MODELING SEDIMENT YIELD USING ArcSWAT AND ANALYZING THE MOST PROMINENT REMEDIAL MEASURES: CASES OF MELKA WAKENA RESERVOIR, ETHIOPIA

By

Dereje Tolosa

Advisor

Dr. Tilahun Derib

ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF THECHNOLOGY

SCHOOL OF GRADUATE STUDIES

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A thesis submitted in partial fulfillment of the degree of Masters of Science in Civil Engineering (Major in Hydraulic Engineering)

By

Dereje Tolosa

Advisor

Dr. Tilahun Derib

July 2015

Certification

This is to certify that the thesis prepared by Dereje Tolosa, entitled: **Modeling Sediment yield using ArcSWAT and analyzing the most prominent remedial measures: cases of Melka Wakena reservoir, Ethiopia** and submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering (major in Hydraulic Engineering).

As a member of the board of examiners of the MSc. Thesis open defense examination, we certify that we have read, evaluated the thesis prepared by Dereje Tolosa and examined the candidate. We recommended that the thesis be accepted as fulfilling the thesis requirement for the degree of Master of Science in Civil Engineering (major in Hydraulic Engineering)

Tilahun Derib,PhD	____________________	___________________
(Thesis Advisor)	Signature	Date
Agizew Nigussie, PhD	______________________	_________________
(Internal Examiner)	Signature	Date
Yonas Michael,PhD	________________________	__________________
(External Examiner)	Signature	Date
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Dereje Tolosa Moti

Deretolosa@gmail.com

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DEDICATION

I dedicate this thesis to my beloved father ***TOLOSA MOTI,*** *who poured me the spirit of hard working. Dad may God rest your soul always in peace!*

ABSTRACT

Sediment accumulation in a reservoir is a serious problem that threatens sustainability of the reservoir and has severe consequence on reservoir productivity during its operation time. Therefore, this study was initiated to model sediment inflow and to suggest mitigation measures for Melka Wakena reservoir which is located in the highlands of Arsi Zonal Administration of Wabi Shebele river basin about 280 km south east of Addis Ababa. The ArcGIS interface Soil and Water Assessment Tool (ArcSWAT) was used to model the soil erosion in the watershed. The input data were Metrological, Hydrological, land use/land cover map and soil map which were collected from concerned government offices. The result showed that statistical model performance measures of the coefficient of determination (r^2) of 0.894, the Nash–Sutcliffe simulation efficiency (E_{NS}) of 0.862 and percent difference (D) of 0.31, for calibration and 0.825, 0.77 and -0.011, respectively for validation, indicated good performance of the model simulation of Sediment load from the watershed on yearly time step. The model result showed that 1637.2 tons/Km^2/year of sediment load have been flowing to the reservoir from the watershed. This indicates 0.63% of a total storage capacity lost per year. The annual economic loss due to reservoir sedimentation is 2.36 million birr. Subbasin 3, 2, 11 and 9 ranks first to fourth according to their Sediment yield respectively and found as critical subbasins. Soil and Water conservation program at critical subbasins with vegetation screens upstream of reservoir was found the best and feasible option to reduce sediment inflow into the reservoir.

Key Words

Melka Wakena Reservoir, Reservoir Sedimentation, ArcSWAT, DEM, Calibration, Validation.

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ACRONYMS

BCEOM	French Engineering Consultant
CN	Curve Number
DEM	Digital Elevation Model
E_{NS}	Nash-Sutcliffe Simulation Efficiency
EUROSEM	European Soil Erosion Model
GIS	Geographic Information System
HRU	Hydrological Response Unit
ICOLD	International Commission for Large Dams
LH-OAT	Latin Hypercube One-factor-at-a time
MWIE	Ministry of Water, Irrigation and Energy
MRS	Mean relative sensitivity
MUSLE	Modified Universal Soil Loss Equation
pcpSTAT	Precipitation Statistical Parameters calculator
r^2	Coefficient of determination
SCS	Soil Conservation Service
SG	Specific Gravity
ArcSWAT	ArcGIS interface Soil and Water Assessment Tool
USDA	United State Department of Agriculture
USLE	Universal Soil Loss Equation
UTM	Universal Transvers Mercator
WEPP	Water Erosion Prediction Project
WXGEN	Soil and Water Assessment Tool Weather Generator model

1 INTRODUCTION

1.1 Background

The construction of a dam and creation of an impounded river reach area usually change the stream natural conditions. Concerning the Sedimentological aspect, the dams cause a reduction on the flow velocity, thus causing the gradual deposition of those sediments carried by the stream resulting in the sedimentation, gradually diminishing the reservoir storage capacity. Therefore, it may come to hinder the reservoir operation, besides causing several kinds of environmental problems.

Sediment yield refers to the amount of sediment exported by a basin over a period of time, which is also the amount that will enter into a reservoir. Rainfall and runoff are the main cause of sediment yield from watershed and transport of the same to the reservoirs.

The amount of sediment deposit depends on the types of sediment in the river system, the shape of the reservoir, the detention storage time and the operating procedures. The stream, when entering the reservoir, has its cross-section areas enlarged, while the speed of the current decreases, thus creating conditions for sediment deposition. The heaviest particles, such as gravel and thick sand, are the first ones to be settled, while finest sediments enter into the reservoir. Hence the finest particles don’t mix readily with the reservoir water; it may be deposited near the base of the dam.

As the sedimentation increases, the reservoir storage capacity decreases, the influence of backwater increases for the upstream, the velocities in the lake increase and more sediment come to flow towards downstream, thus diminishing the particles trap efficiency. Often, more than 90% of the incoming sediment load is trapped and deposited in horizontal strata or thin bands across the bottom of the reservoir [1]. Study of White, R [2] showed that worldwide around 40,000 large reservoirs suffer from sedimentation and it is estimated that between 0.5% and 1% of the total storage capacity is lost per year.

The annual sediment load of the entire world's rivers together is varies between 24 and 30 billion tons for a water inflow of 40000 km^3, i.e. an average sediment content of 0.6 to 0.75 T/1000 m^3 of water but it varies enormously according to the river and the discharge [1]. The accumulated sediment storage in world reservoirs has been evaluated as 2000 million m^3 for dams 35 years old on average, i.e. in the range of 57 billion m^3 per year, i.e. 0.8 % of the total storage per year.

Sedimentation in reservoirs also has influence on dam structural stability. A river system consists of a continuous balance between erosion and accretion, where sand is picked up due to the river flow and deposited elsewhere in the river. If the inflow of sediment is blocked due to a dam structure, the equilibrium of the river morphology is disturbed and the river channel downstream of the dam starts to erode to compensate for the lack in sand particles.

The total yearly loss due to sedimentation is about 18.6 billion US dollar (excluding downstream impacts) and with downstream impacts considered the annual cost is about 21 billion US dollar.

Sedimentation, from runoff and erosion, is also a major water quality issue for many lakes and reservoirs. Upstream sediment flows are accelerated significantly beyond natural conditions due to unsuitable agricultural practices in some areas and the rapid conversion of rural lands into urban and suburban land uses in other areas. Infilling with sediment can result in a decrease of water storage capacity and may result in an increase in water treatment costs or a decrease in electrical production capability.

According to the study report of MWIE [3] Sediment transport process has affected Melka Wakena reservoir watershed unless an appropriate watershed management interventions and strategies should be applied. It is due to high runoff discharges that imposing huge sediment yield and reducing capacity of the reservoir continuously.

The main questions that have to be answered are: how much is the soil erosion in the Upper Melka Wakena Reservoir watershed? How much is the Sediment yield of each subbasin? How much is economic loss due to reservoir sedimentation? And which methods are effective to preserve the reservoir capacity?

1.2 Problem statement

With the fast growing population and the density of livestock in the basin, there is pressure on the natural resources that resulting in even forest clearing and overgrazing. High intensity rain storms cause significant erosion and associated sedimentation, increasing the cost of operation & maintenance and shortening lifespan of water resources infrastructure. Therefore, it is important to maintain the storage capacity of the reservoir and prolong its economic life by taking appropriate measures that could reduce the rate of siltation. This would be possible if we know the amount of sediment yield in the watershed. Thus, assessment and analysis of soil erosion, sediment yield and their intake and deposition in reservoir is essential. So this study attempts to model sedimentation process of Melka Wakena watershed by integrating spatially integrated hydrological parameters , digital elevation model (DEM) , land use and soil map with the ArcGIS interface Soil and Water Assessment Tool (ArcSWAT).

1.3 Objective

A study on soil erosion, sediment yield and runoff from the watershed of Melka Wakena Reservoir was initiated with the following objectives.

1.3.1 General objective

- To estimate the sediment yield of Melka Wakena reservoir watershed by using Soil and Water Assessment Tool (Arc SWAT) model which is an ArcGIS interface and analyzing the most prominent remedial measures that preserve storage capacity of the reservoir.

1.3.2 Specific Objectives

- To map and identify catchments based on sediment source
- To estimate economic loss due to reservoir sedimentation

1.4 Description of study area

1.4.1 Overview

Melka Wakena Hydro-Electric power plant is located in the highlands of Arsi Zonal Administration about some 280 km south east of Addis Ababa. It lies 7^o N of the equator. The power plant is at the Wabi-Shebelle river, a large water course flowing along the south-east coast of the country toward the territory of Somalia. The site is somewhat above the Melka Wakena falls of Wabi Shebelle river and the watershed area of the river above the site is 4388 Km^2.

The construction of the plant was started in 1983 and commissioned in 1988.The head work, which is an earth and rock fill dam is constructed by local materials. The total length of the dam along the 10m crests of which 7m road way is 1800m and 38m high. The dam creates a reservoir with the surface area of 8160 hectares of the 763Mm^3 storage capacity. The reservoir provides water withdrawal upto 60m^3/sec to the open headrace canal.

The water level at the head and tail section of the open canal is 2507m and 2504.3m respectively. The canal originates at the dam site and terminates at the crossing of the canyonage of the Wabi Shebele and Hako rivers. The total length of the canal is 7.217 Km and the bottom slope is 0.000262m.

1.4.2 Climate and hydrology

As regards the topography, the watershed is located in the area of the Ethiopian vast high plateau with average ground surface elevation of 2700 m surrounded by a series of extinct volcanoes. The vegetation prevailing on the watershed area is the savanna wood.

The climate in project area is subequatorial type. The mean air temperature in the region is 13.6-14.2^{o}C and the season air temperature fluctuations are insignificant. The mean annual absolute humidity is 68 percent; during a year the humidity varies from 61 percent in the cold time to 78 percent in warm season.

The rain is brought to the project area mainly by equatorial monsoon. The annual precipitation here totals about 700 mm with its seasonal distribution; the dry season continues from November to February, when the precipitation makes up only 8-12 percent of the total sum and the prolonged rainy season from March to October.

The mean monthly wind velocity is small and varies between 1.8 and 3m/sec. the additional water losses due to the evaporation from the storage reservoir for an average year are 850 mm [24]. The runoff regime features two season; the flood period from June to October when about 75 percent of the runoff pass and the dry-weather period which last 7 months from November to March.

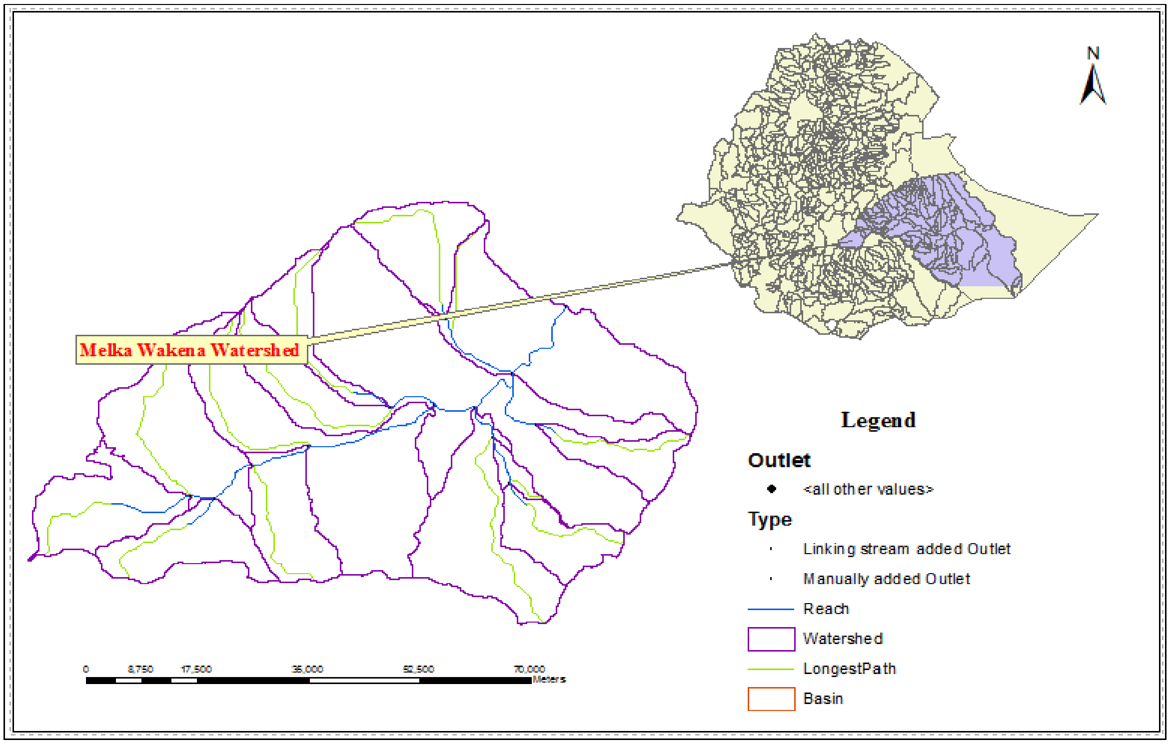


Figure 1.1: Location map of study watershed

Table 1.1: Main parameters of reservoir and the project structures of Melka Wakena

Parameter	Quantity
Watershed area(Km^2)	4388
Mean annual runoff (Mm^3)	810
Reservoir storage : Total storage (Mm^3) Live storage (Mm^3) Dead storage (Mm^3)	763 606 157
Surcharge water level of reservoir (m.abs.)	2326.07
Dead storage level (m.abs.)	2315.17

Normal head water level (m.abs.)	2324.17
Capacity of hydroelectric station (MW)	153
Firm power output (M KWh/year)	311
Head (m) : Design	297
Minimum	294
Maximum	301.4
Water discharge through the structure (m^3/sec)	
Flood control spillway	460
Bottom outlet	30
Headrace canal	60

1.5 Outline of the thesis

The first chapters discuss about introduction, research area description, Problem Statement, research questions and the objective of the study. The second chapter contains the literature review. In the literature review the erosion and sedimentation concept were discussed. It also thoroughly discussed about reservoir sedimentation and its mitigation measures. The catchment soil erosion and hydrological models and pertinent past work done in the area elaborated under literature review.

Chapter three discusses about method and methodology used in the study. The chapter deals with three sections. The first section discussed about ArcSWAT model input. The second section about ArcSWAT model description and the last section discussed thoroughly about the mechanism of model setup.

The fourth chapter covers the result and discussion part of the study. Here, in the first section the model result was compared to measured value through model calibration and validation. In the second section the subbasin of the watershed mapped and identified depending on their sediment yield. The last section of the chapter assesses reservoir sedimentation measure and provides best option reducing sediment inflow into the reservoir. The last chapter concludes about the study and provides recommendation for future research.

2 LITERATURE REVIEW

2.1 Erosion and Sedimentation

2.1.1 Soil Erosion Processes

Soil erosion involves detachment, transport and deposition of soil particles (including plant nutrients and organic matter) by water or wind. The process may be natural or accelerated by human interference in the environment. As the study by L.Van Rijn [5] the two major types of erosion are geologic erosion and accelerated erosion

Geologic erosion, usually referred to as natural erosion acting over long geological periods, occurs when the soil is in its natural environment. Natural erosion rates exist under natural or undisturbed environmental conditions. Usually under natural geologic erosion rates, soil properties and soil profiles develop to approach an equilibrium condition [6].This type of erosion has contributed to the formation of soils and their distribution on the surface of the earth. This long-time eroding process caused most of the present topographic features.

Accelerated erosion is soil loss in excess of geologic erosion. It is normally associated with changes in natural cover or soil conditions and is caused primarily by water and wind. The forces involved in accelerated erosion are (1) attacking forces which remove and transport the soil particles and (2) resisting forces which retard erosion. Hereafter, accelerated erosion will be referred to as soil erosion or simply erosion.

Erosion by water is induced by the natural occurring events of rainfall or snowmelt, or artificially by irrigation and other types of sprinkler application of water to the surface. Detachment of individual soil particles may occur when water strikes the surface by overcoming the interconnecting forces holding the soil particles together. This is commonly referred to as raindrop splash.

As the inducing events of rainfall continue, water infiltrates into the soil at a rate controlled by the intensity of water hitting the surface and the infiltration capacity of the vertical soil profile. Water that is not infiltrated begins to pond on the surface. When sufficient depth is achieved at the surface, water flow will begin in the direction of the steepest slope that is unimpeded. This begins the hydrologic process referred to as overland flow or runoff.

According to study by William W. Doe III et.al [7] the removal of a uniform thin layer of soil by raindrop splash or water runoff is called sheet erosion. This thin layer of topsoil often disappears gradually, making it difficult to monitor because the damage is not immediately perceptible. This insidious process is often overlooked until the subsoil is exposed. Soil particles may be dissolved or suspended in the overland flow, beginning the process of sediment transport.

Watersheds, or catchments, are commonly divided into the upland areas and channels. In the upland areas overland flow is conceptually divided between rill flow mechanisms and inter-rill flow mechanisms, which occur on hill slopes. As overland flow converges from various portions of the upland area and becomes more concentrated, it becomes sufficiently erosive to form shallow channels, referred to as rills. Additional soil particles may become detached as water flows through these rills. In the inter-rill areas, runoff occurs as a very thin, broad sheet, sometimes referred to as sheet flow. Both detachment and transport may occur in the rill and inter-rill areas. As erosive power increases, the small rills may converge to form larger surface channels, called gulley.

