.

The second stage was sampling or training phase, where limited numbers of pixels were sampled then digitized and assigned corresponding land use type. During training, sample statistics and feature space were simultaneously displayed. The former usually have the standard deviation of samples. This value was checked when a sample was selected to ensure that it was kept to a minimum. Feature space showed graphical distribution of the selected samples of any two bands. Pixels belonging to the same class and therefore representing the same land cover and close to each other in the same feature space. It enabled judgment to be made where different classes were spectorally distinguished and class corresponded to only one spectoral cluster.

The third stage involved land use classification, where the processed satellite images for 1975, 1987 and 2001 were used to classify different land use types within catchment. Thematic land use maps for these images were then prepared. The classification of different land use and their areal extent were accomplished through Gaussian Maximum likelihood Classifier. This technique is one of the decision algorithms used in supervised classification. It is known to produce the best results compared to other classifiers (Onyando, 2000; Mekonnen, 2005). The classifier assumes that the feature vectors of every land use class are statistically distributed according to multivariate normal distribution density function (ITC ILWIS, 2001; Onyando *et al*., 2005). Training samples were used to estimate the parameters of distribution.

The post classification comparison, where images were compared at the pixel level was also done. By using this method, it was possible to observe directly which classes had changed to other classes. In other words, location and direction of change were identified. The whole processing chain for change detection using satellite remote sensing data was presented in a tabular form.

3.3 Model Components and Parameters

Before the SWAT model was applied for simulations in this study, conceptual parameters of the model were to be determined. These conceptual parameters included baseflow factor, evaporation from groundwater coefficient and minimum depth in shallow aquifer. These parameters and their boundary conditions are as given in Appendix 2.

The boundary conditions were used to express minimum and maximum possible values of parameters. The minimum values for Baseflow alpha factor (*Alpha_BF)*, Depth of water (*GWQmn)*, Revap coefficient (*GW_Revap)*, and Minimum depth (*Revapmn)* were 0.0, 0.0, 0.02, and 0.0. The maximum values for Baseflow alpha factor (*Alpha_BF)*, Depth of water (*GWQmn)*, Revap coefficient (*GW_Revap)* and Minimum depth (*Revapmn)* were 1, 4000, 0.2 and 3000 which were determined based on trial tests. They were intended to restrict the optimal parameters during model calibration. To evaluate the changes of surface runoff and sediment yield due to land use changes, changes were visually observed from simulated hydrographs from the model.

The SWAT model required several physical parameters, in addition to daily rainfall data. In this study, the required files were prepared by characterizing the catchment according to its unique properties of land use/land cover and soils in AGWA and input into SWAT model for Wundanyi River catchment hydrological simulation. The land use/cover and soils data were overlaid to get unique properties of land use/cover and soils. The main physical parameters for the SWAT model were the Curve Number (CN), Hydrologic Soil Group and Land Cover. Other parameters which were derived from these key physical parameters included; soil water retention, soil parameters and hydraulic conductivity.

3.3.1 Curve Numbers

The curve number (CN) is a dimensionless index that describes runoff as a range between 1 and 100, with 100 indicating maximum runoff potential. The CN values for this study were derived by overlaying the hydrologic soil group and land use/cover for the using the AGWA model tool. The CN values were assigned to each cover complex which comprised hydrologic soil group, land use and treatment condition.

3.3.2 Hydrologic Soil Group and Cover Condition

The hydrologic condition which indicates the effects of cover type and treatment on infiltration and runoff was estimated from the density of plant and residue cover for each of sub-catchments. The Hydrologic soil groups were categorised depending on soil physical characteristics such as soil texture, soil structure, hydraulic saturated conductivity, soil depth and sealing susceptibility. The soil parameters which included dominant soil type, coefficient of variation of KS, maximum relative soil saturation, net capillary drive, soil erodibility factor, fractional clay content, fractional silt content and fractional sand content were derived from soil map using GIS. Each soil type based on FAO classification was then assigned a hydraulic conductivity value. For each sub-catchment, appropriate hydrologic soil groups were then assigned by use of the GIS.

3.3.4 Evaluation of the Impact of Land Use Change on Catchment Hydrology

Hydrological response is an integrated indicator of catchment condition, and changes in land use/ cover may affect the overall health and function of a catchment. Such changes vary spatially and occur at different rates through time. The hydrologic change was evaluated both spatially, using SWAT model, and temporally, using satellite image of 1975, 1987 and 2001 respectively acquired over 30 years. Simulated catchment response in the form of surface runoff depth, total sediment yield and evapotranspiration were used as indicators of catchment condition.

3.3.5 Estimation of Surface Runoff

In estimating the surface runoff the study catchment was delineated using AGWA model into sub-catchments and stream channels that were characterized according to their unique land cover and soil properties. These properties were used by the AGWA model to generate input hydrologic parameters for SWAT model. The curve numbers for each sub-catchment were selected based on the cover type, hydrologic soil group, and the percentage of the impervious areas from the look up table inbuilt in the model. The soil types were converted to hydrologic soil groups and overlaid with the land cover. The overlays were made to identify unique land cover-soil group polygons. The SCS curve numbers for each land cover-soil group combinations were generated by the SWAT model and then assigned to each sub-catchment as shown in Appendix 2. To estimate surface runoff, the observed rainfall and the curve numbers were substituted in equation (2.21) and the values for the pre-change period of 1975-1984 and the post-change period 1985-1994 and 1995-2004 were obtained and recorded in a tabular form.

3.3.6 Simulation of Surface Runoff, Sediment Yield and Evapotranspiration

The SWAT model was used to simulate surface runoff, sediment yield and evapotranspiration to evaluate the impact of land use change on the hydrology response for Wundanyi River catchment. Three decadal land use changes were evaluated between 1975 and 2004. The first decade was considered as a pre-change and the rest as post-change. For the pre-change period, simulated surface runoff, sediment yield and evapotranspiration data were obtained from 1975 to 1984 using the land use grid map of 1975. For the post-change periods, simulated surface runoff, sediment yield and evapotranspiration data were obtained from 1985 to 1994 and 1995 to 2004 using land use grid maps of 1987 and 2001. The methodological approach of model application is as shown in Figure 5.

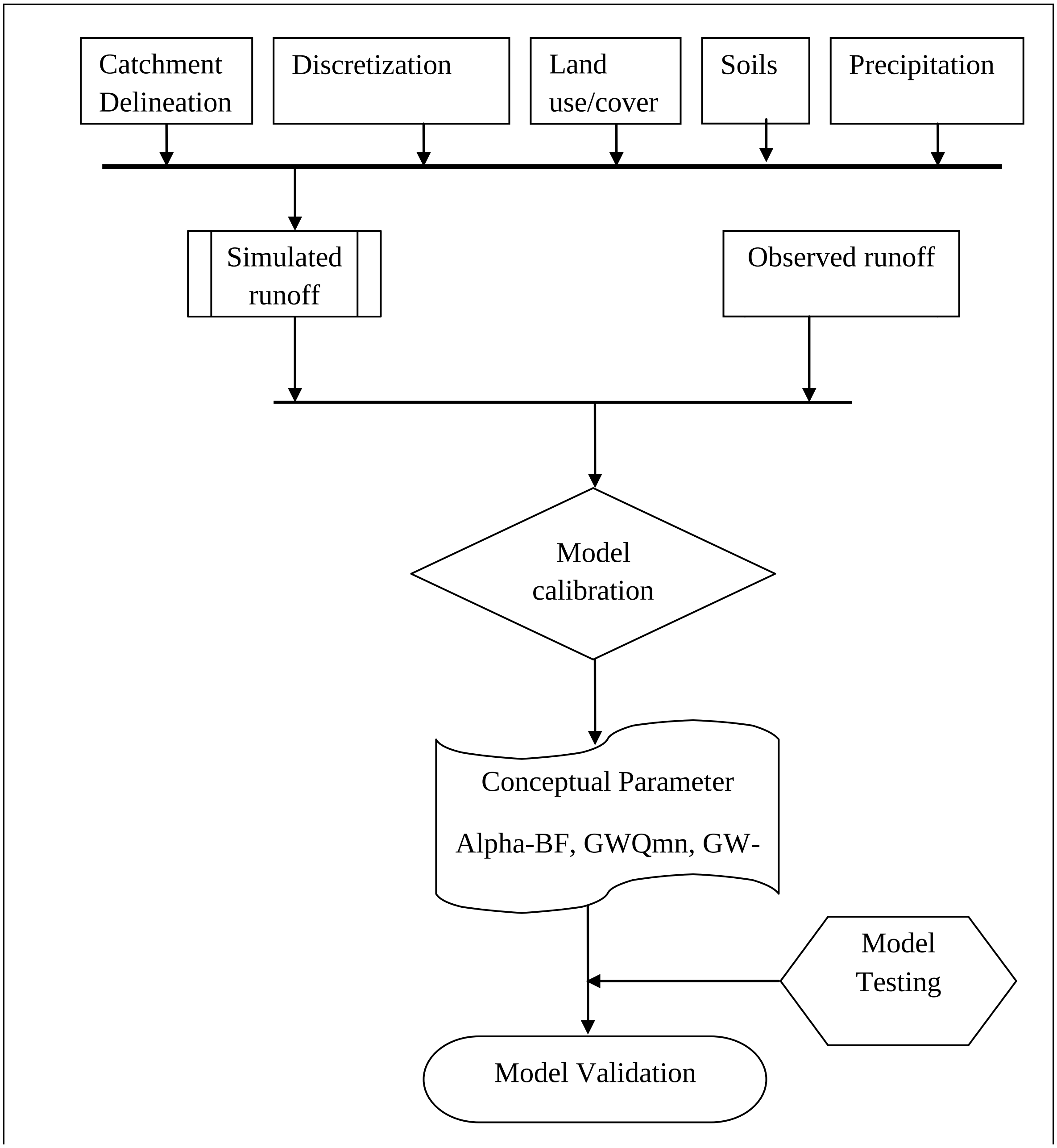


Figure 5: Schematic diagram of methodology of model application

To do simulation, the AGWA model tool was used to first delineate and subdivide the catchment into sub catchments. Then the catchment was overlaid with land use/cover for 1975, 1987 and 2001 and soil data. The five simulation processing steps were: (1) location identification and catchment delineation; (2) catchment subdivision; (3) land-cover and soils parameterization; (4) preparation of parameter and rainfall input files; and (5) model execution and visualization and comparison of results.

