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HYDROLOGIC MODELING AND UNCERTAINTY ANALYSIS OF AN UNGAUGED WATERSHED USING MAPWINDOW-SWAT

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Hydrologic Modeling and Uncertainty Analysis of an Ungauged Watershed Using MapWindow-SWAT

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February, 2010.

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ABSTRACT

Modeling of an ungauged watershed with the associated uncertainties of the input data is presented. The MapWindow versions of the Soil and Water Assessment Tool (SWAT) have been applied to a complex and ungauged watershed of about 248,000ha in an area close to the Niger River, Nigeria. The Kwara State Government of Nigeria in collaboration with the newly relocated former Zimbabwean farmers now occupied the largest portion of this watershed for an "Agricultural Estate Initiative ". The government and these farmers are decision makers who need to take appropriate actions despite little or no data availability. SWAT being a physically based model, allow the use of Geographical Information System (GIS) inputs like the Digital Elevation Model(DEM), landuse and soil maps. The MapWindow-SWAT(MSWAT) involves processes like the Watershed Delineation, Hydrological Response Units (HRUs) Process and the SWAT run. The watershed was delineated into 11 subbasins and 28 HRUs. There were 8 landuse classes and 5 soil types. The model was able to simulate and forecast for several years(1990-2016). The results look 'reasonable' since there is no observed data from the watershed for statistical validation. However, using the Water Balance equation as a validation criteria, the correlation coefficient between the simulated rainfall and runoff was 0.84 for the subbasin 11 (outlet). Thereafter, the uncertainties in the continuous numerical input (i.e. rainfall) was examined using the Data Uncertainty Engine (DUE). One parameter exponential probability model was used for the daily rainfall amount based on the histogram. 700 realizations were generated from this uncertain input. Randomly selected numbers of the realizations were prepared and used as inputs into the MWSWAT model. It was surprising that there were no changes in the results when compared to the initial 'real' value (outflows from outlet) although other parameters of the model were kept constant.

KEYWORDS

GIS Applications

Uncertainty Analysis

Semi-distributed parameter model

Geographical Information Systems (GIS)

Streamflow modeling

Soil and Water Assessment Tool (SWAT)

Land Use management

Digital Elevation Model (DEM)

Water Quality

ACRONYMS

ARMA- Autoregressive Moving Average

AWD – Automatic Watershed Delineation

COM – Component Object Model

DEM- Digital Elevation Model

DUE - Data Uncertainty Engine

EESD - Environment and Sustainable Developement

EPA - Environmental Protection Agency

ET - Evapotranspiration

GLCC - Global Land Cover Characterization

HRUs - Hydrological Response Units

LCLC - Land Cover and Land Change

MCMC- Markov Chain Monte Carlo

MUSLE - Modified Universal Soil Loss Equation

MWSWAT - MapWindow SWAT

SWAT – Soil and Water Assessment Tool

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1.0 CHAPTER ONE: INTRODUCTION

1.1 THEORETICAL FRAMEWORK

In basic terms, hydrology can be defined as the study of the movement of the earth´s water through a cycle and the transportation of the contents such as sediments and pollutants in the water as it flows. In other words, hydrology could be said to be applied science concerned with the occurrence, distribution and circulation of the waters of the earth. Furthermore, this can be described as a distinct geo-science with a strong interdisciplinary flavor. Although the focus of hydrology is on water and its cyclical movement through the environment, it provides for an holistic approach which may more closely investigate how water, the environment and human activities are mutually dependent and interactive(Watson and Burnett, 1995).

In practical terms, it is often tedious and expensive to determine several parameters that interplay in hydrological process. For instance, the field determinations of water quantity and quality are tasking. Variables like the runoff, sediment load, pesticides effects on plants, evaporation, etc. are very difficult to measure in the field. Hydrologists, regional geographers and agricultural development planners are often faced with the tasks of determining the short and long term effects of natural variables like temperature, rainfall, solar radiation, land use and land use changes on the environment. The only feasible solution to this would be to use a reliable hydrological model. But this is a "non´-starter" since in several regions of the world, there are challenges of data unreliability and non-availability. Good management decisions using hydrological model are often based on good data input and technical know-how. Therefore, it is very important to have both reliable data and hydrological model.

In recent times, there have been issues of analyzing the uncertainties in the input data , so that the managers and decision makers would be able to know the confidence level when applying the model for management decisions. This is not negotiable when it comes to sensitive management decisions that have both human and economic consequences.

1.2 MULTI-DISCIPLINARY NATURE OF THE PROJECT.

Hydrological modeling of a watershed and uncertainty analysis of the model input data is not an easy task. There are challenges revealed at each stages of the modeling procedure. To apply the MapWindow-SWAT tool effectively for management alternatives for the area of interest, collaborations among farmers, soil and crop scientists and hydrologists would be ideal. The Geographical Information Systems (GIS) know-how cannot be compromised here. Computer programming and statistical knowledge are really important to achieve the ultimate goal. This study just looks at the generation of streamflow and water quality data forn each sub-basins of the watershed. It would be desirable to run scenarios for various management options based on the results of this flow study which would require a further suite of experts on particular crops, irrigation regimes, and chemical applications for crop improvement.

1.3 PROJECT JUSTIFICATION

The importance of hydrological modeling in decision support systems cannot be over-emphasized. Hydrological models have aided several management decisions in evaluating the impacts of variables like precipitation, land use changes and soil types on natural resources like water. This study consists of generating useful information about water quantity and quality in an ungauged basin. The end users of this model would be newly relocated "Zimbabwean farmers" in Nigeria now called "Nigeria farmers" in Odu Local Government, Kwara State, Nigeria. Although the basin is ungauged, however, the results should be 'sensible' to certain extent for good management planning and decision making. It is equally important to estimate the uncertainties in any of the model inputs which would help in knowing the confidence level of the model result.

1.4 OBJECTIVES AND AIMS OF THE STUDY.

The primary objectives of this thesis are:

- Using the available input data (Digital Elevation Model(DEM), land use, soil map and climate data) to predict the water quantity and quality of the ungauged basin using the MapWindow version of SWAT (MWSWAT),
- Using the Data Uncertainty Engine (DUE) to generate various realizations of the numeric continuous variable(i.e., Rainfall) input of the model and
- Using some of these realizations in the modeling procedure to quantify the uncertainties associated with the input.

1.5 THESIS ORGANIZATION

In Chapter 1, the reader is introduced to the theoretical background of the study. The interdisciplinary, objectives and justification of the project are discussed.

Chapter 2 informs the reader about the hydrological modeling and further explains the necessary terminology and concepts.

Chapter 3 deals with the overall project methodology. Data acquisition issue, geo-processing and preparation as model inputs are discussed. This is followed by the description of the MapWindow-SWAT, its requirements and work flow. Also, Uncertainty Analysis concept and DUE mechanism are discussed.

Chapter 4 details the results from MWSWAT. Descriptions and graphical interpretations of the results are also shown.

Finally, in Chapter 5, the conclusions based on the model results are stated. This also includes recommendations and future research in an ungauged basin.

2.0 CHAPTER TWO: STATE OF THE ART

The basic terms which anchored hydrological modeling and uncertainty analysis would be discussed in this chapter. In particular, there would be an extensive literature review of some research outputs of various authors in this field of study to support each step of the project.

2.1 HYDROLOGICAL PROCESS

Hydrologic process can be defined as the natural system in which water moves between land, atmosphere and the ocean cyclically as shown in Figure 1. Human actions interrupt these cycles and the consequences of which now threaten the living existence of man on earth.

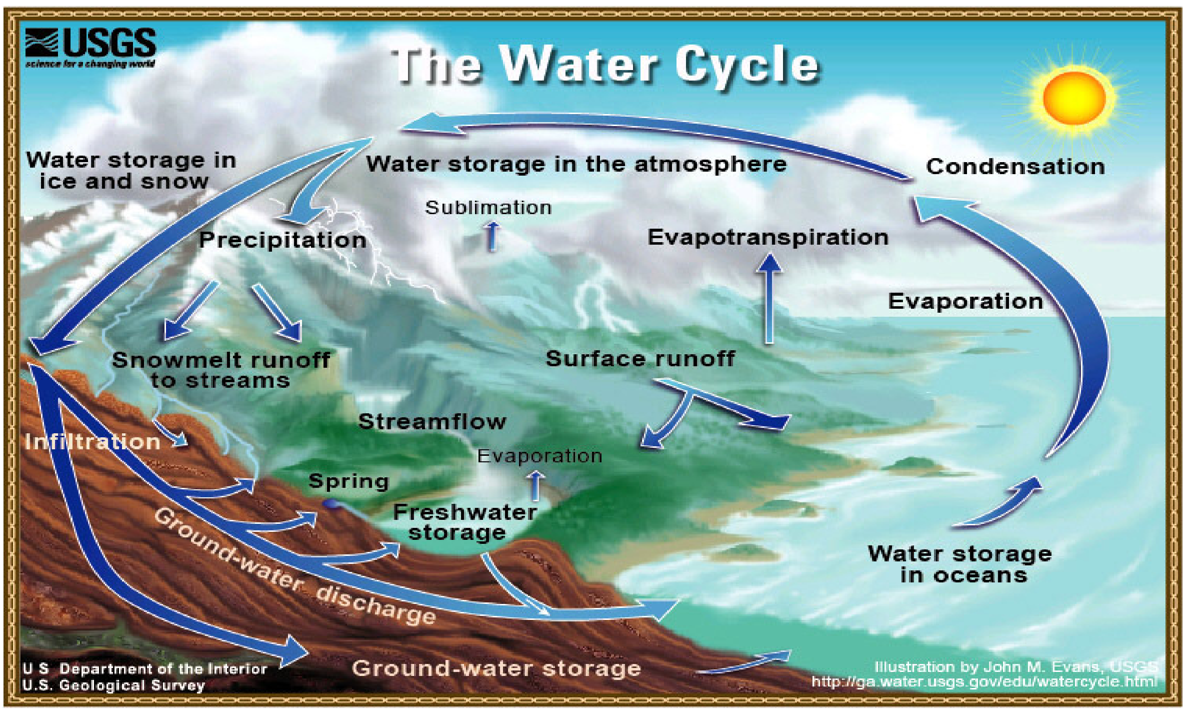


Figure 1: The Hydrologic Process of any Typical Watershed. (Source: Uhlenbrook, 2008)

Hydrologic cycle is composed of several natural processes which have interactions and they can be represented or simplified using a mathematical model (Yevjevich,1972a; 1972b)

Uhlenbrook (2006) outlined the following as the processes that are represented in hydrological cycle;

- precipitation,
- interception (including utilization by ecosystems, man and irrigation),
- absorption into earth materials and uptake by plants (including percolation),
- water movement from shallow to deep aquifers,
- surface flow,
- subsurface flow and
- Water losses in the form of evaporation, transpiration and seepage.

It is highly important to differentiate between surface and subsurface flow. Surface flow can be described as the flow of water through the earth surface like stream, rivers or surface-runoff, whereas sub-surface flow would be defined as the flow of water through the earth materials. These earth materials are heterogeneous, therefore the flow through them tends to follow the path of least resistance.

Mathematical models applications in water resources design, management and decision support systems have been in consideration since early sixties(Özis, 1973a). Having longer years of historical records for hydrological modeling often provide a better model representation which is common in the developed world because of good data collection techniques, whereas, in the developing country such as Nigeria, there are cases of poor data quality and intermittent data recording (Özis, 1973a; 1973b).

2.2 HYDROLOGICAL MODELING METHODS

Mathematical models are needed daily mainly in overcoming challenges of decision making. Rational formula modeling method is one of the earliest types of hydrological models (Mulvaney, 1851). This is the quantitative expression of flood flow rates in relation to rainfall and watershed area of relatively small catchments. The method was based on the concept of the 'time of concentration' which means that the time required for water to flow from the most remote point of the area to the outlet. Sherman (1932) developed the unit hydrograph concept of modeling on the basis of superposition. This superposition concept involved many assumptions such as; the catchments behave like a linear, dynamic, time variant causative system with respect to the rainfall-runoff transformation. In the 1960 and 70s, systems approach was used for the analysis of complex dynamic systems(Lewarne, 2009). The response function was obtained from the analysis of input and output data and represented by mathematical expressions. The response function carried no physical significance of the system. At about this time, computers became more widely accessible, and powerful enough to significantly assist in modeling process. There are numerous hydrological models and they can be grouped by pollutants addressed, complexity of pollutant sources, whether the model is steady state or dynamic, and the time period modeled. Also important in determining the selection of model is whether it distributed (i.e. capable of predicting multiple points within a river) or lumped.

2.2.1 Physical "Deterministic" Models

These models are based on complex physical theory and require large amount of data and computational time. Hence, the models are very costly to develop and operate (Liddament et. al., 1981). These models are distributed by means of non linear partial differential equations which describe the hydrologic processes. It has been noted that analytical solutions are generally not available to solve the equations. Hence resort must be made to adopt the partial differential equations; include finite difference method (Freeze, 1971), finite element methods (Beven, 1977; Ross et. al., 1979), integral finite difference and boundary integral methods which are difficult and time consuming. Simplifications have been made and kinematic wave theory was used alternatively. The models offer the ability to simulate the complete runoff and the effect of catchment changes which is particularly important in case of resource management. One of the major advantages of deterministic models is that these models offer the internal view of the process which enables improve understanding of the hydrological system. Système Hydrologique Europèen (SHE) is one of the well known distributed models (Abbott et. al., 1986; Gosain et. al., 2009). SHE, ACRU, SWAT and VTI share the description of being semi-distributed, quasi-based daily time step models for watershed-scale modeling. It allows for spatially distributed water flow and sediment transport modeling. Processes are represented by either finite difference sub-models of partial differential equations or by derived empirical equations. They simulate the interaction between land use and climate changes as they impact on in-stream water quality, with varying consideration of groundwater interactions. Other similar international models include RORB, Xinanjiang, Tank model, ARNO, TOPMODEL, UBC, HBV, AGNPS, GWLF, HSPF and MohidLand (Lewarne, 2009)

2.2.2 Stochastic Models

Stochastic hydrological models are the types of models that use mathematical concepts and statistical principles to derive results from the inputs. Examples are models that use neural networks principles, regression analysis techniques etc (Lewarne, 2009). These types of models are very common in water resources forecasting where the rainfall, runoff and antecedent moisture content are related.

2.3 HYDROLOGICAL MODELING STANDARD EQUATION

Hydrological Models like SWAT have many equations. Hydrological water balance equation is the fundamental equation upon which others are 'anchored'. This is given as:

$$P = R + ET + \Delta s/\Delta t \qquad (1)$$

Where;

P = Precipitation,

R = Runoff,

ET = Evapotranspiration and

$\Delta s/\Delta t$ = change in storage over time

The storage expressed in Equation (1) can be in some forms. Uhlenbrook (2006) lists the following as the form of storage in hydrological cycle:

- Atmosphere
- soil water/groundwater
- oceans
- ice caps, glaciers, snow
- Rivers, lakes
- surface storage (interception) and
- biosphere.

Uhlenbrook (2006) further stated that water balance does not stand in isolation for hydrological studies, and is used in conjunction with the surface energy balance which represents evapotranspiration processes more accurately. This is further explained by the following Equation (2):

$$R_n = \lambda E + H + G + \Delta s/\Delta t \qquad (2)$$

Where:

R_n = Net Radiation,

λE = Latent heat (the same as evapotranspiration, ET)

H= Sensible heat

G = Soil heat flux and

$\Delta s/\Delta t$ = change in storage

Assuming G and $\Delta s/\Delta t$ are negligible, then the equation can further be simplified as;

$$R_n = \lambda E + H \qquad (3)$$

Several other important equations used in setting up SWAT models are identified and summarized in Table 1 shown below (Uhlenbrook (2006; Watson and Burnet, 1996; Neitsch et. al., 2005; Lewarne, 2009)).

Table 1: Equations used in Hydrological Models*

Equation	**Uses**
The Manning´s Roughness Coefficient	Used for Overland and Channel flow analysis to calculate the time of concentration in watersheds
Overland Flow Sediment Transport sub routine	This equation make use of the 2D total sediment load conservation equation
Penman-Monteith (ET) equation (Monteith 1965)	Simulates evapotranspiration
Richards equation	Used for calculation flow in Unsaturated zone.
Lane´s Method	Used for calculation of transmission losses through leaching channel beds
Soil Conservation Service (SCS) Curve Number(CN) Method.	This is an index used in the determinations of correlation between rainfall and runoff
The Modified Universal Soil loss equation (MUSLE)	This helps in erosion study taking into account several factors like the erodibility, land cover, soil slope etc.
The Green & Ampt. equation	This method helps in calculating infiltration
Darcy´s Law and the Mass Conservation of 2D laminar flow	They are used for groundwater saturated flow.

***(Modified from Lewarne, 2009)**

2.4 DESCRIPTION OF SWAT MODEL

SWAT stands for Soil and Water Assessment Tool, developed by the United States Department of Agriculture - Agricultural Research Service (USDA- ARS). SWAT is developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time (Neitch et. al., 2005). SWAT is a physically based model, therefore the watershed is divided into a number of sub-basins based on a given digital elevation model (DEM) map instead of using regression equations to describe the input-output relationship. Within each sub-basin, soil and landuse maps are overlaid to create a number of unique hydrological response units (HRU) (Yang et. al., 2007). SWAT simulates surface and subsurface processes, accounting for vadose processes (i.e. infiltration, evaporation, plant uptake, lateral flows, and percolation into aquifer). Runoff volume is calculated using the Curve Number Method (SCS, 1972). Sediment yield from each sub-basin is generated using the MUSLE equation (Williams, 1995). The model updates the C factor of the MUSLE on a daily basis using information from the crop growth module. The routing phase controls the movement of water using the variable storage method or the Muskingum method (Cunge, 1969; Chow et. al., 1988; Yang et. al., 2007). Figure 2 shows the workflow of the modules of SWAT.