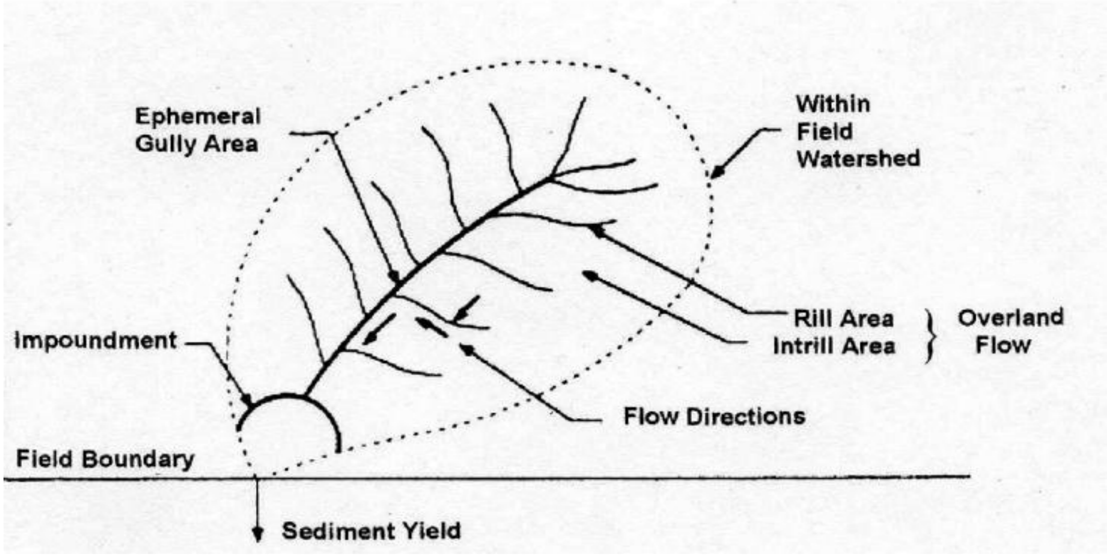


Figure 2.1: Schematic representation of rill,inter-rill areas and gulley on a sub-watershed [8].

Finally, if sufficient water continues down slope it will reach well-defined channels, through which both water and sediment will be carried downstream towards the watershed outlet.

If at any point along the water flow path the velocity is decreased (e.g., change in slope), some soil particles may be deposited because the reduced flows cannot carry as much sediment. The transport capacity is the maximum amount of sediment that a given flow can carry without net deposition occurring. The detachment capacity, which is the ability of the overland flow overcoming the interconnecting forces holding the soil particles together, and transport capacity are interrelated and it is their interaction that controls the patterns and magnitudes of erosion and deposition. The character of the processes is closely linked to which capacity is the limiting factor.

The amount of sediment actually leaving a site or watershed is a function of the erosional and depositional processes – both surface and channel – that occur up slope of the discharge point. The amount (mass) of sediment being carried is called the sediment load. The velocity of entrained sediment passing a given point is the sediment rate. Sediment yield is the amount of eroded soil that is delivered to a point in the watershed that is remote from the origin of the detached soil particles. In a watershed, sediment yield includes erosion from slopes, channels and mass wasting (slumping, sliding, falling, etc.), minus the sediment that is deposited after it is eroded, but before it reaches the point of interest [6].

2.1.2 Cohesive and Non-cohesive sediments

As confirmed by study of Grabowski RC [9] cohesive sediments are a heterogeneous mixture composed of clay, silt and organic matter in solid, liquid or gaseous phases with a particle diameter of less than 60 µm whereas non-cohesive sediments are primarily composed of fine and medium sands and have a particle diameter of more than 60 µm.

Cohesive sediments widely exist in rivers, lakes, reservoirs and stick together due to the action of electrostatic force or flocculation; they act at very small distances and are affected by the clay mineralogy, ion content and composition, pH and temperature. The major transportation method of cohesive sediments is in suspension state by convection, turbulent diffusion and gravity settling. Generally, flocculation increases the settling velocity of cohesive sediments, thus being responsible for deposition [10].

2.1.3 Grain size and sediment transport

A simple illustration of the relationship between grain size and flow velocity with sediment transport method is provided by the Hjulstrom diagram (Figure 2.2). Figure 2.2 shows that whether a river will erode, transport or deposit sediments. The diagram also shows the relationship between grain sizes and flow velocity and transport mode.

When the flow cannot move, the sediment particle, i.e. the grain size, is large and flow velocity is low, the deposition of the particle occurs. Further, when the grain size is small, even smaller flow can erode the particles, and in between these grain sizes, flow can sustain bed load transport. Also, high velocity is required to erode finer particles, which is explained by the cohesive nature of the fine sediment. According to the diagram, flow velocity is able to sustain particle transport between clay and pebbles or even cobbles.

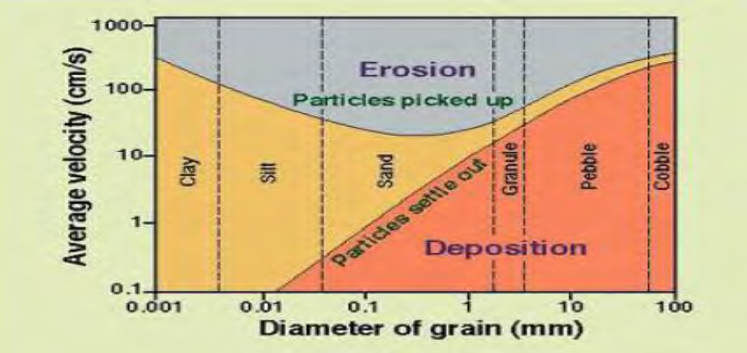


Figure 2.2: Hjulstrom diagram. [11]

2.1.4 Sediment transport Equation

Sediment transport equations are used to determine the sediment transport capacity for a specific set of flow condition. The first step in evaluating sediment transport is to select one or more of available equations for use in solving the problem. The selection is not straight forward, since the result of different formulas can give drastically different results and it is usually not possible to determine the one providing best result. Additionally some of the methods are considerably more complex than the other. The initial consideration is to decide what portion of sediment transport need to be estimated. If it is desirable to know the contribution of bed load and suspended load to the bed-material discharge, formula for each are available. Other formulas provide direct determination of bed material discharge. A common feature of all sediment transport equation is that wash load is not included since it is governed by upstream supply.

Wash load consists of fine materials that are finer than those found in the bed. The amount of wash load depends mainly on the supply from the watershed, not on the hydraulics of the river. Consequently, it is difficult to predict the wash load based on the hydraulic characteristics of a river. Most total load equations are therefore, total bed material load equation.

A second consideration in deciding what formulas to use is the type of stream or river condition that exist. It is important to select formula that was developed under conditions similar to the problem.

In addition to the use of purely analytical or empirical formulas ,there are methods available for evaluating bed material discharge based on measured suspended load and other normal stream flow measurement. By use of observed data these result are usually more accurate and reliable than those given by other formulas. In using any sediment transport methodology, consideration should be given to solution by size fraction. Different transport capacity can be expected for different sediment size and some loss in accuracy may result from a calculation from based on a single representative grain size. The most commonly used sediment transport equations L.van Rijn [5] are the following.

1. Shield equation

Shields used the concept of excess shear responsible for the transport and presented a dimmentionally homogeneous equation.

$$\frac{q_b \Delta}{qS} = 10(\tau_o - \tau_c)/\rho g \Delta d \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.1$$

Where qb is bed load per unit width, q is Unit discharge in the channel.

Equation 2.1 is dimensionally homogeneous, and can be used for any system of unit and it is based on the range $0.06 < \Delta < 3.2$ and $1.56 \text{ mm} < d < 2.47\text{mm}$.

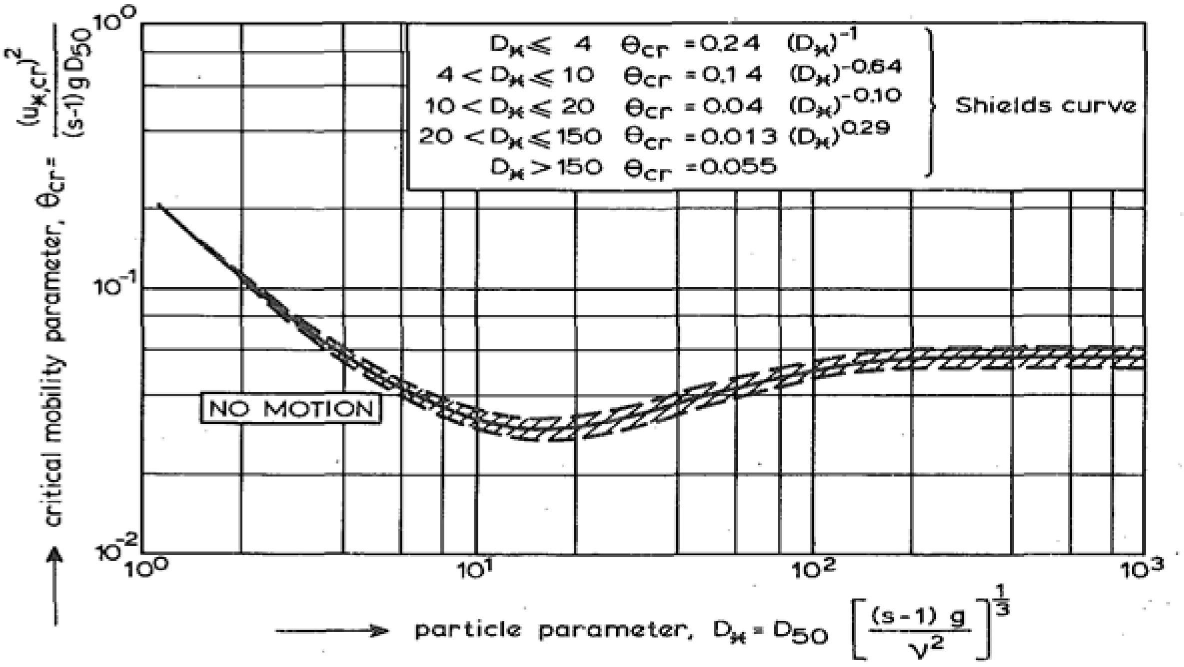


Figure 2.3: Initiation of motion (Shield curve)

According to Shield initiation of motion and sediment transport must depend on at least, boundary shear stress, sediment and fluid density (buoyancy) and grain size of sediment. The result determined a non-dimensional grouping that combines these factors and served to collapse a great range of experimental data to single curve (Figure 2.3).

2. Einstein Equation

Introducing probability concepts of sediment movement Einstein developed an empirical relationship $\phi = f(\varphi)$……………………………………..…………………...……………………2.2

Where φ is shear intensity or flow parameter and ϕ is transport parameter

3. Meyer- peter and Muller formula

Equation 2.3 is the Meyer-peter,Muller equation which is a simple and commonly used equation for evaluating the bed material transport in a cobble-bed stream. Most of the data used in developing the equation were obtained in flows with little or no suspended load. A common form of the equation is:-

$$q_b = \frac{12.85}{\sqrt{p}\,\gamma_s}(\tau_o - \tau_c)^{1.5} \qquad \text{……….2.3}$$

Where qb is Bed load transport rate in volume per unit width for specific size of sediment, τ_o is tractive force (boundary shear stress), ρ is density of water, τ_c is Critical tractive force and γ_s is specific weight of sediment.

2.2 Reservoir Sedimentation

2.2.1 Reservoir sedimentation processes

The principal sedimentation processes in reservoirs fall into three basic categories:

1. Deltaic deposition of primarily Coarse materials.

2. Deposition of fine sediments from homogeneous flow.

3. Transport and deposition of usually fine sediment from stratified flow.

Delta deposits are formed where streams enter the reservoir pool and coarse materials are deposited from a homogeneous (non-stratified) flow as velocity and transport capacity diminishes. The delta may be divided into two zones, the topset bed and the foreset bed (Figure2.3). The topset bed has a milder slope than the now-submerged river.

Particles of bed material size predominate in delta topset deposits, but finer particles also can be present. Wash load particles begin to predominate downstream of the topset deposits. The transition from topset to foreset beds in the delta typically coincides with the plunge point of the density current. That is, it marks the transition from non-stratified to stratified flow. In practice, the location of the plunge point is mobile and particularly sensitive to changes in discharge.

Driven by the density differences between the sediment-laden inflow and the clear water in the reservoir, the density current plunges beneath the clear water and moves toward the dam as a submerged current. Where there is inadequate sediment concentration or depth for a density current to form, non-stratified flow will occur throughout the reservoir.

Sediments will settle out of the density current and be deposited along the length of the reservoir as the current moves toward the dam. Under unfavorable conditions, such as inadequate bottom slope or insufficient flood duration, the density current will dissipate before it reaches the dam.

Both density currents and homogeneous flow tend to deposit sediments in horizontal strata or thin bands across the floor of the reservoir. Under favorable conditions a density current can transport silts and clays many tens of kilometers until its motion is blocked by the dam structure or an upstream cofferdam. At this point, it will create a muddy lake of sediment-laden water, which will gradually settle to form deposits of (typically) fine-grained material.

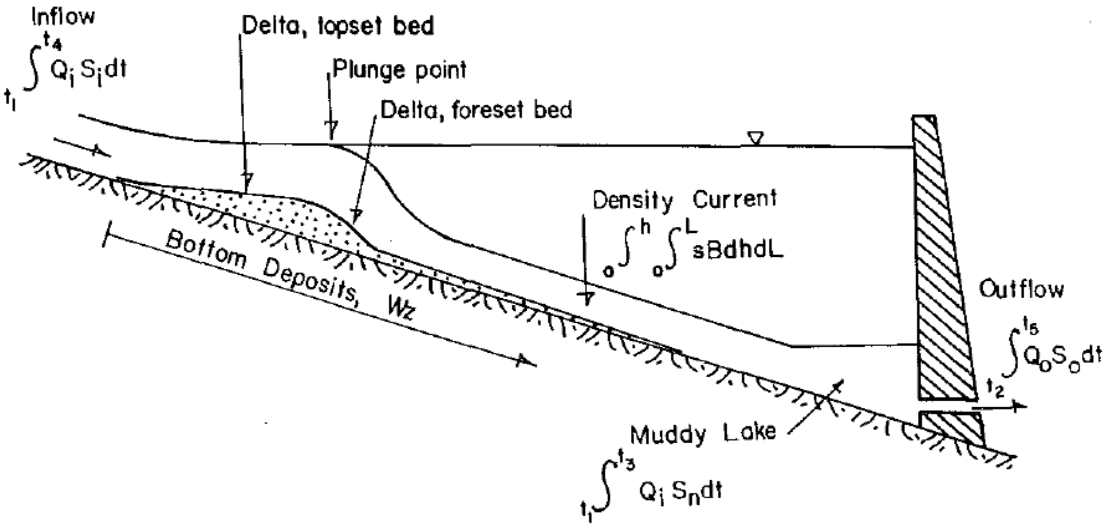


Figure 2.4: Schematic representation of Siltation process in Reservoir [12].

Where Q is river discharge, s is bed slope, h is thickness of turbid water in muddy lake and L is length of turbid water.

2.2.2 Main impacts of reservoirs sedimentation

2.2.2.1 Storage loss

It is usually the main impact for dams devoted to water storage as their benefit is quite proportional to the storage. This impact is lower for dams devoted to hydropower: their benefit may possibly be reduced by fewer than 20% when the reservoir is 80% filled (including a large part in the designed dead storage).

2.2.2.2 Turbines abrasion:

Sediment coarser than 0.1 mm may greatly accelerate the erosion of turbines parts; even smaller grain sizes may cause damages if containing quartz. It may be the main siltation problem for high head hydropower. Also sediment concentration and total head are important factors.

2.2.2.3 Downstream impacts

River reaches downstream of dams suffer large environmental impacts due to flow changes, reduction of sediment load, altered nutrient dynamics, temperature changes, and the presence of the migration barrier imposed by the structure and the upstream impoundment. Clear water released from the reservoir will cause downstream erosion and possibly bank failures.

Sediment trapping by dams can even affect coastal morphology. It sometimes becomes a major factor contributing to the rapid shoreline recession and subsidence. One way of reducing this impact may be to build run-of-river hydroelectric projects which would allow passage of 100% of the fines and an important portion of the bed load.

2.3 Reservoir sedimentation management options

2.3.1 Sediment trapping upstream of the dam

There are only two strategies to reduce the sediment yield entering a reservoir: either prevent erosion or trap eroded sediment before it reaches the reservoir. The rehabilitation of some watersheds can dramatically reduce the rate at which sediment, nutrients, and other contaminants are delivered to a reservoir. The preventive method is through vegetative measure which is planting and establishment of quick growing vegetation. Sediment could trap before it reaches the reservoir through structural measures.

These measures include structural terraces, flood interception and diversion works, channel protection and stabilization works, check dams and silt trapping dams.

2.3.2 Sediment Routing

Sediment routing includes any method to manipulate reservoir hydraulics, geometry, or both, to pass sediment through or around reservoir or intake areas while minimizing objectionable deposition. Routing is the most environmentally benign sediment management strategy. Sediment routing techniques include sediment passing through and sediment by pass.

2.3.2.1 Sediment pass through

It may be by seasonal drawdown, by drawdown adapted to floods or by turbidity currents. This requires initial implementation of the necessary bottom gates to be designed with great care.

A reservoir operated under seasonal drawdown is either partially or completely emptied during the beginning of flood season. Seasonal drawdown is conducted during a predetermined period each year, as opposed to flood routing, which requires that the reservoir level be drawn down for individual flood events when they occur. At some sites routing can be implemented at very low cost. A major disadvantage of sediment routing is that a significant amount of water must be released during floods to transport sediments. Sediment routing is most applicable at hydrologically small reservoirs where the water discharged by large sediment-transporting floods exceeds the reservoir capacity, making water available for sediment release without infringing on beneficial uses. Analysis of this intervention showed that the reservoir could last 20 to 50 years longer.

2.3.2.2 Sediment Bypass for Reservoirs

When topographic conditions are favorable (for this reason also the site selection is important), a large-capacity channel or tunnel can be constructed to bypass sediment-laden flow around the reservoir or part of it. It may be built initially and possibly used for flood control during construction. Most may also be built according to precise needs after years or decades of operation. Such tunnel may be associated with a low dam in the upstream part of the reservoir. It may bypass some hundred m3/s or even thousand m3/s of water. This solution may have much future for large schemes. As confirmed by the study of ICOLD [13] the bypass system managed to control 90% of the sediment.

2.3.3 Sediment flushing

Hydraulic flushing involves reservoir drawdown by opening a low-level outlet to temporarily establish riverine flow along the impounded reach, eroding a channel through the deposits and flushing the eroded sediment through the outlet. Unlike sediment routing, which attempts to prevent deposition during flood events, flushing uses drawdown and emptying to scour and release sediment after it has been deposited. Usually flushing is less efficient if the sediment is coarse or is consolidated clay materials.

The width of a flushing channel within sediments is often in the range of 100 m and may reach few hundred m; flushing is thus much more efficient in narrow valleys.

2.3.4 Managing the silt storage

It is usually difficult to drawdown completely the large hydropower reservoirs but it is usually possible to drawdown the reservoir by 20 % or 30 % at the flood time in order to store the sediment in the dead storage and to pass through most sediment when the dead storage is full. Corresponding gates may be 20 to 50 m under the dam crest. Turbines abrasion may be a key problem for high head hydropower and many de-silting underground chambers along head race tunnels designed for avoiding it proofed costly and poorly efficient. The stored sediment may be flushed from time to time or dredged permanently.

2.3.5 Removing stored sediment

Sediment deposits may be mechanically removed from reservoirs by dry excavation or hydraulic dredging and hydro-suction.

2.3.5.1 Dry Excavation

All methods of mechanical excavation are costly because of the large volumes of material involved and, frequently, the difficulty of obtaining suitable sites for placement of the excavated material within an economic distance of the impoundment. However, once sediments are deposited in a reservoir, excavation may be the best management option available. It was concluded that dry excavation while the reservoir is empty may be the most economically feasible countermeasure even if reduced power production and water production is taken into consideration [13].