Step 1: The catchment outline was first created (catchment delineation), which was a grid based on the designated outlet (pour point) of the study area. The outlet location was covered by the GIS coverage (such as would be the case for a runoff gauging station); it was therefore used to designate the drainage outlet.

Step 2: A polygon shapefile was built from the catchment outline grid created in Step 1. To create the stream lines, the threshold number of cells was set to 2,500, and the catchment was divided into model elements (sub-catchment) required by the SWAT model.

Step 3: The catchment which was created in Step 2 was intersected with soil and land use/cover data, and parameters necessary for the hydrologic model runs were determined through a series of GIS analyses and look-up tables. The hydrologic parameters were added to the polygon and stream channel tables to facilitate the generation of input parameter files. At this point, the sensitivity analyses were done by manually altering parameters for each model element.

Step 4: Rainfall input files were built at this stage. The daily rainfall values were provided for rainfall gauging stations within the catchment. Precipitation files were created for uniform rainfall data.

Step 5: After Step 4, all necessary input data had been prepared. The catchment had been subdivided into model elements; hydrologic parameters had been determined for each element; and rainfall files had been created. Then the SWAT model which is inbuilt in AGWA model was run to simulate the surface runoff, sediment yield and evapotranspiration for this study area. The AGWA model automatically imported the model results and added them to the polygon and stream map tables for display. The model was toggled while viewing various model outputs for both upland and channel elements, enabling the problem areas to be identified visually. For the various land use/cover scenes, the model was parameterized and attached the results to a given scene. Results were then compared on an absolute basis for the model element.

The SWAT model was run for each of the pre-change and post-change periods. In this case, ten years of surface runoff data was generated. The beginning data of simulation was January 1st 1975 to 31st December 1984 for the pre-change period. While that of the post-change period, simulation data began on January 1st 1985 to 31st December 1994 and January 1st 1995 to 31st December 2004 respectively.

The results were viewed and compared among the variability during the pre-change and post-change periods for each of the three periods considered. The focus was more on the surface runoff, sediment yield and evapotranspiration generated from the catchment.

From the simulated surface runoff, sediment yield and evapontranspiration data of the pre-change and post-change periods, the surface runoff, sediment yield and evapontranspiration hydrographs were developed. The deviations of the hydrographs between the pre-change and post-change periods were used to assess the impacts of land use change on the Wundanyi River catchment hydrology response.

3.3.7 Model Calibration and Validation

Models are used to represent hydrologic responses of the catchments and they enable studies of very complex problems. The reliability of the model results depend on the parameter estimation. Since SWAT model was developed for different catchments where conditions and catchment parameters do not resemble the ones for Wundanyi River catchment, there was need to determine conceptual parameters using data from the study catchment before undertaking simulations.

The calibration and validation processes were therefore carried out in this study using the split sample method. This method involved dividing the data into two sets, where one set of the data was used for calibration and other for validation processes. In this study the data was divided into two decades based on the available land use maps and the hydrologic data sets. The first decade of data from 1975 to 1984 was used for calibration while the second decade data from 1985 to 1994 was used for validation. After the validation was done, the model was used in simulation of catchment hydrology response for the period between 1975 and 2004.

In both cases of calibration and validation, it was assumed that there were no significant changes in land use in a decade hence the use of one land use map per decade. Calibration was performed by comparing simulated annual stream flows with measured values at the main catchment outlet No. 3LA7. The SWAT model was run first using default parameters set by AGWA, and then the model was run while adjusting conceptual values as given in Appendix 7. The adjustments were done within recommended ranges of maximum and minimum values. A number of simulations were run while iteratively adjusting conceptual parameters to match simulated flows with the observed flows. The process was carried out by changing one parameter while holding others constant as the simulation was being done.

During the calibration process, the Nash and Sutcliffe efficiency whose value varies from less than 0.0 for poor fit to 1.0 for perfect fit was used as an objective function. The parameter combination which gave the highest value of efficiency was taken as being the representative of the catchment. These parameters were used for simulation in validation decade to verify their validity for use with other data sets within the same catchment.

The determination of key conceptual parameters was carried out through sensitivity analysis process. The sensitivity analysis is the process of determining the rate of change in the model output with respect to changes in model parameters. The sensitivity analysis was done before calibration to identify the key parameters and parameter precision according to Moriasi *et al*. (2007). In this study, the process was carried out by changing the *Alpha-BF* parameter while holding other parameters constant. The process was repeated for the *GwQmn*, *Gw-Revap* and *Revapmn* parameters.

3.3.8 Model Performance Criteria

The model performance assessment involved comparing simulated results and measured values using both the statistical methods and visual observation through graphical displays. The statistical techniques that were used in this study were the Nash and Sutcliffe Efficiency (NSE), and RMSE-observation Standard Deviation Ratio (RSR). The NSE Efficiency is given as:

$$NSE = \frac{\sum_{i=1}^{n}\left(Y_o - Y_{av}\right)^2 - \sum_{i=1}^{n}\left(Y_o - Y_s\right)^2}{\sum_{i=1}^{n}\left(Y_O - Y_{av}\right)^2} \qquad (3.1)$$

where NSE is the Nash and Sutcliffe Efficiency, Y_o is the observed discharge, Y_{av} is the average observed discharge, and Ys is the simulated discharge.

The Nash and Sutcliffe coefficient method expresses the proportion of the variance of the observed flows that can be accounted for by the model and provides a direct measure of the ability of the model to reproduce the observed flows. When NSE $\leq$ 0.5, it indicates that the model simulation does not correspond to the observed values and there is no strong correlation between the observed and simulated flows. In other words, it defines the relative percentage difference between average simulation and measured data time series over any given *n* time steps (Tolson and Shoemaker, 2007). This method was preferred in this study to that of the index of agreement (*d*), because the index is overly sensitive to extreme values due to squared differences (Legates and McCabe, 1999).

The RSR was calculated as a ratio of RMSE and standard deviation of measured data as:

$$RSR = \frac{RMSE}{STDEVobs} = \left[\frac{\sqrt{\sum_{i=1}^{n} (Y_O - Y_s)^2}}{\sqrt{\sum_{i=1}^{n} (Y_O - Y_{av})^2}} \right] \tag{3.2}$$

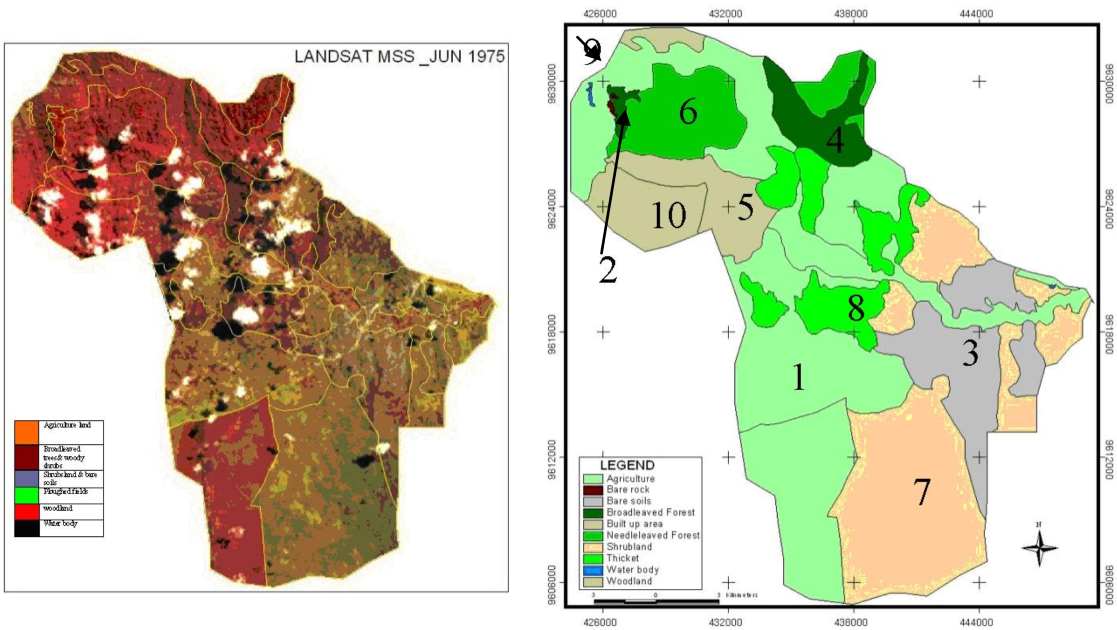
The RSR incorporates the benefits of error index statistics and includes a normalization factor. The RSR varies from the optimal value of 0.0, which indicates zero RMSE or residual variation and therefore perfect model simulation. It was used in this study to test and ascertain whether or not the model was simulating catchment hydrology with low residual errors.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Land Use and Land Cover in Wundanyi River Catchment