The importance of SWAT over other hydrologic models already mentioned in this report include the fact that input and output text files can be stored in a geodatabase (Olivera et. al., 2006). Other advantage include its being an open source hydrologic model.

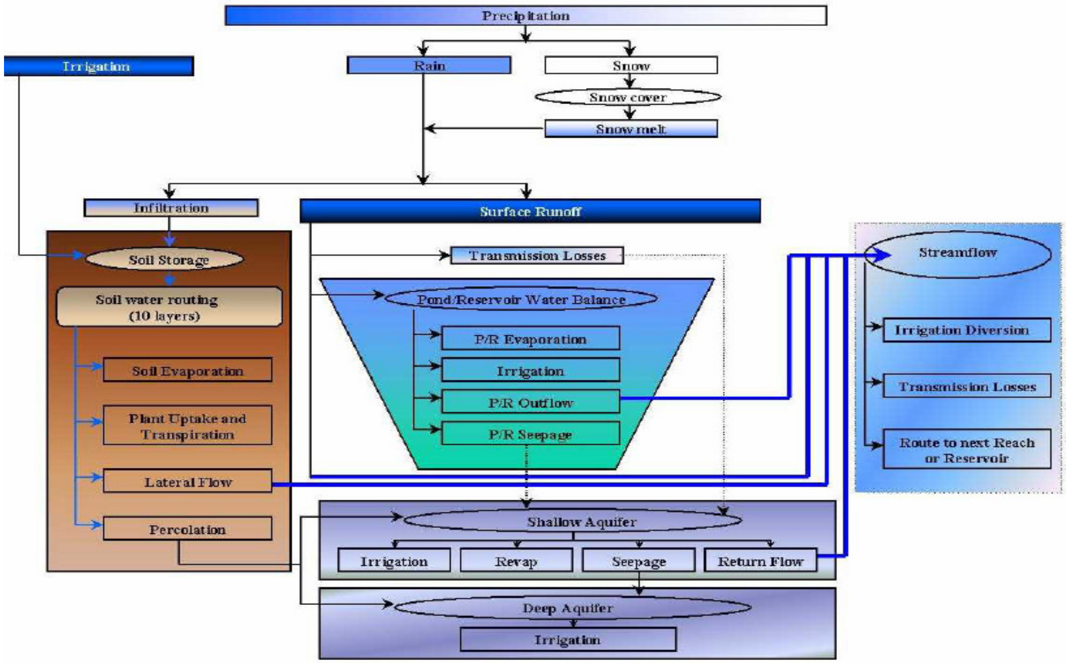


Figure 2: The Workflow of SWAT Modules. (Source: Uhlenbrook, 2008)

2.4.1 An Overview of SWAT Historical Development.

SWAT has undergone some significant improvement since its creation in 1990s.

Neitsch et. al. (2008) outlined some of these improvements as:

- SWAT94.2: Multiple hydrologic response units (HRUs) were incorporated.
- SWAT96.2: Auto-fertilization and auto-irrigation added as management options; canopy storage of water incorporated; etc
- SWAT98.1: Snow melt routines improved; in-stream water quality improved; nutrient cycling routines expanded; etc
- SWAT99.2: Nutrient cycling routines improved, rice/wetland routines improved, reservoir/pond/wetland nutrient removal by settling added; bank storage of water in reach added; etc
- SWAT2000: Bacteria transport routines added; Green & Ampt infiltration added; weather generator improved; etc.

- SWAT2005: Bacteria transport routines improved; weather forecast scenarios added; sub-daily precipitation generator added; etc

2.4.2 GIS-SWAT Interface Development

It was an historical achievement when GIS was coupled with SWAT for easy manipulation of input data like the landuse, DEM, soil map, masking etc. GRASS-SWAT was developed by Srinivasan and Arnold (1994). Later the ArcView version of SWAT was developed to help generate and inputs from ArcView 3.x GIS (Di Luzio et. al., 2004a, 2004b). There is now a recent version which has the functionality of being able to include including soil data input from both the USDA-NRCC State Soil Geographic (STATSGO) and Soil Survey Geographic (SSURGO) database (USDA-NRCS, 2007a, 2007b). There is an alternative version called the "Automated Geospatial Watershed Assessment (AGWA)" which uses the SWAT2000 modeling framework and could also use the KINEROSS2 model (Miller et. al., 2007).

ArcGIS versions 9.1 & 9.2 (ArcSWAT) have been developed that use geodatabase approach and a programming structure consistent with Component Object Model (COM) protocol (Olivera et. al., 2006; SWAT, 2007).

The Waterbase project of the United Nations University which has a broader aim of advancing the practice of Integrated Water Resources Management (IWRM) in developing countries came out with the MapWindow interface version of SWAT. MapWindow is an open source GIS software which has several advantages. This tool was coupled with SWAT to produce "MWSWAT". The design is based around three basic steps which include: watershed delineation, HRU definition and SWAT step up and run (George et. al., 2007).

A variety of other tools have been developed to support executions of SWAT simulations, including:

- the interactive SWAT (i_SWAT) software which supports SWAT simulations using a Windows interface with an Access database;
- the Conservation Reserve Program (CRP) Decision Support System (CRPDSS) developed by Rao et. al. (2006);
- the AUTORUN system used by Kannan et. al. (2007), which facilitates repeated SWAT simulations with variations in selected parameters;
- a generic interface (iSWAT) program (Abbaspour et. al., 2007), which automates parameter selection and aggregation for iterative SWAT calibration simulations.
- The SWATPLOT tool which is a standalone software developed also by the Waterbase group in 2009.

2.4.3 SWAT Applications

SWAT have been applied widely mostly in United States and European Union where there is being assessment of climate change or other impacts on the natural resources.(Gassman et al; 2007). In the US, one of the major applications of SWAT was within the Hydrologic Unit Model (HUMUS) which was carried out to support the USDA analyzes of the Resources Conservation Act Assessment of 1997(Gassman et. al., 2007; Arnold et. al., 1999). This system was applied to simulate the hydrology and pollutant loss within each of the 2,149 United States Geological Survey (USGS) 8 digit Hydrologic Cataloging Unit (HCU) watersheds (Gassman et. al., 2007; Arnold et al 1999; Seaber et al 1987). Other applications in the US are reported by Mausbach and Dedrick (2004), Borah et. al. (2006), Shirmohammadi et. al. (2006), Benham et. al. (2006), etc. Gassman et. al. (2007) also did detailed survey of other applications worldwide.

In European Union likewise, SWAT have been applied widely. Volk et. al. (2007) and van Griensven et. al. (2006) describe SWAT application approaches within in the context of the European Union (EU) Water Framework Directive. There are some European Commission (EC) projects also the like Climate Hydrochemistry and Economics of

Surface water Systems (CHESS) project where SWAT have been used to quantify the impact of climate change on several watershed (CHESS, 2001); EUROHARP project (EUROHARP, 2006) and TempQsim project which focused on testing the ability of SWAT and five other models to simulate intermittent stream conditions that exist in southern Europe (TempQsim, 2006).

2.5 UNCERTAINTY ANALYSIS

In recent times, decisions about natural resource management are being made based on complex models of hydrological systems (Benke, 2006). Decision-makers need to know the confidence level of the models' results. It is very important for decision-makers or managers to know the estimated impacts of one land-use scenario as compared to others and uncertainties involved. Traditional risk assessment is a sub-set of uncertainty modeling (Benke, 2006). For example, whereas risk may be characterized by a single point estimate of probability of an adverse event, uncertainty analysis provides an error band and confidence on the estimate. Uncertainty modeling also provides information and insight on the sources of uncertainty in results from a predictive model, such as errors in inputs, outputs and parameters. On the broader term, uncertainty analysis also includes sensitivity analysis, parameter optimization, lack of knowledge and context, and characterization of subjective data and linguistic imprecision (Benke, 2006). Analysis of uncertainty is often neglected in the evaluation of complex systems, such as computational models used in hydrology, spatial systems or ecology (Benke, 2006). Prediction uncertainty arises from a variety of sources, such as input measurements, calibration accuracy, parameter estimation and lack of domain knowledge. Currently, various different approaches have been applied for analyzing the impact of uncertainty in parameters and inputs on predictions of streamflow and other important variables (Srikanthan and McMahon, 2001). Very common methods are the Taylor's Series Error Propagation method or the Markov Chain Monte Carlo (MCMC) series (Benke. 2006; Huevelink, 2009)

2.5.1 Data Uncertainty Engine (DUE)

This is open source software developed by Brown and Huevelink (2007) for:

- assessing uncertainties in environmental data; and
- generating realizations of uncertain data for use in uncertainty propagation analyses:

Data may be loaded into DUE either from the file or accessible database. Some of the objects supported by DUE include spatial vectors, spatial rasters, time-series of spatial data, simple time-series and objects that are constant in space and time. Attributes supported by DUE include numeric continuous data(e.g. rainfall),discrete numeric variables (e.g. bird counts) and categorical variables (e.g. land-cover) (Brown and Huevelink, 2007).

2.5.2 Uncertainty in Climatological Data

In this section, the sources and type of empirical uncertainty associated within the numerical continuous variable (i.e. Rainfall) is discussed. The observed variable is "Precipitation depth", which is defined as the depth of liquid water accumulated during a defined time interval on a horizontal surface (Barca et. al., 2005). Precipitation data are probably used more extensively than any of the other meteorological variables in relation to water resources. Scientists, engineers, and resource managers use them in applications that range from crop production forecast, to climate change detection and impact analyses.

Barca et. al. (2005) documented empirical uncertainty in rainfall as:

- *"Accuracy and precision required: Raw data should be available and corrected for systematic errors. For both macro- and meso-scale: 0.1 mm should be the definition of precipitation as opposed to no precipitation.*
- *Instrument precision: 0.2 mm or less;*
- *Instrument accuracy: ±1 mm for <=20 mm; ±5% for >20 mm;*

- *Measurement depth or height: 1.0 m ± 0.2 m (AASC, 1985); 30 cm minimum (WMO, 1983).*
- *Exposure consideration: AASC (1985) and EPA (1987) suggest the sensor be no closer than four times the obstruction's height.*
- *Associated measurements: Detailed topographic database to allow spatial aggregation/disaggregation;*
- *Metadata about data reliability: altitude, instrument type, station description, etc".*

As for the instrumental inaccuracy, the main sources of uncertainty to are (WMO, 1983; Barca et. al., 2005):

- Gauge type;
- Gauge height;
- Windshield;
- Exposure;
- Inadequate gauge network;
- Wind speed;

2.5.3 Probability Density Function (pdf) of Precipitation

Rainfall process consists of two distinct processes (Barca et. al., 2005; Srikanthan McMahon, 2001):

• A discrete process describing the wet/dry day variability;

• A continuous process describing the rainfall amounts on wet days

Srikanthan and McMahon (2001) did classify the daily rainfall generation into four different groups which are; two-part models, transition probability matrix models, resampling models and time series models of the ARMA type.

Considering the rainfall occurrence models it is divided into two main parts, those based on Markov Chains and those based on the alternating renewal process (Srikanthan and McMahon, 200)). On the Markov Chains, Jimoh and Webster (1996) determined the highest order of a Markov Chain model for daily rainfall occurrences of five locations in Nigeria using the Akaike Information Criteria (AIC) (introduced by Akaike (1974)) and the Bayesian Information Criterion (BIC)(proposed by Schwarz (1978)). They concluded that AIC consistently gave a higher order for Markov Chain than BIC. Also, in the alternating renewal process, the daily rainfall data is analyzed as a sequence of alternating wet and dry spells of varying length. This is based on the assumption that the wet and dry spells are independent and the distribution may not be the same for wet and dry spells.

Srikanthan and McMahon (2001) reported that the following distributions had been considered for daily rainfall occurrence:

- Logarithmic series (Williams. 1947),
- modified logarithmic series (Green, 1964) ,
- truncated negative binomial distribution (Buishand, 1977) and
- truncated geometric distribution (Roldan and Woolhisier, 1982)

They equally reported the following distribution for daily rainfall amount:

- two-parameter Gamma distribution (Jones et. al., 1972),
- mixed Exponential distribution (Woolhiser and Pedgram, 1979)
- a skewed Normal distribution (Bardossy and Plat, 1992)

In this same vein, Barca et. al., (2005) did categorize the following procedures and the corresponding models which have been used in daily rainfall amount modeling:

i. Models represented by the process by means of an unique distribution:

- a lognormal, exponential representation (Shoji and Kitaura, 2006);
- a gamma distribution (Manik and Sidle, 2003; Williams, 1997),
- a Weibull model (Kottegoda et. al., 2003),
- a Kappa and skewed normal representation (Chapman, 1997; Arnold et. al., 2000) and
- a beta distribution (Kottegoda et. al., 2003);

ii. Models by representation of the process using a combination of the same distributions with different parameters:

- a sum of gamma distributions each of them associated to a single day of the observed period (Dunn, 2003);
- a sum of the different exponential distributions (Kottegoda et. al., 2003);

iii. Models represented by means of a Gaussian distribution after a data transformation: an anamorphosis process (Kottegoda et. al., 2003),

- log transformation of the observations (Allerup et. al., 1982)
- a transformation of raw data by a power close to the square root for reducing the upper tail of the empirical distribution of data (Hutchinson, 1998);

iv. Models by separating the occurrence of rainy days (discrete) model and the total daily amounts of rainfall (continuous) model:

- 1st and 2nd order Markov Chains using a truncated binomial negative distribution,
- truncated geometric distribution (Chapman, 1997; Arnold et al., 2000) and
- simple binomial model (Williams, 1997) for a discrete occurrence.

Concluding this chapter, the concepts and equations which are the “backbone” for hydrologic modeling and uncertainty analysis have been discussed. Various research outputs have been quoted and used to support some of the modeling that will used in this study.

3.0 CHAPTER THREE: METHODOLOGY

This chapter deals extensively with the hydrological description of the study area. The work flow (of the methodology), step by step outline of SWAT modeling and uncertainty analysis technique using DUE would also be discussed.

3.1 STUDY AREA

The case study for this project is taken from the central part of Nigeria. Nigeria covers an area of 924,000 sq km. From the Atlantic Ocean in the south extending to the fringes of the Sahara desert, the climate is characterized by relatively high temperatures throughout the year. It is arid in the north, becoming increasingly humid moving towards the south. Except for the coastal zone, where it rains all year round, rainfall is seasonal with distinct wet and dry seasons. The country has extensive groundwater resources located in seven recognized sedimentary hydro-geological areas together with local groundwater in shallow alluvial (Fadama) aquifers, adjacent to major rivers (Federal Ministry of Water Resources, 2006).

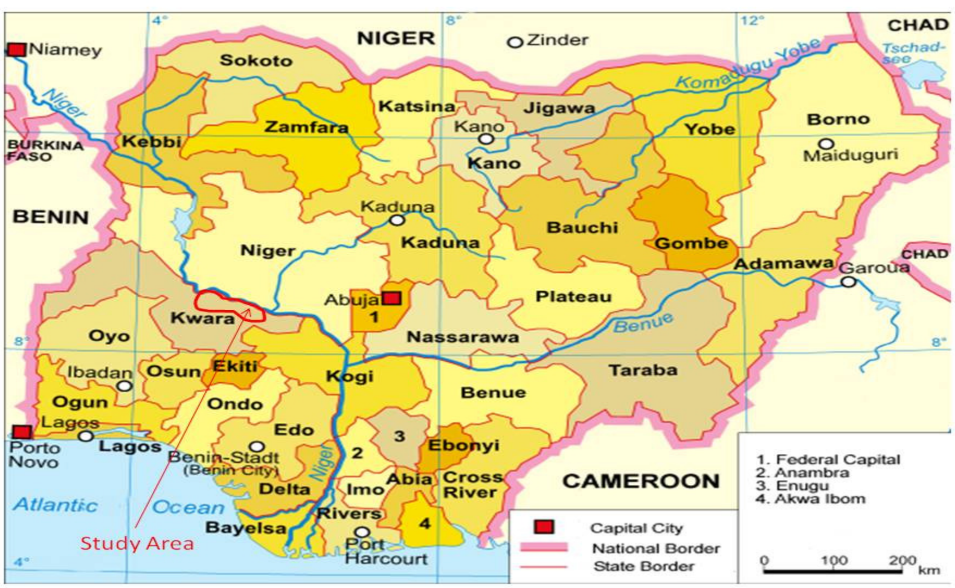


Figure 3: Map of Nigeria (with the 36 States) Showing the Study Area(Source: Kwara State Government, 2009)

3.1.1 The Project Location in Nigeria.

This case study site is located in Edu Local Government Area of Kwara State at about 110 km North East of Ilorin, the Kwara State Capital. The project sites can be reached either through Bacita or Shonga. The study site is about 250,000 ha lies to the right bank of River Niger within the flood plain downstream of Jebba. The availability of water resources have been the major attraction when this site was chosen for the newly arrived Zimbabwean farmers to Nigeria in 2004. Figure 4 Shows the Google map of the area at lies beside Niger River.