2.3.6 Phased dam construction

It may be difficult to avoid the reservoir siltation but many earth fill irrigation dams may be designed for an easy level increase after 20 or 100 years of operation. Raising by 5 m a 30 m high dam may quite double the storage when necessary.

2.4 Soil erosion and hydrological models

Sustainable land management and water resources development are threatened by soil erosion and sediment-related problems. In response to such threats, there is an urgent need to estimate soil loss and identify risky areas for improved catchment-based erosion control and sediment management strategies.

These models are generally meant to describe the physical processes controlling the transformation of precipitation to runoff and detachment and transport of sediments.

Tremendous numbers of soil erosion and sediment transport models have been developed based on laboratory, field, analytical and numerical methods such as finite difference and finite element. Generally, as cited by Lulseged Tamene [14] there are two main types of model formulation for predicting soil erosion, which are empirically and physically based.

According to U. C. Kothyari [15] Empirical models are based on extensive experimental results and input-output relationships. Such models have constraints of applicability to regions and ecological conditions others than from which data were used in their development. Examples of empirical models include methods such as the Universal Soil Loss Equation (USLE), the Modified Universal Soil Loss Equation (MUSLE).

The Universal Soil Loss Equation (USLE) model was suggested first based on the concept of the separation and transport of particles from rainfall by Wischmeier W.H and Smith DD [16] in order to calculate the amount of soil erosion in agricultural areas. The parameters of the USLE method hold good estimate of amount of detached soil at plot-size areas.

The Modified Universal Soil Loss Equation (MUSLE) was modified from the USLE by Williams, J.R [17] by replacing the factor R (rainfall factor) with a runoff factor. The MUSLE considers both surface erosion and sediment movement in the catchment. Physical process-based models are based on computation of erosion using mathematical representations of fundamental hydrologic and erosion processes incorporating soil detachment and transport [8] .They are useful for inferring the distribution, magnitude, and past, present and future behavior of a process with limited observations. Such models may be applied across multiple landscapes and situations because the mathematical relationships are derived from physical laws, which must be obeyed under all circumstances. Some examples of process-based deterministic models include the

Water Erosion Prediction Project (WEPP) and European Soil Erosion Model (EUROSEM). The major limitation of these models is that they are too complicated for initial assessment of erosion reconnaissance surveys and suffer from high computational costs. These models also require high input with high spatial resolution in order to apply them to the full range of field conditions.

Recently, spatially distributed terrain-based models that emphasize the effect of terrain shape and topographic complexity on erosion/distribution processes have been in common use. This is due to the development of digital elevation models (DEMs) and GIS which have promoted the application of distributed soil erosion and sediment delivery models at the catchment scale. The central idea behind their theory is that topography is the dominant control over the spatial variation of hydrological processes and therefore topographic forms with additional basic soil and land cover related parameters can permit rapid estimation of spatial patterns over substantial areas and complex landscapes [14].

Selection of models is generally determined by the objective at hand, resources available and detail and scale of investigation required. Because, it is difficult to reliably apply most of the models developed in the “data-rich” Western regions to developing countries, where both data availability and quality are critically poor. Considering the above issues, the physically based distributed model ArcGIS interface Soil and water assessment tool (SWAT) was applied in this study.

ArcGIS interface Soil and Water Assessment Tool (ArcSWAT) is a physical process based model to simulate the process at catchment scale. It divides a catchment or basin in to sub-basins by hydrological response unit (HRU) based on soil type, land use and management practice. Thus, dividing the basin into HRU will simulate the hydrological process in detail. The model uses the MUSLE to estimate sediment yields and Bagnold's equation to route the sediment loads. It is one of the watershed models for long term impact analysis. It is widely applied in many parts of United States and many other countries including Ethiopia.

2.4.1 Application of ArcSWAT Model

ArcSWAT can be used to simulate a single watershed or a system of multiple hydrologically connected watersheds. The first step in setting up a watershed simulation is to partition the watershed into subunits. ArcSWAT allows several different subunits to be defined within watershed. According to J.G. Arnold et.al [18] each watershed is first divided into subbasins and then in hydrologic response units (HRUs) based on the land use and soil distributions.

The first level of subdivision is the sub basin. Sub basins possess a geographic position in the water shade and are spatially related to one another. The sub basin delineation may be obtained from sub watershed boundaries that are defined by surface topography so that the entire area within the sub basin flows to the sub basin outlet. A sub basin will contain at least one HRU, a tributary channel and main channel or reach.

The land area in a sub basin may divide into hydrologic response units (HRUs) that possess unique land use / management / soil attributes. HRUs are used in most ArcSWAT runs since they simplify a run by lumping all similar soil land use areas into a single response unit. Loadings (runoff with sediment etc) from each HRU are calculate separately and ten summed together to determine the total loadings from sub basin.

One reach or main channel is associate with each sub basin in a watershed. Loadings from sub basin enter the channel network of the watershed in associated reach segment. Out flow from the upstream reach will also enter reach segment.

Tributary channel inputs are used to calculate the time of concentration for channelized flow of runoff generated within the sub basin and transmission losses from runoff as it flows to the main channel.

Water bodies within the watershed should be modeled as ponds, wetland or reservoirs. Two water bodies (ponds / wetlands) may be defined within each sub basin. Water entering these impoundments is generated in the sub basin (i.e, they cannot receive water originating in other sub basin).In contrast, reservoirs receive water contributed to the channel network from all upstream sub basin. ArcSWAT directly models the loading of water, sediment and nutrients from land areas in a watershed. However, some watersheds will have loading to the stream network from source not associated within the land area. These are referred to as point sources.

In order to account for the loadings from point sources, SWAT allows users to add daily or average daily loading data for point source to the main channel network. These loadings are then routed through the channel network along with the loadings generated by the land area.

2.5 Erosion Class of Subbasin

Subbasins can be classified as low, medium and high erosion class depending on their sediment yield (Table 2.1). This classification is used to give priority for critical subbasin. According to Sanjeet Kumar et.al [19] subbasin of watershed classified as high erosion class subbasin if the annual sediment yield of the subbasin is greater than 20 tons/ha.

Table 2.1: Erosion Class Classification [19].

Sediment yield (tons/Km^2/year)	Sediment yield (tons/ha/year)	Erosion class
0-500	0-5	Low
500-2000	5-20	Medium
>2000	>20	High

2.6 Previous study

The first study conducted in the area is the Wabe Shebelle river basin integrated master plan by BCEOM and MWIE [20]. According to the report the mean annual suspended sediment load transports of Melka Wakena watershed were 25.1 tons/Km^2/year, and mean annual sediment load is calculated with the approximate equation of:- Qs annual (Million m^3) is equal to

$$Q_s = \{[2.9283 \times \ln(watershed\ area\ Km^2) - 24.011] - 0.6\} \times 1.25$$

According to the detailed project report of Melka Wakena hydropower project by all-union designing, surveying and research institute the average long term sediment load at Melka Wakena reservoir was estimated at 74000 ton/year at the mean annual sediment flow of 2.35Kg/s. And they conclude that erosion was not a problem and there is no need to plan soil conservation work. However, the current situation of the area is changed due to deforestation and land use change.

Hurni, H [22] is the other researcher conduct research to estimate the rates of soil formation around the watershed. The research estimated the rates of soil formation for Ethiopia. Accordingly result showed that the ranges of the tolerable soil loss level for the various agro-ecological zones of Ethiopia were varies between 2 and 18t/ha/year. As shown in Table 2.2 Welega, Kefa and Shewa Zone are the most area where soil erosion is high.

Table 2.2: Zonal Variability of soil erosion rates [22].

Zone	Soil erosion rates (tons/ha/year)	Soil erosion rates (tons/Km^2/year)
Gonder, Rift valley	6-10	600-1000
Gojam, Arsi regions	10-14	1000-1400
Welega, Kefa, Shewa	18-22	1800-2200
Gamo gofa	10-14	1000-1400
Kenya border	6-10	600-1000

3 METHODS AND METHODOLOGY

3.1 Arc SWAT Model Input

Arc SWAT model which is an ArcGIS interface needed input files including the digital elevation model (DEM), land cover, and soil layers. Observed maximum and minimum temperature, precipitation, solar radiation, wind speed and relative humidity can be incorporated. If observed weather data are not available, weather can be generated. A negative 99.0 (-99.0) should be inserted for missing data. This value tells ArcSWAT to generate missing data for that day. ArcSWAT was used to create the initial model input files. It processes mapped land use, Slope and soils data as well as a Digital Elevation Model (DEM) to create a set of default model input files. The DEM can be utilized by ArcSWAT to delineate basin or watershed and subbasin boundaries, calculate subbasin average slopes and delineate the stream network. Within each subbasin, HRUs are created by the model. Study of M.Winchell et.al [23] shows HRU creation in ArcSWAT requires land use and soil threshold inputs in order to define the level of spatial detail to include in the model. These thresholds are applied to each subbasin and function to control the size and number of HRUs created. The model calculates surface runoff and sediment transport for each HRU. All model inputs map were preprocessed and re projected to WGS 1984 UTM Zone 37N (Transverse Mercator of Northern hemisphere zone 37) projection. The Sources and preparation of the basic model inputs are described in the following sections.

3.1.1 Digital Elevation Model (DEM)

Topography was defined by a Digital Elevation Model (DEM), which describes the elevation of any point in a given area at a specific spatial resolution as a digital file [6]. A digital elevation model is needed for raster-based hydrological analysis in a GIS. DEM of the study area with the resolution of 90m by 90m was found and it is used to analyze the drainage patterns of the land-surface terrain. Subbasin parameters such as slope, slope length, and defining of the stream network with its characteristics such as channel slope, length, and width was derived from the DEM.

3.1.2 Soil Data

The soils database describes the surface and upper subsurface of a watershed and is used to determine a water budget for the soil profile, daily runoff and erosion. ArcSWAT model requires textural properties and physico-chemical-properties for each soil layers. In this database all the soil in the area are represented, and coupled with its characteristics. Based on data obtained from Ministry of water, irrigation and energy five soil types namely, Luvisols, Vertisols, Nitosols, Andosols and Cambisols are common in the watershed and Table 3.1 shows the major soil of Melka Wakena watershed with their percentage of coverage.

Table 3.1: Major soil of Melka Wakena Watershed

Name of soil	SWAT soil class	Hydrologic soil group	Percentage of total area
Andosols	Humic Andosols	B	6.55
Cambisols	Vertic Cambisols	C	0.62
Chernozems	Luvic Chernozems	A	30.63
Vertisols	Eutric Vertisols	C	25.35
Luvisols	Chromic Luvisols	B	27.95
Nitisols	Humic Nitisols	B	8.63
Leptosols	Lithic Leptosols	A	0.26

3.1.3 Land Use / Land Cover

Land use and cover affect surface erosion, water runoff, and Evapotranspiration in a watershed. The available land use /cover map for the study area was taken from Ministry of Water, irrigation and Energy of Ethiopia. As shown in Table 3.2 the land use and land cover of the area are Afroalpine, dense forest, open grassland, open forest moderately cultivated and intensively cultivated in increasing order of their area coverage.

Table 3.2: Land use/land cover of Melka Wakena Watershed

Land cover type	SWAT land use class	SWAT code	Percentage of total area
Afroalpine	Forest Evergreen	FRSE	2.76
Dense Forest	Forest Deciduous	FRSD	9.36
Intensively cultivated	Durum Wheat	DWHT	48.58
Moderately cultivated	Corn	CORN	13.0
Open forest	Forest Mixed	FRST	13.35
Open grassland	Pasture	PAST	12.94

3.1.4 Meteorological Data

The weather variables for driving the hydrological balance are precipitation, air temperature, solar radiation, wind speed and relative humidity. ArcSWAT requires daily data of precipitation when the SCS curve number method is chosen to model surface runoff. Maximum and minimum daily air temperature, daily solar radiations are also required. Most of the raw data are not complete; therefore missing data are generated by weather generator.

The ArcSWAT weather generator model WXGEN input file contains statistical data needed to generate representative daily climate data for the subbasins. Climatic data will be generated in two instances: when the user specifies that simulated weather will be used or when measured data is missing.

The metrological input of the model were prepared first by analyzing, modifying, and entering in the right format which is Text (Tab delimited) of the daily data and secondly obtaining and analyzing the required monthly statistical weather parameters for the weather generator (i.e. Awasa station) . The missing values within the meteorological input (i.e. Hunte , Kofele ,Meraro and Robe stations) will be generated by the weather generator.

These monthly statistical weather parameters for the weather generator were estimated by using empirical formula in the ArcSWAT user manual, pcpSTAT and dewpoint software which were designed by Stefan Liersch in 2003. PcpSTAT calculates statistical parameters of average daily precipitation data. Dewpoint calculate the average daily dewpoint temperature per month using daily air temperature and humidity data. The calculated parameters are given in appendix 1.

The weather generator first independently generates precipitation for the day. Then maximum temperature, minimum temperature, solar radiation and relative humidity are generated based on the presence or absence of rain for the day. Finally, wind speed generated independently.

The daily precipitation generator is a Markov chain-Skewed model [24]. A first-order Markov chain is used to define the day as wet or dry. When a wet day is generated, a Skewed distribution is used to generate precipitation amount.

With the first-order Markov chain model, the probability of rain on a given day is conditioned on the wet or dry status of the previous day. A wet day is defined as a day with 0.1 mm of rain or more. The probability of wet or dry day is given by Equation 3.1 and 3.2.

$$P_i\left(\frac{D}{W}\right)=1-P_i\left(\frac{W}{W}\right) \qquad \text{………………………………………………………………………….3.1}$$

$$P_i\left(\frac{D}{D}\right)=1-P_i\left(\frac{W}{D}\right) \qquad \text{………………………………………………………………………….3.2}$$

Where P_i (D/W) is probability of dry day on a day i given a wet day on a day i-1 and P_i (D/D) is probability of dry day on a day i given a dry day on a day i-1

To define a day as wet or dry, ArcSWAT generates a random number between 0.0 and 1.0. This random number is then compared to the appropriate wet-dry probability. If the random number is equal to or less than the wet-dry probability, the day is defined as wet day. If random number is greater than the wet-dry probability, the day is defined as dry.

3.1.5 Hydrological data

Time series of runoff volume read from records of observed data which were obtained from Hydrology department of Water, irrigation and energy of Ethiopia and sediment yield obtained by using regional equation are used to perform Sensitivity analysis, calibrate and validation of the ArcSWAT model.

Regional sediment equation is used to compute Suspended sediment load when measured load is not available for the study area [21]. Then bed load is taken as 20% of suspended sediment load. This equation was developed from main hydropower sites in Ethiopia (Table 3.3). Coefficient of determination (r^2) value of the Equation 3.1 is 0.9.

Suspended sediment inflow (ton/km^2/year) = $44085 * A^{(-0.57083)} * RO^{(0.4674)}$ ………………….…3.3

Where A is Watershed area (km^2) and RO is Annual runoff (mm/year).

Sediment load of Melka Wakena watershed is calculated using Equation 3.1 with annual runoff record of Wabi at Melka Wakena station.

Table 3.3: Data used to derive regional sediment equation for large dams in Ethiopia [21].

Hydropower reservoirs	Tons/Km2/year	Watershed area (Km2)	Annual runoff (mm/yr)
Gibe III	1900	34400	450
Tekeze Dam	1283	30390	123
Karadobi Dam	1150	82230	350
Wabi Shebele at Hamaro	296	63455	49

Table 3.4: Metrological and Hydrological data used in the study

Data Type	Year of record	Stations name	Source	Frequency
Precipitation	1985-2013	• Awasa • Hunte • Kofele • Meraro • Robe	National Metrological Agency of Ethiopia	Daily
Temperature	1985-2013			Daily
Relative humidity	2000-2013			Daily
Wind speed	1991-2013			Daily
River flow	1989-2000	• Asasa • Furuna at Adaba • Herero • Leliso at Adaba • Maribo at Adaba • Maribo at Changuity • Ukuma • Wabi at Bridge • Wabi at Melka Wakena	Ministry of Water, Irrigation and Energy of Ethiopia	Daily
Sediment load	1989-2000	Wabi at Melka Wakena	Regional Equation	Yearly

3.2 ArcSWAT Model Description

3.2.1 Overview of ArcSWAT Model

The Soil and Water Assessment Tool (SWAT) model is developed by the USDA Agricultural Research Service [23], which simulates the land phase of the hydrologic cycle in daily basis. SWAT predicts surface runoff using the Soil Conservation Service (SCS) curve number (CN) method and it used daily rainfall data as an input. The modified universal soil-loss equation is used to predict the sediment loss. The SWAT model is designed to route water and sediments from individual watersheds through the river systems. It can incorporate the tanks and the reservoirs/check dam off-stream as well as on-stream. The agricultural areas can also be integrated with respect to its management practices.

The ArcSWAT ArcGIS extension evolved from AVSWAT2000 an ArcView extension developed for an earlier version of SWAT [23] .The interface requires the designation of land use, soil, weather, groundwater, water use, management, soil chemistry, pond, and stream water quality data, as well as the simulation period, in order to ensure a successful simulation.

The major advantage of the model is that unlike the other conventional conceptual simulation models, it does not require much calibration and therefore can be used on ungagged watersheds; it is physically based; it uses readily available inputs; it is computationally efficient to operate on large basins in a reasonable time; it is continuous time and capable of simulating long periods for computing the effects of management changes [25].

3.2.2 Hydrological component of ArcSWAT model

SWAT in the land phase simulates the hydrological cycle based on the water balance equation. Equation 3.1 used to determine the soil water content of the watershed.

$$SW_t = SW_o + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw} \right)_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots....3.4$$

Where SW_t is the final soil water content (mm), SW_0 is the initial soil water content (mm), t is time (days), R_{day} is the amount of precipitation on day i (mm), Q_{surf} is the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), W_{seep} is the amount of water entering the vadose level zone from the soil profile on day i (mm), and Q_{gw} is the amount of return flow on day i (mm) [26].

3.2.3 Sediment component of ArcSWAT model

Erosion and sediment yield in SWAT are estimated for each HRU with the Modified Universal Soil Loss Equation (MUSLE). It uses the amount of runoff to simulate erosion and sediment yield. The hydrology module/component supplies estimates of runoff volume and peak runoff rate, which, with the subbasin area, are used to calculate the runoff erosive energy variable. The crop management factor is recalculated every day that runoff occurs. It is a function of above ground biomass, residue on the soil surface, and the minimum crop factor for the plant [25].

3.2.4 Routing phase of the hydrologic model

The studies by Setegn et.al [26] show that sediment transport in the channel network consists of two components operating simultaneously, which are deposition and degradation. To determine the deposition and degradation process the maximum concentration of sediment is calculated using Equation 3.2.

$$Conc_{sed,ch,mx} = C_{sp} * V_{ch,pk}^{sp\exp} \quad \text{…………………………………………………………...….3.5}$$

Where $Conc_{sed,ch,mx}$ is the maximum concentration of sediment that can be transported by the water (ton/m^3 or kg/L), C_{sp} is the coefficient defined by the user, $V_{ch,pk}$ is the peak channel velocity (m/s), and sp exp is an exponent parameter for calculating sediment re-entrained in channel sediment routing that is defined by the user and set at 1.5 for this particular study. It normally varies between 1 and 2.