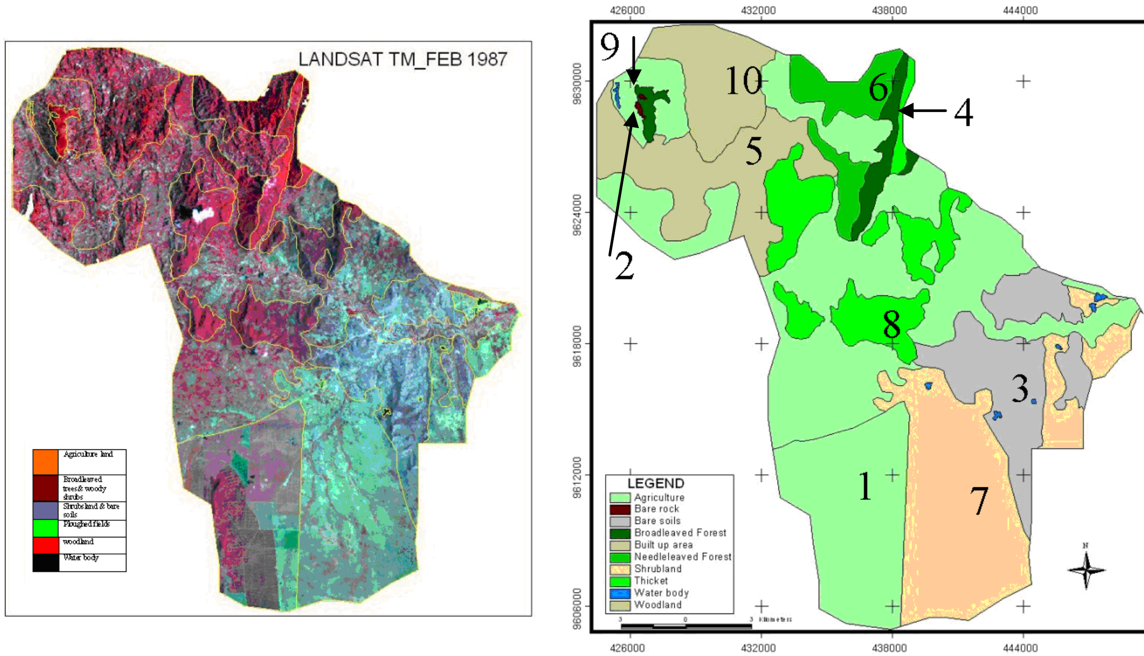
The land use types for Wundanyi River catchment were classified using Land Cover Classification System into ten classes namely; Agricultural land, Shrublands, Thicket, Woodland, Needleleaved closed canopy forest, Broadleaved closed canopy forest, Bare soils, Built-up areas, Water body and Bare rock. Digital land use/cover maps were developed separately for each year using the ten classes.



(a) (b)

Figure 6: (a) Landsat Mss-1975 (b) Processed Land use map of 1975

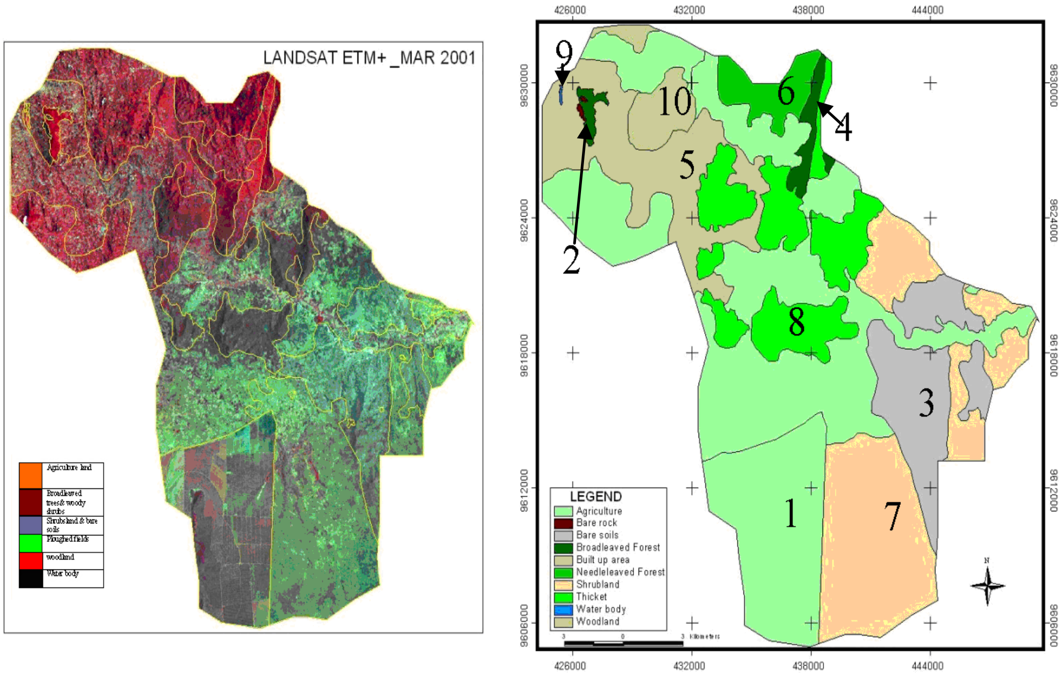
Figure 6a shows the landsat MSS-Jun 1975 while the classified land use/cover map for 1975 is given in Figure 6b. Figure 6a shows most of the polygons were covered in bright red which was solar infra-red radiation by healthy chlorophyll-rich vegetation. Dark red colour represented broad leaved trees or woody shrubs seen on hillsides and as strings of dark red lining stream channels, fault lines and hillside gully valleys in many parts of the image. The bright bluish areas had high reflectance in all wave-lengths. These were areas of either open pasture or Shrubland, bare soil, overgrazed land, just harvested fields, roads or built up areas. There were Patches of dark red represented trees or shrub vegetation. In agricultural lands, the bright tones were an indication of cleared or fallow fields at the time of the year in June. The greenish tones were ploughed fields. Water bodies like Kishen dam was indicated in black colour tones. Woodlands in the image appeared as red mottled tones. Figure 6b show notable large agricultural land label 1 and small built-up area label 5 in the catchment. Also notable was needleleaved forest label 6 and woodland label 10 classes. The land use/cover map of 1975 was used as the base map.



(a) (b)

Figure 7: (a) Landsat TM-Feb 1987 (b) Processed Land use map of 1987

Figure 7a shows landsat TM_Feb 1987 and that of the classified land use/cover map for 1987 is given in Figure 7b. Figure 7a shows some polygons which are covered in bright red that was solar infra-red radiation by healthy chlorophyll-rich vegetation. Dark red colour represented broad leaved trees or woody shrubs seen on hillsides and as strings of dark red lining stream channels, fault lines and hillside gully valleys in many parts of the image. The bright bluish areas had high reflectance in all wave-lengths. These were areas of either open pasture or Shrubland, bare soil, overgrazed land, just harvested fields, roads and built up areas. There were Patches of dark red represented trees or shrub vegetation. In agricultural lands, the bright tones were an indication of cleared or fallow fields at the time of the year in February. The greenish tones were ploughed fields. Water bodies like Kishen dam was indicated in black colour tones. Woodlands in the image appeared as red mottled tones. Figure 7b show notable decrease in agricultural land label 1 and an increase built-up area label 5 in the catchment as compared to the base map of 1975. In addition, a notable decrease in needleleaved forest label 6 and woodland label 10.



(a) **(b)**

Figure 8: (a) Landsat ETM+ 2001 (b) Processed Land use map of 2001

Figure 8a shows the landsat ETM+_Mar 2001 and Figure 8b shows the classified land use/cover map for 2001. Figure 8a shows polygons that are covered in bright red which was solar infra-red radiation by healthy chlorophyll-rich vegetation and have decreased in area. Dark red colour represented broad leaved trees or woody shrubs seen on hillsides and have also decreased in area and as strings of dark red lining stream channels, fault lines and hillside gully valleys in many parts of the image could not be notice. The bright bluish areas had high reflectance in all wave-lengths could be seen the area had increased. These were areas of open pasture or shrubland, bare soil, overgrazed land, just harvested fields, roads or built up. There were Patches of dark red representing trees or shrub vegetation. In agricultural lands, the bright tones were an indication of cleared or fallow fields at the time of the year in March. The greenish tones were ploughed fields. Water bodies like Kishen dam were indicated in black colour tones. Woodlands in the image appeared as red mottled tones. Figure 8b indicated notable decrease in agricultural land label 1 and increase in built up area label 5 in the catchment than the base map of land use/cover map 1975 and land use/cover map 1987 respectively. In addition, a notable decrease in needleleaved forest label 6 and woodland label 10.This therefore appears that there was substantial change in land use in the catchment.