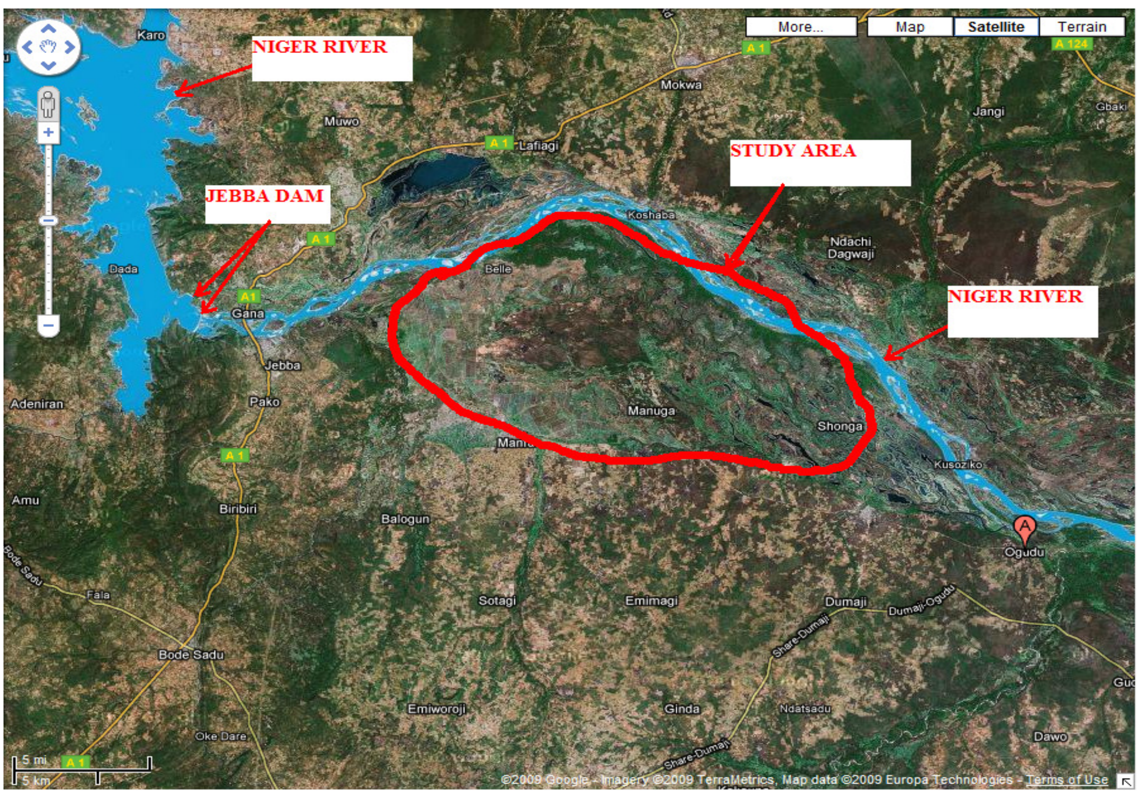


Figure 4: Google Map of the Study Area.

3.1.2 Climate and Hydrology of the Study Area.

The climate in the project area is tropical continental with pronounced wet and dry seasons and steady high temperatures. The nearest meteorological stations are Ibadan, Ilorin, Jebba, Bacita and Bida. Maximum rainfall is during the month of September and drops to zero in December. The rainy season with a duration of about 218 days, starts in April and ends in October .The main hydrological feature of the area is the Niger River which flows north-south and then west-east bisecting the area from the Nupe sandstone uplands(Federal Ministry of Water Resources, 2006).

3.1.3 Land Capability and Soils

The case study area comprises of three landform units viz: floodplain, river alluvial plain and piedmont alluvial plain. The floodplain occurs on both sides of the Niger River but major parts lie on the left bank of the river. The plain on both sides of the river is almost flat and has very gentle slope of 0.5 percent (Federal Ministry of Water Resources, 2006). The soils of the area are generally fairly moderate in inherent fertility status. The natural vegetation predominant in the area is the savannah, with heavy growth along the river streams (riverside forests). In the floodplains, mostly rice is grown, followed by sugar cane, while cassava, corn, yams and guinea corn prevail in the sandy uplands.

3.1.4 Agricultural Estate Initiative of the Kwara State Government.

This case study area covers the agricultural estate pilot project of the Zimbabwean farmers and the Kwara State Government of Nigeria. The white farmers were allocated about 1000 ha of each as the first phase of the agricultural estate. Figures 5 through 7 show the project area and the changing land use pattern of the area.

Figure 5: The “Nigerian Farmers” During Farm Operation (Source: Kwara State Government,2009)

Figure 6: The Planting Operation on the Farm (Source: Kwara State Government, 2009)

Figure 7: Already tilled land for Farm Operation (Source: Kwara State Government, 2009)

3.2 MWSWAT INSTALLATION REQUIREMENT

It is very important that the following requirements are met before the setting up of MWSWAT (George et. al., 2007; Leon, 2009)

- Microsoft Windows (any version)
- Microsoft Access, as the interface uses an Access database
- A tool like WordPad or Notepad that enables reading ASCII text files.
- A tool like WinZip that can uncompressed .zip files

The steps needed in installing MWSWAT involve:

i. Install MapWindow by running MapWindow47SR.exe

ii. Install MWSWAT by running MWSWAT.exe. It will create a folder *C:\Program Files\MapWindow\Plugins\MWSWAT* containing

- createHRU.dll and MWSWAT.dll - these constitute the MWSWAT plug-in
- mwswat.mdb - a database that will be copied for new projects
- crop.dat, fert.dat, pest.dat, till.dat, urban.dat - SWAT data files, in a subfolder *Databases*
- swat2005.exe - the SWAT executable, plus a script runswat.bat
- WAT2005.mdb - SWAT reference data, in the subfolder *Databases*
- A collection of weather generator (.wgn) files in the subfolder *Databases\USWeather*

3.3 DATA COLLECTION AND GEO – PREPROCESSING

For the GIS interface, MapWindow (http://www.mapwindow.com/) was selected as the main platform for development. This is basically because of being open an source software which does not require an expensive licensing. MapWindow is downloadable native Windows tool, and has been developing rapidly since it became open source (George et. al., 2007; Leon, 2009). The MapWindow architecture is designed for easy extensions as “plug-ins”. The main data sources for watershed modeling include the DEM, landuse and soil type map. The GIS capabilities within MapWindow allow pre-processing (such as clipping, projecting and editing) the digital information to feed into the SWAT model. Figure 8 shows the global grid in which DEM tiles are provided from the SRTM 90m digital elevation data.

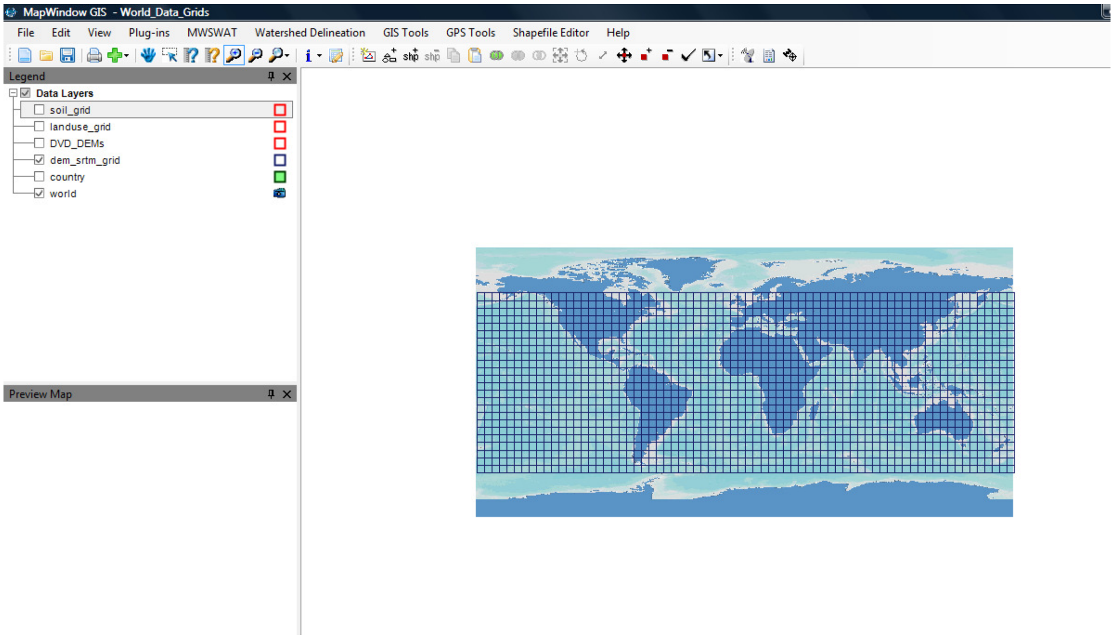


Figure 8: Global grid for SRTM DEM tiles in MapWindow

3.3.1 Digital Elevation Model (DEM)

SRTM Processed 90m Digital Elevation Data Version 3 can be downloaded from the International Centre for Tropical Agriculture (CIAT) website (http://srtm.csi.cgiar.org/).

This DEM has the following format:

ArcView Ascii Grid Files in 5° x 5° tiles (Lat/Long, decimal degrees)

Metadata included in header:

ncols 6000

nrows 6000

xllcorner -120

yllcorner 25

cellsize 0.000833333333333

NODATA_value -9999

The data are in ARC GRID format, in decimal degrees and datum WGS84. They are derived from the USGS/NASA SRTM data. CIAT have processed this data to provide seamless continuous topography surfaces (Leon, 2009)

3.3.2 Land Use Data

The landuse data was provided by Dr Karim Abbaspour of Eawag, Switzerland. (http://www.eawag.ch/index_EN): Landuse data was constructed from the USGS Global Land Cover Characterization (GLCC) database (http://edcsns17.cr.usgs.gov/glcc/glcc.html). This map has a spatial resolution of 1 Kilometer and 24 classes of landuse representation. The parameterizations of the landuse classes (e.g. leaf area index, maximum stomata conductance, and maximum root depth, optimal and minimum temperature for plant growth) is based on the available SWAT landuse classes and literature research. The following file can be exported as GeoTiff raster:

Africa – af_landuse.zip, af_landuse_newres.zip (af_land_1, af_land_2)

3.3.3 Soil Source Data

The soil data was also provided by Dr Karim Abbaspour of Eawag (http://www.eawag.ch/index_EN): Soil map was produced by the Food and Agriculture Organization of the United Nations. Almost 5000 soil types at a spatial resolution of 10 kilometers are differentiated and some soil properties for two layers (0-30 cm and 30-100 cm depth) are provided.

The following file can be exported as GeoTiff raster :

Africa – af_soil.zip (af_soil_1, af_soil_2)

3.3.4 Projected Coordinated System

It is very important to transform the processed images from the Geographic Coordinate Systems (WGS 1984) to a Transverse Mercator Projection (UTM). All the GIS inputs must be in the same UTM projections. The project area falls between Zones 32 and 33. The GIS data would be masked by a “Focus Mask” which covers the project area. Thus, the area would be clipped from the two zones, added together and then transform to the appropriate projected coordinate system.

3.4 STEP 1: DEM (WATERSHED DELINEATION)

First and foremost, the workflow used for this study is given in Figure 9a. The various steps and actions would be discussed also. To start the Automatic Watershed Delineation (AUD), the DEM would be loaded first. The next step is to activate the AUD plug-in the MapWindow. This may take a few minutes. The name of the elevation map grid is displayed in the *DEM* text box on the Automatic Watershed Delineation (AWD) dialog box (Figure 9b). It is very important for the ‘Elevation Units’ to be Meters and that the ‘Burn-in Existing Stream Polyline’ option is not checked. The ‘Focusing Mask’ may be manually selected or from the file if there is a shapefile that already demarcate the area of interest . The first part of the watershed delineation tool may then be run. This can take a few minutes. The threshold size for subbasins is set next. It can be set by area, in various units such as sq km or hectares, or by number (#) of cells. Now the second Run button to delineate the stream network can be clicked. In order to complete the whole process, there is need to define the outlet of the watershed. Also, a prepared shapefile could be used or manually done. The MWSWAT interface will mark the AUD done and enable the second step if everything is okay (Figure 10).

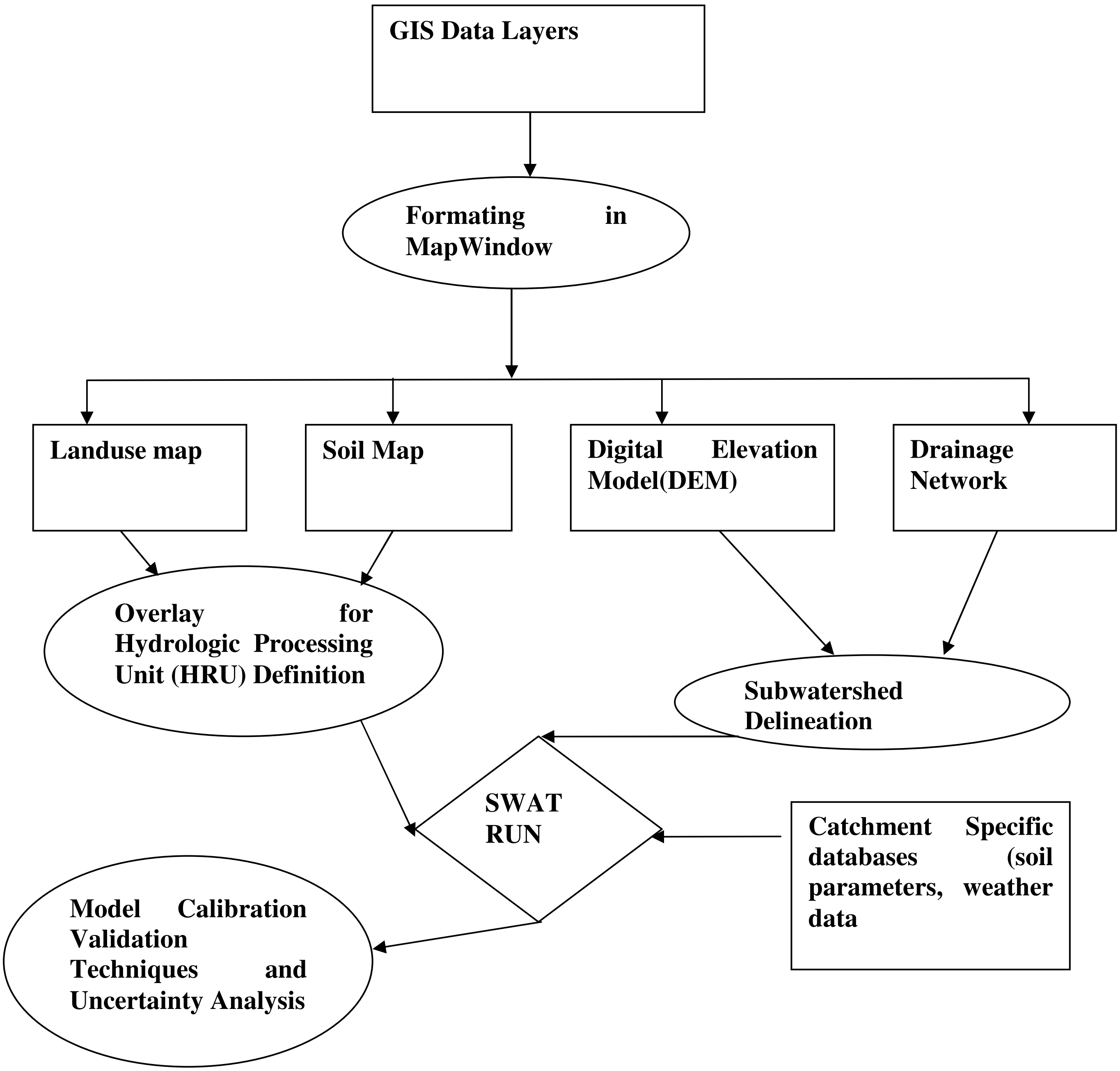


Figure 9a: The Work Flow of the Modeling Process.

