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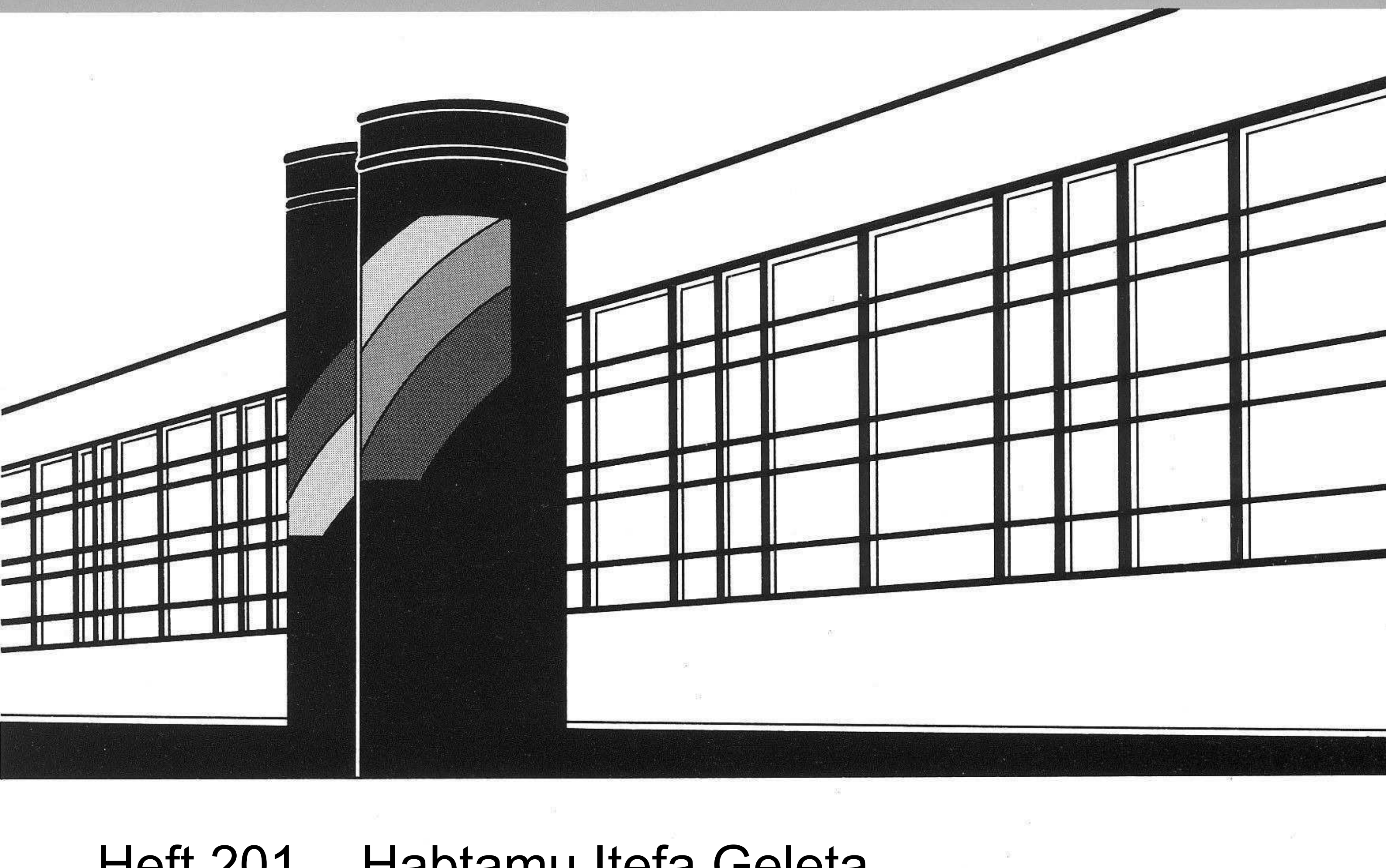

Heft 201

Habtamu Itefa Geleta

Watershed Sediment Yield Modeling for Data Scarce Areas

Watershed Sediment Yield Modeling for Data Scarce Areas

Von der Fakultät Bau- und Umweltingenieurwissenschaften der
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Vorgelegt von

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Habtamu Itefa Geleta

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ABBREVIATIONS AND ACRONYMS

CN	Curve Number
DEM	Digital Elevation Model
ERFAC	Erodibility Factor
FAO	Food and Agriculture Organization of the United Nation
FMWRE	Federal Ministry of Water Resources of Ethiopia
LH-OAT	Latin Hypercube Once at a Time
MUSLE	Modified Universal Soil Loss Equation
NMSA	National Meteorology Service Agency
NSE	Nash-Sutcliffe Efficiency
PARASOL	Parametric Solution
PCP	Precipitation
RUSLE	Revised Universal Soil Loss Equation
SCS	Soil Conservation Service
SSY	Suspended Sediment Yield
SPAW	Soil Plant Air Water
SWAT	Soil Water Assessment Tool
SYLD	Sediment Yield
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation

ABSTRACT

The sustainability and service life of reservoirs depends on the amount of sediment storage. Reservoir sedimentation is a critical problem in reducing the service life of dams. The sedimentation problem is the consequence of watersheds sediment supply to the river networks and then to the reservoir. River bank sediment deposition is another consequence of excess sediment supply from the upstream watersheds. The deposition of sediment on bank of a river causes change in flow regime and as result flooding may happen to the adjoining areas. The degree of severity of river bank sediment deposition or reservoir sedimentation can be analyzed with the availability of information on the sediment load from the upstream watersheds. Physically based models are appropriate tools for sediment modelling and prediction at the outlet point of a watershed. Nevertheless, the applicability of the existing physically based models is limited to data availability which restricts their application to data scarce areas. Therefore, this research has been undertaken to analyze the fundamental watershed soil parameters, geomorphologic parameters and hydrologic parameters and thereafter suggest an alternative sediment yield estimation method that can be applied to data scarce areas.