The peak channel velocity, $V_{ch,pk,}$ is calculated by using Equation 3.3.

$$V_{ch,pk} = \frac{prf * q_{ch}}{A_{ch}} \quad \text{……………………………………………………………….…….3.6}$$

Where prf is the peak rate adjustment factor (a user specified parameter), q_{ch} is the average rate of flow (m^3/ s), and A_{ch} is the cross sectional area of flow (m^2).

The maximum concentration of sediment ($Conc_{sed,ch,mx}$) that is calculated from the previous equation is compared to the concentration of sediment in the reach at the beginning of the time step $Conc_{sed,ch,i}$. If $Conc_{sed,ch,i} > Conc_{sed,ch,mx}$, deposition is the dominant process in the reach segment, Equation 3.4 used to calculate the net amount of sediment deposited in the reach.

$$Sed_{dep} = \left(Conc_{sed,ch,i} - Conc_{sed,ch,mx}\right) * V_{ch} \quad \ldots\ldots 3.7$$

Where Sed_{dep} is the amount of sediment deposited in the reach segment (metric tons) and V_{ch} is the volume of water in the reach segment (m^3).

If $Conc_{sed,ch,i} < Conc_{sed,ch,mx}$ degradation is the dominant process in the reach segment and the net amount of sediment re-entrained is calculated by Equation 3.5.

$$Sed_{\deg} = \left(Conc_{sed,ch,mx} - Conc_{sed,ch,i}\right) * V_{ch} * K_{ch} * C_{ch} \quad \ldots\ldots 3.8$$

In which, Sed_{deg} is the amount of sediment re-entrained in the reach segment (metric tons) , K_{ch} is the channel erodibility factor (cm/hr/pa), and C_{ch} is the channel cover factor.

The channel erodibility factor (K_{ch}) is conceptually similar to the soil erodibility factor in the Universal Soil Loss Equation (USLE) [18]. Channel erodibility is a function of properties of the bed or bank materials. In general, values for channel erodibility are an order of magnitude smaller than values for soil erodibility. The channel cover can be defined as a ratio of degradation from a channel with a specified vegetative cover to the corresponding degradation from a channel with no vegetative cover [18]. The vegetation affects degradation by reducing the stream velocity, and consequently its erosive power, near the bed surface.

Once the amount of deposition and degradation is calculated, Equation 3.6 is used to determine the final amount of sediment in a reach.

$$Sed_{ch} = Sed_{ch,i} - Sed_{dep} + Sed_{deg} \quad \ldots\ldots 3.9$$

In which, Sed_{ch} is the amount of suspended sediment in the reach (metric tons), $Sed_{ch,i}$ is the amount of suspended sediment in the reach at the beginning of the time period (metric tons), Sed_{dep} is the amount of sediment deposited in the reach segment (metric tons), and Sed_{deg} is the amount of sediment re-entrained in the reach segment (metric tons).

Finally Equation 3.7 is used to calculate the amount of sediment transported out of the reach.

$$Sed_{out} = Sed_{ch} * \frac{V_{out}}{V_{ch}} \quad \ldots\ldots 3.10$$

In which, Sed_{out} is the amount of sediment transported out of the reach (t), Sed_{ch} is the amount of suspended sediment in the reach (t), V_{out} is the volume of out flow during the time step (m^3), and V_{ch} is the volume of water in the reach segment (m^3).

3.3 ArcSWAT Model Setup

3.3.1 Watershed delineation

The first step in creating ArcSWAT model input is delineation of the watershed from a DEM. Inputs entered into the ArcSWAT model were organized to have spatial characteristics. Before going in hand with spatial input data i.e. the soil map, Land use / land cover map and the DEM were projected into the same projection called UTM Zone 37N, which is a projection parameters for Ethiopia. A watershed was partitioned into a number of sub-basins, for modeling purposes. The watershed delineation process includes five major steps, DEM setup, stream definition, outlet and inlet definition, watershed outlets selection and definition and calculation of sub-basin parameters. For the stream definition the threshold based stream definition option was used to define the minimum size of the sub-basins.

3.3.2 Hydrological Response Units (HRUs)

The land area in a sub-basin was divided into HRUs. The HRU analysis tool in ArcSWAT helped to load land use, soil layers and slope map to the project. The delineated watershed by ArcSWAT and the prepared land use and soil layers were overlayed 100 %. HRU analysis in ArcSWAT includes divisions of HRUs by slope classes in addition to land use and soils. The multiple slope option (an option which considers different slope classes for HRU definition) was selected. The land use / land cover, soil and slope map was reclassified in order to correspond with the parameters in the ArcSWAT database. After reclassifying the land use, soil and slope in ArcSWAT database, all these physical properties were made to be overlaid for HRU definition. For this thesis a 5% threshold value for land use, 5 % for soil and 10 % for slope were used. The HRU distribution in this study was determined by assigning multiple HRU to each sub-basin.

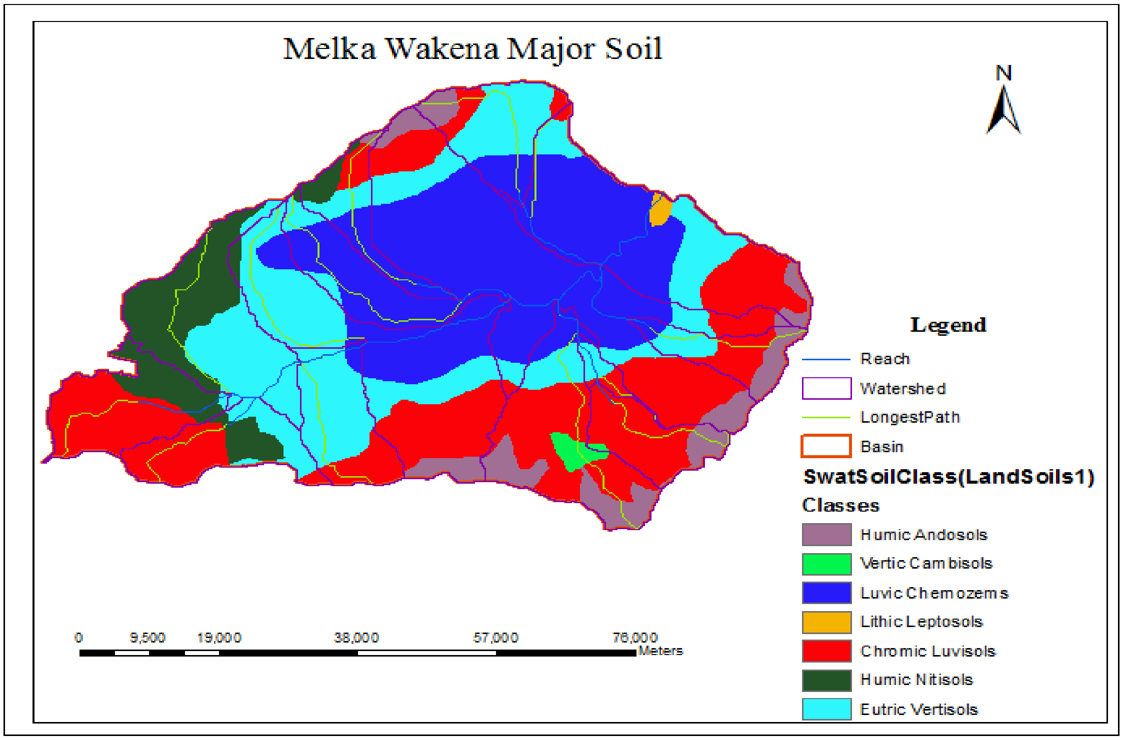


Figure 3.1: Major Soil of Melka Wakena Watershed

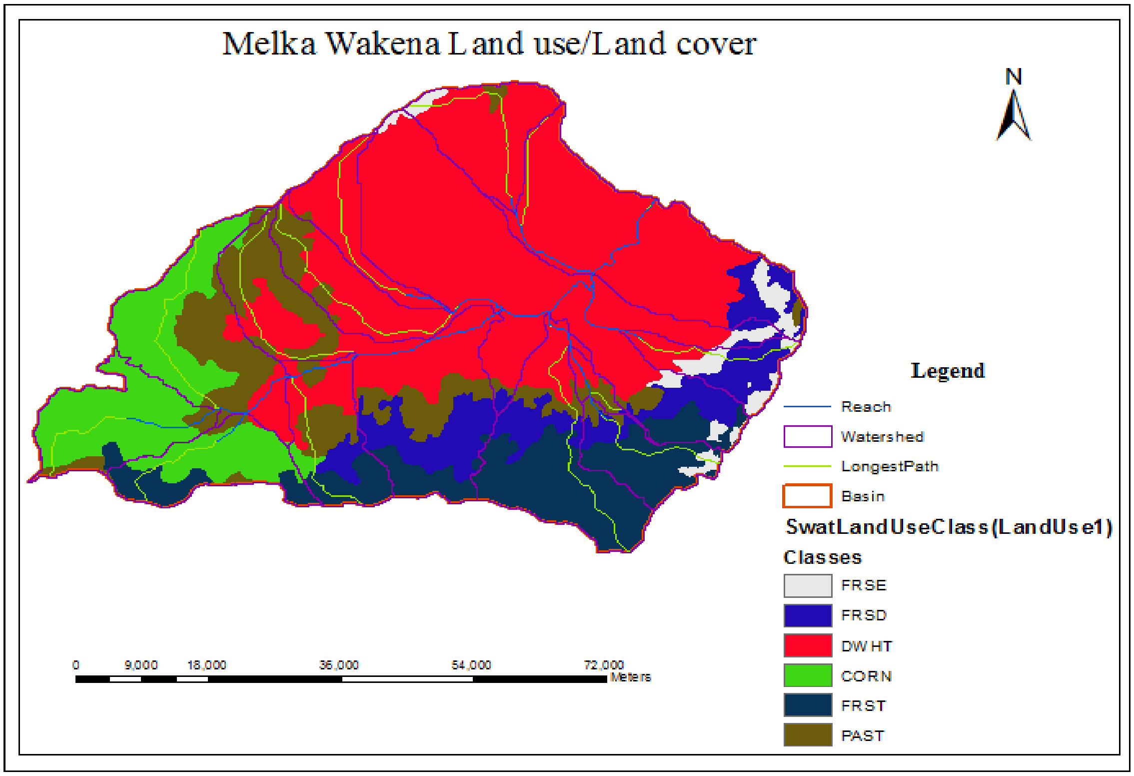


Figure 3.2: Land use/ land cover of Melka Wakena Watershed

With 5% threshold of soil map Figure 3.1 shows Luvic Chernozems, Chromic Luvisols and Eutric Vertisols ranks first to third with their percentage of watershed area coverage. Figure 3.2 shows that land use of the watershed is dominated by intensive and moderate cultivation and all land use of the area are reclassified in order to correspond with the parameters in the SWAT database. In Figure 3.2 where FRSE is Afroalpine, FRSD is Dense forest, DWHT is Intensively cultivated, CORN is Moderately cultivated, FRST is Open forest and PAST is Open grassland land cover of the watershed according to ArcSWAT database.

3.3.3 Write Weather Data

Metrological or weather data are then loaded into the model in text (tab delimited) format. The ArcSWAT database is linked to the layers data in order to find all the parameters necessary for estimating the sediment yield at each HRU.

3.3.4 Sensitivity analysis

After a thorough preprocessing of the required input for ArcSWAT model, flow simulation was performed for eleven years of recording periods starting from 1989 through 1999. The first year of which was used as a warm up period and the simulation was then used for sensitivity analysis of hydrologic parameters and for calibration of the model. The sensitivity analysis was made using a built-in ArcSWAT sensitivity analysis tool that uses the Latin Hypercube One-factor-At-a-Time (LH-OAT). After the analysis, the mean relative sensitivity (MRS) of the parameters was used to rank the parameters, and their category of sensitivity was also defined based on the Lenhart.T, et.al [27] classification. The study result divided sensitivity into four classes: small to negligible ($0<MRS<0.05$), medium ($0.05<MRS<0.2$), high ($0.20<MRS<1.0$), and very high ($MRS>1.0$).

3.3.5 Model Calibration

The aim of model calibration is to achieve a reduction in model uncertainty by efficiently extracting information contained in the calibration data. It involves the comparison of model simulation with an observed data on predefined objective function and adjusting parameters to improve closeness.

ArcSWAT model can be calibrated both manually and automatically. The manual calibration is most widely used calibration and involves visual comparison of observed and simulated data.

It uses trial and error to adjust the parameters and closeness is evaluated with several criteria and especially recommended for the application of more complicated models in which a good graphical representation is a prerequisite. Alternatively, an automatic calibration involves the use of a numerical algorithm, which finds the optimum of a given numerical objective function. This is carried out by applying the model to numerous combinations and permutations of parameter levels, in order to find the best parameter set in terms of satisfying the criterion of accuracy.

In this thesis work both Manual and automatic calibration methods were applied. First the parameters were automatically calibrated for flow for the period of 1990 to 1994 until the model simulation results were acceptable as per the model performance measures. Next, the final parameter values that were automatically calibrated were used as the initial values for the manual calibration procedure of flow. The model was calibrated for sediment for the period of 1990 to 1995 for yearly time step. The graphical and statistical approaches were used to evaluate the ArcSWAT model performance a number of times until the acceptable values were obtained for flow and sediment independently.

3.3.6 Model Validation

In order to utilize any predictive watershed model for estimating the effectiveness of future potential management practices the model must be first calibrated to measured data and should then be tested (without further parameter adjustment) against an independent set of measured data. This testing of a model on an independent data set is commonly referred to as model validation. Validation ensures that the calibrated parameters set performs reasonably well under an independent data set.

Monthly Stream flow data of four years from 1995 to 1998 were used for flow validation and total sediment load of four years 1996 to 2000 were used for Sediment validation. The three statistical model performance measures used in calibration procedure were also used in validating stream flow.

3.3.7 Model Efficiency

Three methods for goodness-of-fit measures of model predictions were used during the calibration and validation periods, these three numerical model performance measures are coefficient of determination (r^2 coefficient) , the Nash-Suttcliffe simulation efficiency (E_{NS}) and percent difference D. The r^2 and E_{NS} measures how well trends in the measured data are reproduced by the simulated results over a specified time period and for a specified time step. In this study, these measures were computed of a monthly time step for flow and of a yearly time step for sediment calibration and validation.

The r^2 coefficient measures the fraction of the variation in the measured data that is replicated in the simulated model results and it is calculated for n time steps using Equation 3.8.

$$r^2 = \frac{\left[\sum_{i=1}^{n}(q_{si}-\bar{q}_s)(q_{oi}-\bar{q}_o)\right]^2}{\sum_{i=1}^{n}(q_{si}-\bar{q}_s)^2\sum_{i=1}^{n}(q_{oi}-\bar{q}_o)^2} \quad \text{………………………………………...…..3.11}$$

Where q_{si} is the simulated values of the quantity in each model time step, $\bar{q}_s$ is the average simulated value of the quantity in each model time step, q_{oi} is the measured values of the quantity in each model time step and $\bar{q}_o$ is the average measured value of the quantity in each model time step.

The range of values for r^2 is 1.0 (best) to 0.0 (bad). A value of 0.0 for r^2 means that none of the variance in the measured data is replicated by the model predictions. On the other hand, a value of 1.0 indicates that all of the variance in the measured data is replicated by the model predictions.

E_{NS} is computed for n time steps using Equation 3.9. It measures how well the simulated results predict the measured data relative to simply predicting the quantity of interest by using the average of the measured data over the period of comparison.

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n}(q_{oi}-q_{si})^2}{\sum_{i=1}^{n}(q_{oi}-\bar{q}_o)^2} \quad \text{…………………………………………………...……...3.12}$$

Where q_{oi} is the measured values of the quantity in each model time step, q_{si} is the simulated values of the quantity in each model time step and $\overline{q}_o$ is the average measured value of the quantity in each model time step.

The Nash-Suttcliffe simulation efficiency (E_{NS}) values range from 1.0 (best) to negative infinity. A value of 0.0 for E_{NS} means that the model predictions are just as accurate as using the measured data average to predict the measured data. E_{NS} values less than 0.0 indicate the measured data average is a better predictor of the measured data than the model predictions while a value greater than 0.0 indicates the model is a better predictor of the measured data than the measured data average.

The percent difference D measures the average difference between the simulated and measured values for a given quantity over the entire calibration or validation period in the study and it is calculated for n time using Equation 3.10.

$$D=\left[\frac{\left(\sum_{i=1}^{n} q_{si}-\sum_{i=1}^{n} q_{oi}\right)}{\sum_{i=1}^{n} q_{oi}}\right]*100 \quad \text{……………………………………………………….3.13}$$

Where q_{si} is the simulated values of the quantity in each model time step and q_{oi} is the measured values of the quantity in each model time step.

A value close to 0% is best for D. However, higher values for D are acceptable if the accuracy in which the observed data were gathered is relatively poor.

Generally, according to study by Santhi . C et.al [28] for an acceptable calibration of hydrology model the three numerical model performance measures value fulfill $D = \pm 15\%$, $r^2 > 0.6$ and $E_{NS} > 0.5$.

3.4 ArcSWAT model application to Melka Wakena watershed

Watershed models contain many parameters, some of which cannot be measured and must be estimated. To utilize any predictive watershed model for estimating the effectiveness of future management practices, the model needs to be calibrated by adjusting some or all of the estimated model parameters. Then, using an independent set of measured data, the model also needs to be tested and validated without any additional change to the model parameters.

Model calibration requires reasonable incremental changes to the adjustable model parameters until simulated results match measured data within some acceptable range of comparison.

The validation step ensures that the simulated results from the calibrated model match measured data from a completely independent data set within the acceptable range of comparison. A calibrated and validated watershed model generally is considered capable of making reasonable simulations of stream flow under widely varying climate or land-use change scenarios. A watershed model without a successful validation process still may have the capability of providing simulations of stream flow and Sediment load under varying climatic and land-use scenarios that can be reasonably compared. In this context, the relative differences between simulations may be reasonable, but absolute values of simulated stream flow and sediment load are not likely to be reasonable.

In this study, the ArcSWAT2009 version model was first run without calibration (uncalibrated model run) for the January 1989 to December 2012 time-period to identify the parameters to which the model is most sensitive. The model then was calibrated by adjusting those parameters through manual and automatic calibration to reasonably predict the January 1990 to December 1994 measured stream flow dataset. The model then was validated using the January 1995 to December 1998 measured stream flow dataset to demonstrate the model’s capability of reasonably simulating stream flow in the Melka Wakena Basin.

Then sediment load from the watershed was calibrated from January 1990 to December 1995 and validated from January 1996 to December 2000 for measure sediment load dataset.

4 RESULT AND DISCUSSION

4.1 Flow Calibration and Validation

4.1.1 Sensitivity Analysis

After the pre-processing of the data and ArcSWAT model set up the sensitivity analysis was carried out for a period of ten years which included both the Warm up period of (from January 1st , 1989 to December 31st 1989) and the calibration period (from January 1st , 1990 to December 31st 1994).