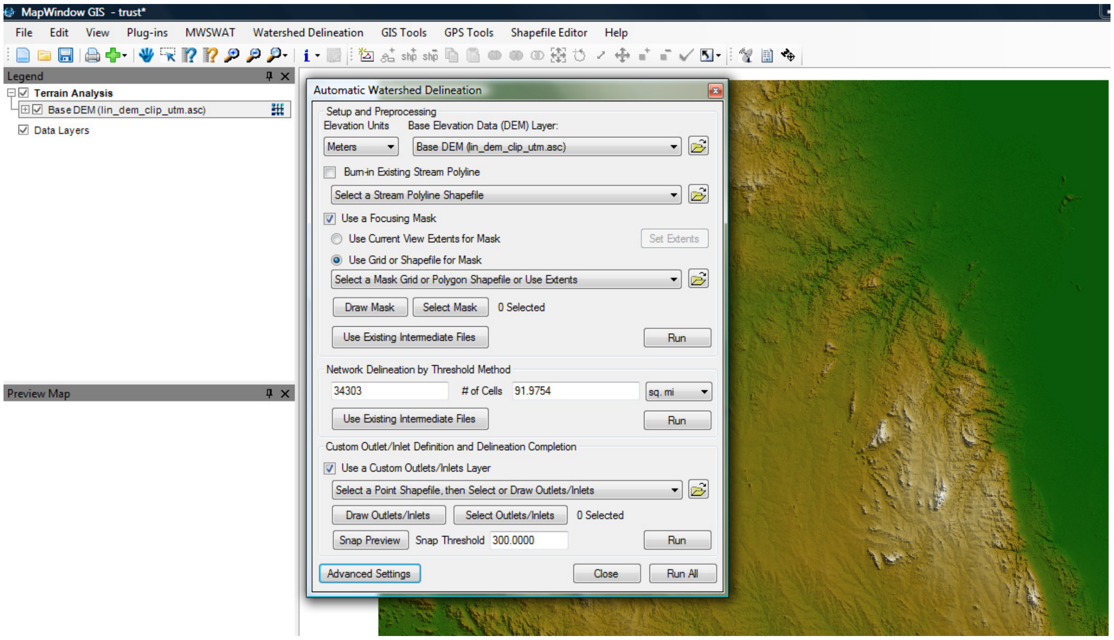


Figure 9b: The Automatic Watershed Delineation Procedure

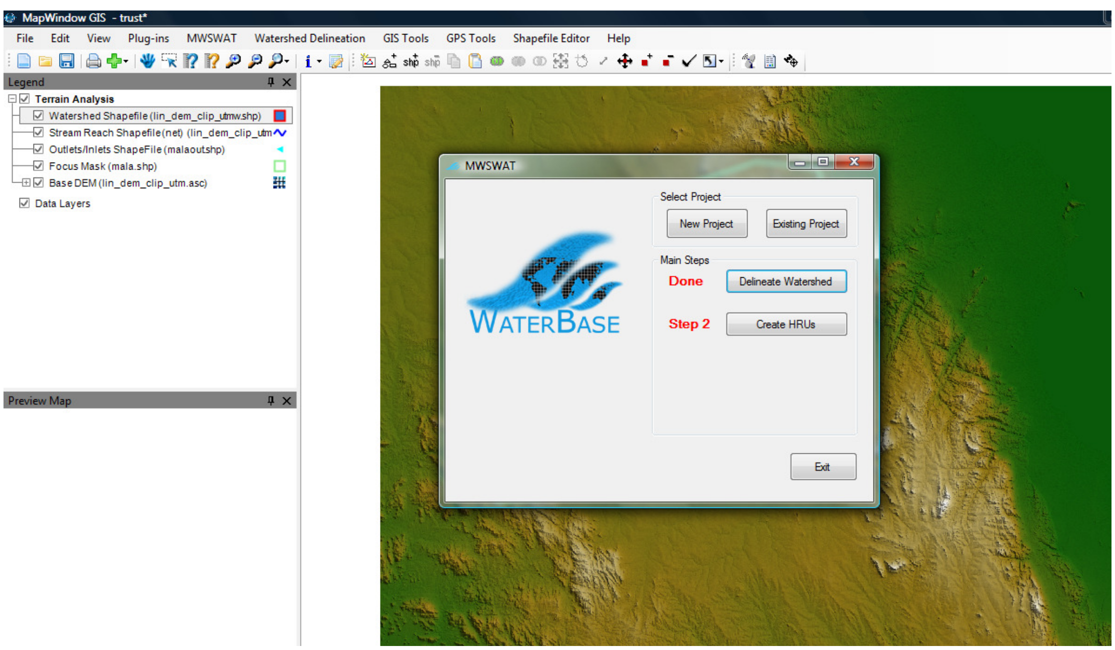


Figure 10: The Automatic Watershed Delineation Procedure Completed, and Step 2 enabled.

3.5 STEP 2: CREATING THE HYDROLOGICAL RESPONSE UNITS (HRUs)

This step calculates the details of the Hydrological Response Units (HRUs) that are used by SWAT. This is basically dividing the basins into smaller pieces each of which has a particular soil/landuse (crop)/slope range combination. The landuse and soil maps would be added to the enabled template as shown in Figure 11. The relevant tables for the landuse classes (from the global landuse classes) and for the soil (from global soils) are read respectively. This may take a few seconds as relevant database are read. The last two will take a few seconds as the relevant database tables are read. The slope bands would needs to be created. This is to create an intermediate point for slopes to divide HRUs into those with average slope for 0-10% and those with average slopes in the range 10% to the top limit. The 'Read' button can be clicked. After these operations, it would be discovered that the sub-basins have been numbered. A shapefile called 'FullHRUs' should also have been created. This shapefile allows seeing in each subbasin where potential HRUs are physically located. There are options of either splitting or exempting landuse classes depending on the aim of analysis (Figure 12). This Step 2 is now reported as done and now available various reports concerning the subbasin, topographic and HRUs properties.

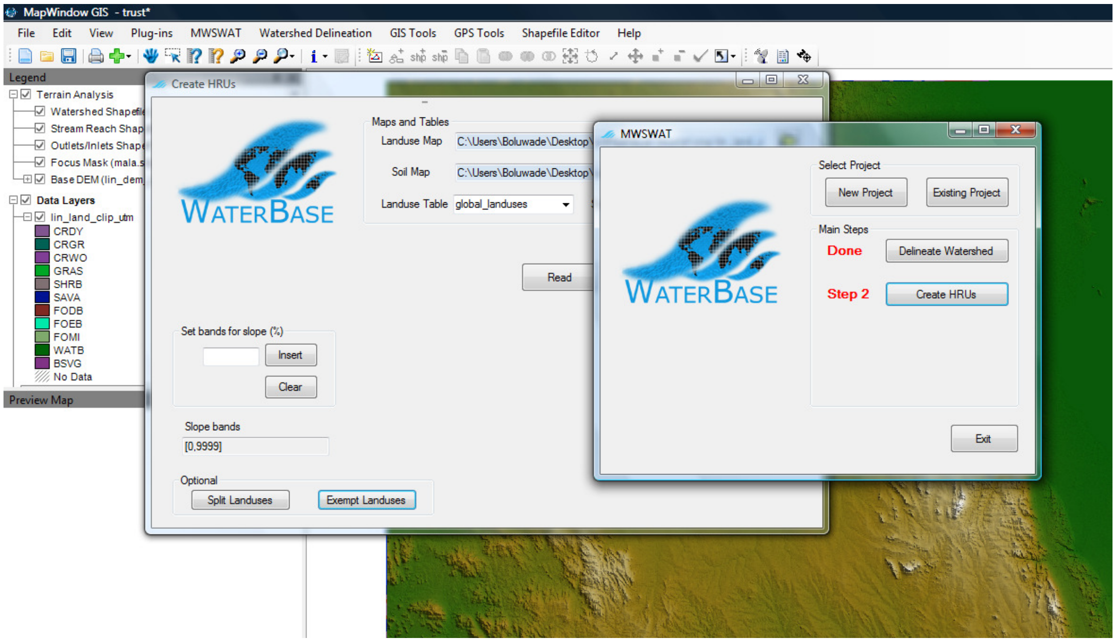


Figure 11: The Hydrological Response Unit (HRUs) Procedure.

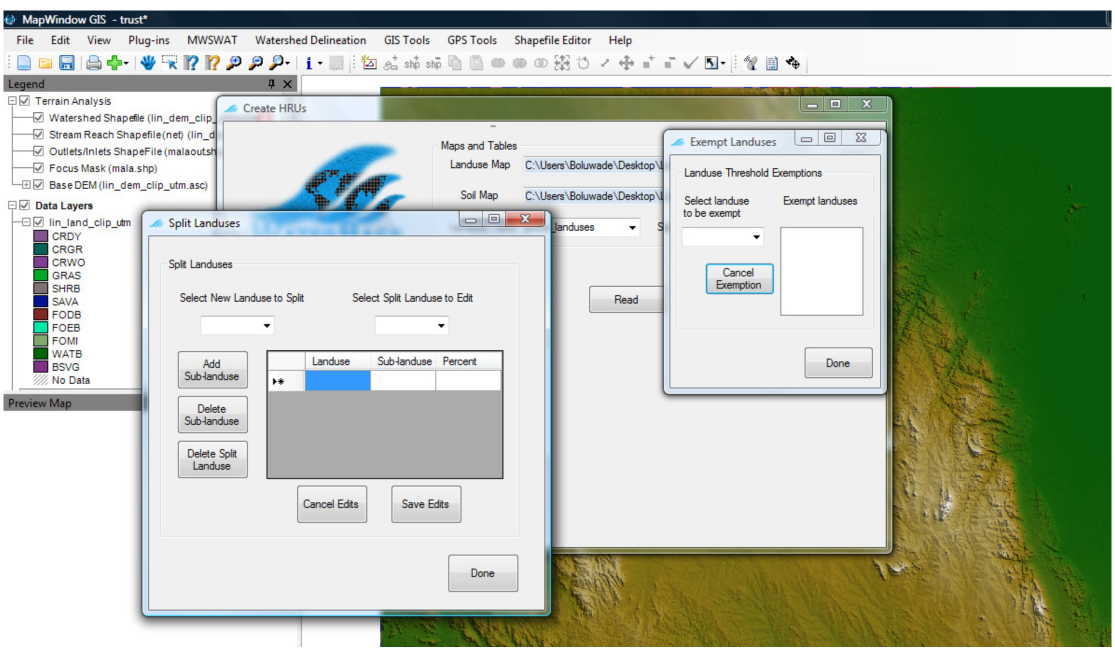


Figure 12: Splitting or Exempting Landuse Class Options

3.6 STEP 3: SWAT SETUP AND RUN

It is now ready to write the SWAT input files and run SWAT (Figure 13). Next, there is need to choose the source of weather data. A common mode is to use actual weather data for maximum and minimum temperature and precipitation, and a weather generator file that will simulate other weather factors (solar radiation, wind speed, and relative humidity). It is highly important to provide a weather generator file for your basin, and data for precipitation and temperature. The weather generator file is prepared from the local climatic condition of the area. The SWAT manual gives the procedure to follow in providing the weather generator file. Normally for the first run, the global weather data (downloaded from the Waterbase website: www.waterbase.org) is recommended (Leon, 2009). Then MWSWAT looks for the nearest 6 weather stations in that file, generates the temperature and precipitation data for them, and then associates each subbasin with the nearest weather station from amongst those six (Figures 13 and 14). Then the files could be 'written' which may takes some times if several years are being simulated. After this, then SWAT can be run which will launch the SWAT executable in a DOS prompt window (Figure 15). If the run is successful the DOS window will close and a message box will say that SWAT was run successfully otherwise an error report will be generated detailing what went wrong.

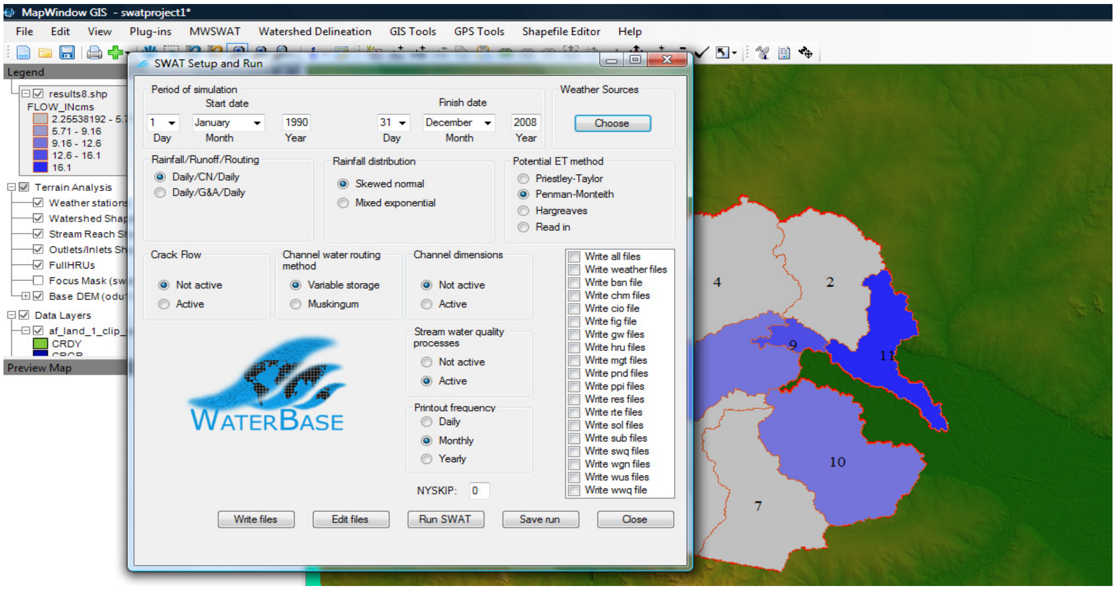


Figure 13: SWAT Setup and Run Procedure.

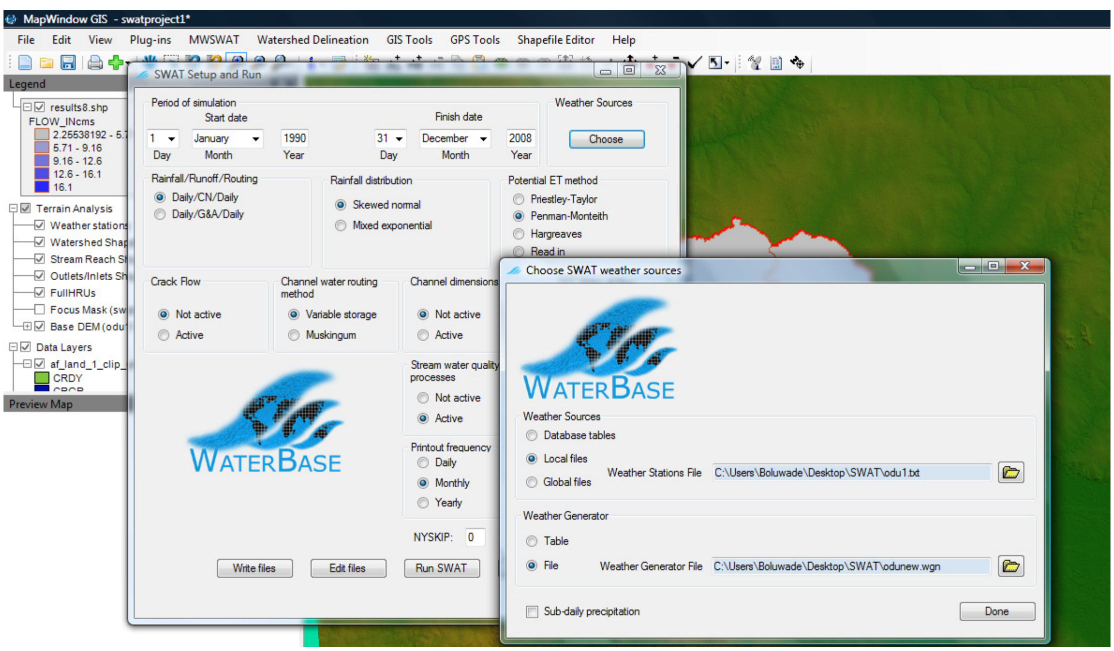


Figure 14: Choosing the Weather Sources Process.

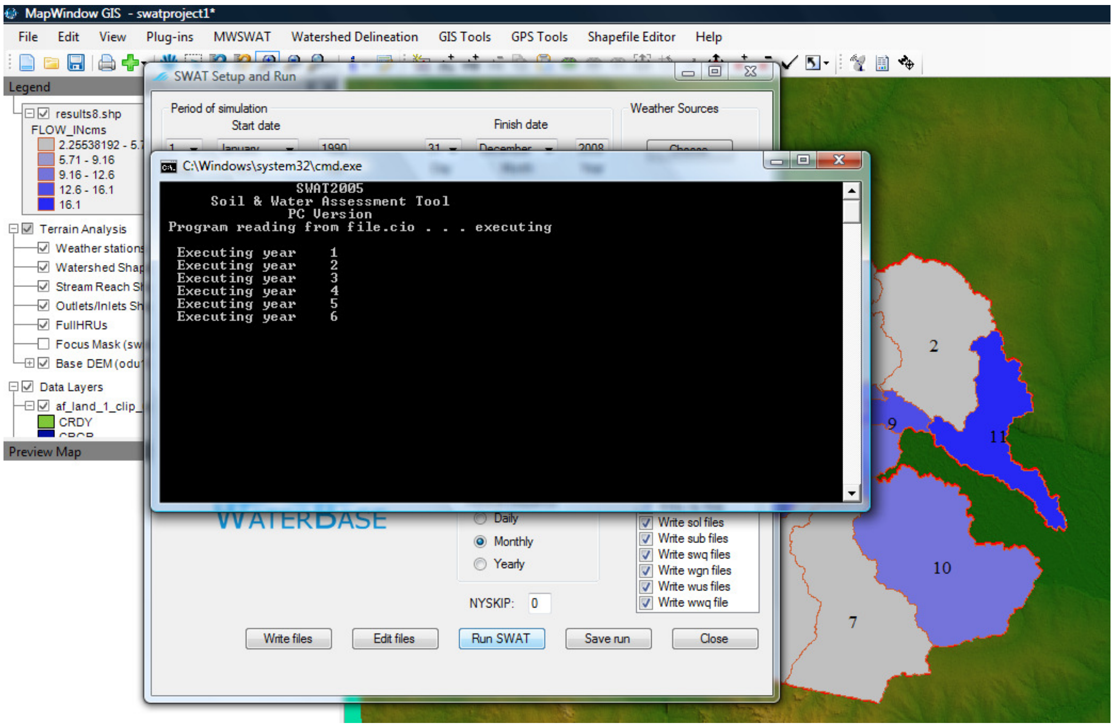


Figure 15: Running SWAT.

3.7 STEP 4: VISUALIZATION OF THE RESULTS

The SWAT outputs by can be visualized in two different forms. Firstly, there is a stand-alone SWATPLOT application which can give the SWAT plots of the results in 'csv' file format. Secondly, shapefile could also be created on the MapWindow interface. The idea is to make a results shapefile showing the subbasins of the watershed, and then to display one of the SWAT outputs by coloring the subbasins according to the value of the output. This involves making the output values an attribute of the shapefile. The outputs can be visualized either statically or dynamically.