A Soil erodibility estimation equation has been derived from soil data of the Upper Awash basin in Ethiopia and has been evaluated for its applicability to the FAO (1998) world soil database. The evaluation has been made with reference to the equation of Williams et al. (1984). According to the evaluation result, for 80 % of the World Soil Database the relative error of the proposed equation as compared to the equation of Williams et al. (1984) has been estimated to be less than 20 %. This indicates that with easily measurable soil parameters like the percentage of sand, silt and clay, a reasonable soil erodibility factor can be predicted.

SWAT2005 model has been applied to the Awash basin and two selected subbasins (Fincha and Gudar) of the Blue Nile basin. The model has been calibrated to measured sediment data available at different locations in the selected river basins. After the model calibration the spatial pattern of soil loss rates and erosion risk area has been identified. The erosion risk has been found to increase in areas with highest annual rainfall depth and agriculture dominated areas. Moreover, areas with steep slope have shown more vulnerability to erosion.

The geomorphologic parameters of the watersheds have been combined with the soil erodibility factor, peak surface runoff and stream flow elements to formulate an alternative empirical model of sediment yield estimation. The empirical model has been derived from the Upper Awash basin based on the SWAT2005 model results. Two equations have been

formulated, i.e. an equation which can predict sediment outflow from a single watershed and a routing equation which can predict net sediment flux from multiple and interconnected watersheds. The scope of applicability of the developed empirical models has been evaluated for different watersheds in various climatic zones and satisfactory results have been obtained.

The findings of this research provide an alternative solution for the estimation of soil erodibility and net sediment outflow from various watersheds. Moreover, the flexibility of the sediment outflow equation is a special aspect of the research findings that makes the formulated empirical model successfully applicable to different watersheds. Therefore, in the absence of measured sediment data sufficient for the application of physically based models, the formulated empirical model can be used for sediment prediction.

ZUSAMMENFASSUNG

Ziel dieser Forschungsarbeit ist die Entwicklung eines Sedimentertragsmodells für Gebiete mit geringer Datengrundlage, für die eine Anwendung physikalisch basierter Modelle nicht praktikabel ist. Dieses allgemeine Forschungsziel beinhaltet folgende Teilaufgaben:

1. Formulierung einer einfachen Gleichung zur Abschätzung der Bodenerodierbarkeit, die auf einfach messbaren Bodenparametern basiert.
2. Abschätzung der räumlichen Verteilung der Bodenverlustrate, sowie die zeitliche Verteilung des Sedimentaustrags im Upper Awash basin und ausgewählten Teileinzugsgebieten des Blue Nile in Äthiopien. Dafür wird ein SWAT2005 Modell erstellt und an Hand von zuvor identifizierter und priorisierter Parameter, die den Sedimentaustrag bestimmen, kalibriert und validiert.
3. Formulierung einer alternativen Methode zur Abschätzung des Sedimentertrags.
4. Evaluation der Anwendbarkeit der alternativen Sedimentaustragsabschätzungsmethode für unterschiedliche Einzugsgebietscharakteristiken unter verschiedenen hydro-klimatischen Bedingungen.

Es werden verschiedene der bereits bestehenden Gleichungen zur Abschätzung der Bodenerodierbarkeit untersucht. Da jedoch diese zumeist einen empirischen Charakter haben und deren Parameter aus einem bestimmten Gebiet stammen, wird die Anwendbarkeit auf andere Gebiete oft in Frage gestellt. Die Gleichung von Williams et al. (1984) und Shirazi und Boersma (1984) sind allgemein anerkannt, doch ist die Anwendbarkeit dieser Gleichung für datenlimitierte Gebiete äußerst schwierig. Weiterhin sind einige Eingangsparameter, wie der organische Kohlenstoffgehalt für die Williams Gleichung und die primären Partikel-Fraktionen für die Shirazi und Boaersma Gleichung, nur schwierig in-situ messbar. Die Unzulänglichkeiten dieser Primärdaten kann durch Fehlerfortpflanzung zu großen Unsicherheiten führen. Dies gilt insbesondere für den organischen Kohlenstoffgehalt, der durch das Verbrennen einer Bodenprobe bestimmt wird. Daher werden in dieser Arbeit nur einfach messbare Bodenparameter eingesetzt, um die Bodenerodierbarkeit vorherzusagen.

Die dementsprechend aufgestellte Gleichung wurde auf ihre Anwendbarkeit für unterschiedliche Böden untersucht. Für 80 % der Bodenklassen der Weltbodendatenbank der FAO gilt, dass der relative Fehler dieser Gleichung im Vergleich zur Williams Gleichung um 20 % geringer ist. Dies deutet darauf hin, dass mittels einfach messbarer Bodenparameter, wie die Prozentanteile von Sand, Schluff und Lehm, ein sinnvoller Bodenerodierbarkeitsfaktor vorhergesagt werden kann.