Even though 27 parameters with ten intervals of Latin Hypercube (LH) sampling (totally 270 iterations) were used for the sensitivity analysis, only 8 of them revealed meaningful effect on the monthly flow simulation of the Melka Wakena watershed.

As shown in Table 4.1, the first three parameters showed a relatively high sensitivity, being the soil evaporation compensation factor (ESCO) the most sensitive of all. And the other most sensitive parameters are maximum potential leaf area index (blai), Initial SCS CN II value (CN2) available water capacity (SOL_AWC), soil depth (sol_z), and Threshold water depth in the shallow aquifer for flow (GWQMN). The detail sensitivity output of optimized parameters is shown in appendix 1.

Table 4.1: Relative sensitivity values of the flow parameters

Parameter	**rank**	**Mean Sensitivity**	**Category**
Soil evaporation compensation factor; ESCO	1	0.358	high
Maximum potential leaf area index ;blai	2	0.230	high
Initial SCS CN II value; CN2	3	0.207	high
Soil depth [mm]; sol_z	4	0.194	medium
Available water capacity [mm WATER/mm soil]; SOL_AWC	5	0.173	medium
Threshold water depth in the shallow aquifer for flow [mm]; GWQMN	6	0.140	medium
Maximum canopy storage [mm]; Canmx	7	0.124	medium
Groundwater "revap" coefficient ;GW_REVAP	8	0.103	medium
Plant uptake compensation factor Epco	9	0.0286	small
Base flow alpha factor ; ALPHA_BF	10	0.0168	small

4.1.2 Flow Calibration

Flow calibration was performed for a period of five years from January 1st, 1990 to December 31st, 1994 using the sensitive parameters identified. However, flow was simulated for six years from January 1st, 1989 to December 31st, 1994 within which the first year was considered as a warm up period.

As discussed previously in the methodology section, the flow was calibrated first automatically through autocalibration tool in ArcSWAT for 500, 1000, 2500 and 5000 number of trials before the process is terminated. From these trials the result of 5000 number of trials fulfills the requirement for the three numerical model performance measures suggested by Santhi.C et.al [28]. Then using the best parameter values result of autocalibration, the model was calibrated manually by making delicate adjustments to ensure best fitting of the simulated flow curves with the gauged flow curve. Manipulation of the parameter values were carried out within the allowable ranges recommended by ArcSWAT User's manual.

The calibration results in Table 4.2 show that there is a good agreement between the simulated and gauged monthly flows. This is demonstrated by the goodness-of-fit measures correlation coefficient (R^2 = 0.822), the Nash-Suttcliffe Simulation efficiency (E_{NS}=0.806) and the percent difference (D= -10.725%) value. The result fulfilled the requirement suggested by Santhi, C et.al [28].

Table 4.2: Calibration statistics of average monthly simulated and gauged flows at the outlet of Melka Wakena watershed.

Period (Monthly)	Average flow (m^3/sec)		D (%)	r^2	E_{NS}
	Gauged	Simulated			
1990-1994	22.77	20.33	-10.725	0.822	0.806

As shown in Table 4.3 the calibrated value of initial SCS CN II value and Available water capacity of soil are increased by 18% and 25% of ArcSWAT default value respectively. The initial/default and finally calibrated values of sensitive parameters are given in Table 4.3.

Table 4.3: Inputs Used in Model Calibration Initial and final values of the calibration parameters, plus possible ranges where applicable.

No.	Parameters	Description	Range	Initial value	Calibrated value
1	CN2	Initial SCS CN II value	±25%	51	+18%
2	ESCO	Soil evaporation compensation factor	0-1	0.95	0.5
3	GW_REVAP	Groundwater "revap" coefficient	0.02-0.2	0.02	0.165
4	GWQMN	Threshold water depth in the shallow aquifer for flow [mm]	0-5000	0	0.6
5	SOL_AWC	Available water capacity [mm water/mm soil]	±25%	0.24	+25%
6	SOL_Z	Soil depth [mm]	±25%	560	+25%
7	BLAI	Maximum potential leaf area index	0-1	0.36	0.54
8	Canmx	Maximum canopy storage [mm]	0-10	0	0

As shown in Figure 4.1, peak values are slightly underestimated during 1992 and 1994. This is due to unreliable precipitation data given as an input to the model or gauged flow used for the calibration. However, the overall flow trend is well simulated by the model. Besides, as described in the calibration statistics, the percentage error of the simulated flow is -10.725%, which is well within the acceptable range of ±15%. Hence, ArcSWAT proved to perform well in simulating the flows of Melka Wakena watershed.

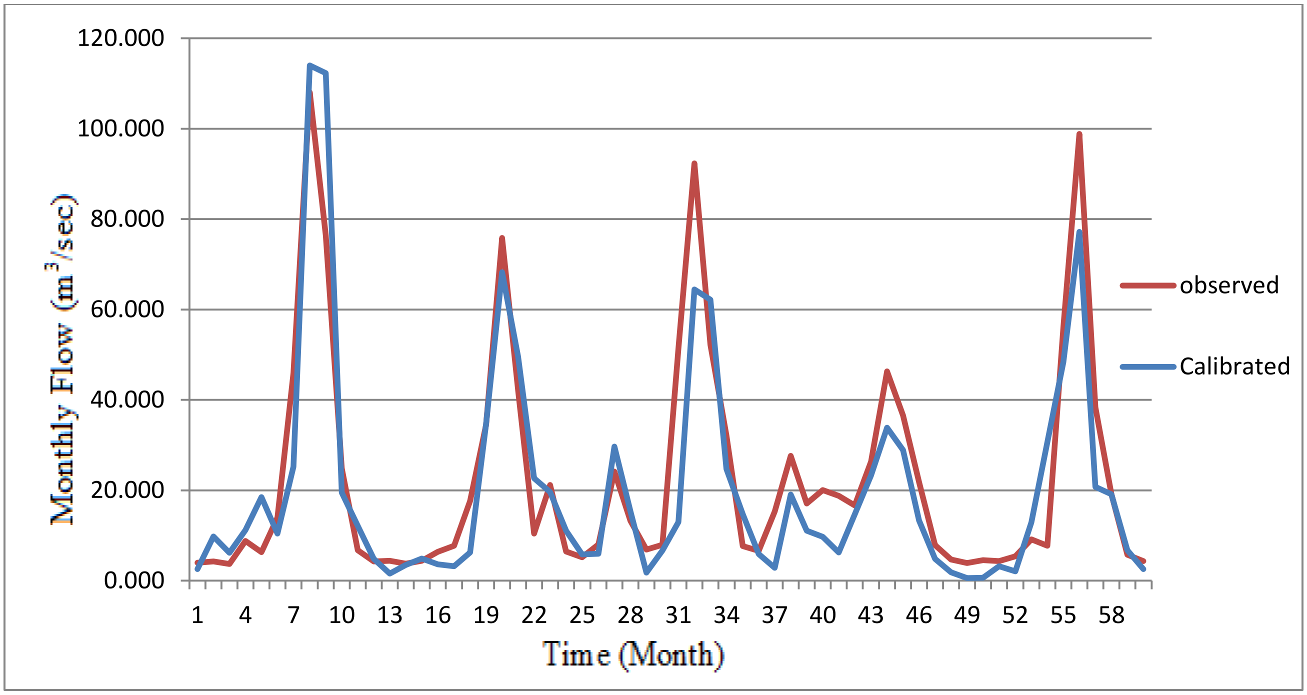


Figure 4.1: Comparison of observed monthly flow with simulated (calibrated) monthly flow of Melka Wakena watershed.

4.1.3 Flow Validation

As it is mentioned above the purpose of model validation is to establish whether the model has an ability to estimate output hydrology for other time periods or conditions than those for which the parameter values were adjusted to fit. Model validation involves re-running the model using input data independent of data used in calibration (e.g. differing time period), but keeping the calibrated parameters unchanged. In this case, flow data from a period from January 1, 1995 to December 31, 1998 from Wabi at Melka Wakena gauging station were used to validate the model for a monthly time-period. As with the calibration, the three goodness-of-fit measures were calculated and model-to-data Plots were inspected.

A good agreement between monthly observed and simulated flows at the outlet of the watershed station during validation processes are shown by Table 4.4 and the goodness-of-fit measures the coefficient of correlation (r^2 =0.765) , the Nash-Suttcliffe simulation efficiency (E_{NS} =0.613) and the percent difference (D= -3.412%) value.

Table 4.4: Validation statistics of average monthly simulated and gauged flows at the outlet of Melka Wakena watershed.

Period (Monthly)	Average flow (m^3/sec)		D (%)	r^2	E_{NS}
	Gauged	Simulated			
1995-1998	23.844	23.811	-0.1414	0.7971	0.6615

Generally, this validation/calibration check illustrates the accuracy of the model for simulating time-periods outside of the calibration time period. Since the model performed as well in the validation period of 1995-1998, as for the calibration period of 1990-1994 at Melka Wakena gauge as indicated in Table 4.4 and Figure 4.2 hence the set of sensitive parameters listed in Table 4.3 during calibration process for the watershed can be taken as the representative set of parameters for the Melka Wakena watershed.

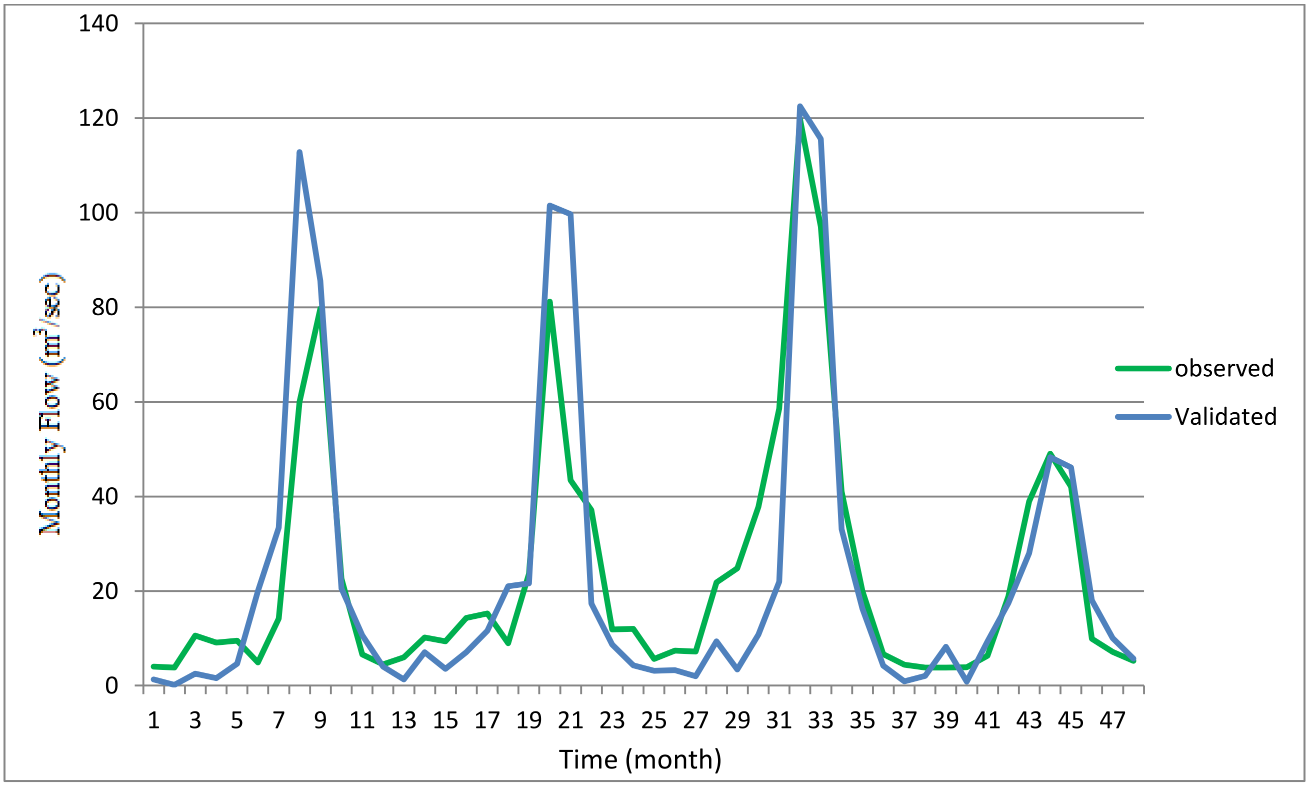


Figure 4.2: Comparison of observed monthly flow with validated monthly flow of Melka Wakena watershed.

4.2 Sediment Calibration and Validation

4.2.1 Sediment Calibration

Sediment calibration must be done after the hydrologic calibration is completed, and it is extremely sensitive to the hydrology, particularly the amount and timing of surface runoff that is predicted by the model.

The most sensitive parameters for prediction of sediment yield in Melka Wakena watershed is USLE equation support practice factor (USLE_P). The other parameters like exponent parameter for calculating sediment re entrained in channel sediment routing, channel erodibility factor and channel cover factor are less sensitive. These sensitivity result show that the sediment load of the watershed is dominated with the upland than originated from the channel. These parameters are listed in Table 4.5 with their calibrated value.

Table 4.5: Inputs Used in Model Calibration Initial and final values of the parameters for sediment yield, plus possible ranges where applicable.

Parameter	Range	Initial value	Calibrated value
Channel cover factor (CH-COV)	0-1	0	0.78
Channel erodibility factor (CH-EROD)	0-1	0	0.36
Linear factor for channel sediment Routing (SPCON)	0.0001-0.01	0.0001	0.005
Exponential factor for channel sediment routing (SPEXP)	1-2	1	2
USLE equation support practice factor (USLE_P)	0-1	1	0.9

ArcSWAT model is calibrated for sediment by comparing model simulated yield with measured yield. However due to the absence of measured sediment yield for Melka Wakena watershed the result of regional equation described in Method and Methodology section is used as measured sediment yield.

Then the model calibration was performed using yearly measured and simulated yield for the period of 1989 to 1995 and the first year was used as warm up period. Hence the output of regional equation is in yearly time step, both calibration and validation of sediment is done in yearly time step. The SWAT model was found to simulate well on yearly basis of sediment yield (Figure 4.5). Coefficient of determination (r^2) value and Nash-Sutcliffe model efficiency (E_{NS}) statistic computed between the simulated and observed yearly sediment yields for the calibration periods are 0.894 and 0.862 respectively (Table 4.6 and Figure 4.3). The sediment calibration results displayed a 0.31 % difference between the simulated and average observed yearly load. Calibration results show that model performance is good with simulation of yearly sediment yield.

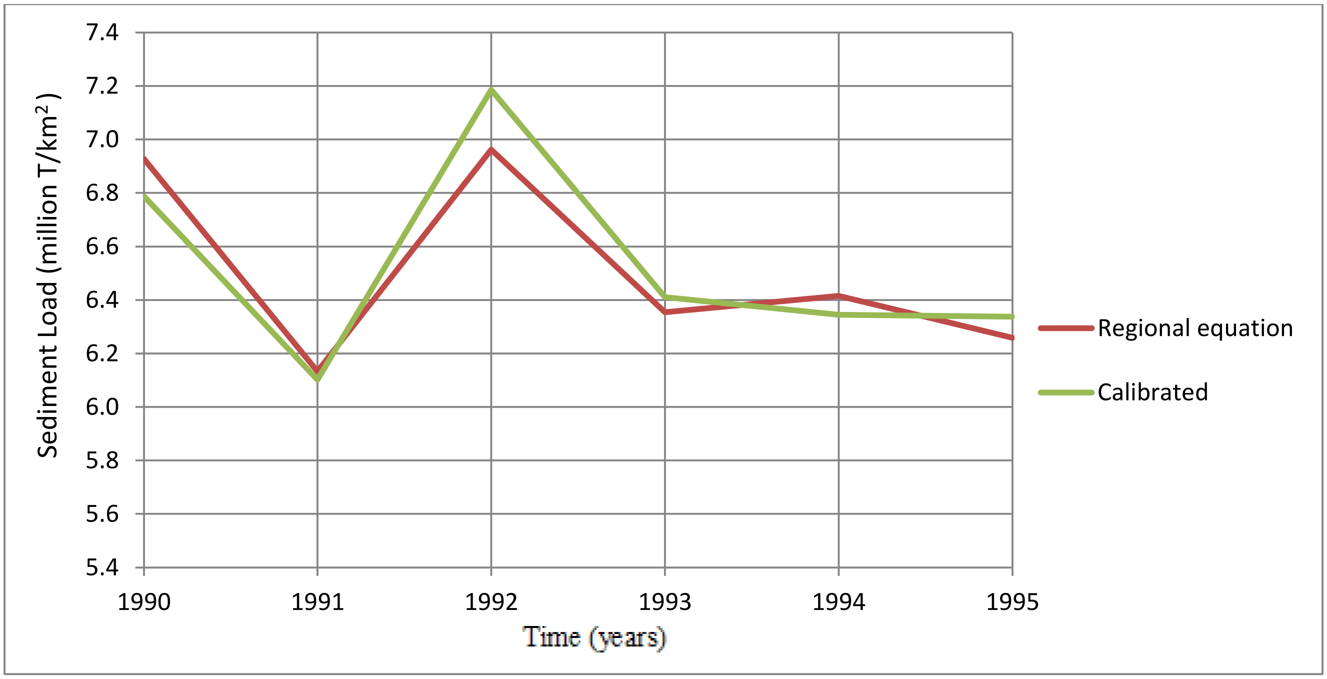


Figure 4.3: Comparison of measured (regional equation) yearly sediment yield with calibrated yearly sediment yield of Melka Wakena watershed.

As shown in Table 4.6 the output of SWAT model with USLE equation support practice factor the most sensitive parameter for sediment yield modeling of Melka Wakena watershed, the average sediment yield for year 1990 to 1995 is 6.53 million tons/Km^2/year which is slitely greater than the measured average sediment yield of the watershed.

Table 4.6: Calibration statistics of average yearly simulated and measured sediment yield at the outlet of Melka Wakena watershed.

Period (Yearly)	Average sediment yield (million tons/year)		D (%)	r^2	E_{NS}
	Regional equation	Simulated			
1990-1995	6.51	6.53	0.31	0.894	0.862

4.2.2 Sediment Validation

SWAT model was validated against sediment yield for the period 1996 to 2000 using the same parameters, which were adjusted during calibration processes. Yearly model simulated sediment yield against yearly measured sediment yield were compared graphically as shown in Figure 4.7 and presented with statistical parameters in Table 4.7. Coefficient of determination (r^2) value, Nash-Sutcliffe model efficiency (E_{NS}) and deviation of mean sediment (D) statistics were computed between the simulated and observed yearly sediment yields for the validation periods that provides 0.825, 0.77and -0.011% respectively.