3.8 DATA UNCERTAINTY ENGINE (DUE)

This software is developed by Brown and Huevelink (2005). This is downloadable from the Harmoni rib website. That the following requirement must be met to run DUE:

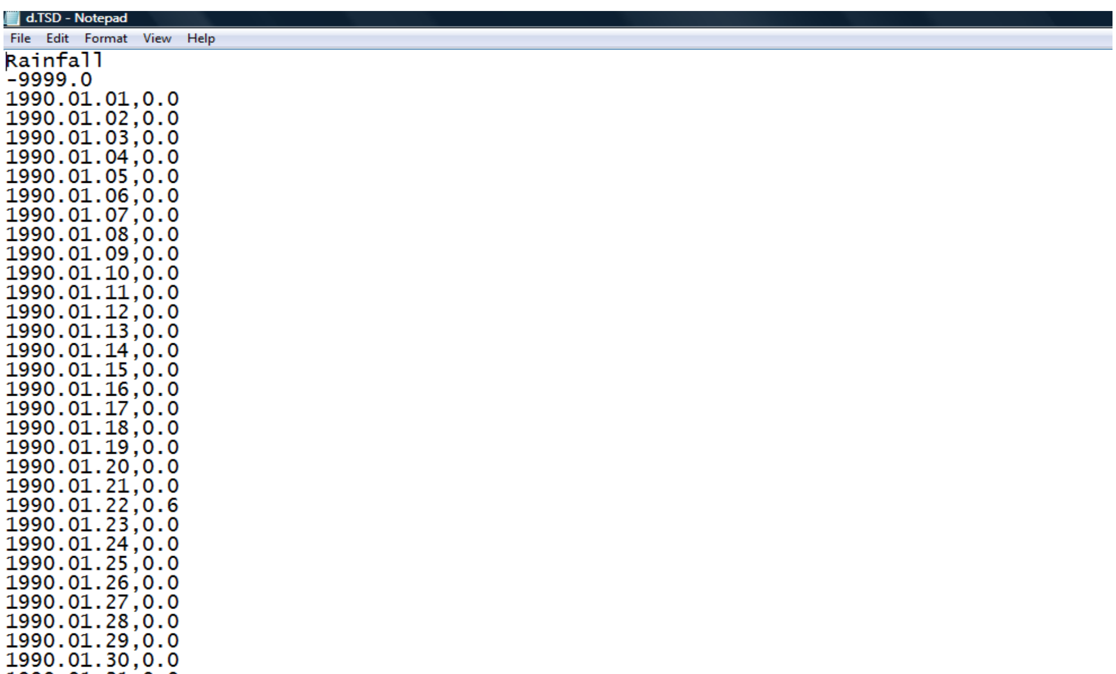
- The JavaTM Runtime Environment (JRE) Version 1.6.0 or higher. The use of JRE Version 1.6.0 or higher is essential for the correction operation of the DUE Graphical User Interface. The JRE is free software and may be downloaded from the Sun website: http://java.sun.com/j2se/index.jsp
- The DUE executable, DUE.jar, and associated resources in DUE_3.1.zip;
- Microsoft Windows 98/2000/NT/XP Operating System (OS). The software has not been tested on other OS but will be available for Linux, UNIX, Macintosh or other platforms shortly. On a Windows platform, you will need:
- A minimum of 32MB of RAM and ~50MB of hard-disk space free.
- For many practical applications of DUE, including simulation from large datasets (more than ~100,000 values), more RAM may be required. A minimum of 512MB is recommended.

This tool could be used to determine the uncertainties in the variables position or attributes. Brown and Huevelink (2005) reported that; "*the specification of a probability model for different types of attribute, including continuous numerical attributes (e.g. rainfall), discrete numerical attributes (e.g. bird counts) and categorical attributes (e.g. land-cover). The attributes may be constant in space and time or may vary in space or time. Combined space-time functionality is currently limited to spatial raster data (in 2D). Furthermore, an assumption of temporal independence is required when assessing uncertainty for spatial time-series (i.e. the uncertainties at different times are unrelated)*".

A continuous numerical data i.e. precipitation will be analyzed. Defining a probability model for rainfall could be a bit 'tricky' because of the need to separate the rainfall occurrence and total rainfall amount. Daily Rainfall amount would be analyzed.

The steps to be followed are:

- There is need to prepare the data with a '.TSD' file extensions as shown in Figure 16.
- The file is loaded into DUE as shown in Figure 17 with various properties of the variable defined
- The use of expert judgment OR sample data to help define a probability model after plotting the histogram of the data as shown in Figure 18
- Validate the probability model as shown in Figure 19.
- Generalize the realizations for the uncertain data as shown in Figure 20.



d.TSD - Notepad

File Edit Format View Help

```
Rainfall
-9999.0
1990.01.01,0.0
1990.01.02,0.0
1990.01.03,0.0
1990.01.04,0.0
1990.01.05,0.0
1990.01.06,0.0
1990.01.07,0.0
1990.01.08,0.0
1990.01.09,0.0
1990.01.10,0.0
1990.01.11,0.0
1990.01.12,0.0
1990.01.13,0.0
1990.01.14,0.0
1990.01.15,0.0
1990.01.16,0.0
1990.01.17,0.0
1990.01.18,0.0
1990.01.19,0.0
1990.01.20,0.0
1990.01.21,0.0
1990.01.22,0.6
1990.01.23,0.0
1990.01.24,0.0
1990.01.25,0.0
1990.01.26,0.0
1990.01.27,0.0
1990.01.28,0.0
1990.01.29,0.0
1990.01.30,0.0
```

Figure 16: The Data Format in Data Uncertainty Engine (DUE)

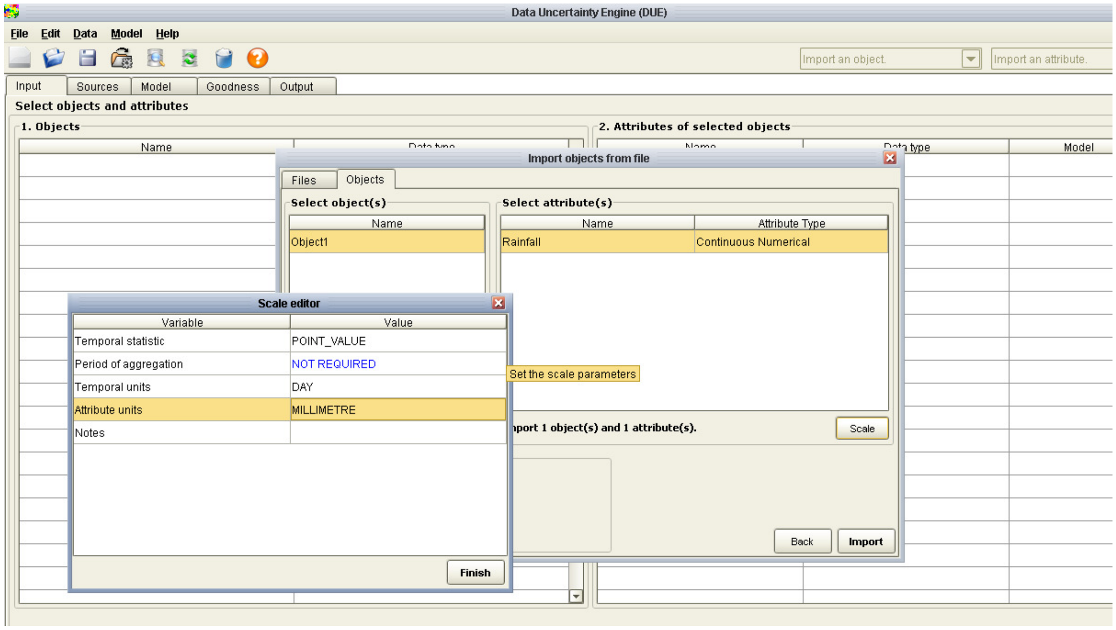


Figure 17: Loading data into DUE with the Properties Defined.

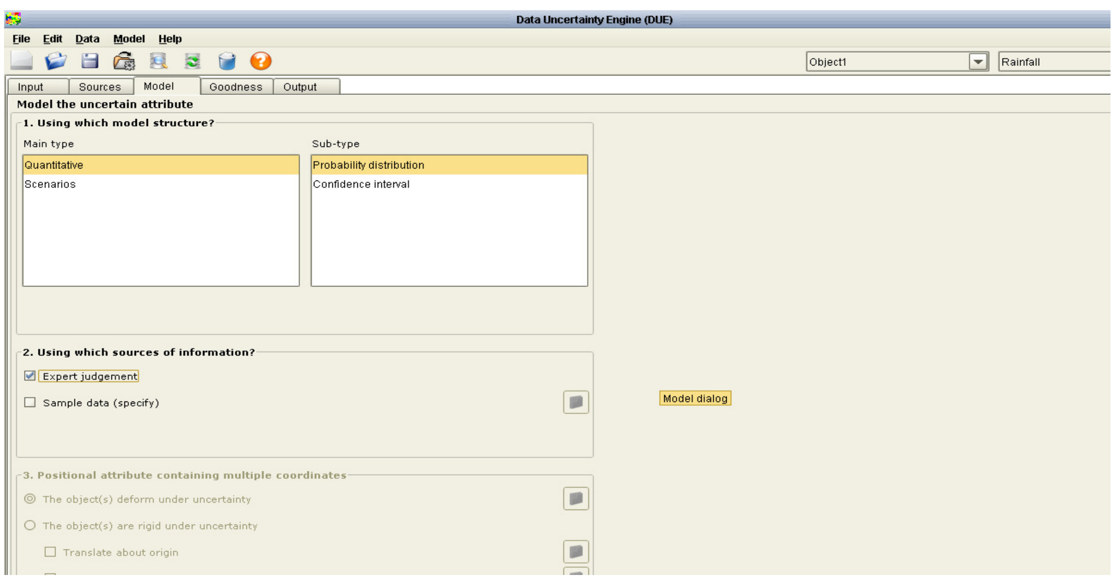


Figure 18: Using the Expert Judgment to Define the Probability Model.

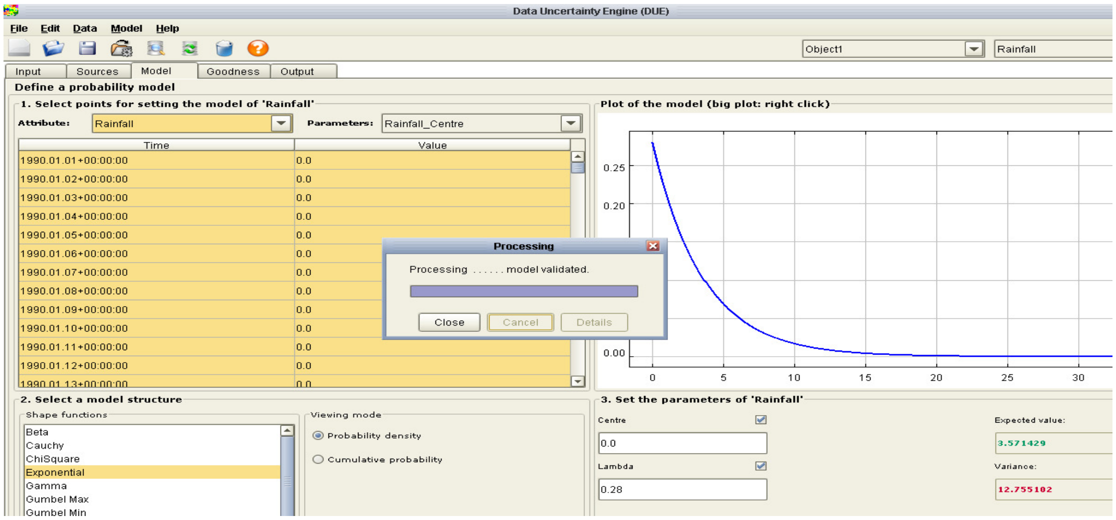


Figure 19: Validating the Probability Model in DUE

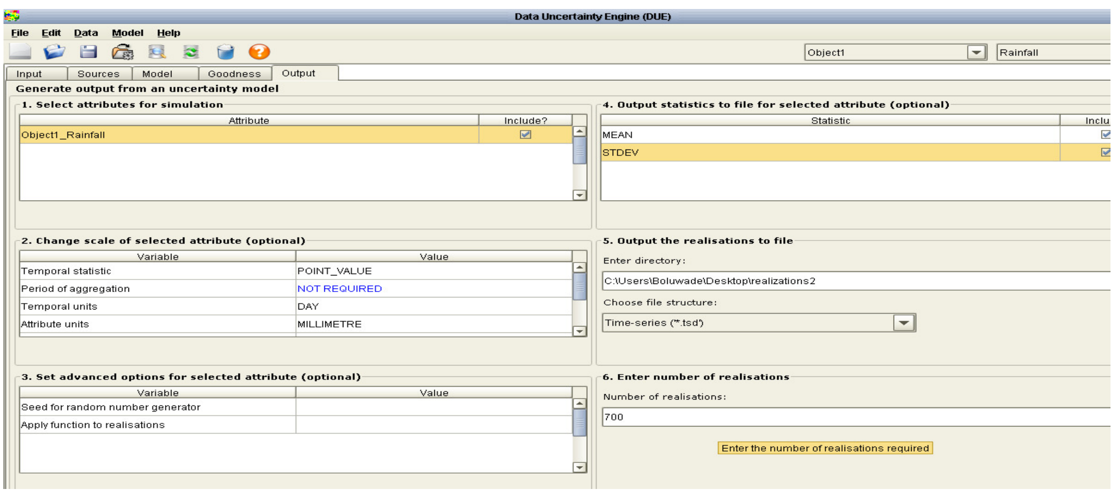


Figure 20: Generalizing the Realizations for the Uncertain Data.

In conclusion, this chapter have been able to give the step by step procedures followed in executing this project. In fact, there is enough information for any interested reader who may like to do similar work in future in the area of hydrological modeling using MWSWAT and uncertainty analysis using DUE.

4.0 CHAPTER FOUR: RESULTS AND DISCUSSION

This chapter will present and discuss results from the hydrological modeling and the uncertainty analysis. These results involves various derived maps and tables which give very important information for the watershed.

4.1 GIS INPUTS AND WATERSHED DELINEATION

All the various steps explained in Chapter 3 of this project were carefully followed and executed. Figure 21 below shows the delineated watershed with the subbasins already numbered using the DEM as the background. A total of 11 subbasins were derived after the AUD procedure. All the GIS inputs have been projected to the WGS 1984 UTM-Zone 32N.

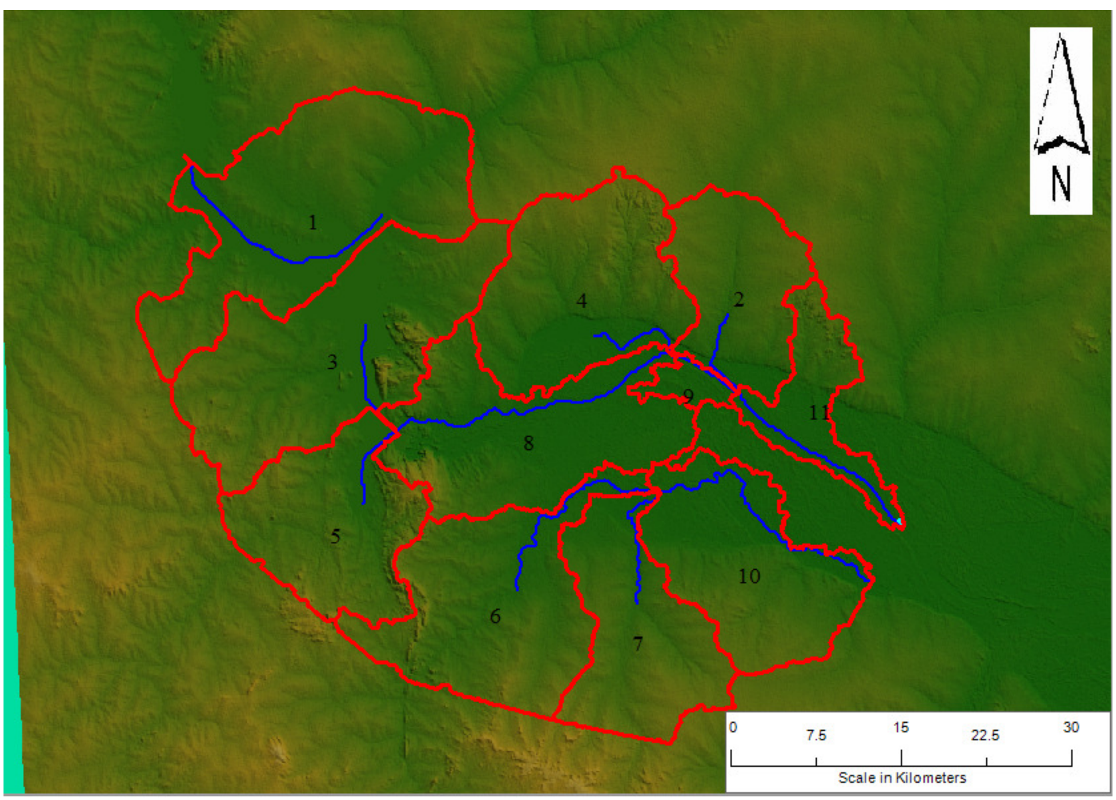


Figure 21: The DEM, Stream Network and Subbasins Numbered.

Figures 22 and 23 show the geo-processed landuse and soil map respectively. Figure 24 show the slope map result after dividing the HRUs into those with the average of 0-10% and those with average slopes in the range 10% to the top limit. A few extraction of the topographic report can be seen the Figure 25. Table 2 gives the summary of the landuse, soil type and slope bands of the watershed. Savannah vegetation has the dominant area in the watershed. This is in right agreement with the "ground truth" fact based on the author's knowledge and experience of the area.