Table 6 : Relative Change of Land use/cover types in the Wundanyi River Catchment

Land use/cover classes	Land use map of 1975		Land use map of 1987		Land use map of 2001		Relative change of land use/cover (%)	
	(Ha)	(%)	(Ha)	(%)	(Ha)	(%)	75- 87	75-01
Agriculture	13445.6	38.0	14918.8	41.9	14821.1	41.6	11.0	10.0
Bare rock	21.1	0.06	21.1	0.06	21.1	0.06	0.0	0.0
Bare soil	3493.2	9.8	3491.7	9.8	3294.9	9.2	-0.05	-5.7
Broadleaved Forest	1430.7	4.0	736.1	2.1	576.7	1.6	-48.6	-59.7
Built-up area	1640.9	4.6	3332.6	9.3	4202.1	11.8	103.0	156.0
Needleleaved Forest	2727.1	7.7	1427.9	4.0	949.2	2.7	-47.6	-65.0
Shrublands	8327.2	24.4	6419.8	18.0	6751.3	18.9	-22.9	-18.9
Thicket	2700.0	7.6	3120.8	8.8	4009.9	11.2	15.6	48.5
Water body	20.0	0.06	61.3	0.17	8.7	0.02	207.0	-56.5
Woodland	1840.4	5.2	2116.3	5.9	1011.3	2.8	15.0	-45.0

A positive value in a different column indicates an increase in area between the dates

A negative value in a different column indicates a decrease in area between the dates

Table 6 shows the overall statistics of the land use classifications of the catchment. From the estimates , results showed that there has been a significant increase of Agricultural land, whose area had shown increased from 13445.56 to 14918.77ha in 1975 and 1987 respectively and slight decreased from 14918.77 to 14821.133ha in 1987 and 2001 respectively. This may be due to the demarcation of forest land which could have prohibited any further clearing of forest for agriculture and also due to the increase in settlement. In the case of the forest land, there has been a significant loss in the broadleaved forest, needleleaved forest, and woodland whose areas have shown decreasing trends of broadleaved forest (1430.709, 736.071 and 576.709ha in 1975, 1987 and 2001 respectively), trends of needleleaved forest (2727.135, 1427.896 and 949.240ha in 1975, 1987 and 2001 respectively) and trends of woodland (1840.417, 2116.759 and

1011.326ha in 1975, 1987 and 2001 respectively). Therefore this gave an overall forest reduction of 57% between 1975 and 2004.

The results also show that there was an increase in the area under settlement that is built up areas between 1975 and 2004 of 156% as shown by trend of built up areas (1640.858, 3332.589 and 4202.059ha in 1975, 1987 and 2001 respectively). This resulted in clearance of the forest to pave way for agricultural land and settlement. For shrublands, there was a slight decrease in the trends (8327.151, 6419.769 and 6751.256ha in 1975, 1987 and 2001 respectively). The results also showed that the thicket land increased from 2699.979, 3120.808 and 4009.889ha in 1975, 1987 and 2001 respectively. This can be attributed to the change of woodland to thicket. For the water body, the results show an increase of 19.954 to 61.264ha in 1975 to 1987 followed decrease from 61.264 to 8.676ha in 1987 to 2001 respectively. This can be attributed to the reduction in rainfall both intensity and distribution coupled with deforestation and soil erosion and eventual siltation of the water body. It appears that the change in land use (reduction in forest land 57%, water body 56.5% and woodland 45%, increase in agriculture 10%, built up area 156% and thicket 48.5%) the results show significantly changes in land use in the catchment.

4.2 Evaluation of the Impact of Land Use Change on Wundanyi River Catchment

To evaluate the impact of land use change on hydrology response for Wundanyi River catchment estimation of annual surface runoff and simulation annual surface runoff, annual sediment yield and evapontranspiration were used.

4.2.1 Estimation of Annual Surface Runoff

The depth of surface runoff was estimated using Soil Conservation Service (SCS) method. Table 7 shows the estimated surface runoff for the pre-change period 1975-1984. The results showed notable low surface runoff in 1976 and 1980. This could have been contributed by the corresponding low rainfall in the catchment in the same years. Also notable was a high surface runoff in 1977, 1983 and 1984. The rainfall in 1983 and 1984 were relatively low. Thus the increased surface runoff could have been caused by the impact of land use change. However, the results show that the average depth per year was 18.15cm for the pre-change period 1975-1984.

Table 7: Annual Surface Runoff, Q for period 1(1975-1984)

PEAK RUNOFF, Q = (P-0.2S)^2/(P-0.8S)							
Year	P (cm)	S	0.2S	(P-0.2S)^2	0.8S	P+0.8S	Q (cm)
1975	54.23	49.65	9.93	1962.49	39.72	93.95	20.89
1976	28.05	104.00	20.8	52.56	83.2	111.25	0.47
1977	84.29	89.24	17.84	4415.60	71.39	155.82	28.34
1978	46.89	93.94	18.79	789.61	75.15	122.04	6.47
1979	38.4	49.65	9.93	810.54	39.72	78.12	10.38
1980	33.37	84.67	16.93	270.27	67.73	101.10	2.67
1981	38.25	49.65	9.93	802.02	39.72	77.97	10.29
1982	62.87	71.64	14.33	2356.13	57.13	120.18	19.61
1983	94.14	63.50	12.70	6632.47	50.80	144.94	45.76
1984	80.32	59.58	11.92	4678.56	47.66	127.98	36.57
Average							18.15

Table 8 shows the estimated surface runoff for the post-change period 1985-1994. The results showed low surface runoff in 1986 and 1987. This could have been contributed by the corresponding low rainfall in the catchment in the same years. Also notable was a high surface runoff in 1989, 1992 and 1994. These corresponded to the high rainfall in 1989, 1992 but not in 1994. The rainfall in 1994 was relatively low. However, the results showed that the average depth per year was 18.11cm for the post-change period 1985-1994.

Table 8: Annual Surface Runoff, Q for period 2a (1985-1994)

PEAK RUNOFF, Q= (P-0.2S)^2/(P-.8S)							
Year	P (cm)	S	0.2S	(P-0.2S)^2	0.8S	P+0.8S	Q (cm)
1985	45.42	42.35	8.47	1365.30	33.88	79.30	17.22
1986	55.47	104.00	20.80	1202.00	83.2	138.67	8.67
1987	34.71	89.24	17.84	284.60	71.39	106.10	2.68
1988	60.95	93.94	18.79	1777.47	75.15	136.10	13.06
1989	48.59	42.35	8.47	1609.61	33.88	82.47	19.52
1990	74.77	84.67	16.93	3345.47	67.73	142.50	23.48
1991	59.34	42.35	8.47	2587.76	33.88	93.22	27.76
1992	60.77	71.64	14.33	2156.67	57.13	117.90	18.29
1993	53.74	63.50	12.70	1684.28	50.80	101.54	16.59
1994	76.83	59.58	11.92	4213.31	47.66	124.49	33.84
Average							18.11

Table 9 shows the estimated surface runoff for post-change period 1995-2004. The results showed notable low surface runoff in the year 1996 and 2003 respectively. This could have been contributed by the corresponding low rainfall in the catchment in the same years. Also notable `years are 1998, 2002 and 2004 respectively. These corresponded to the high rainfall in the year 1998, 2002 and 2004 respectively. The results showed that the average depth per year was 28.75cm for the post-change period 1995- 2004.

Table 9: Annual Surface Runoff, Q for period 2b (1995-2004)

PEAK RUNOFF, Q=(P-0.2S)^2/(P-0.8S)							
Year	P (cm)	S	0.2S	(P-0.2S)^2	0.8S	P + 0.8S	Q (cm)
1995	43.35	42.35	8.47	1216.61	33.88	77.23	15.75
1996	47.69	104.00	20.80	723.07	83.20	130.89	5.52
1997	71.48	55.76	11.15	3639.71	44.60	116.08	31.36
1998	113.98	41.35	8.27	11174.60	33.08	147.06	75.99
1999	43.98	34.64	6.93	1372.70	27.71	71.69	19.15
2000	54.37	37.95	7.59	2188.37	30.36	84.73	25.83
2001	57.95	42.35	8.47	2448.27	33.88	91.83	26.66
2002	79.85	37.95	7.59	5221.51	30.36	110.21	47.38
2003	21.04	98.78	19.76	1.64	79.02	100.06	0.016
2004	79.99	52.02	10.40	4842.77	41.62	121.61	39.82
Average							28.75

The results given in the pre-change period 1975-1984 and post-change period 1995-2004 for annual surface runoff resulting from rainfall between the two periods showed a significant difference in amounts generated**.** This difference in amounts of generated surface runoff could have been caused by the impact of land use change. Therefore the results showed a 58% increase in depth surface runoff for the two periods. Also results given in the pre-change period 1975-1984 and post-change period 1985-1994 for annual surface runoff resulting from rainfall between the two periods showed a slightly negative difference in amount generated. The surface runoff in post- change period 1985-1994 was expected to be higher than pre-change period 1975-1984 given the high percentage difference of deforestation and built up areas. The possible reasons for negative difference could be physiographic; including the small holder farms characterized by hand tillage, and mixed cropping which increase storage and pondage. However, the results of periods 1975-1984 and 1995-2004 agree closely with the work done by Bosh and Hewlett (1982). The study concluded that the removal of forest almost invariably leads to higher stream flow.

Figure 9 shows the deviation in total estimated annual surface runoff results from the pre-change period 1975-1984 results and post-change period of 1985-1994 and 1995-2004 respectively. From the estimates, total estimated annual surface runoff in the post-change period 1995-2004 had significantly higher depth of flows than the post-change period 1985-1994 and pre-change period 1975-1984. For example ,in the first year of estimation post-change period 1995-2004 the depth of surface runoff was at 58mm while post-change period 1985-1994 was at 39mm and pre-change period 1975-1984 was at 20mm.