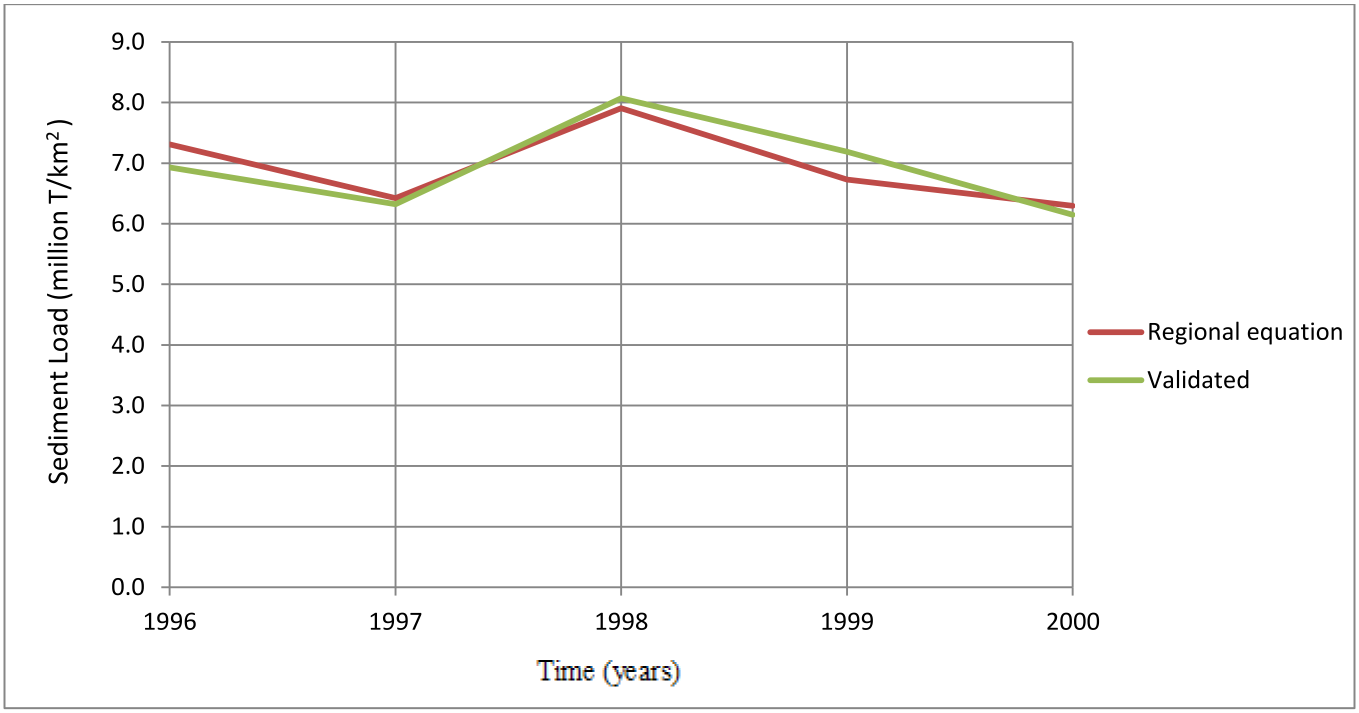


Figure 4.4: Comparison of measured (regional equation) yearly sediment yield with validated yearly sediment yield of Melka Wakena watershed.

Table 4.7: Validation statistics of average yearly simulated and measured sediment yield at the outlet of Melka Wakena watershed.

Period (Yearly)	Average sediment yield (million tons/year)		D (%)	r^2	E_{NS}
	Regional equation	Simulated			
1996-2000	6.932	6.931	-0.011	0.825	0.77

Here Table 4.7 and Figure 4.4 present the result of statistical value during the validation process with an average sediment yield of 6.93 million tons/Km^2/year which is almost equal with the measured average value for the year 1996 to 2000.

Generally, ArcSWAT simulated annual sediment yields with existing condition for the Melka Wakena watershed for the years 1989-2012 were in the range of 7.51 to 36.56 tons/ha/year with the twenty four-year average of 16.372 tons/ha/year as shown in the appendix 1.

Therefore sediment volume from the watershed that inflow into the reservoir with the 16.372 tons/ha/year or 1637.2 tons/Km^2/year and Specific gravity of sediment SG equal to 1.5 is 1091.5 m^3/Km^2/year.

Table 4.8: Sediment yield of Melka Wakena watershed

Number of year Col.1	Sediment yield of watershed (m^3/Km^2/year) Col.2	Watershed area (Km^2) Col.3	Sediment deposited in reservoir (Mm^3) Col.4=col.1*col.2*col.3
1	1091.5	4388	4.8
10	1091.5	4388	47.9
20	1091.5	4388	95.8
30	1091.5	4388	143.7
33	1091.5	4388	158.1
40	1091.5	4388	191.6
50	1091.5	4388	239.5

According to Melka Wakena detailed project report final publication [4], the dead storage of the reservoir is about 157Mm^3. Therefore as show in Table 4.8 the reservoir dead storage will filled total by sediment in about 33 years (i.e in 2022 GC) when the watershed condition continue with the currently existing condition.

In another word the total storage of the reservoir is 763Mm^3 and the annual sediment inflow into the reservoir is 4.79Mm^3 which is 0.63% of the total storage per year. This 0.63% of total storage loss per year justifies the report of ICOLD committee on reservoir sedimentation [1], which says the annual loss of storage of world reservoir is between 0.5% and 1% of total storage.

The study conducted by BCEOM and MWIE [20] under estimate the sediment yield from Melka Wakena watershed. According to the report the mean annual suspended sediment load is 74,596 m^3 which is much smaller than the result obtained in this thesis. This is due to pressure on the watershed which leads to deforestation and land use change of the area.

As the study area is found in Arsi Zone, the sediment yield of watershed obtained using SWAT model which is 16.4 ton/ha/year exceeds the maximum tolerable soil loss rate of 14 ton/ha/year suggested by Hurni.H [22] for the area.

Therefore, these facts show us how much the Melka Wakena reservoir is threatened by Sediment inflow from the watershed unless proper measure is taken.

4.3 Critical Subbasin of Melka Wakena Watershed

Study of Sanjeet Kumar, et.al [19] confirmed that subbasins can be classified as low, medium and high erosion class depending on their sediment yield. This classification is used to give priority for critical subbasin.

Table 4.9 and Figure 4.5 shows 13 subbasins created during watershed delineation process. This is done through five major steps. First DEM is loaded into the model and threshold based stream definition option was selected to define the minimum size of the subbasin. Then outlet and inlet of each reach and the whole watershed is selected. Finally parameters of the subbasin are calculated to finish the process.

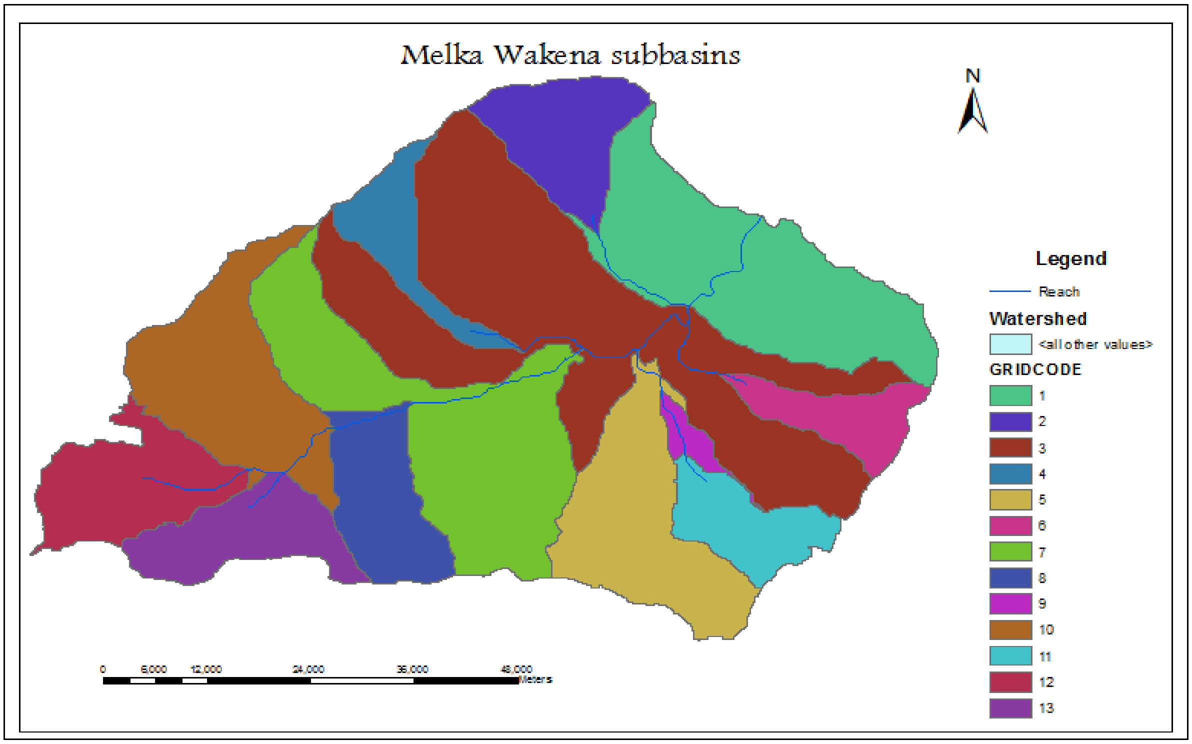


Figure 4.5: Subbasins of Melka Wakena watershed

Table 4.9: Erosion class of Melka Wakena Subbasin.

Subbasin	Sediment Yield (tons/Km^2/year)	Erosion class	Rank
2	3447.4	High	2
3	3656.7	High	1
4	759.75	Medium	11
5	2117.5	High	5
6	2001.1	High	6
7	982.86	Medium	8
8	750.8	Medium	12
9	2129.6	High	4
10	869.2	Medium	9
11	3288.3	High	3
12	769.85	Medium	10
13	1533.88	Medium	7

Among this subbasins, subbasin 3, 2 and 11 falls under high erosion class and ranking 1st to 3rd respectively in their sediment yield. As presented in the previous chapter land use of this subbasin which fall under high erosion class is characterized by intensive cultivation. This shows that the cultivation practices in the area accelerate runoff which leads to high sediment susceptibility of the watershed.

4.4 Economic loss due to sedimentation

Sedimentation leads to reservoir storage capacity depletion over time reducing available water for production of electricity. This effect of sedimentation is addressed in this section to give the general overview of economic loss resulting from storage loss due to sedimentation with some assumptions.

First to calculate annual economic loss, the live storage loss per year was estimated as shown in the previous section which is 4.79Mm^3 with the assumption that storage loss rate in each year is the same. Then the annual live storage loss is converted into energy loss which when multiplied by the unit price gives the value of lost live storage at the end of the year.

The annual live storage loss due to sedimentation is converted to energy (KWh) using energy equivalent for Melka Wakena hydropower station which is equal to 0.7082KWh/m^3 [29]. Here the main assumption is that all the water volume, which would have been saved if the active storage was never silted up, would pass through the turbine.

In order to predict economic loss from sedimentation accurately it is necessary to specify firm and surplus power price which defines water value variation with time. However, to make such analysis accurate estimate of seasonal storage loss must be obtained which is not possible with available sediment data and data on seasonal variation power price is also not available. Therefore, an average energy price of 0.6943 birr/KWh [30] was taken.

Annual energy loss due to sedimentation is equal to Annual live storage loss multiplying by energy equivalent. This is 4.79Mm^3 multiplying by 0.7082 KWh/m^3 which is equal to 3.4*10^{6}KWh.

Therefore, annual Economic loss due to reservoir sedimentation is equal to Annual energy loss multiplying by average energy price. This is 3.4*10^6KWh multiplying by 0.6943 birr/KWh which is equal to 2.361 million Birr.

Table 4.10: Economic losses due to reservoir sedimentation

Years Col.1	Storage loss (Mm^3) Col.2	Energy equivalent (Kwh/m^3) Col.3	Energy loss (10^6 Kwh) Col.4=col.2*col.3	Energy price (birr/Kwh) Col.5	Economic loss (million birr) Col.6=col.4*col5
1	4.79	0.7082	3.4	0.6943	2.361
5	23.95	0.7082	16.96	0.6943	11.78
10	47.9	0.7082	33.93	0.6943	23.56
15	71.85	0.7082	50.9	0.6943	35.33
20	95.8	0.7082	67.85	0.6943	47.11
25	119.75	0.7082	84.81	0.6943	58.9

As shown in Table 4.10 with the constant rate of annual storage loss and with the current energy price of the country, 58.9 million birr is lost due to Melka Wakena reservoir silt up with in twenty five years. This indicates how much reservoir sedimentation has negative impact on the growth of our country. Therefore, analyzing the most prominent remedial measures that reduce sediment yield of watershed is given priority.

4.5 Analysis of Reservoir Sedimentation remedial Measures

Once the major sediment source areas are known, the next step will be to determine what type of conservation activities can be adopted that is feasible to the study area to reduce soil loss and downstream delivery.

One of the methods to pass sediment loads through a reservoir is sluicing. Successful sluicing depends on the availability of excess water and relatively large bottom outlet at the dam. For successful flushing the reservoir capacity to mean annual runoff ratio should be quite small, say less than 0.2 year. However, in the case of Melka Wakena reservoir the reservoir capacity to mean annual runoff ratio is equal to 0.942 year which is larger than 0.2 year. Therefore, Sluicing is not feasible for the Melka Wakena reservoir.

Sediment deposits may be mechanically removed from reservoirs by dry excavation or hydraulic dredging and hydro-suction. However, Sediment removal by dredging to recover lost storage capacity should be seen as a last resort as the removal of sediment deposit is extremely expensive as high as 20 USD/m^3 [31], as it requires site specific equipment and disposal creates new social and environmental problems. Mechanical excavation is usually much more expensive than dredging due to high transport cost and double handling. Therefore, removal through mechanical excavation and dredging is not feasible for Melka Wakena reservoir.

When topographic conditions are favorable, a large-capacity channel or tunnel can be constructed to bypass sediment-laden flow around the reservoir or part of it. However, as the study area is found above Melka Wakena fall it is not suitable to construct channel and the construction of the tunnel costs much comparing to economic value obtained by reserving the storage capacity of the reservoir. Therefore sediment bypassing is also not feasible for the site.

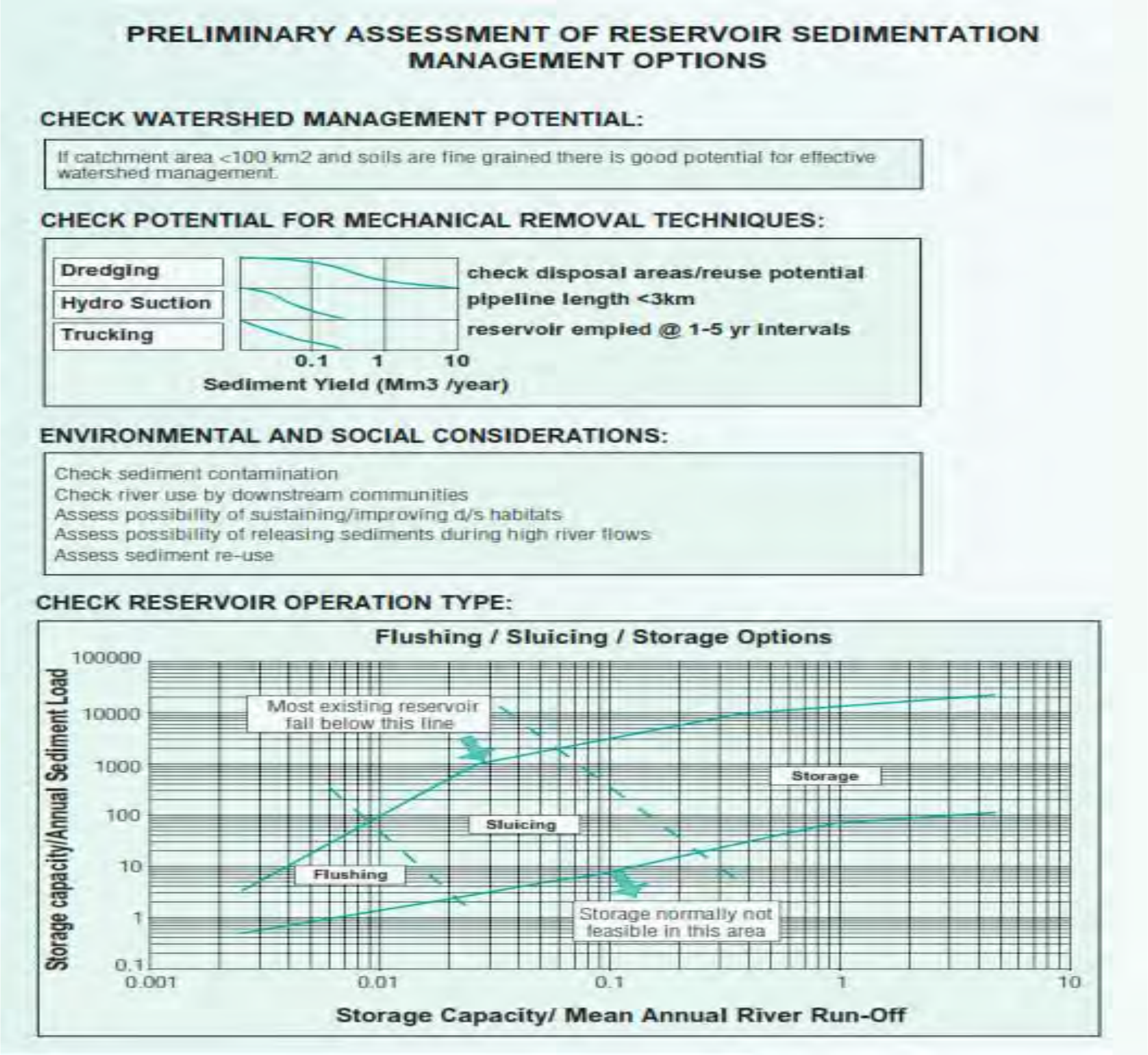
The implementation of soil-water conservation programs is important to limit erosion. These include farming practices, control of overgrazing and control of gully erosion. Gully erosion can be controlled through terraces on steep slope and small check dam. Soil and water conservation program is effective in small catchment when combined with other method. As discussed in the section of erosion class of subbasin, subbasins are ranked as their sediment yield. Therefore, for critical subbasin having small area like subbasin 2, 11 and 9 when soil-water conservation program is applied with vegetation screens upstream of reservoir, it is possible to reduce sediment flow into the reservoir. Here for attaining better result continuous follow up is needed.

As cited by Tadesse Tufa [32], Figure 4.6 show that the preliminary assessment of reservoir management options. According to this study, for effective watershed management option the catchment area should less than 100 Km^2.

To apply mechanical removal techniques two things are considered. The first consideration is that the length of disposal area from reservoir should be less than 3Km. If this condition is fulfilled check for environmental and social aspect. The environmental and social consideration is from sediment contamination and downstream use of the river point of view.

The ratio of storage capacity to mean annual river runoff is the consideration for reservoir operation sediment management option. Flushing and sluicing option is possible at reservoir when the storage capacity to mean annual river runoff ratio should be less than 0.2 year.

Therefore, through preliminary assessment of reservoir sedimentation management options criteria consideration soil and water conservation program for critical subbasin 2, 11 and 9 with vegetation screen upstream of reservoir is considered as most prominent remedial measures to preserve the storage capacity of Melka Wakena reservoir.