Table 2: The Landuse, Soil and Slope Distribution Results*

Landuse		**Area[ha]**	**%Watershed**
	BSVG	5509.08	2.22
	WATB	27562.91	11.11
	SAVA	207828.61	83.77
	SHRB	865.17	0.35
	GRAS	1445.75	0.58
	CRWO	2024.82	0.82
	CRGR	2550.61	1.03
	CRDY	296.76	0.12
Soil			
	Nd8-1a-1572	35137.9	14.16
	J2-1-2a-1326	24634.88	9.93
	Nd3-1565	28487.43	11.48
	Lf26-a-1443	135355.26	54.56
	I-Nd-1276	24468.24	9.86
	Nd8-1a-1572	35137.9	14.16
Slope			
	0-10	240459.27	96.93
	10/01/94	7624.45	3.07

*The acronyms for the various landuse and soil types can be seen in Appendix A.

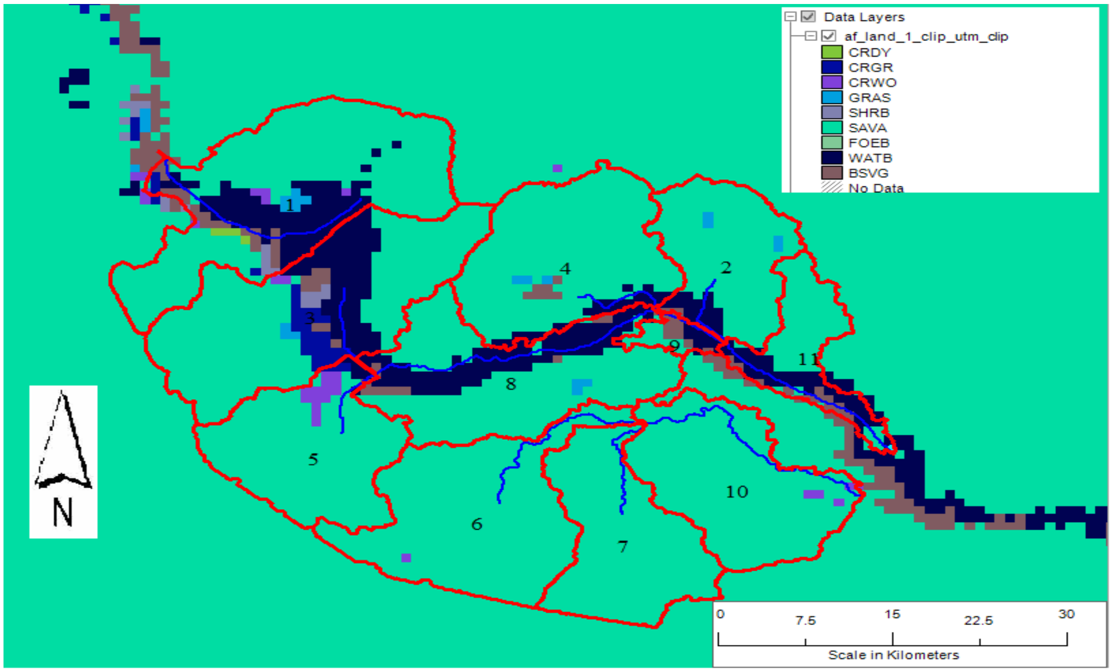


Figure 22: The Geo-processed Landuse Map with the Sub-basins.

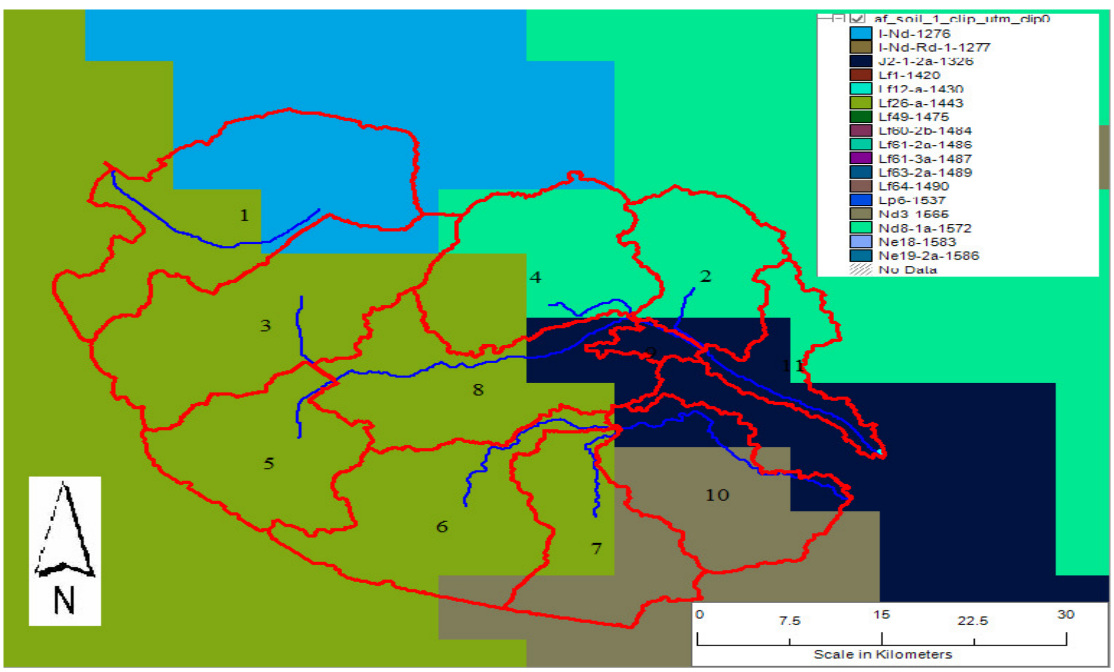


Figure 23: The Geo-processed Soil Map with the Sub-basins

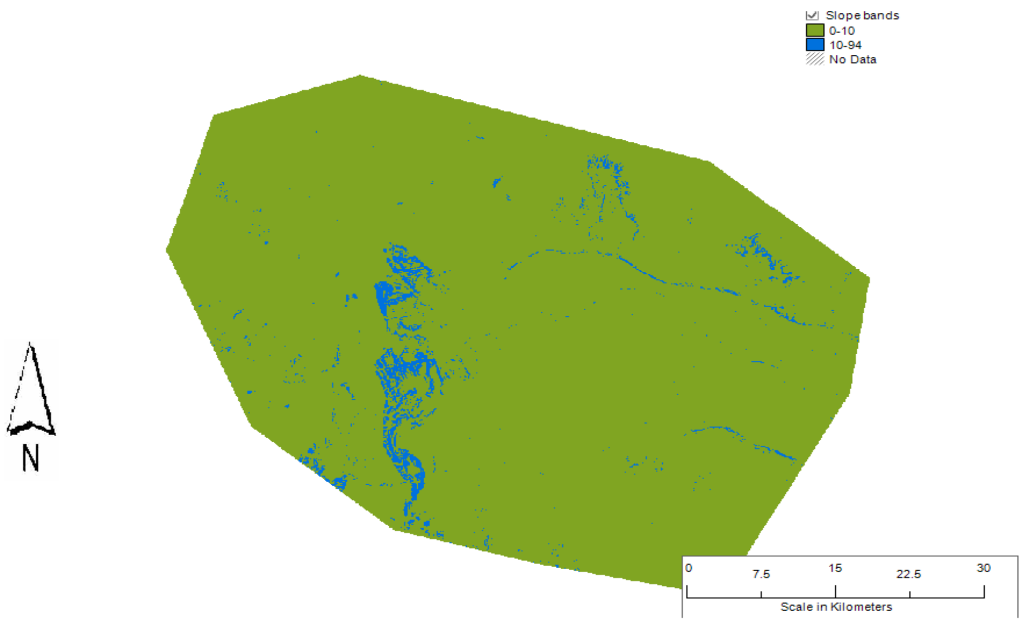
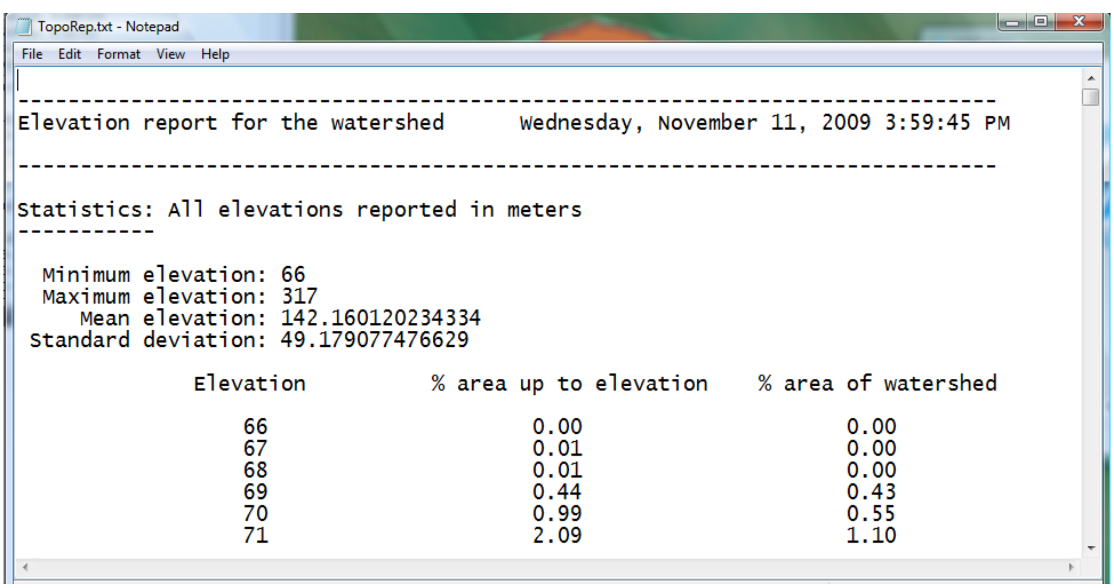


Figure 24: The Slope Map Result with the Average 0-10% and 10% to the Upper Limit




```
-----------------------------------------------------------------------------
Elevation report for the watershed      Wednesday, November 11, 2009 3:59:45 PM

-----------------------------------------------------------------------------

Statistics: All elevations reported in meters
-----------

  Minimum elevation: 66
  Maximum elevation: 317
     Mean elevation: 142.160120234334
 Standard deviation: 49.179077476629

              Elevation          % area up to elevation    % area of watershed

                   66                    0.00                     0.00
                   67                    0.01                     0.00
                   68                    0.01                     0.00
                   69                    0.44                     0.43
                   70                    0.99                     0.55
                   71                    2.09                     1.10
```

Figure 25: Extracted Part of the Topographic Report.

4.2 HYDROLOGICAL RESPONSE UNITS (HRUS)

The results of HRUs can be seen in Figure 26. The numerical values can be seen in Figure 27 There are 28 HRUs created after the HRU analyses. This shows that there are 3 different landuse classes in the watershed with savannah being the dominant class. In general, the HRUs in Figure 27 signify the classification of the watershed into hydrologic zones based on the hydrologic boundaries. In other words, the classifications give the response of these zones to recharge and discharge patterns based on water level trends, depth to water, hydrological and hydrogeological environments.

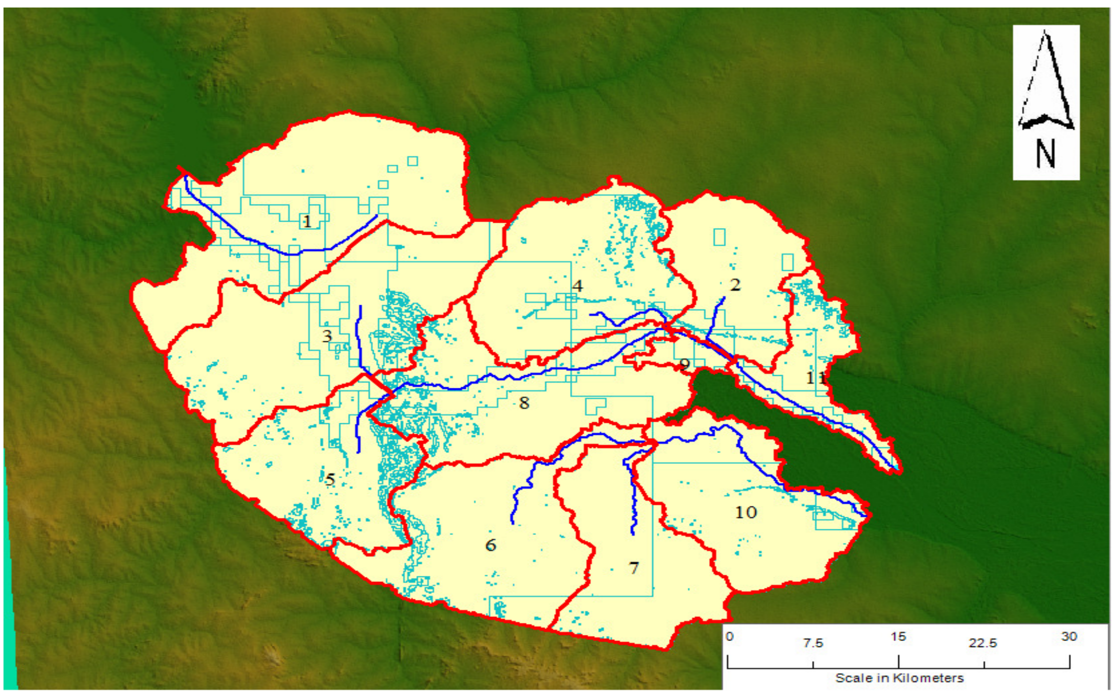
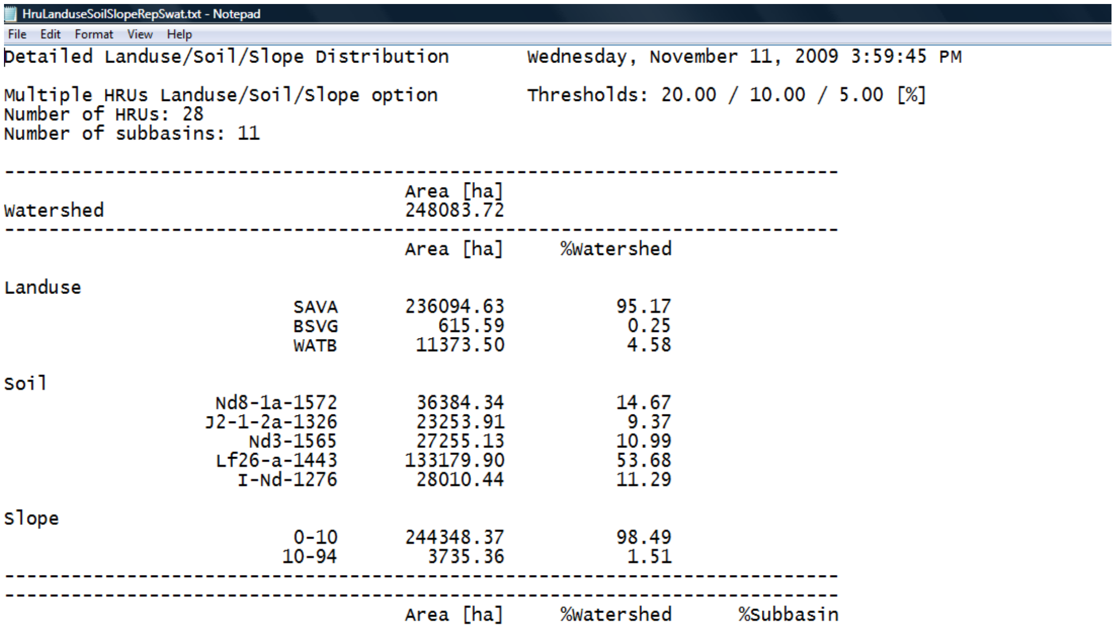


Figure 26: The Hydrological Response Unit (HRUs) Results in MapWindow.



```
HruLanduseSoilSlopeRepSwat.txt - Notepad
File  Edit  Format  View  Help
Detailed Landuse/Soil/Slope Distribution       Wednesday, November 11, 2009 3:59:45 PM

Multiple HRUs Landuse/Soil/Slope option        Thresholds: 20.00 / 10.00 / 5.00 [%]
Number of HRUs: 28
Number of subbasins: 11

---------------------------------------------------------------------------
                                    Area [ha]
Watershed                           248083.72
---------------------------------------------------------------------------
                                    Area [ha]     %Watershed

Landuse
                          SAVA      236094.63          95.17
                          BSVG         615.59           0.25
                          WATB       11373.50           4.58

Soil
                   Nd8-1a-1572       36384.34          14.67
                  J2-1-2a-1326       23253.91           9.37
                      Nd3-1565       27255.13          10.99
                   Lf26-a-1443      133179.90          53.68
                    I-Nd-1276        28010.44          11.29

Slope
                          0-10      244348.37          98.49
                         10-94        3735.36           1.51
---------------------------------------------------------------------------
---------------------------------------------------------------------------
                                    Area [ha]     %Watershed       %Subbasin
```

Figure 27: The Extracted part of the Hydrological Response Units (HRUs) Result

4.3 MWSWAT OUTPUTS

After running the model, more than sixty variables in form of water quality or quantity are generated. In the recent version of SWAT (version 2005) which is used for this analysis, the outlet subbasin which has the highest number in the subbasin numbering would be used to validate the model. The flow outside this subbasin is shown in Figure 28. This is an ungauged basin where there is now flow data to compare with the simulated results, however, the results from model should make some sense to certain extent. Comparing Figures 28 and 29 which show the sediment concentration and outflow discharge in subbasin 11, the higher the flow, the lesser the sediment concentration. Lower discharge also, should bring higher sediment concentration, which make some sense in the figures. Also, there is the law of water balance which means the precipitation equals the runoff, soil - water storage and the evapotranspiration. If the effect of the soil- water storage and evapotranspiration is considered negligible, then the higher the precipitation, the higher the runoff or positively strong correlated. This was computed, and a correlation coefficient of 0.84 was derived with the linear plot shown in Figure 30. This support the basic fact that, the higher the precipitation, the higher the runoff. It also make sense in Figure 30 that the precipitation is the independent (predictor) while the outflow (runoff) is the dependent (response) variables respectively. The time series plot of the simulated and discharge for the outlet(subbasin 11) from the year 1990 to 2016 can be seen in Figure 31. In SWAT analysis, normally the first “ two years” of the time series result is considered the “model warming up” period, therefore, deductions came be made after that. Looking at Figure 31 closely, it would be seen that the time series clearly shows the seasonality properties with “high spikes” which still falls within the “high rainfall period” in the watershed based on the authors experience of the area. There is also consistency between the peak precipitation and peak flow which justifies the correlation coefficient of 0.84 discussed earlier.