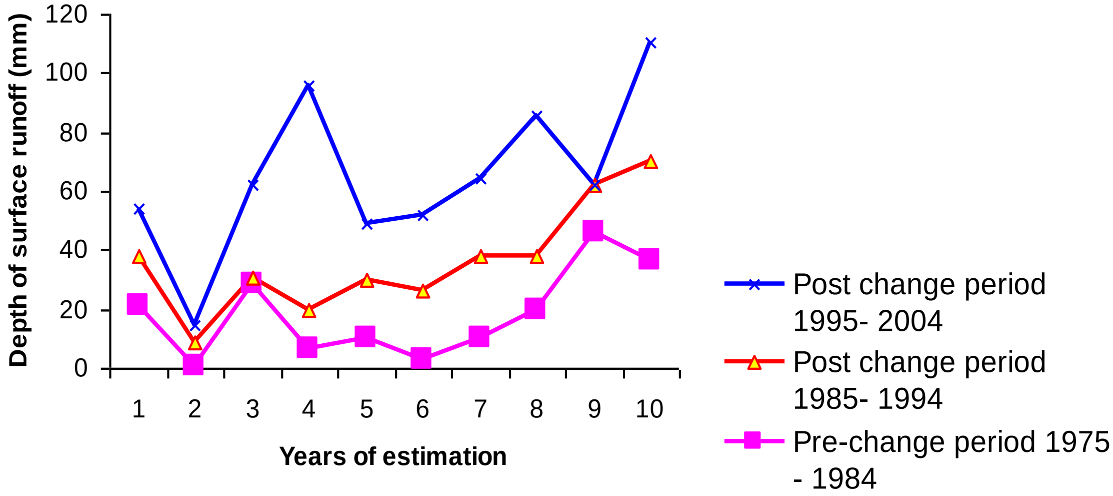


Figure 9: Deviation in Total Estimated Annual Surface Runoff

Clearly the finding indicates that the impact of land use change has a negative effect on total estimated annual surface runoff (reduction in forest land 57% and increase agriculture land and built up area by 10% and 156%) resulted in substantial difference in total estimated surface runoff in the catchment.

4.2.2 Annual Surface Runoff and Sediment Yield Simulated using SWAT Model

The depth of surface runoff was simulated to mark pre-change and post-change periods as shown in Table 10. The results shows simulated annual surface runoff for pre-change period 1975-1984, post-change period 1985-1984 and 1995-2004. In this post-change period 1995-2004 simulation, the average depth per year of surface runoff was higher than the other simulations for pre-change period 1975-1984 and post-change period 1985-1994 respectively. In general, the findings indicate that the total annual depth of surface runoff depth increased as a function of land use/cover change within the catchment. This increase depth of average surface runoff could be attributed to the impacts of land use changes on catchment over the said periods.

Table 10: Annual simulated surface runoff

Year of simulation	Depth of surface runoff (mm) for Pre-change period 1975 - 1984	Depth of surface runoff (mm) for Post change period 1985- 1994	Depth of surface runoff (mm) for Post change period 1995- 2004
1	9.5	22.0	125.0
2	7.5	21.0	155.0
3	1.5	7.0	85.0
4	1.5	6.0	95.0
5	18.0	28.0	180.0
6	0.0	19.0	115.0
7	6.0	25.0	140.0
8	0.8	2.5.0	98.0
9	0.5	8.0	75.0
10	1.0	4.0	50.0
Average	8.74	14.25	99.30

From results given for simulation periods 1975-1984 and 1995-2004 showed a 90.56mm increase in average depth of surface runoff. This indicated a significant difference in the amounts generated**.** Also this was demonstrated by the results for simulation periods of 1975-1984 and 1985-1994. The results agree closely with the work done by Li *et al*. (2007). The study concluded that total deforestation to agriculture increases surface runoff ratio from 0.15 to 0.44 and the annual stream flow by 35-36%, depending on the location of the catchment. However in this study, there was no total deforestation to agriculture because agroforestry is practiced. The catchment is situated in a hilly area. Therefore, the higher increase of surface runoff may be as result of using the converted land from forest to agriculture with minimal conservation principles being applied. This led to the increase in the flow of water and consequently decreases infiltration while at the same time increased surface runoff. These results indicate that the land use change have had impact on catchment hydrology as show by simulated surface runoff trends for both periods.

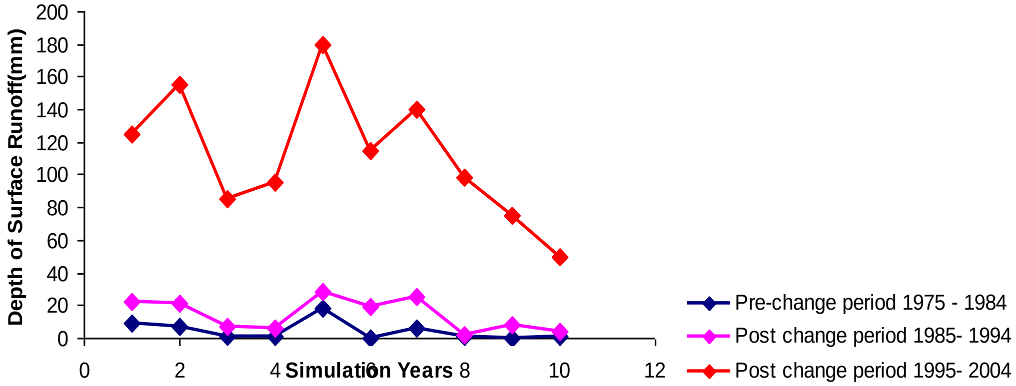


Figure 10: Deviation in Simulated Annual Surface Runoff

Figure 10 shows the deviation in simulated annual surface runoff results from the pre-change period 1975-1984 and post-change period of 1985-1994 and 1995-2004 respectively. Simulated annual surface runoff in the post-change period 1995-2004 had significantly higher depth of annual surface runoff than post-change period 1985-1994 and pre-change period 1975-1984 in all the simulation years. For example in the first simulation year post-change period 1995-2004 the depth of annual surface runoff was at 120mm while post-change period 1985-1994 was at 20mm and pre-change period 1975-1984 was at 9mm. These findings reflected the observed changes in estimated annual surface runoff for the same time periods in the study area. It appears that the change of land use in catchment (57% reduction in forest land and increase agriculture and built up area of 10% and 156%) resulted in substantial difference in simulated annual surface runoff in the catchment. The finding indicates the effects on hydrologic response of the transition the catchment had undergone over the past 30 years.

In general, simulated results indicate that land use changes within the Wundanyi River catchment have altered its hydrologic response. These localized changes were associated with vegetation transition and built up areas. Reduced estimates of percent forest cover, and surface roughness in conjunction with increased impervious surfaces resulted in increased simulated surface runoff. These results followed the conclusions of Kepner *et al*. (2000), who showed that rapid urbanization in the towns within the San Pedro catchment over the past 20 years had became an important factor in altering land-cover composition and hydrology patterns.

4.3.1 Annual Sediment Yield Simulated using SWAT Model

The annual Sediment yield was simulated to mark pre-change and post-change periods using the Modified Universal Soil Loss Equation model (MUSLE model).

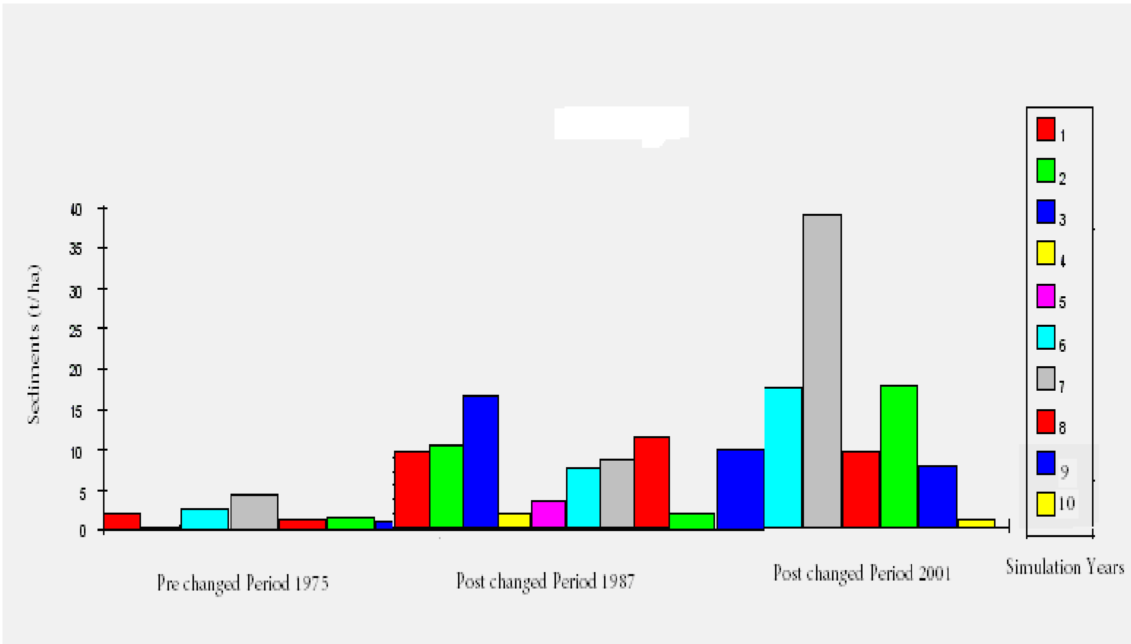


Figure 11: Annual Sediment Yield for Wundanyi River Catchment

Figure 11 shows annual simulated sediment yield for the pre-change period 1975-1985 and for post-change period 1985-1994 and 1995-2004. The annual simulated sediment yield in the post-change period has significantly higher sediment yield than post-change period 1985-1994 and pre-change period 1975-1984 in all simulation years. For example in the seventh simulation year post-change period 1995-2004 the sediment yield was at 40t/ha while post-change period 1985-1994 was at 10t/ha/yr and pre-change period was at 4t/ha/yr. The findings indicate that the impact of land use change has a negative effect on catchment hydrology. It appears that the impacts of land use change (forest land reduction 57%, increase in agriculture and built up area by 10 and 156%) results in substantial difference in sediment yield in the catchment. The increase in sediment yield from an average of 0.432 t/ha in the pre-change period to 20.10 t/ha in the post- change period indicates the impacts of land use changes on the catchment hydrology. The results agree closely with the work done by Fasthali (2003) in Sar-chi catchment, where the findings had an increase of 94% sediment yield due to land use changes to agriculture. In this study, sediment yield increased by 19.77t/ha between the period 1975 and 2001.