Das physikalisch basierte SWAT2005 Modell wird zur Ermittlung des Sedimentertrags des Upper Awash Einzugsgebiets und der beiden Teileinzugsgebiete des Blue Nile eingesetzt. Das

Modell wird erfolgreich für die beiden Einzugsgebiete kalibriert und validiert, so dass der Modellbewertungsstandard eine gute bis sehr gute Performanz zeigt.

Für beiden Untersuchungsgebiete wird eine räumliche Verteilung der Bodenverlustrate analysiert. Die Bodenverlustrate des Upper Awash Einzugsgebiets liegt in einem Bereich zwischen 0,73 t/ha/a und 224 t/ha/a, wobei 56% der Flächen eine nicht tolerierbare Bodenverlustrate von mehr als 10 t/ha/a aufweisen. In ähnlicher Weise wird der Nettosedimentaustrag aus dem gesamten Untersuchungsgebiet zwischen 69 Mio. m^3 und 231 Mio. m^3 pro Jahr eingeschätzt. Dabei tritt der höchste Sedimentaustrag aus dem Untersuchungsgebiet in der Regenzeit auf. Im Gudar Teileinzugsgebiet beläuft sich die Bodenverlustrate auf ca. 1,46 t/ha/a bis 78,11 t/ha/a. Etwa 93,7% des Teileinzugsgebiets fallen in die Kategorie einer nicht tolerierbaren Bodenverlustrate. Gleichermaßen beträgt im Fincha Teileinzugsgebiet die Bodenverlustrate zwischen 6,57 t/ha/a und 256,6 t/ha/a. Etwa 99 % dieses Teileinzugsgebiets haben nicht tolerierbare Bodenverlustraten.

Verschiedene geomorphologische und hydrologische Faktoren, die den Sedimentertrag in einem Einzugsgebiet beeinflussen, werden analysiert und es wird eine Priorisierung vorgenommen. Dabei stellt sich heraus, dass die Einzugsgebietsgröße, das Einzugsgebietsgefälle und das mittlere Gefälle des Gewässers die beherrschenden geomorphologischen Faktoren sind, während der Abfluss den wichtigsten hydrologischen Faktor darstellt.

Mit der Kombination unterschiedlicher Einzugsgebietsfaktoren wird ein alternatives empirisches Regressionsmodell für die Sedimentertragsabschätzung formuliert. Die Eingangsparameter für das entwickelte alternative Sedimentmodell sind der Bodenerodierbarkeitsfaktor, der Spitzenoberflächenabfluss, das durchschnittliche Gefälle des Einzugsgebiets, die Fläche des Einzugsgebiets, der Gewässerabfluss und das durchschnittliche Gefälle des Flusses. Der Bodenerodierbarkeitsfaktor wird an Hand der neuen Methode zur Abschätzung der Bodenerodierbarkeit berechnet. Der Spitzenabfluss wird mit der Rational-Method-Formel berechnet. Die Fläche des Einzugsgebiets, das durchschnittliche Gefälle und das Flussgefälle werden aus dem SWAT2005- Modell extrahiert. Die Abflusstiefe, die bei der Rational-Method zur Abschätzung des Spitzenabflusses benötigt wird, sowie der Gewässerabfluss für das empirische Modell stammen aus den Kalibrierungsergebnissen des SWAT2005 Modells. Unabhängige Einzugsgebiete oberhalb des Kunture Pegels im Upper Awash Einzugsgebiet werden ausgesucht, um ein nichtlineares Regressionsmodell, das auf den beschriebenen Einzugsgebietsparametern basiert, aufzustellen.

In diesem Modell wurde ein Exponent X eingeführt, der wiederum eine Funktion verschiedener geomorphologischer Einzugsgebietsparameter ist.

Der mögliche Anwendungsbereich des Modells wurde für verschiedene Einzugsgebiete in unterschiedlichen hydro-klimatischen Zonen getestet. Das Mojo Teileinzugsgebiet im Upper Awash Einzugsgebiet und das Finch und Gudar Teileinzugsgebiet im Blue Nile Einzugsgebiet wurden zur Modellevaluation ausgesucht. Die Leistungsfähigkeit des Modells zeigt im Vergleich mit dem SWAT2005-Modell zufriedenstellende Ergebnisse. Das empirische Modell ist in der Lage, den Sedimentaustrag aus den einzelnen Einzugsgebieten vorherzusagen. Bei großen Einzugsgebieten ist es jedoch unpraktikabel die gesamte Fläche als einzelnes Einzugsgebiet zu betrachten und die vorgeschlagene Gleichung zu verwenden. Für diesen Fall ist es erforderlich, das große Einzugsgebiet in eine gewisse Anzahl kleinerer Teileinzugsgebiete zu unterteilen, was zu einem Netzwerk von verschiedenen Flussabschnitten und kaskadierenden Einzugsgebieten führt.

Mit dieser Vorgehensweise lässt sich der Sedimentaustrag durch die alternative empirische Gleichung vorhersagen, so dass die Nettosedimentmenge aus einem vernetzten Einzugsgebiet durch Sedimentrouting analysiert werden kann.