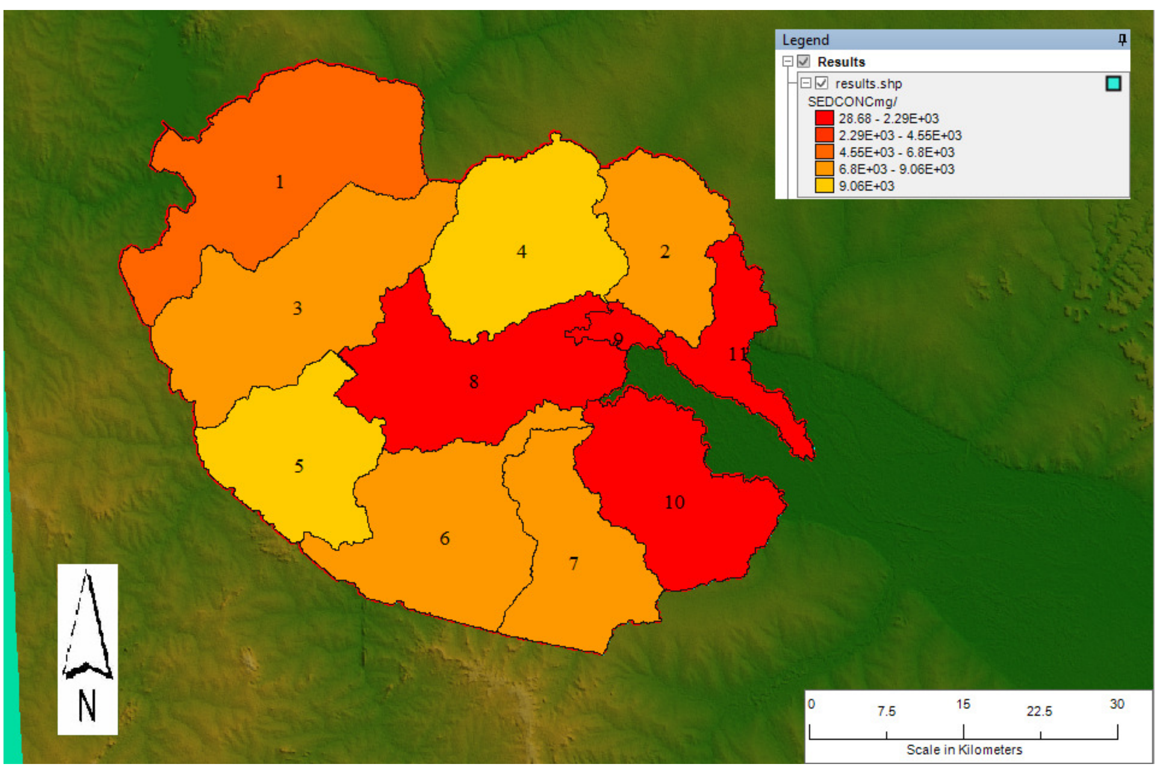


Figure 28: The Sediment Concentration of the Watershed.

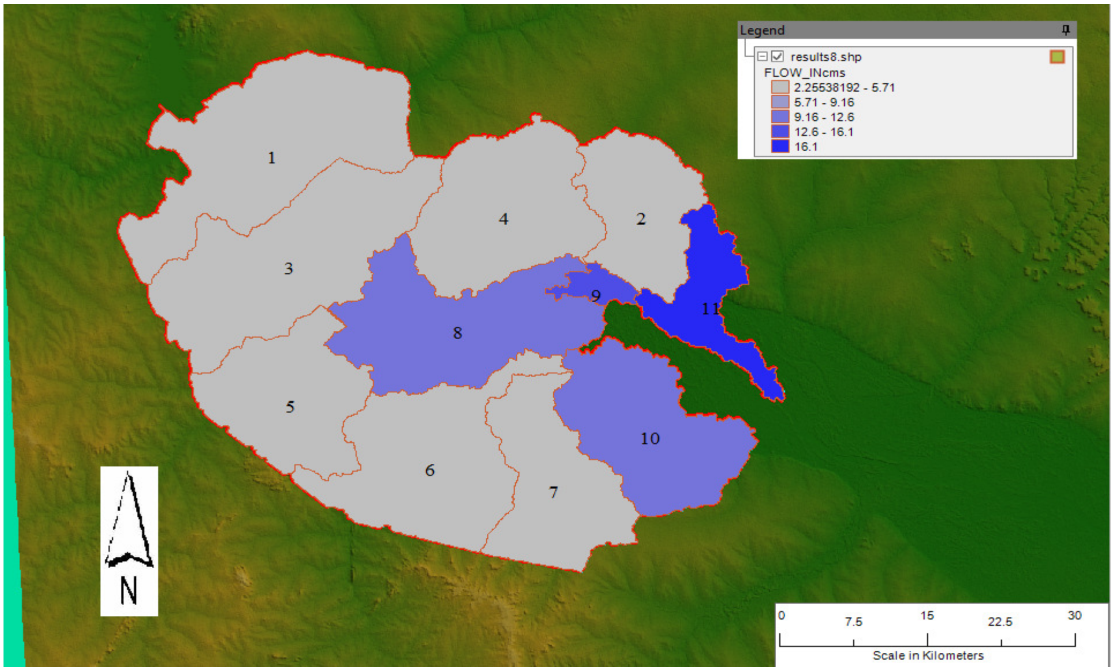


Figure 29: The Flow in the Watershed.

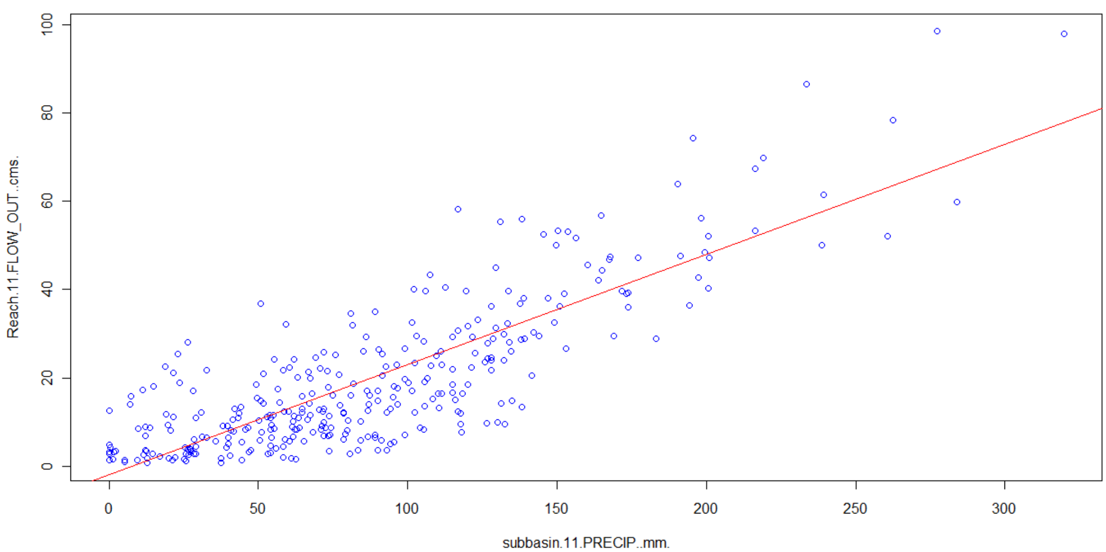


Figure 30: The Linear Plot of the Flow and Precipitation in Subbasin 11.

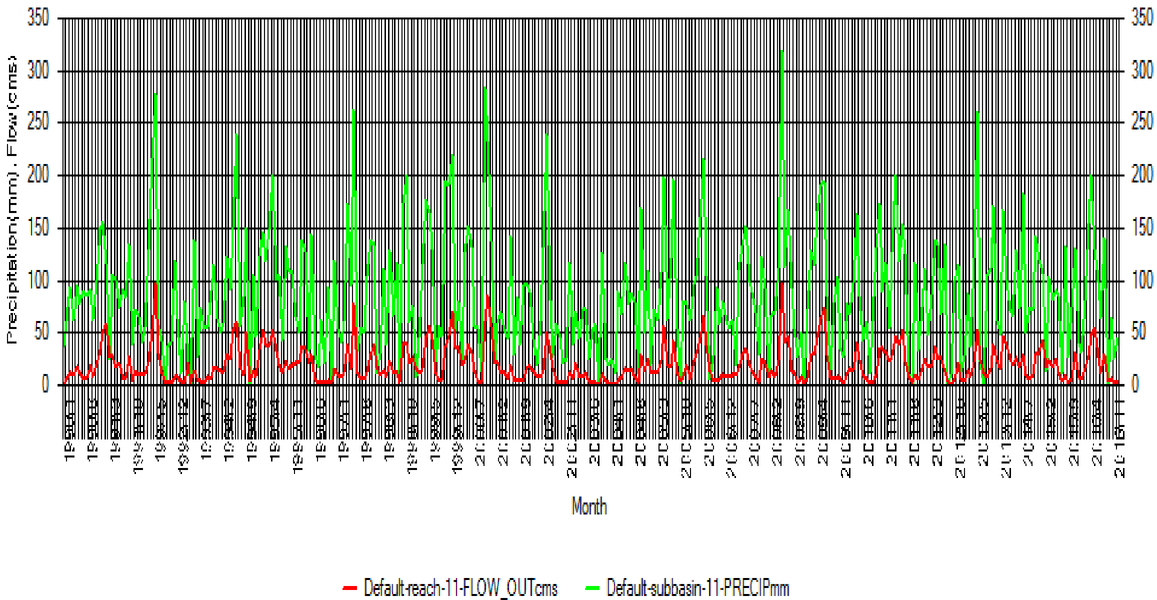


Figure 31: The Time Series Plot of the Simulated Precipitation and Discharge for the Outlet (Subbasin 11)

4.4 UNCERTAINTY ANALYSIS

The uncertainties in the numerical continuous data input i.e. rainfall was carried out. The rainfall amount for each day was modeled. The probability density function of the rainfall data was determined by plotting the histogram of the data. This is shown in Figure 32. Out of the entire available probability model in DUE, exponential function is the only pdf that could be used in this scenario. The exponential distribution is a one-parameter, continuous distribution. It is commonly expressed in terms of its mean, θ, and the inverse of its mean, λ. The exponential probability function is given as:

$$f(x) = \frac{1}{\theta} e^{-\frac{x}{\theta}} = \lambda e^{-\lambda x} \quad , x \geq 0 \qquad (4)$$

The mean (θ) = 1/ λ, where θ is 3.5 from the rainfall data. Therefore λ, is 0.2857

During the analysis, 700 realizations were generated using the DUE. Out of these realizations, about 5 were selected (through simple random sampling) and examined. It was discovered that, these realizations did preserve the structure of the original data as shown in Figures 33 and 34. Figure 35 shows the results of the realization using one as an example. Three of the realizations were prepared and used as inputs in MWSWAT in order to quantify the uncertainties associated with the rainfall input. It was very surprising that there is no change in the flow outputs compared to the real rainfall data, although, all other variables were kept constant. Figure 36 shows the time series of the realizations results compared with the real data.

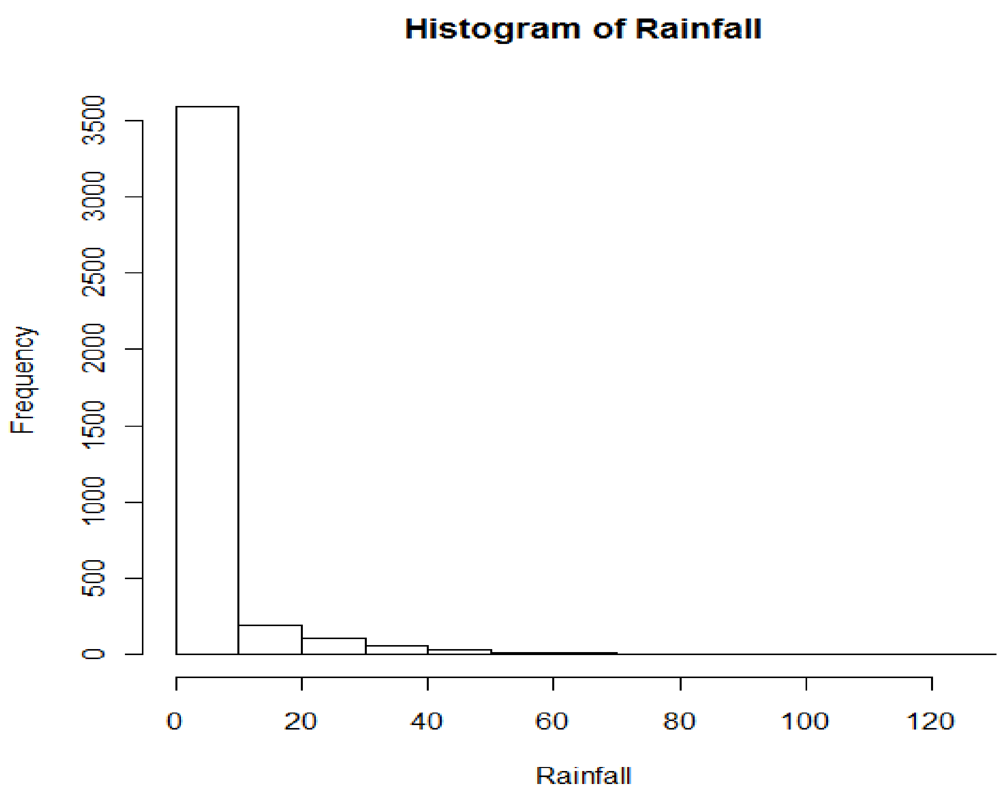


Figure 32: The Histogram of the Rainfall Data.

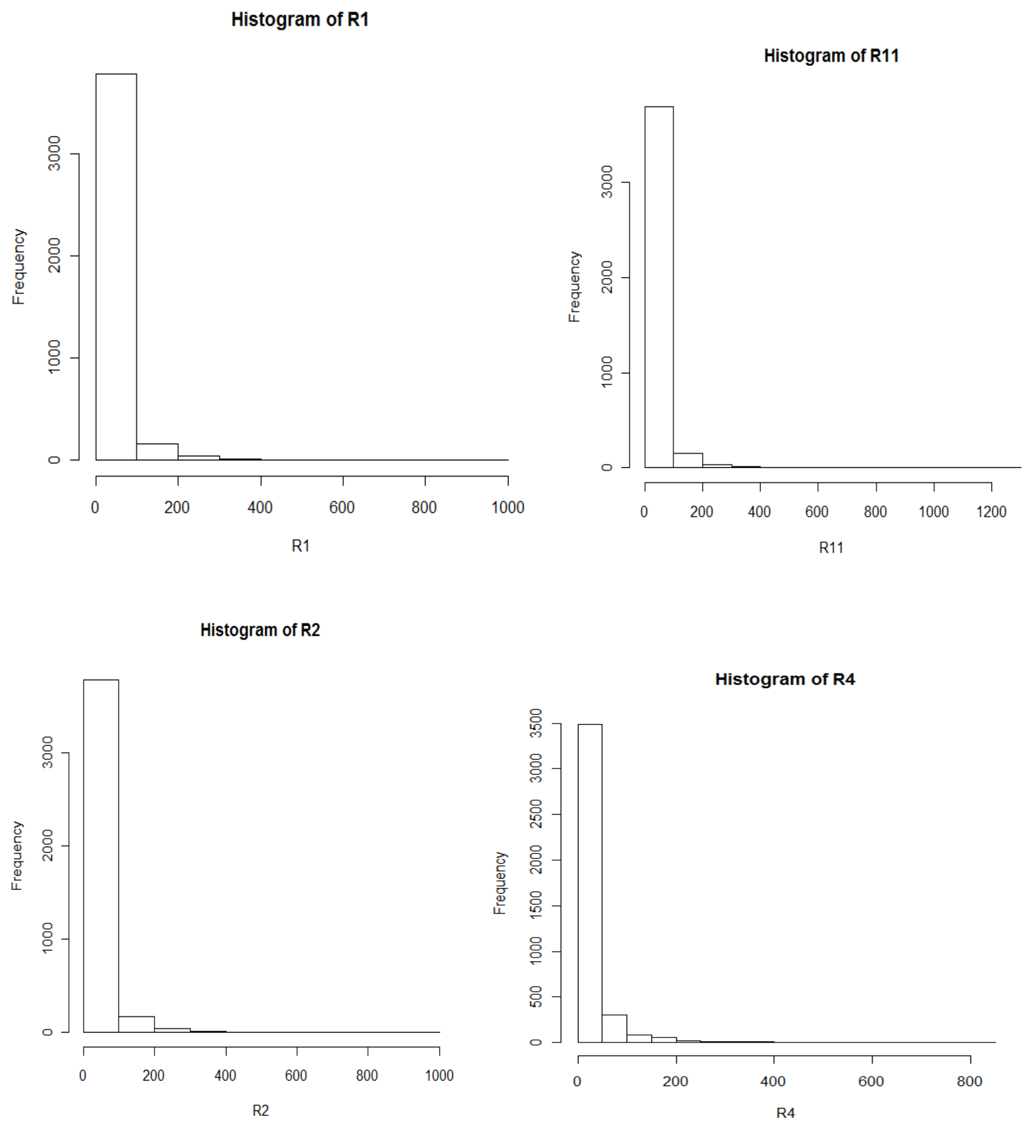


Figure 33: The Histogram plots of the Randomly Selected Realizations(1,11,2,4)