4.2.3 Potential Evapotranspiration

The evapotranspiration was simulated to mark pre-change and post-change periods as shown in Table 11. The results shows simulated annual evapotranspiration for pre-change period 1975-1984, post-change period 1985-1984 and 1995-2004. In this post-change period 1995-2004 simulation, the average annual evapotranspiration was higher than the other simulations for pre-change period 1975-1984 and post-change period 1985-1994 respectively. This increase depth of average annual evapontranspiration could be attributed to the impacts of land use changes on catchment over the said periods. From results given for simulation periods 1975-1984 and 1995-2004 showed a 206mm increase in average annual evapotranspiration. This indicated a significant difference in the amounts simulated**.** The results agree closely with the work done by Marloes (2009). The study concluded that total deforestation to agriculture increases annual evapotranspiration, depending on the location of the catchment.

Table 11: Annual Simulated Evapotranspiration

Year of simulation	Evapotranspiration (mm) for Pre-change period 1975 - 1984	Evapotranspiration (mm) for post-change period 1985-1994	Evapotranspiration (mm) for post-change period 1995-2004
1	190	234	244
2	240	320	494
3	417	525	780
4	490	389	645
5	244	469	329
6	246	654	608
7	364	560	544
8	456	388	608
9	418	369	552
10	216	627	532
Average	328	454	534

Figure 12 shows the deviation in simulated annual evapotranspiration results from the pre-change period 1975-1984 and post-change period of 1985-1994 and 1995-2004 respectively. Simulated annual evapotranspiration in the post-change period 1995-2004 had significantly higher value of annual evapotranspiration than post-change period 1985-1994 and pre-change period 1975-1984 in all the simulation years. For example in the first simulation year post-change period 1995-2004 the value of annual evapotranspiration was at 244mm while post-change period 1985-1994 was at 234mm and pre-change period 1975-1984 was at 190mm. It appears that the change of land use in catchment (57% reduction in forest land and increase agriculture and built up area of 10% and 156%) resulted in substantial difference in simulated annual evapotranspiration in the catchment. The finding indicates the effects on hydrologic response of the catchment that had undergone over the last 30 years.

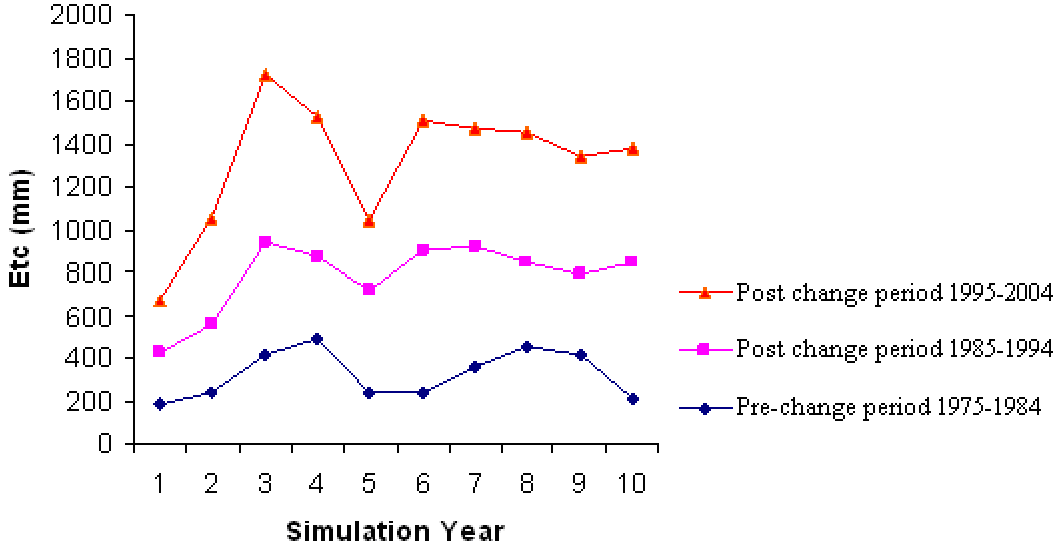


Figure 12: Deviation of Simulated Annual Evapotranspiration

4.3 Model Calibration and Validation

4.3.1 Results of Model Calibration

The model calibration was carried out using the split data results for the first decade from 1975 to 1984 where the grid land use map for 1975 was used as shown Table 12.

Table 12 : Observed and Predicted Stream Flows from 1975-1984

Year	Observed Stream flow(m^3/s)	Predicted Stream flow (m^3/s)
1975	26.319	27.43
1976	79.877	69.60
1977	286.13	300.00
1978	6.04	17.85
1979	1.95	16.25
1980	63.69	60.90
1981	7.29	8.90
1982	229.53	260.00
1983	127.81	134.00
1984	12.11	10.90

From the result in Table 12 were used to determine the conceptual parameter as explained below. The model conceptual parameters were varied several times until flows which indicated the highest NSE and lowest RSR were achieved. The calculated Nash Sutcliffe coefficient (NSE) and RMSE- observation Standard Deviation Ratio (RSR) were 0.75 and 0.25 respectively. The RSR approached 0.0 showing that the root mean square errors were low and therefore the model can satisfactorily evaluate catchment hydrology response with reasonable accuracy. An RSR value of 0.25 is within a very good range of model performance which indicates that the model can be applied to evaluate catchment hydrology for Wundanyi River catchment. This was done to ensure that the predicted results closely matched the observed values as shown in Figure 13.

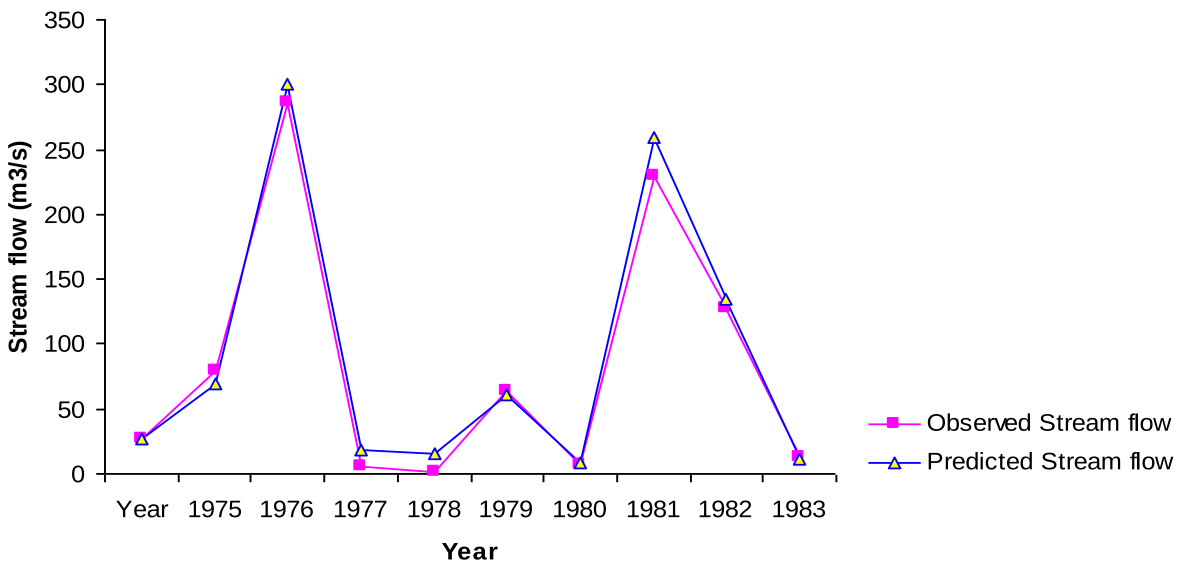


Figure 13: Observed and Predicted stream flows after model calibration

The results shown in Figure13 indicates that 1976-1977, 1979 and 1980-1983 had above normal flows while the years with below normal flow were 1975,1977-1978and 1980. The most severe floods have occurred in1976 and 19980-1983. There was a marked reduction of flow in the period 1975-1976, 1977-1978 and 1979-1980 recorded at 3LA7. These periods were drought periods and factors such as increased domestic and agricultural usage of river water could have contributed to this. After 1980, the flow increased again and this could be attributed to increased rainfall in 1981 and 1982 as shown in Appendix 5 coupled with less river water usage. People would use less of the river water since there would be enough rain for agricultural activities and they would also harvest rainwater for other uses.

The three performance criteria indicate that conceptual parameters modified or adjusted during the calibration represented catchment hydrology response. The optimized SWAT model conceptual parameters are presented in Table 13.

Table 13: The SWAT Model Conceptual parameters obtained through calibration

Parameter	Description	Final
Alpha_BF	Baseflow alpha factor in days, which refers to groundwater flow response to recharge. When set to zero, there is no connection to groundwater (no return flow). Consequently when rainfall stops, the hydrographs falling limb immediately drops.	0.5
GWQmn	Depth of water in mm required in the shallow aquifer before return flow can occur.	3000
GW_Revap	'Revap' coefficient indicates how restricted water flow is from the shallow aquifer into the unsaturated zone to be taken up by plants.	0.15
Revapmn	This the minimum depth in mm that must be present before water from shallow aquifer can percolate into the unsaturated zone or deep aquifer	2500

4.3.2 Results of Model Validation

The model validation was carried out using split data results for the second decade from 1985 to 1994 where the grid land use map for 1987 was used as shown Table 14.