Ein alternativer Sedimentroutingfaktor wird eingeführt. Dieser Faktor ist eine Funktion der Veränderung der Fließgeschwindigkeit und der Änderung der durchschnittlichen Flussbreite zweier aneinandergrenzender Flussabschnitte.

Die vorgeschlagene Routing-Gleichung wird auf die zusammenhängenden Einzugsgebiete und Flusssysteme des Upper Awash, des Gudar und Fincha angewendet und evaluiert. Der an Hand des entwickelten Routingfaktors berechnete Sedimentaustrag wird mit dem SWAT2005 Modellergebnis verglichen. Hierbei werden zufriedenstellende übereinstimmunge erreicht.

Zusammenfassend lässt sich festhalten, dass in dieser Forschungsarbeit eine alternative Gleichung zur Abschätzung der Bodenerodierbarkeit und ein alternatives empirisches Modell für die Abschätzung des Sedimentaustrags erfolgreich aufgestellt werden. Diese alternativen Gleichungen stellen hilfreiche Werkzeuge zur Vorhersage des Sedimentaustrags für Einzugsgebiete mit geringer Datengrundlage dar. Weiterhin kann die Bodenverlustkarte die den spezifischen Grad der Bodenverlustrate im Upper Awash Einzugsgebiet sowie den Gudar und Fincha Teileinzugsgebieten aufzeigt für eine sinnvolle Festlegung von Verbesserungsmaßnahmen dienen. Solche Bodenverlustkarten dienen als Entscheidungshilfe, in welchen Teilen der erosionsgefährdeten Gebiete Boden- und Wasserschutzmaßnahmen zuerst angewendet werden soll.

1. INTRODUCTION

1.1 Background and justification

Soil loss rate is defined as the amount of soil eroded from a specified area in a specified time period. It is expressed as the amount of soil detached and transported per unit area and per unit time. The detachment of the soil particles from their parent soil matrix is the preliminary start of the soil loss rate and the initiation of erosion. Soil erosion is a complex process that is related to the soil property, climate (rainfall depth and intensity), topography, land cover pattern and human influence. The rainfall drop and the surface runoff that is generated from the rainfall events are the main mechanisms of soil detachment and transport process respectively. During the rainfall event, the splashes from raindrops detach individual soil particles and make them easily transportable. The rate and intensity of the detachment of the soil depends on the characteristics of the soil, the intensity and duration of the rainfall event. Soils whose particles are strongly bound together, mainly soil texture with a higher clay percentage are less prone to the detachment processes. Similarly, soil textures that are dominated by sand are less susceptible to detachment and transport processes because of their higher infiltration rate. In contrast, the presence of high silt content in soil texture facilitates soil detachment and transportability.

The dynamic nature of land use and land cover change due to anthropogenic effects is another factor for the occurrence of soil erosion. The pattern of agricultural practice and the change in land cover conditions play a fundamental role. Consequently, the temporal and spatial variability of land use and land cover is one of the crucial aspects to be considered when analyzing the soil erosion and sediment yield. Undisturbed soils and soils that exist under a dense cover of vegetation are rich in organic content. Such soils have high infiltration rates and as a result of this, the rain drop that falls from the plant canopy after dissipating its potential energy has less capability to detach and transport the soil particles. Moreover, the presence of high organic matter in soils decreases soil erodibility factor because the organic content facilitates soil infiltration rate.

The resulting water erosion due to either the high rainfall intensity or the pre-saturated soil conditions is the main cause of the formation of rills and gullies. Rills are small ditches that are formed in agricultural fields and are the main causes for the initiation of land erosion. Gullies are relatively large ditches that can’t be leveled by simple farm operations. Thus, the formation of gullies is an indication of the occurrence of severe erosion in the area. Once a gulley network is formed in a catchment area, the soil particles from the parent soil matrices can be easily transported to the adjoining river bodies.

The RUSLE, Revised Universal Soil Loss Equation (Renard et al. 1997), is the most widely used soil loss estimation method. The equation is the update of the original Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978). In RUSLE, the rainfall runoff factor of the original USLE was replaced by the rainfall erosivity factor while K, LS, C and P are the same parameters as in the original USLE factors. The RUSLE and its components are described below.

$$A = R \times K \times LS \times C \times P \tag{1.1}$$

where

A = Annual soil loss from sheet and rill erosion (t/ha/yr)
R = Rainfall erosivity factor
K = Soil erodibility factor
LS = Slope length and steepness factor
C = Cover and managment factor
P = Support practice factor

The soil that is eroded from the land surface is delivered to the nearby river section where it is defined as sediment yield. The sediment yield from the watershed is the net sediment flux resulting from the upland erosion and in the lowland deposition and transport into the river networks. Soil eroded from the upland catchment causes depletion of fertile agricultural land and the resulting sediment delivered to the river networks creates river morphological change and reservoir sedimentation problems.

The sediment delivery of a river network to a downstream section is influenced by the combined effect of geomorphologic and hydro-climatic parameters. As a result, there is a need to understand the interrelated natural processes and phenomena that play a fundamental role in erosion generation and sediment transportation at a large river basin scale. The quantity of sediment discharged at the outlet point of a river network or a basin is the sediment flux resulting from land surface erosion, river bank erosion and flood plain deposition. Erosion and deposition of sediment at different watershed sections depend on climatic factors and geomorphologic factors such as watershed slope, watershed length, watershed area, flow velocity, drainage length etc.