PRELIMINARY ASSESSMENT OF RESERVOIR SEDIMENTATION MANAGEMENT OPTIONS

CHECK WATERSHED MANAGEMENT POTENTIAL:

If catchment area <100 km2 and soils are fine grained there is good potential for effective watershed management.

CHECK POTENTIAL FOR MECHANICAL REMOVAL TECHNIQUES:

check disposal areas/reuse potential

pipeline length <3km

reservoir empied @ 1-5 yr intervals

ENVIRONMENTAL AND SOCIAL CONSIDERATIONS:

Check sediment contamination

Check river use by downstream communities

Assess possibility of sustaining/improving d/s habitats

Assess possibility of releasing sediments during high river flows

Assess sediment re-use

CHECK RESERVOIR OPERATION TYPE:

Most existing reservoir fall below this line

Storage normally not feasible in this area

Figure 4.6: Preliminary assessment of reservoir sedimentation management option [32].

5 CONCLUSION AND RECOMMENDATION

The final part of this thesis includes the conclusion and recommendation regarding modeling sediment yield of Melka Wakena watershed and the mitigation option reducing reservoir sedimentation. The first section of the chapter presents the conclusion of the thesis and the second section present, recommendations toward future steps in the study area.

5.1 Conclusion

The storage capacity of the reservoir influenced with sediment. In regard, this research modeled sediment yield of Melka Wakena watershed and suggest the best and feasible mitigation measure reducing sediment inflow into the reservoir.

The ArcGIS interface Soil and Water Assessment Tool (ArcSWAT) was used for modeling the sediment inflow into the reservoir. The model uses DEM, land use/land cover map, Soil map and metrological data as an input. The data were collected from Ministry of Water, Irrigation and Energy and National Metrological Agency of Ethiopia.

Watershed parameters were derived from DEM and categorized into 13 subbasins. Subbasins were further divided into HRU based on land use and soil data. The result indicated that the subbasin had 114 HRUs with a threshold value of 5% for land use, 5 % for soil and 10 % for slope.

Furthermore, the study has shown that the model could adequately represent well stream flow for monthly time step. The developed model performance evaluation of the station Wabi at Melka Wakena showed that (r^2=0.822 and E_{NS}=0.81) for calibration and (r^2=0.79 and E_{NS}=0.66) for validation. It indicated that the model can represent the actual condition of the watershed.

Following calibration and validation of stream flow, the ArcSWAT model calibrated and validated again for sediment load of yearly time step. It is shown that the total sediment load from Melka Wakena watershed could be represented well by ArcSWAT with (r^2 =0.894 and E_{NS}=0.862) for calibration and (r^2 =0.825 and E_{NS}=0.77) for validation.

The result of the calibrated and validated model shows that, the annual sediment inflow into the reservoir is 4.79Mm^3 which is 0.63% of the total storage per year. The economic loss due to this storage loss by sedimentation is about 2.361 million birr per year.

Soil and water conservation program at critical subbasin with vegetation screen upstream of reservoir is recommended as the best and feasible mitigation measure to reduce the sediment flow into the reservoir.

5.2 Recommendation

- Sediment reduces the life time of the reservoir. Therefore, sediment trap means should be exercised in upstream of the watershed. This can be achieved through soil and water conservation program at critical subbasin with vegetation screen upstream of reservoir with continuous follow up by stakeholders.
- Also more research is necessary to forecast sediment yield of each subbasin for daily and monthly time step under different land use/land cover scenario to improve decision making of the stakeholder.
- The model result will boost if the data quality and quantity is increased. However, there is sever data scarcity in Melka Wakena reservoir watershed especially data on sediment concentration or load of the main reach. The gap should be bridged by increasing the number and quality of climatological and hydrometric networks evenly over the river basin.
- Finally, since the methods used in this thesis have proved valuable through calibration and validation for assessing stream flow and sediment yield of Melka Wakena watershed, it would be beneficial to apply the method to other watershed having the same characteristics in the region.

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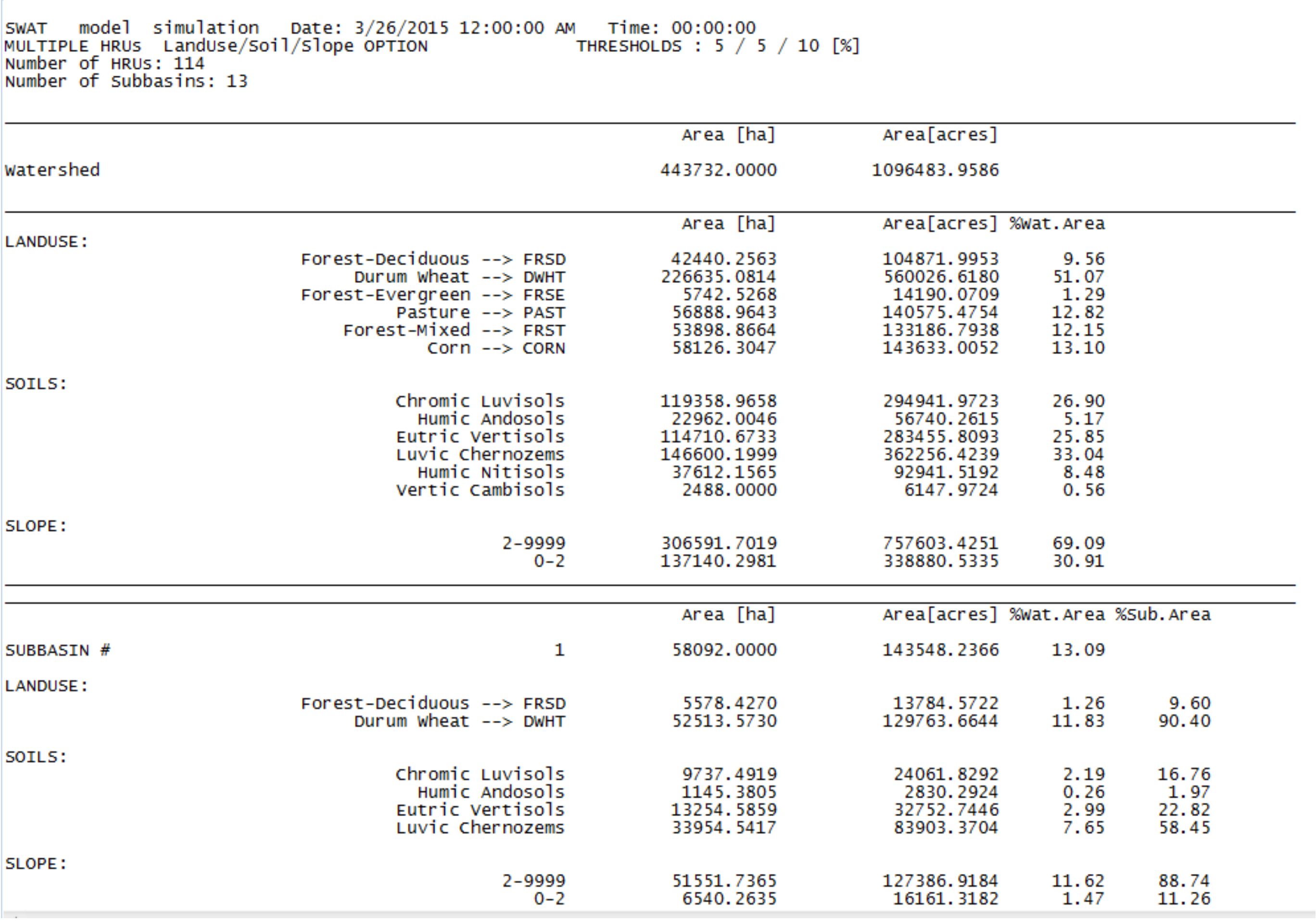
APPENDIX

1.HRU Analysis Report



```
SWAT   model  simulation   Date: 3/26/2015 12:00:00 AM   Time: 00:00:00
MULTIPLE HRUs  LandUse/Soil/Slope OPTION            THRESHOLDS : 5 / 5 / 10 [%]
Number of HRUs: 114
Number of Subbasins: 13

                                                           Area [ha]          Area[acres]

Watershed                                                 443732.0000        1096483.9586


                                                           Area [ha]          Area[acres] %Wat.Area
LANDUSE:
                                Forest-Deciduous --> FRSD   42440.2563         104871.9953     9.56
                                     Durum Wheat --> DWHT  226635.0814         560026.6180    51.07
                                Forest-Evergreen --> FRSE    5742.5268          14190.0709     1.29
                                         Pasture --> PAST   56888.9643         140575.4754    12.82
                                    Forest-Mixed --> FRST   53898.8664         133186.7938    12.15
                                            Corn --> CORN   58126.3047         143633.0052    13.10

SOILS:
                                       Chromic Luvisols   119358.9658         294941.9723    26.90
                                         Humic Andosols    22962.0046          56740.2615     5.17
                                       Eutric Vertisols   114710.6733         283455.8093    25.85
                                       Luvic Chernozems   146600.1999         362256.4239    33.04
                                         Humic Nitisols    37612.1565          92941.5192     8.48
                                       Vertic Cambisols     2488.0000           6147.9724     0.56

SLOPE:
                                                 2-9999   306591.7019         757603.4251    69.09
                                                    0-2   137140.2981         338880.5335    30.91


                                                           Area [ha]          Area[acres] %Wat.Area %Sub.Area

SUBBASIN #                                            1    58092.0000         143548.2366    13.09

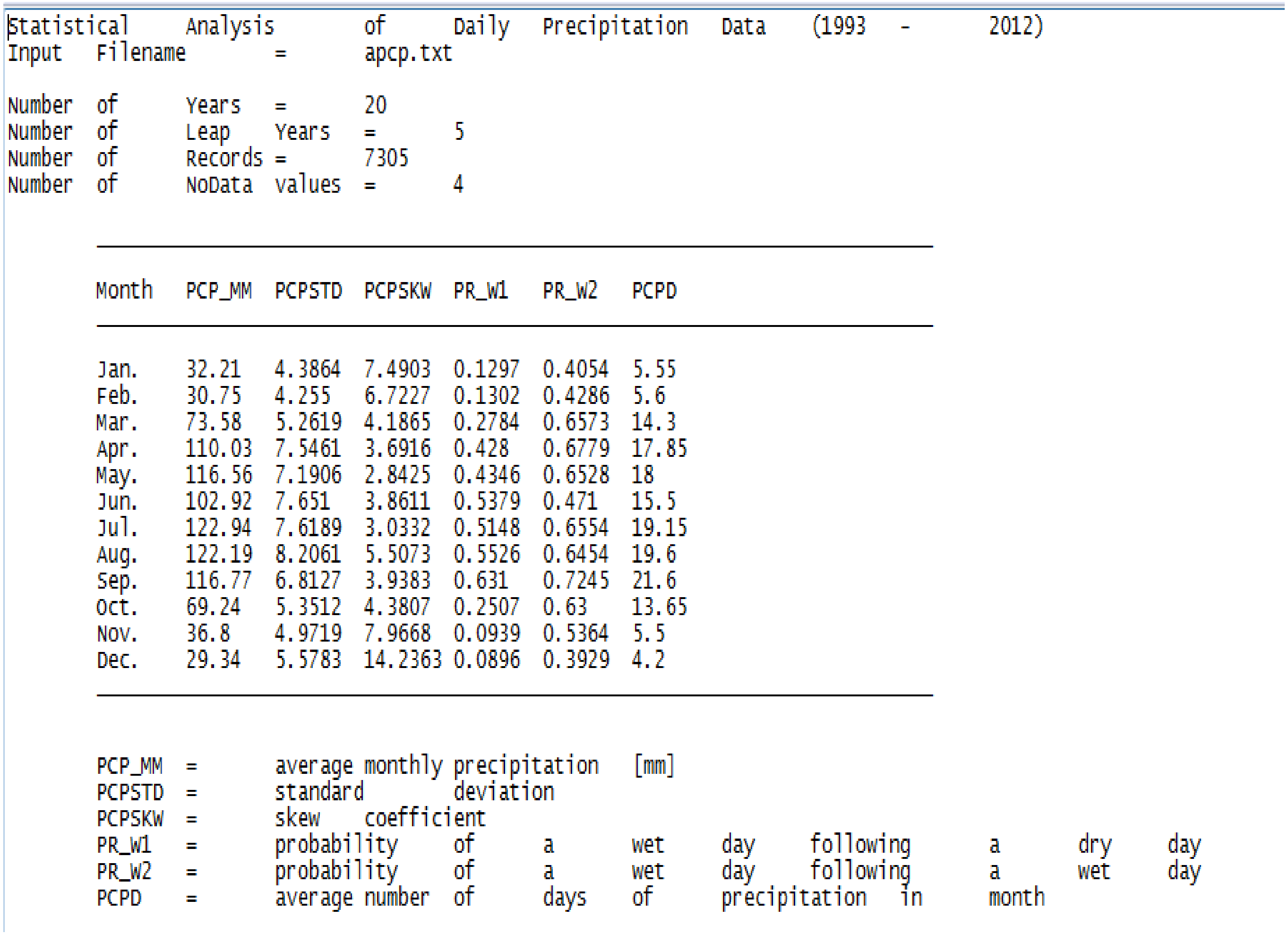
LANDUSE:
                                Forest-Deciduous --> FRSD    5578.4270          13784.5722     1.26      9.60
                                     Durum Wheat --> DWHT   52513.5730         129763.6644    11.83     90.40

SOILS:
                                       Chromic Luvisols     9737.4919          24061.8292     2.19     16.76
                                         Humic Andosols     1145.3805           2830.2924     0.26      1.97
                                       Eutric Vertisols    13254.5859          32752.7446     2.99     22.82
                                       Luvic Chernozems    33954.5417          83903.3704     7.65     58.45

SLOPE:
                                                 2-9999    51551.7365         127386.9184    11.62     88.74
                                                    0-2     6540.2635          16161.3182     1.47     11.26
```

2 Calculated Weather parameter for Weather generator

A/ Parameter calculated using pcpSTAT



```
Statistical     Analysis        of      Daily   Precipitation   Data    (1993   -       2012)
Input   Filename        =       apcp.txt

Number  of      Years   =       20
Number  of      Leap    Years   =       5
Number  of      Records =       7305
Number  of      NoData  values  =       4

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

        Month   PCP_MM  PCPSTD  PCPSKW  PR_W1   PR_W2   PCPD

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

        Jan.    32.21   4.3864  7.4903  0.1297  0.4054  5.55
        Feb.    30.75   4.255   6.7227  0.1302  0.4286  5.6
        Mar.    73.58   5.2619  4.1865  0.2784  0.6573  14.3
        Apr.    110.03  7.5461  3.6916  0.428   0.6779  17.85
        May.    116.56  7.1906  2.8425  0.4346  0.6528  18
        Jun.    102.92  7.651   3.8611  0.5379  0.471   15.5
        Jul.    122.94  7.6189  3.0332  0.5148  0.6554  19.15
        Aug.    122.19  8.2061  5.5073  0.5526  0.6454  19.6
        Sep.    116.77  6.8127  3.9383  0.631   0.7245  21.6
        Oct.    69.24   5.3512  4.3807  0.2507  0.63    13.65
        Nov.    36.8    4.9719  7.9668  0.0939  0.5364  5.5
        Dec.    29.34   5.5783  14.2363 0.0896  0.3929  4.2

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

        PCP_MM  =       average monthly precipitation   [mm]
        PCPSTD  =       standard        deviation
        PCPSKW  =       skew    coefficient
        PR_W1   =       probability     of      a       wet     day     following       a       dry     day
        PR_W2   =       probability     of      a       wet     day     following       a       wet     day
        PCPD    =       average number  of      days    of      precipitation   in      month
```

B/ Parameter calculated using formula in the ArcSWAT user manual

month	TMPSTDMX	TMPSTDMN	SOLARAV	WNDAV
Jan.	1.249665056	2.479994375	8.5	0.812544803
Feb.	1.32279878	2.27061905	17.4	0.828947729
Mar.	1.709771152	2.09894435	21.1	0.860394265
Apr.	1.993197487	1.659650562	15.1	0.746296296
May	1.543325506	1.386874916	8.9	0.842114695
Jun.	1.345542632	1.456398179	2.9	1.035185185
Jul.	1.486937043	1.425865932	5.2	0.95483871
Aug.	1.437085027	1.340158563	12.1	0.902688172
Sep.	1.404644491	1.444256092	15.4	0.699444444
Oct.	1.51149394	2.216736857	15.6	0.603763441
Nov.	1.204800735	2.310636419	11.3	0.666851852
Dec.	1.17596323	2.259713464	3.8	0.760573477

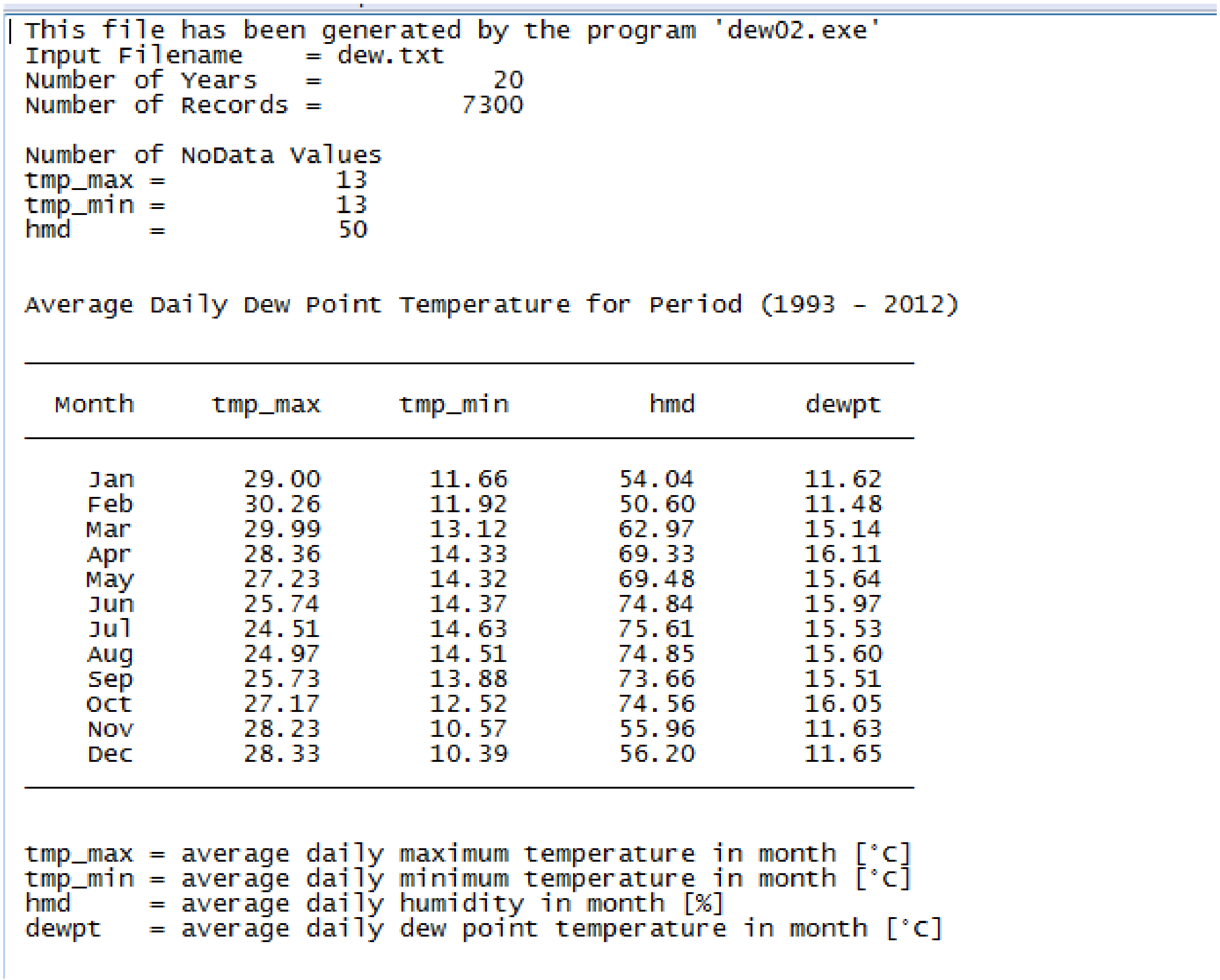
Where: TMPSTDMX= Standard deviation for daily maximum air temperature in month (^oC)