Table 14: Observed and Predicted Stream Flow from 1985-1994

Year	Observed Stream flow(m^3/s)	Predicted Stream flow (m^3/s)
1985	51.45	60.00
1986	32.76	34.23
1987	19.63	25.75
1988	8.34	9.25
1989	180.09	160.26
1990	190.32	180.67
1991	84.88	130.64
1992	31.67	30.65
1993	74.23	58.54
1994	149.79	167.80

The model validation results for period 1985 to 1994 where 1987 land use grid map was used indicate whether the model is capable of evaluating catchment hydrology. The calculated Nash and Sutcliffe efficiency and RSR error index were 0.94 and 0.06 respectively. The NSE coefficient shows that the model can evaluate catchment hydrology response within acceptable accuracy. However, the performance is higher than that for calibration. Regardless of low performance during the calibration, the results indicate that the model could with fair accuracy evaluate catchment hydrology response. Figure 14 indicates that the model evaluated the flows fairly well. The results show a value of Nash and Sutcliffe efficiency of 0.94 which approached unity indicating that the predicted flows were approximating the observed stream flows.

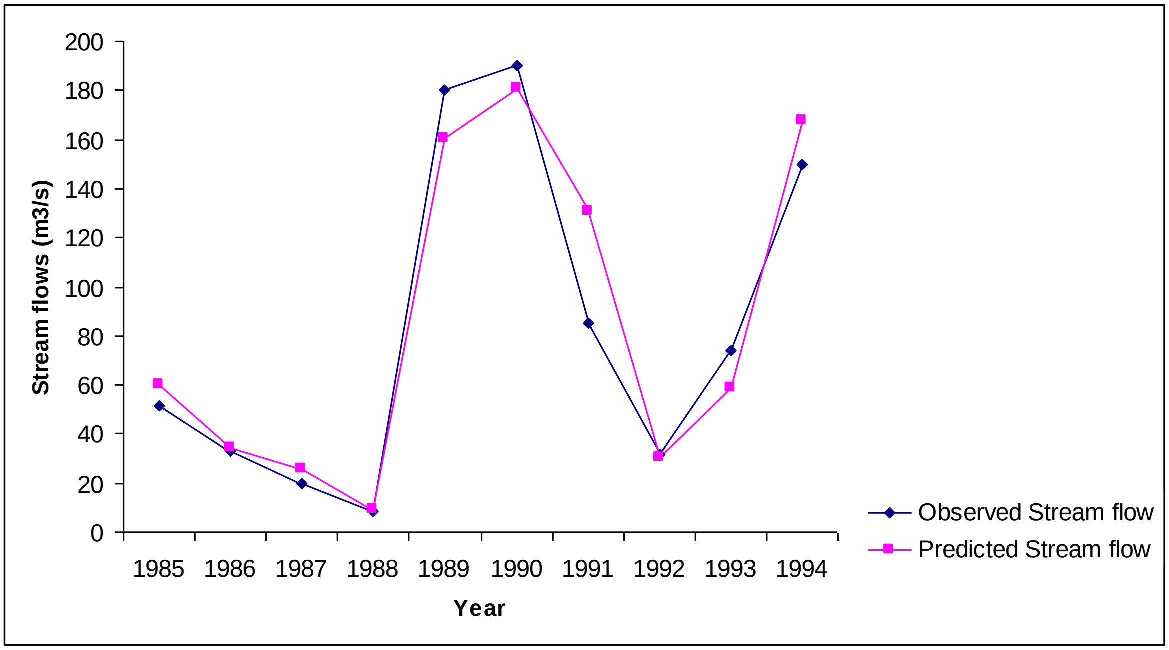


Figure 14: Observed and Predicted streamflows after model validation

The results in Figure14 indicate that 1988-1992 and 1993-1994 had above normal flows while the years with below normal flow were 1986-1988 and 1992. The most severe floods occurred in1988-1991 and 1994. There was a marked reduction of flow in the period 1987 and 1992 recorded at 3LA7. These periods were drought periods and factors such as increased domestic and agricultural usage of river water could have contributed to this. After 1992, the flow increased again and this could be attributed to increased rainfall in 1993 and 1994 as shown in Appendix 6 coupled with less river water usage. People would use less of the river water since there would be enough rain for agricultural activities and they would also harvest rainwater for other uses.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The overall objective of the study was to evaluate the impact of land use on catchment hydrology in the Wundanyi River catchment for effective catchment management. In this catchment, therefore is one of the catchments that have undergone rapid land use changes over the last 30 years. Changes of land use in the catchment were characterised and quantified using remote sensing and GIS.

The overall land use reduction under the forest land that is broadleaved forest, needleleaved forest, shrubland and woodland were 59.7%, 65.0%, 18.9% and 45%. These give average reduction under forest land of 57%. The agriculture, built-up area and thicket increased by 10.0%, 156% and 48.5% respectively. The results showed that there was significant land use change in the catchment.

The *NSE* values obtained for Wandanyi River catchment was 0.75 during calibration and 0.94 upon validation. The RSR index error values obtained were 0.25 during calibration and 0.06 upon validation. Results show that SWAT model adequately simulated the surface runoff for the study catchment with Nash and Sutcliffe calculated coefficients (NSE) of 0.75 for calibration and 0.94 for validation and RSR index error values of 0.25 and 0.06 respectively.

The average annual surface runoff obtained for pre-change period 1975-1984, post-change period 1985-1994 and 1995-2004 were 8.74, 14.25 and 99.30mm respectively. The average annual sediment yield obtained for pre-change period 1975-1984, post-change period 1985-1994 and 1995-2004 were 0.42, 5.75 and 20.10t/ha/yr respectively. The average annual evapotranspiration obtained for pre-change period 1975-1984, post-change period 1985-1994 and 1995-2004 were 328, 454 and 534mm respectively. This high increase in average annual surface runoff, sediment yield and evapotranspiration indicates that there was an impact on catchment hydrology. Therefore the results showed that land use change has significant impact on the catchment hydrology.

In this regard it can be concluded that the combination of Remote Sensing, GIS and the SWAT model provides a useful technique in evaluating the impact of land use change on catchment hydrology which is essential in selecting and developing viable catchment management options that will promote sustainable utilization of land and water resources.

5.2 Recommendations

Land use changes are the most significant factors driving hydrological changes such as runoff volume, timing, and variability. The simplest method to assess these effects on catchment hydrology is by comparing stream flow and runoff generated from catchment areas with contrasting land use types. Hence a comprehensive analysis is necessary to facilitate evaluation of the impact of land use change on catchment hydrology in terms of the accuracy of simulated data compared to measured flow and constituent values such as surface runoff and sediment yield. In this study, evaluation of impacts of land use changes on catchment hydrology were demonstrated by presenting three decadal periods of study consisting of pre-change period 1975-1984, post-change period 1985-1994 and 1995-2004. The first decade was taken as base in evaluating the hydrologic response of the Wundanyi River catchment to land use/cover change for the three decades using the SWAT model. These periods significantly differ in their representation of hydrologic processes and operating at different temporal and spatial scales. Input parameters for the SWAT model were obtained using AGWA in conjunction with readily available topographic and soil data and three classified satellite images detailing land use/cover over the study area. The results indicate that catchment hydrologic response in the catchment has been altered to favour increased average annual surface runoff due to land use/cover change during the period from 1975 to 2004, and consequently it was at risk for decreased water quality and related impacts to the land degradation. It was necessary to obtain a much broader base of data in order to make inferences about the impact land use change on catchment hydrology and the catchment was ungauged.

In this study, SWAT model parameters for Wandanyi River catchment were developed through calibration and validated for surface runoff simulation for the study area. Based on the results of the statistical tests conducted on the model's performance, it is recommended for surface runoff and sediment yield estimation of the catchment. However, further research in this model is herein recommended to test its validity and use in other catchments. Moreover, further work to investigate the impact of land use change on hydrological response for large catchment should be carried out that is catchment with areas great than 10,000km^2. Likewise, it is also recommended that more work should be carried out using high resolution satellite images and of recent time to evaluate the impact of land use change on catchment hydrology in Wundanyi River catchment.