Understanding the order of significance of different geomorphologic and hydro-climatic factors is helpful to adapt or formulate appropriate sediment yield modeling strategies. Studies have been conducted to analyze the combined effects of basin parameters and fluvial processes. To estimate sediment yield, different empirical models were developed based on basin hydrologic and geomorphologic parameters ((Kornev and Kostyakov 1937, Glushkov and Polliakov 1946): *[cited from Summer and Walling 2002*], Williams and Berndt 1977, Milliman and Syvitski 1992, Tamene et al. 2006, Grauso et al. 2008). However, they are limited to certain boundary conditions and cannot be widely applied because they were developed based on data driven parameters of a specific area.

Physically based models are other helpful tools to analyze watershed sediment yield at different spatial scales. Model calibration and validation is a mandatory procedure when using physically based models for a watershed sediment yield analysis. Once the models are calibrated, the result can be taken as a representative value and can be used for further analysis. Similarly, for basin sediment yield modeling, different scenarios can be analyzed after extraction of the spatially variable basin parameters. The reliability of the results of physically based models depends on the quality of the hydro-climatic and hydraulic input data. The presence of erroneous values of any of the input data parameters may lead to a wrong conclusion on the model result. Beside that, the tiresome and lengthy calibration and validation work of physically based models needs a wide range of professional expertise and reliable data sources.

Available empirical models are limited with respect to time and space, while physically based models have limited applicability for data scarce areas. Existing empirical models mostly consider "black box" watershed processes which hinder the consideration of spatial variability. However, physically based models are intensively data dependent and need reliable and representative data sets. In data limited areas, there is a lack of empirical models for sediment estimation and insufficient application history of physically based models. Therefore, there is a need for investigating and formulating an alternative solution for modeling of watershed sediment yield with a specific focus on data scarce areas.

Consideration of the hydro-climatic and geomorphologic watershed factors that take part in the sediment generation and transportation can strengthen the understanding of the entire watershed sediment related phenomena. Besides that, analyzing the interdependency of hydro-climatic and geomorphologic properties of a watershed can help to devise alternative sediment modeling options. With due consideration to parameters governing most likely sediment yield, empirical models are preferable, especially for data limited areas where physically based models cannot be applied. Different investigations recently conducted, revealed the importance of empirical models and future prospects in modeling of watershed sediment yield. It was recommended that further detailed studies have to be undertaken to establish a simplified general model for watershed sediment yield (Liebault et al. 2002, Tamene et al. 2006, Restrepo et al. 2006). For data scarce areas like Ethiopia, where water resources development is at an infant stage, it is a must to have alternative solutions for sediment modeling.

In Ethiopia, the sediment gauging stations are sparse and measurement have been taken rarely and randomly. However, there is a big demand for sustainable utilization of water resources projects. The government proposed utilization of water resources for agriculture and power generation as a strategy for supplementing the economic growth of the country. Thus, a great number of large and small dams have been planned and constructed during the past two decades. However, the sustainability of the projects is in a critical condition because of reservoir sedimentation problems. In one of the states in the northern part of the country (Tigray regional state), it was planned to construct 500 dams out of which only 54 dams were constructed. The construction of the dams was withdrawn because of sedimentation and seepage problems (Haregeweyn and Poesen 2005). Similar problems have been observed in other states of the country. The limitation of sufficient sediment data was one of the bottlenecks preventing the provision of appropriate safety measures during the design of the projects. Devising an alternative solution by formulating sediment modeling options for data scarce areas can alleviate the problem. Therefore, this research was formulated to devise an alternative solution for the estimation of soil erodibility and to propose an alternative empirical model for sediment yield estimation on a watershed and basin scale for data scarce areas.

1.2 Research goals and methodology

The basic goal of the research was to derive an alternative solution for watershed sediment yield modeling for data scarce areas through the following specific sub-objectives:

- ❖ **Objective 1:** To estimate the soil erodibility factor for the selected study area from one of the available equations and analyze the possibility of establishing an alternative equation with easily measurable or available physical parameters of soil properties.
- ➢ Methodology 1: FAO (1998) World Soil Database has been referenced to extract the properties of the soil in the Awash basin and then to calculate the soil erodibility factor. The reliability of the results from the FAO (1998) soil database has been checked with arbitrarily collected field data and analyzed in the laboratory. The calculated erodibility factor for the selected study area has been used to develop a regression equation which has been applied to establish an alternative estimation method for the soil erodibility factor with easily measurable physical parameters of soil properties. The developed regression equation has been evaluated for its applicability for soils that are different from those of the selected study area.
- ❖ **Objective 2**: To identify the watershed parameters which govern sediment yield and calibrate the SWAT2005 model for both stream flow and sediment yield. Two river basins (Upper Awash and Blue Nile basins) have been considered for application of the SWAT2005 model. Moreover, to identify erosion risk areas in the considered study

basins and analyze the temporal pattern of the sediment outflow from the entire study areas.

- Methodology 2a: The LH-OAT (Latin hypercube once at a time) sensitivity analysis method embedded in SWAT2005 model has been applied to rank the parameters governing the stream flow and sediment yield. The ranked parameters have been used to calibrate the model for both river basins.
- Methodology 2b: Topographic and geomorphologic watershed parameters of the study area have been computed from the 90 m x 90 m DEM using GIS tools. A partial correlation analysis has been applied to analyze the inter-dependability of the parameters as well as the degree of influence of the parameters on watershed sediment yield.