TMPSTDMN= Standard deviation for daily minimum air temperature in month (^oC)

SOLARAV= Average daily solar radiation for month ($MJ/m^2/day$)

WNDAV= Average daily wind speed in month (m/s)

C/ Parameter calculated using dewpoint



```
This file has been generated by the program 'dew02.exe'
Input Filename    = dew.txt
Number of Years   =          20
Number of Records =        7300

Number of NoData Values
tmp_max =            13
tmp_min =            13
hmd     =            50


Average Daily Dew Point Temperature for Period (1993 - 2012)

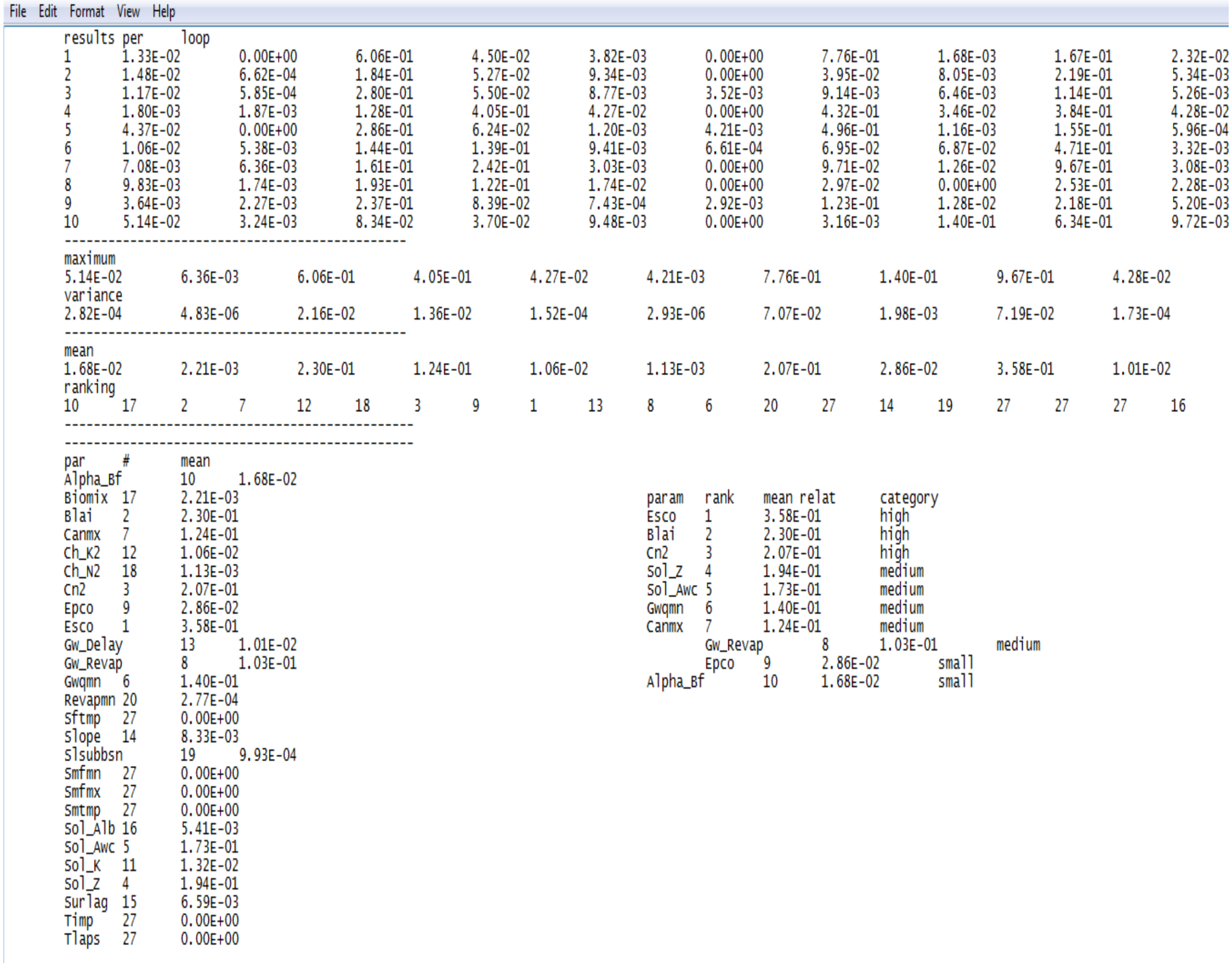
 ________________________________________________________

  Month      tmp_max     tmp_min         hmd       dewpt
 ________________________________________________________

    Jan        29.00       11.66       54.04       11.62
    Feb        30.26       11.92       50.60       11.48
    Mar        29.99       13.12       62.97       15.14
    Apr        28.36       14.33       69.33       16.11
    May        27.23       14.32       69.48       15.64
    Jun        25.74       14.37       74.84       15.97
    Jul        24.51       14.63       75.61       15.53
    Aug        24.97       14.51       74.85       15.60
    Sep        25.73       13.88       73.66       15.51
    Oct        27.17       12.52       74.56       16.05
    Nov        28.23       10.57       55.96       11.63
    Dec        28.33       10.39       56.20       11.65
 ________________________________________________________

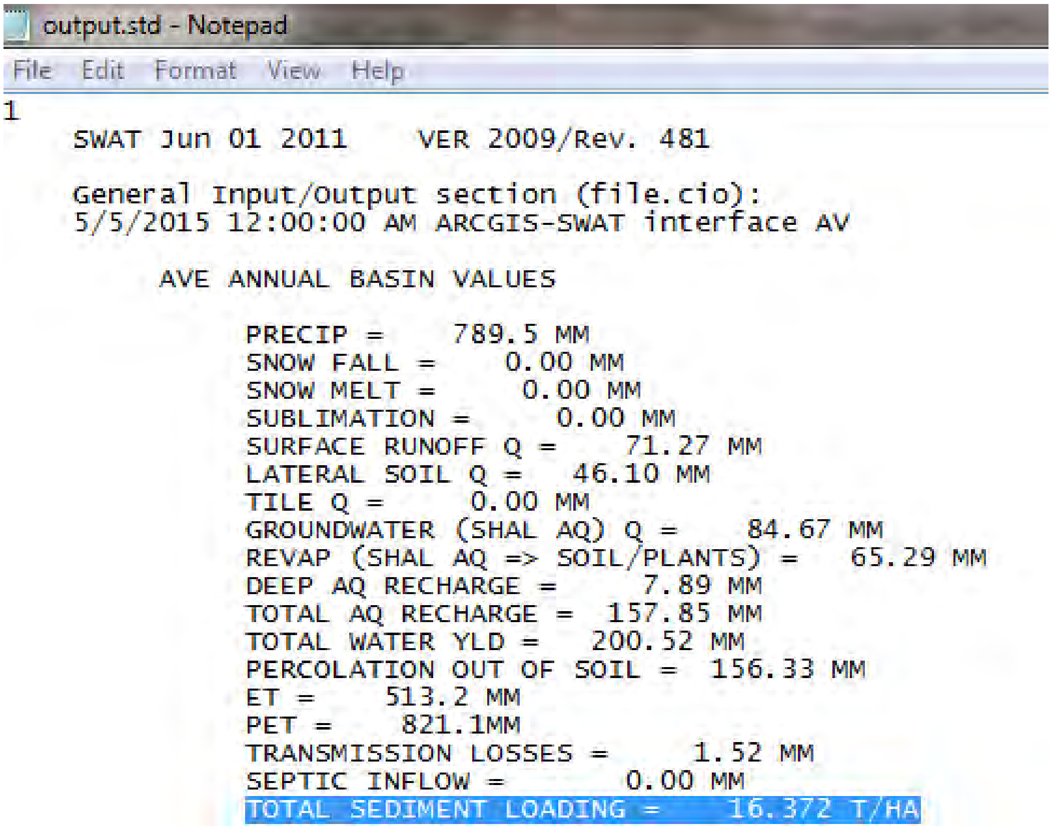

tmp_max = average daily maximum temperature in month [°C]
tmp_min = average daily minimum temperature in month [°C]
hmd     = average daily humidity in month [%]
dewpt   = average daily dew point temperature in month [°C]
```

3 Sensitivity result of flow parameter.



```
results per     loop
1       1.33E-02        0.00E+00        6.06E-01        4.50E-02        3.82E-03        0.00E+00        7.76E-01        1.68E-03        1.67E-01        2.32E-02
2       1.48E-02        6.62E-04        1.84E-01        5.27E-02        9.34E-03        0.00E+00        3.95E-02        8.05E-03        2.19E-01        5.34E-03
3       1.17E-02        5.85E-04        2.80E-01        5.50E-02        8.77E-03        3.52E-03        9.14E-03        6.46E-03        1.14E-01        5.26E-03
4       1.80E-03        1.87E-03        1.28E-01        4.05E-01        4.27E-02        0.00E+00        4.32E-01        3.46E-02        3.84E-01        4.28E-02
5       4.37E-02        0.00E+00        2.86E-01        6.24E-02        1.20E-03        4.21E-03        4.96E-01        1.16E-03        1.55E-01        5.96E-04
6       1.06E-02        5.38E-03        1.44E-01        1.39E-01        9.41E-03        6.61E-04        6.95E-02        6.87E-02        4.71E-01        3.32E-03
7       7.08E-03        6.36E-03        1.61E-01        2.42E-01        3.03E-03        0.00E+00        9.71E-02        1.26E-02        9.67E-01        3.08E-03
8       9.83E-03        1.74E-03        1.93E-01        1.22E-01        1.74E-02        0.00E+00        2.97E-02        0.00E+00        2.53E-01        2.28E-03
9       3.64E-03        2.27E-03        2.37E-01        8.39E-02        7.43E-04        2.92E-03        1.23E-01        1.28E-02        2.18E-01        5.20E-03
10      5.14E-02        3.24E-03        8.34E-02        3.70E-02        9.48E-03        0.00E+00        3.16E-03        1.40E-01        6.34E-01        9.72E-03
-----------------------------------------------
maximum
5.14E-02        6.36E-03        6.06E-01        4.05E-01        4.27E-02        4.21E-03        7.76E-01        1.40E-01        9.67E-01        4.28E-02
variance
2.82E-04        4.83E-06        2.16E-02        1.36E-02        1.52E-04        2.93E-06        7.07E-02        1.98E-03        7.19E-02        1.73E-04
-----------------------------------------------
mean
1.68E-02        2.21E-03        2.30E-01        1.24E-01        1.06E-02        1.13E-03        2.07E-01        2.86E-02        3.58E-01        1.01E-02
ranking
10      17      2       7       12      18      3       9       1       13      8       6       20      27      14      19      27      27      27      16
------------------------------------------------
------------------------------------------------
par     #       mean
Alpha_Bf        10      1.68E-02
Biomix  17      2.21E-03                                                        param   rank    mean relat      category
Blai    2       2.30E-01                                                        Esco    1       3.58E-01        high
Canmx   7       1.24E-01                                                        Blai    2       2.30E-01        high
Ch_K2   12      1.06E-02                                                        Cn2     3       2.07E-01        high
Ch_N2   18      1.13E-03                                                        Sol_Z   4       1.94E-01        medium
Cn2     3       2.07E-01                                                        Sol_Awc 5       1.73E-01        medium
Epco    9       2.86E-02                                                        Gwqmn   6       1.40E-01        medium
Esco    1       3.58E-01                                                        Canmx   7       1.24E-01        medium
Gw_Delay        13      1.01E-02                                                        Gw_Revap        8       1.03E-01        medium
Gw_Revap        8       1.03E-01                                                        Epco    9       2.86E-02        small
Gwqmn   6       1.40E-01                                                        Alpha_Bf        10      1.68E-02        small
Revapmn 20      2.77E-04
Sftmp   27      0.00E+00
Slope   14      8.33E-03
Slsubbsn        19      9.93E-04
Smfmn   27      0.00E+00
Smfmx   27      0.00E+00
Smtmp   27      0.00E+00
Sol_Alb 16      5.41E-03
Sol_Awc 5       1.73E-01
Sol_K   11      1.32E-02
Sol_Z   4       1.94E-01
Surlag  15      6.59E-03
Timp    27      0.00E+00
Tlaps   27      0.00E+00
```

4 Calibrated and validated average annual watershed values



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1
     SWAT Jun 01 2011    VER 2009/Rev. 481

     General Input/Output section (file.cio):
     5/5/2015 12:00:00 AM ARCGIS-SWAT interface AV

          AVE ANNUAL BASIN VALUES

               PRECIP =     789.5 MM
               SNOW FALL =     0.00 MM
               SNOW MELT =     0.00 MM
               SUBLIMATION =     0.00 MM
               SURFACE RUNOFF Q =     71.27 MM
               LATERAL SOIL Q =   46.10 MM
               TILE Q =     0.00 MM
               GROUNDWATER (SHAL AQ) Q =    84.67 MM
               REVAP (SHAL AQ => SOIL/PLANTS) =   65.29 MM
               DEEP AQ RECHARGE =     7.89 MM
               TOTAL AQ RECHARGE =  157.85 MM
               TOTAL WATER YLD =   200.52 MM
               PERCOLATION OUT OF SOIL =  156.33 MM
               ET =    513.2 MM
               PET =    821.1MM
               TRANSMISSION LOSSES =     1.52 MM
               SEPTIC INFLOW =      0.00 MM
               TOTAL SEDIMENT LOADING =    16.372 T/HA
```

5 Sample calculation of sediment load using Regional Equation

			1	2	3=1*2	4	5	6=3*5
year	month	MMC	day of month	monthly mean (m3/sec)	monthly Flow (m3/sec)	area (Mm2)	time (sec)	Volume (m3)
1989	1	12.15995	31	4.54000394	140.7401222	4388	86400	12159946.55
1989	2	17.37179	28	7.180801279	201.0624358	4388	86400	17371794.45
1989	3	19.74708	31	7.372715484	228.55418	4388	86400	19747081.15
1989	4	33.47289	30	12.91392191	387.4176573	4388	86400	33472885.59
1989	5	22.03237	31	8.225944622	255.0042833	4388	86400	22032370.08
1989	6	16.45646	30	6.348944183	190.4683255	4388	86400	16456463.32
1989	7	57.96708	31	21.6424271	670.9152402	4388	86400	57967076.75
1989	8	159.7556	31	59.6458994	1849.022881	4388	86400	159755577
1989	9	112.9293	30	43.56841626	1307.052488	4388	86400	112929334.9
1989	10	81.77448	31	30.53109225	946.4638596	4388	86400	81774477.47
1989	11	27.78442	30	10.7192983	321.5789489	4388	86400	27784421.18
1989	12	35.43723	31	13.2307454	410.1531074	4388	86400	35437228.48
1990	1	13.76594	31	5.139612691	159.3279934	4388	86400	13765938.63
1990	2	46.29934	28	19.13828385	535.8719479	4388	86400	46299336.3
1990	3	84.53005	31	31.5599061	978.3570892	4388	86400	84530052.51
1990	4	110.4454	30	42.610125	1278.30375	4388	86400	110445444
1990	5	44.45721	31	16.59842207	514.5510841	4388	86400	44457213.67
1990	6	25.48403	30	9.831801085	294.9540325	4388	86400	25484028.41
1990	7	66.85528	31	24.9609025	773.7879774	4388	86400	66855281.25
1990	8	198.3053	31	74.03872682	2295.200531	4388	86400	198305325.9
1990	9	104.1321	30	40.17441635	1205.23249	4388	86400	104132087.2
1990	10	43.55442	31	16.26135871	504.1021201	4388	86400	43554423.18
1990	11	20.89417	30	8.061022891	241.8306867	4388	86400	20894171.33
1990	12	13.08144	31	4.884051219	151.4055878	4388	86400	13081442.79
1991	1	11.89018	31	4.439283433	137.6177864	4388	86400	11890176.75
1991	2	23.30634	28	9.633903423	269.7492958	4388	86400	23306339.16
1991	3	40.61726	31	15.16474879	470.1072124	4388	86400	40617263.16
1991	4	31.27862	30	12.06736896	362.0210687	4388	86400	31278620.33
1991	5	31.95773	31	11.93165027	369.8811584	4388	86400	31957732.08
1991	6	13.88603	30	5.357264105	160.7179232	4388	86400	13886028.56
1991	7	59.24106	31	22.11807718	685.6603927	4388	86400	59241057.93
1991	8	176.841	31	66.02487043	2046.770983	4388	86400	176841013
1991	9	110.9171	30	42.79208185	1283.762456	4388	86400	110917076.2
1991	10	21.94027	31	8.191557026	253.9382678	4388	86400	21940266.34
1991	11	17.28221	30	6.667519912	200.0255974	4388	86400	17282211.61
1991	12	13.87274	31	5.179488882	160.5641554	4388	86400	13872743.02

7=6/4	**8**	**9=regional equation**	**10=0.2*9**	**11=9+10**	**12=11*4**
RO (mm)	average RO (mm/yr)	Sus. Sediment inflow (ton/km2/yr)	bed load (ton/km2/yr)	total load (ton/km3/yr)	total load (ton/yr)
2.771182	***11.3356248***	***1142.94044***	***228.588088***	***1371.528528***	***6018267.18***
3.958932					
4.500246					
7.628278					
5.021051					
3.750333					
13.21036					
36.40738					
25.73595					
18.63593					
6.33191					
8.075941					
3.137178	*14.6574891*	*1288.819322*	*257.7638644*	*1546.583187*	*6786407.02*
10.55135					
19.26391					
25.16988					
10.13154					
5.807664					
15.23593					
45.19264					
23.7311					
9.925803					
4.761662					
2.981186					
2.709703	***10.5027068***	***1102.889472***	***220.5778944***	***1323.467366***	***5807374.8***
5.311381					
9.256441					
7.128218					
7.282984					
3.164546					
13.5007					
40.30105					
25.27736					
5.000061					
3.938517					
3.161518					