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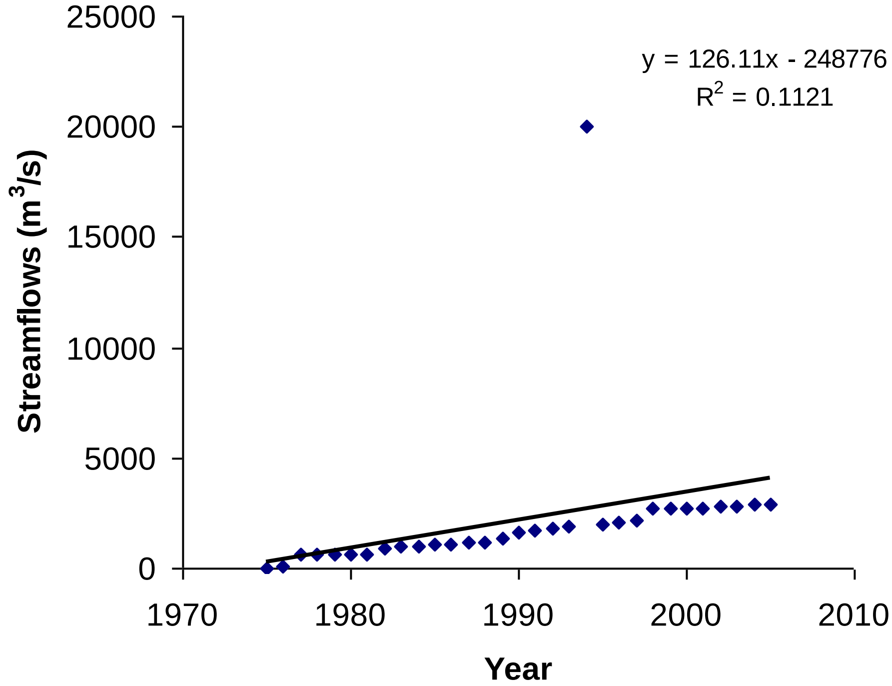
APPENDICES

Appendix 1 : Daily annual streamflow single mass curve

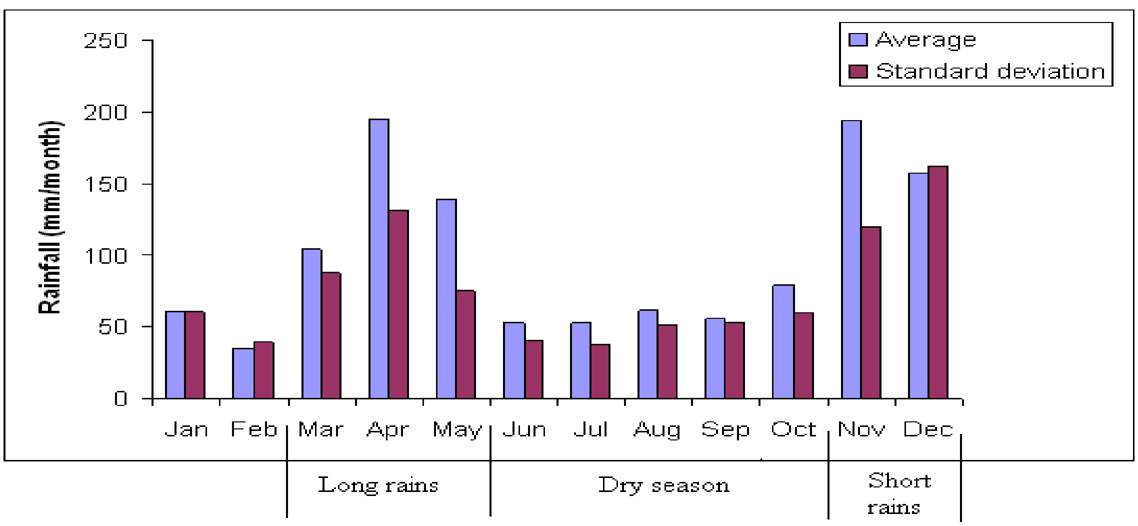
The cumulative stream flow was used to plot single mass curve against time.



Appendix 2: Calculated properties of the generated sub-catchments

ID	SLOPE (%)	CENTROID_X (M)	CENTROID_Y (M)	SOIL_ID	CN	COVER (%)	HYDVALUE	KS (mm/hr)
8	0.4245	425665.36	9628337.80	737	80.2	47.39	2.23	6.89
9	0.5589	433734.31	9627519.91	466	76.1	43.49	2.29	6.42
7	0.6835	432311.19	9625569.06	466	83.6	32.95	2.37	6.61
6	0.5137	427874.43	9625478.07	466	74.8	42.27	2.28	6.75
10	0.3710	438010.88	9623817.33	737	82.1	36.60	2.34	7.36
2	0.0748	438673.34	9613703.44	737	86.3	36.50	2.30	7.34
1	0.1370	435073.71	9614274.10	737	87.0	49.50	2.28	7.33
4	0.1281	439356.83	9610014.77	737	82.5	28.96	2.63	8.59
3	0.1714	437082.81	9607332.19	246	79.7	35.99	2.63	10.59
11	0.1397	445788.91	9616785.48	118	87.0	15.46	2.89	9.78
	0.1566	440052.72	9615864.64	737	88.4	27.78	2.56	8.14

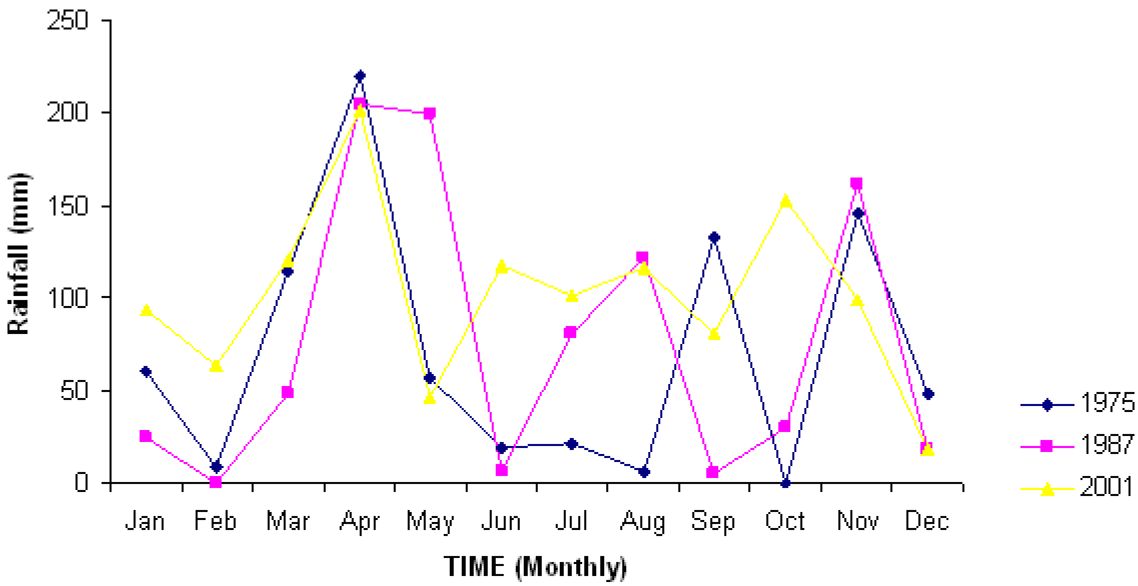
Appendix 3: Distribution of rainfall in Wundanyi River catchment (1970-2004)



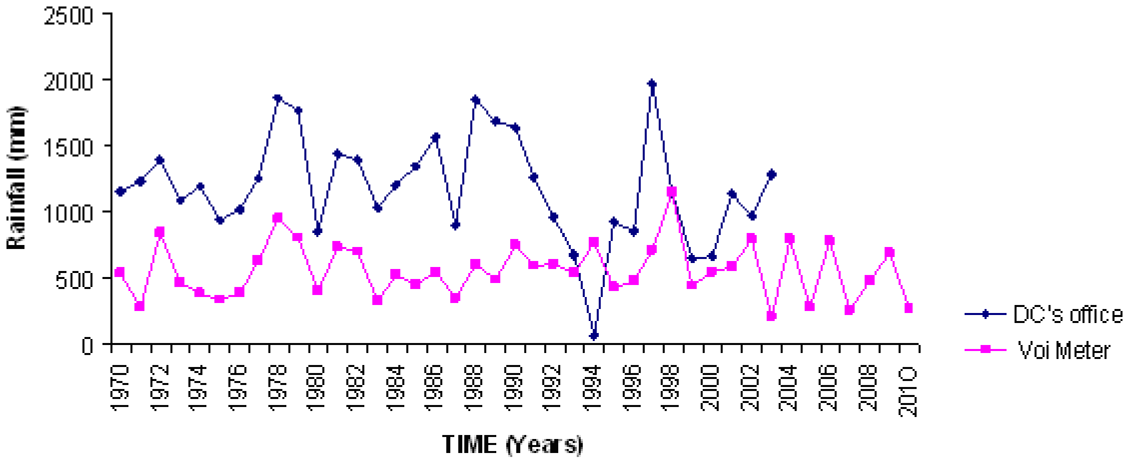
Appendix 4: Average rainfall and standard deviation of the rainfall, DC's office station.

	Annual (mm a-1)		Long rains (mm season-1)		Short rains (mm season-1)	
	Average	St Dev	Average	St Dev	Average	St Dev
1970-2004						
1970s	1288.0	289.2	183.6	125.0	183.6	103.8
1980s	1322.4	313.0	174.4	99.0	212.7	116.4
1990s	1014.9	504.0	95.2	82.8	168.9	199.7
2000s	734.5	321.1	107.9	75.4	81.3	55.8

Appendix 5: Monthly Rainfall Distribution



Appendix 6: Annual rainfall in Wundanyi River Catchment (1970-2010)



Appendix 7: Conceptual Parameters for SWAT Model

Parameter	Description	Minimum	Maximum
Alpha_BF	Baseflow alpha factor in days, which refers to groundwater flow response to recharge. When set to zero, there is no connection to groundwater (no return flow). Consequently when rainfall stops, the hydrographs falling limb immediately drops	0.0	1
GWQmn	Depth of water in mm required in the shallow aquifer before return flow can occur	0.0	4000
GW_Revap	'Revap' coefficient indicates how restricted water flow is from the shallow aquifer into the unsaturated zone to be taken up by plants	0.02	0.2
Revapmn	This is the minimum depth in mm that must be present before water from shallow aquifer can percolate into the unsaturated zone or deep aquifer	0.0	3000

Source: Schuol *et al*. (2008)

Appendix 8: FAO soil units for Wundanyi River catchment