❖ **Objective 3:** To develop an alternative empirical model for watershed sediment yield estimation.

- Methodology 3: After calibrating and validating the SWAT2005 model, the output from SWAT2005 model has been applied in a regression analysis to propose an alternative empirical model for sediment yield estimation. The governing parameters identified in objective 2 have been used as predictor variables in developing the model.

❖ **Objective 4**: To evaluate the scope of the applicability of the developed empirical model of sediment yield estimation.

- Methodology 4: Watersheds that were not included in developing the regression model have been used for the model evaluation. Moreover, the equation has been tested on watersheds in different river basins located in various climatic zones.

1.3 Hypothesis of the research work

Hypothesis 1: The soil erodibility is primarily governed by physical characteristics of the soils. The simplified soil erodibility estimation method to be derived from the easily measurable soil characteristics of Upper Awash basin should reasonably predict the erodibility factor for soils that are different from the study area

Hypothesis 2: The parameters of the watershed to be prioritized for successful calibration of the SWAT2005 model should be proved in the model calibration and validation at different subbasins scale and various climate zones.

Hypothesis 3: The sediment yield from a watershed is governed by the combined effect of geomorphologic and hydrologic characteristics. The sediment yield to be estimated by alternative approach of sediment yield quantification method should reflect the role of different geomorphologic and hydrologic characteristics of a watershed.

2. SOIL ERODIBILITY ESTIMATION METHODS

2.1 Introduction

The strength of the raindrop splashes and depth of the surface runoff occurring from precipitation determines the detachability of the individual soil aggregate and bulk transport of the detached soil particles. The detachability of the soil aggregate from the parent soil depends on the strength with which individual soil particles are bound together. The stronger the particles are bound together, the less they will be susceptible to erosion. The soil susceptibility to erosion is expressed by a soil erodibility factor. Soil erodibility can be assessed by any of three established methods, namely the direct measurement on a natural runoff plot, rainfall simulation studies and predictive relationships.

The direct measurement on a natural plot method and rainfall simulation methods need standardized field experimental plots. The methods give a reliable erodibility factor, however it is costly and time consuming. The predictive relationship approach is the relatively easier method, but the result is less accurate compared to the runoff plot and rainfall simulation methods (Romkens et al. 1977). The predictive approaches are based on the soil's physical, chemical and mineralogical properties. Wischmeier et al. (1971) soil erodibility nomograph is the most commonly used predictive method.

Different attempts had been made to establish the erodibility factor relationships with different soil properties. Olson and Wischmeier (1963), El-Swaify and Dangler (1977), Young and Mutchler (1977), Williams et al. (1984), Shirazi and Boersma (1984), Sharpley and Williams (1990) and Chen et al. (1996) are among the common investigations conducted on soil erodibility estimation equations. These investigations suggest certain empirical relations giving soil erodibility values using certain data sets. However, adaptation of the research results of the investigations to other places still remains a big challenge due to the area specific nature of empirical models or the insufficiency of input data to make necessary adjustments for the specific situations of the area under consideration. Likewise, very few investigations have been done so far for the specific situation of soils in Ethiopia (Fufa et al. 2002, Griffiths and Richards 1989).

The limited availability of an appropriate method for the estimation of soil erodibility factor is the main bottleneck for prediction of a reliable sediment yield. Therefore, there is a need to assess the existing soil erodibility estimation methods with respect to data availability. Moreover, devising an alternative approach for the erodibility estimation with a more simplified input parameter makes calculations more effective. Hence, in this chapter the most commonly used soil erodibility equations have been assessed and suggested as a reference for the derivation of the alternative formula for the estimation of the soil erodibility factor.

2.2 Review of existing methods for soil erodibility estimation

The attempt to establish equations for the determination of a soil erodibility factor started in the early 1950's. Since that time, different empirical relations have been established. Different investigators have suggested various approaches for the estimation of the soil erodibility factor. Wischmeier et al. (1971) developed the most widely used soil erodibility nomograph (figure 2.1). The nomograph was derived from field data collected for over 20 years in the USA on test plots of 22.1 m length, 1.83 m width and 9 % slope. To apply the nomograph five soil parameters are required, which are the percentage of modified silt (0.002-0.1 mm) content, the percentage of modified sand (0.1-2 mm) content, the percentage of organic carbon matter (OM) and classes for structure ($C_{soilstr}$) and permeability (C_{perm}). An algebraic relation was proposed by Wischmeier and Smith (1978) to represent the nomograph for the cases where the silt fraction does not exceed 70 %.

$$K_{USLE} = \frac{0.00021\ M^{1.14}(12 - OM) + 3.25(C_{soilstr} - 2) + 2.5(C_{perm} - 3)}{100} \qquad (2.1)$$

Where

$$M = (m_{silt} + m_{vfs}) \times (100 - m_c)$$

$$OM = 1.7 \times orgC$$

m_{silt} = Percent silt (0.002 mm - 0.05 mm)

m_{vfs} = Percent of fine sand (0.05 mm - 0.10 mm)

m_c = Percent of clay (less than 0.002 mm)

orgC = Percent organic carbon

$C_{soilstr}$ = Soil structure code used in soil classification

C_{perm} = Soil permeability class

The soil structure code used in the equation is defined by the soil class and soil texture as defined by each layer of the soil. Following are notations used for soil structure codes for the different soil structure class.