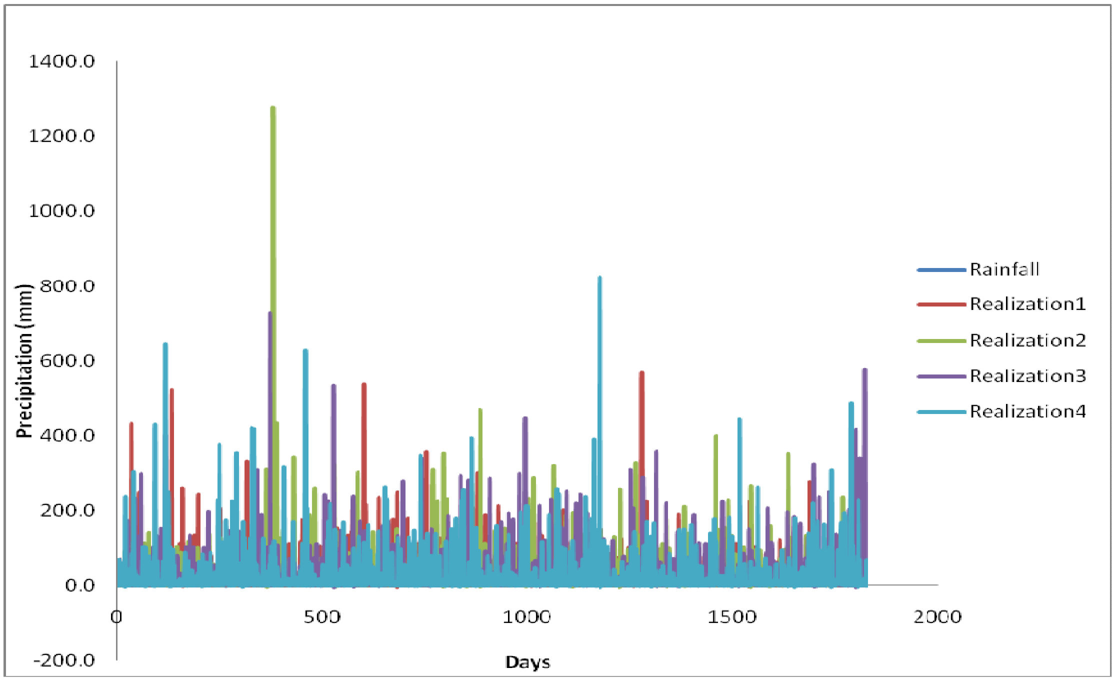
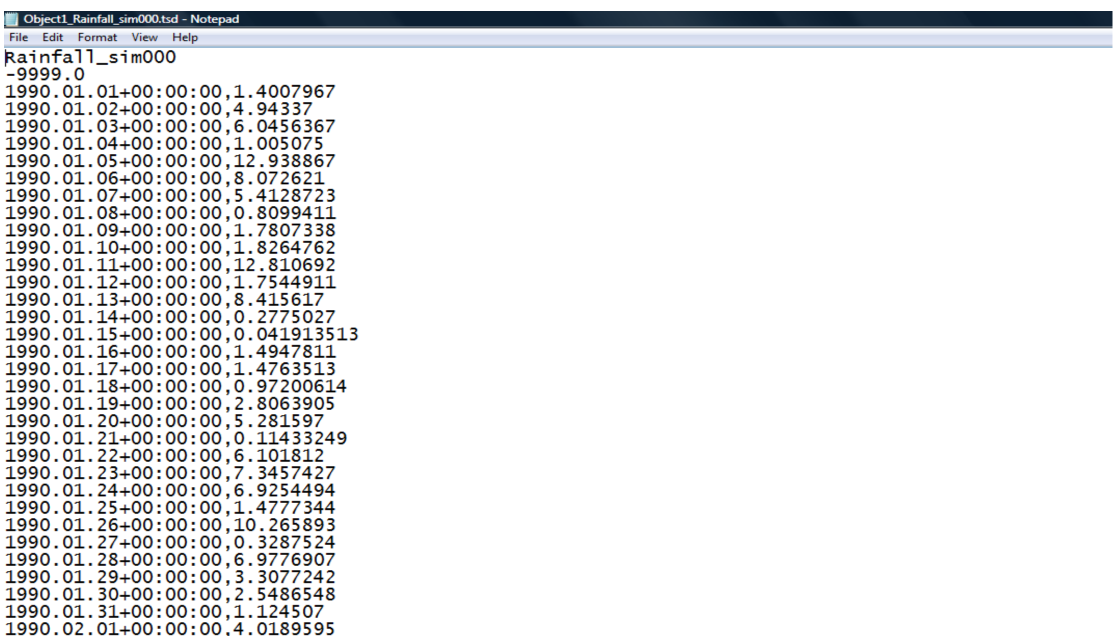


Figure 34: Time Series Plot of the Few Selected Realizations



Object1_Rainfall_sim000.tsd - Notepad
File Edit Format View Help

```
Rainfall_sim000
-9999.0
1990.01.01+00:00:00,1.4007967
1990.01.02+00:00:00,4.94337
1990.01.03+00:00:00,6.0456367
1990.01.04+00:00:00,1.005075
1990.01.05+00:00:00,12.938867
1990.01.06+00:00:00,8.072621
1990.01.07+00:00:00,5.4128723
1990.01.08+00:00:00,0.8099411
1990.01.09+00:00:00,1.7807338
1990.01.10+00:00:00,1.8264762
1990.01.11+00:00:00,12.810692
1990.01.12+00:00:00,1.7544911
1990.01.13+00:00:00,8.415617
1990.01.14+00:00:00,0.2775027
1990.01.15+00:00:00,0.041913513
1990.01.16+00:00:00,1.4947811
1990.01.17+00:00:00,1.4763513
1990.01.18+00:00:00,0.97200614
1990.01.19+00:00:00,2.8063905
1990.01.20+00:00:00,5.281597
1990.01.21+00:00:00,0.11433249
1990.01.22+00:00:00,6.101812
1990.01.23+00:00:00,7.3457427
1990.01.24+00:00:00,6.9254494
1990.01.25+00:00:00,1.4777344
1990.01.26+00:00:00,10.265893
1990.01.27+00:00:00,0.3287524
1990.01.28+00:00:00,6.9776907
1990.01.29+00:00:00,3.3077242
1990.01.30+00:00:00,2.5486548
1990.01.31+00:00:00,1.124507
1990.02.01+00:00:00,4.0189595
```

Figure 35: The Extracted part of one the Realizations in DUE.

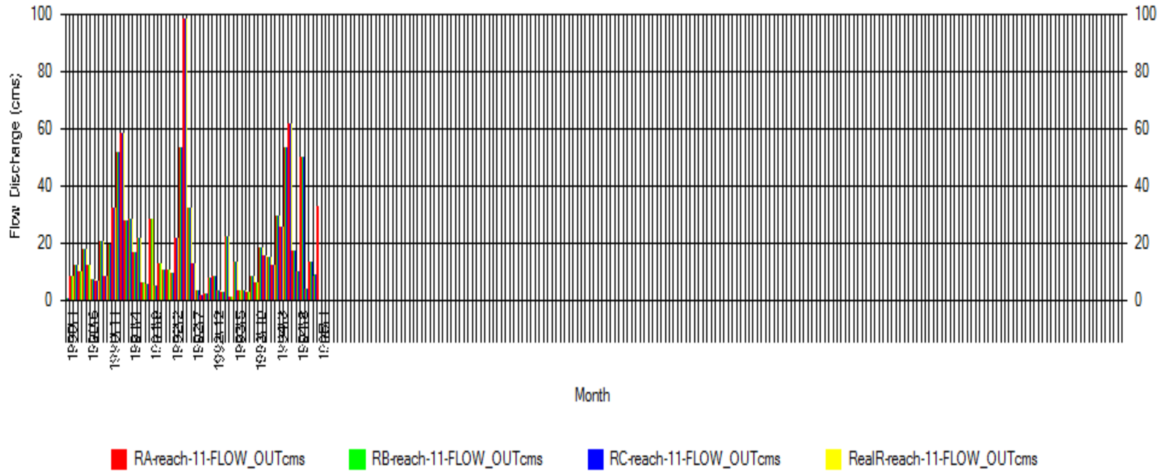


Figure 36: The Time Series Plot of the Discharges in Subbasin 11 using the Realizations.

Concluding this chapter, important results have been discussed which give the importance of MWSWAT for the watershed. The uncertainty analysis looks surprising, but very interesting. Although the output scale of the realizations were increased, however, they did honor the summary statistics. This is in support of what Brown and Huevelink (2005) said that ….."*the output scale of the realisations may be increased (i.e. aggregated). In simulating from a probability model, the realisations must honour the marginal probabilities at each location/time in the dataset, as well as the correlations between points. This can be checked by writing summary statistics for the realisations. For example, the mean and standard deviation should correspond to the parameter values shown in the second "Model" dialog*".

5.0 CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The primary aim of this study was to use the MapWindow version of SWAT to model an ungauged watershed in Kwara State, Nigeria and examine the effect of uncertainties in the numerical continuous input i.e. rainfall. The study aimed to establish the feasibility of using SWAT to model explicitly the water quantity and also various water quality indicators.

Literature reviewed for this study showed that SWAT had not been applied specifically for any watershed in Nigeria. Therefore, successful execution of this model had not been an easy task. Data used for this project have been sourced both locally and globally.

Modeling in an ungauged basin or basin where there is poor data quality has been a major challenge in the hydrological modeling community. The author is fully aware that there should be an observed discharge data in validating the model; however, where there is no observed discharge data, the model´s result should be ‘reasonable’ to certain extent. Variables like the simulated flow and sediment concentration were compared which looks ´reasonable´. There are over sixty variables simulated for this watershed which are very important for the end-users, in this case, the “Nigerian farmers” and the Kwara State Government, Nigeria in general . Considering the usefulness of the MWSWAT’s results, the simulated water flow is very important for its application to agricultural lands (irrigation) or use as a town’s water supply. MWSWAT allows water to be applied on an HRU from any water source within or outside the watershed. Water could also be transferred between reservoirs, reaches and subbasins as well as exported from the watershed. Another very important application of these results would be in the pesticides application. MWSWAT helps to simulate pesticides movement into the stream network through the surface runoff and into the soil profile and aquifer by percolation. This is very important for the farmers because of the ability to control the pesticides application through the open channel irrigation system. Contamination of the water flow through the canals can also be controlled.

Another important advantage of the model's results would be in the farm management plans by the farmers. MWSWAT allows the farmers to define the management activities taking place in every HRUs. The farmers also have the privilege to be able to define the beginning and ending of growing seasons, determine the timing and fertilizer quantity, pesticides and sustainable irrigation scheduling as well as the right time for tillage operation. Equally possible are the ability of MSWAT to be able to help the farmers in determine basic management practices and operations such as grazing which is an important asset.

As much as the applications of the MWSWAT look good for the farmers, it is equally important to know the confidence level of the model's results. One of the ways to do this would be to determine the uncertainties associated with the inputs. In other words, these decision-makers or managers need to know the estimated impacts of one land-use scenario as compared to others and uncertainties involved. The continuous numerical input i.e. rainfall have been analyzed for uncertainties using the Data Uncertainty Engine (DUE). A total of 700 realizations were derived from the rainfall simulation using the one exponential distribution for the total daily rainfall amount. Surprisingly, the randomly selected realizations used as input for the model did not give any changes when compared to the 'real' rainfall data. All other variables of the model were kept constant though.

Finally, to a certain extent, the ´Nigerian farmers' could have a tool and decision support system in order for them to do some hydrological, agricultural or managerial studies of their farm.

5.2 RECOMMENDATIONS

There are certain limitations as to the ´validity' of this model, since there was no observed gauging station in the case study area. It is recommend that, should the results of this model need be apply for any hydrological development (e.g. construction of dam, dyke, etc.), there should be installation of gauging stations at each subbasin for both climatological and hydrological data collections.

Other licensed GIS interface like the ArcGIS or ArcView versions of SWAT could be used and compare with MWSWAT results. The SWAT Calibration and Uncertainty Procedures (SWAT-CUP) developed by Dr. Karim Abbaspour may also be used for the uncertainty analysis for an ungauged basin as this and results compared with DUE.

Velez et. al. (2009) did suggest the use of a hydrological distributed model called ´TETIS´ to extrapolate the calibrations at gauged basins to ungauged ones. This could be a very good future research opportunities for SWAT application in Nigeria.

Many of the GIS data used for this project were sourced through the open geoportal of some global institutions with relatively low resolutions. Therefore, there is high believe that getting the data locally may improve the images' resolution and consequently the MWSWAT results. Having an high hope that the much anticipated Federal Government of Nigeria satellite called; "NigComSat-1" would produce some useful high resolution images when launched. There would be the privileges of acquiring these images locally thereafter. Therefore, the preparation, geo-processing and applications of such images for MWSWAT modeling would be another interesting area of future research.

Finally, the application of the Watershed Modeling System (WMS) which is a comprehensive graphical modeling environment for all phases of watershed hydrology and supports other hydrologic models like the HEC-1, HEC-HMS, TR-20, TR-55, Rational Method, NFF, MODRAT, OC Rational, HSPF, xpswmm, and EPA-SWMM should also be used to model this watershed. WMS also consists of powerful tools to automate modeling processes such as automated basin delineation, geometric parameter calculations, GIS overlay computations (CN, rainfall depth, roughness coefficients, etc.), cross-section extraction from terrain data, etc. It would be interesting to compare the results with MWSWAT.

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APPENDIX A: **The Acronyms for the Landuse Classes.**

AGRL	Agricultural Land-Generic
AGRR	Agricultural Land-Row Crops
AGRC	Agricultural Land-Close-grown
ORCD	Orchard
HAY	Hay
FRST	Forest-Mixed
FRSD	Forest-Deciduous
FRSE	Forest-Evergreen
WETL	Wetlands-Mixed
WETF	Wetlands-Forested
WETN	Wetlands-Non-Forested
PAST	Pasture
SPAS	Summer Pasture
WPAS	Winter Pasture
RNGE	Range-Grasses
RNGB	Range-Brush
SWRN	Southwestern US (Arid) Range
WATR	Water
CORN	Corn
CSIL	Corn Silage
SCRN	Sweet Corn
EGAM	Eastern Gamagrass
GRSG	Grain Sorghum
SGHY	Sorghum Hay
JHGR	Johnsongrass
SUGC	Sugarcane
SWHT	Spring Wheat
WWHT	Winter Wheat
DWHT	Durum Wheat
RYE	Rye
BARL	Spring Barley
OATS	Oats
RICE	Rice
PMIL	Pearl Millet
TIMO	Timothy
BROS	Smooth Bromegrass

BROM	Meadow Bromegrass
FESC	Tall Fescue
BLUG	Kentucky Bluegrass
BERM	Bermudagrass
CWGR	Crested Wheatgrass
WWGR	Western Wheatgrass
SWGR	Slender Wheatgrass
RYEG	Italian (Annual) Ryegrass
RYER	Russian Wildrye
RYEA	Altai Wildrye
SIDE	Sideoats Grama
BBLS	Big Bluestem
LBLS	Little Bluestem
SWCH	Alamo Switchgrass
INDN	Indiangrass
ALFA	Alfalfa
CLVS	Sweetclover
CLVR	Red Clover
CLVA	Alsike Clover
SOYB	Soybean
CWPS	Cowpeas
MUNG	Mung Beans
LIMA	Lima Beans
LENT	Lentils
PNUT	Peanut
FPEA	Field Peas
PEAS	Garden or Canning Peas
SESB	Sesbania
FLAX	Flax
COTS	Upland Cotton-harvested with
COTP	Upland Cotton-harvested with
TOBC	Tobacco
SGBT	Sugarbeet
POTA	Potato
SPOT	Sweetpotato
CRRT	Carrot
ONIO	Onion

SUNF	Sunflower
CANP	Spring Canola-Polish
CANA	Spring Canola-Argentine
ASPR	Asparagus
BROC	Broccoli
CABG	Cabbage
CAUF	Cauliflower
CELR	Celery
LETT	Head Lettuce
SPIN	Spinach
GRBN	Green Beans
CUCM	Cucumber
EGGP	Eggplant
CANT	Cantaloupe
HMEL	Honeydew Melon
WMEL	Watermelon
PEPR	Bell Pepper
STRW	Strawberry
TOMA	Tomato
APPL	Apple
PINE	Pine
OAK	Oak
POPL	Poplar
MESQ	Honey Mesquite
CRDY	DRYLAND CROPLAND AND PASTURE
CRIR	IRRIGATED CROPLAND AND PASTURE
MIXC	MIXED DRYLAND/IRRIGATED CROPL
CRGR	CROPLAND/GRASSLAND MOSAIC
CRWO	CROPLAND/WOODLAND MOSAIC
GRAS	GRASSLAND
SHRB	SHRUBLAND
MIGS	MIXED GRASSLAND/SHRUBLAND
SAVA	SAVANNA
FODB	DECIDUOUS BROADLEAF FOREST
FODN	DECIDUOUS NEEDLELEAF FOREST
FOEB	EVERGREEN BROADLEAF FOREST

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