The codes assigned to soil structure ($C_{soilstr}$) are:

1 = Very fine granular

2 = Fine granular

3 = Medium coarse granular

4 = Blocky, platy, prism like massive

In a similar way, the soil permeability class is defined in terms of the lowest soil hydraulic conductivity. Based on the hydraulic conductivity the C_{perm} can be defined as follows:

1 = Rapid (>15 mm/h)

2 = Moderate to rapid (50 -150 mm/h)

3 = Moderate (15 - 50 mm/h)

4 = Slow to moderate (5 - 15 mm/h)

5 = Slow (1 - 5 mm/h)

6 = Very slow (<1 mm/h)

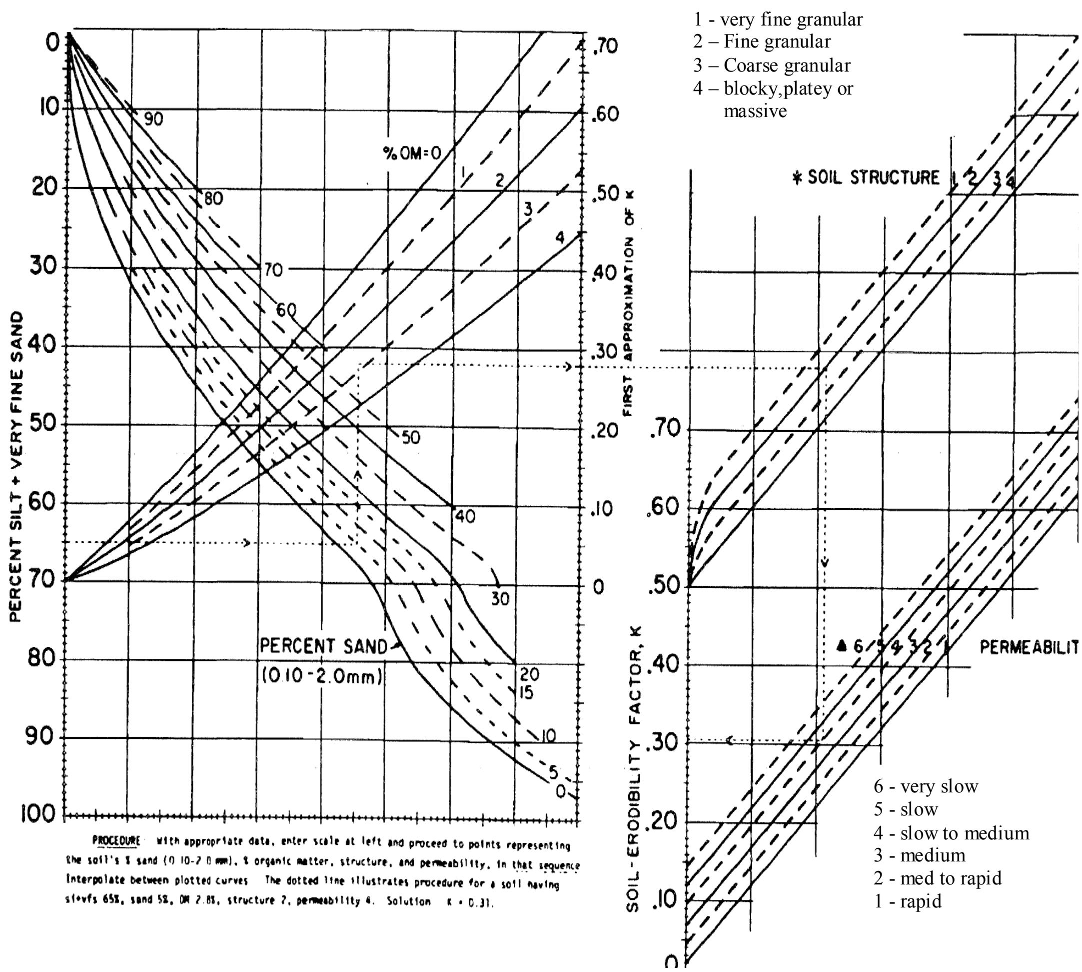


Figure 2.1: Soil erodibility estimation nomograph (Wischmeier et al. 1971)

El-Swaify and Dangler (1977) proposed an erodibility estimation equation based on the physical characteristics of the soil.

$$K = -0.03970 + 0.00311X_1 + 0.00043X_2 + 0.00185X_3 + 0.00258X_4 - 0.00823X_5 \quad (2.2)$$

Where X_1 is the unstable aggregate size fraction with a percentage of less than 0.25 mm, X_2 is the product of percentage of modified silt (0.002 - 0.1 mm) and percentage of modified sand (0.1-2mm), X_3 is the percentage of base saturation, X_4 is the percentage of silt (0.002-0.05 mm), x_5 is the modified percentage of sand (0.1 - 2 mm).

Young and Mutchler (1977) developed the following relationship for upper midwest of USA.

$$K = -0.204 + 0385 X_6 - 0.013 X_7 + 0.247 X_8 + 0.003 X_2 - 0.005 X_9 \qquad (2.3)$$

Where X_6 is an aggregate index, X_7 is the percentage montmorillonite in the soil, X_8 is the bulk density of the 50-125 mm depth in g/cm^3, X_9 is the dispersion ratio.

Romkens et al. (1977) suggested an alternative equation for clay subsoil in the midwest of the USA.

$$K = 0.004 + 0.00023 X_{10} - 0.108 X_{11} \qquad (2.4)$$

Where X_{10} is equivalent to the parameter M (Wischmeier et al. 1971) and x_{11} is the citrate-dithionite-bicarbonate (CDB) extractable percentage of Al_2O_3 plus Fe_2O_3.

Shirazi and Boersma (1984) developed an empirical equation based on a natural plot and simulated rainfall data derived from global data. In the analysis, soils with less than 10 % of rock fragments were considered. The erodibility equation was related to the mean geometric particle diameter.

$$K = 7.594 \left\{ 0.0017 + 0.0494 \exp\left[-\frac{1}{2} \left(\frac{\log(D_g + 1.675}{0.6986} \right)^2 \right] \right\} \qquad (2.5)$$

$$D_g (mm) = \exp(0.01 \sum f_i \times \ln m_i)$$

Where f_i is the primary particle size fraction in percent and m_i is the arithmetic mean of the particle size.

Williams et al. (1984) proposed erodibility equation using soil texture and organic carbon content as an input variable.

$$K = f_{csand} \times f_{cl-si} \times f_{org} \times f_{hisand} \qquad (2.6)$$

$$f_{csand} = (0.2 + 0.3 \exp(-0.0256 m_s (1 - \frac{m_{silt}}{100})))$$

$$f_{cl-si} = (\frac{m_{silt}}{m_c + m_{silt}})^{0.3}$$

$$f_{org} = (1 - \frac{0.25 \, orgC}{orgC + \exp(3.72 - 2.95 \, orgC)}$$

$$f_{hisand} = (1 - \frac{0.7(1 - \frac{m_s}{100})}{(1 - \frac{m_s}{100}) + \exp(-5.51 + 22.9(1 - \frac{m_s}{100}))})$$

Where

m_s = Percentage of fine sand (0.05 mm - 0.10 mm)

m_{silt} = Percentage of silt (0.002 mm - 0.05 mm)

m_c = Percentage of clay (less than 0.002 mm)

orgC = Percentage of organic carbon

2.3 Applicability and comparative assessment of the erodibility estimation methods

Among the described soil erodibility estimation methods, the formulas proposed by Wischmeier and Smith (1978), Williams et al. (1984), Shirazi and Boersma (1984) are most popular and applied world wide (Zhang et al. 2008a). The selection of one of these erodibility equations depends on the availability of input data for the specific area under consideration. The Wischmeier and Smith (1978) equation can be applied to areas that have complete data sets related to soil texture classes, soil organic carbon content, soil permeability and soil structure classes. The equation of Williams et al. (1984) can be applied in areas where there is sufficient data available on the soil texture and soil organic carbon content. The applicability of the Shirazi and Boersma (1984) equation depends on the availability of data pertaining to the calculation of the geometric grain size.

The applicability of the popular erodibility estimation equations have previously been evaluated by comparing them with measured erodibility factors in different parts of the world (Zhang et al. 2008a investigation in China and Wawer et al. 2005 investigation in Poland). Zhang analyzed six sets of comparative soil loss data obtained from field plots of 1 m width, 20 m length, and 15^o slope in continuous fallow land management. The field plots were established in different regions of China representing different dominant soil types. The annual soil loss rate from each plot was measured and then used to compute the erodibility (K) value from the basic RUSLE equation.

$$K = \frac{A}{R \times LS \times C \times P} \qquad (2.7)$$

Where

A = mean annual soil loss (t/ ha/ yr)

R = rainfall erosivity (MJ mm/ ha/ h/ yr)

L = slope length

S = steepness factor

C = crop cover factor

The equations of Wischmeier and Smith (1978), Williams et al. (1984) and Shirazi and Boersma (1984) are applied to calculate the soil erodibility factor for soils of the same type from the plots where measurements are conducted. The result from the measured K value and the result from the computed K value using the suggested equations were compared. The comparison results reveal that all methods overestimate the K values on average by a factor of 7. The highest relative error (RE) is observed using the equation of Wischmeier and Smith (1978) and the smallest relative error was observed using the equation of Shirazi and Boersma (1984) (Zhang et al. 2008a). The following table shows the relative errors for the three methods for different field observations in China soils.

Table 2.1: Estimated K values compared to K values observed in field measurements

Site	measured K	Wischmeier and Smith (1978)		Williams et al. (1984)		Shirazi and Boersma (1984)	
		K_{est}	RE(%)	K_{est}	RE(%)	K_{est}	RE(%)
Binxian	0.021	0.0329	56.7	0.0472	124.8	0.0474	125.7
Xifeng	0.0097	0.0487	402.1	n/a	n/a	n/a	n/a
Huangfuchuan	0.0154	0.0672	336.1	0.0528	242.9	0.0377	144.8
Zizhou	0.0234	0.0738	296.8	0.0625	236.0	0.0459	146.8
Suide	0.0186	0.0711	203.8	0.0606	159.0	0.0428	82.9
Ansai	0.0096	0.0553	476.0	0.0607	532.3	0.0476	395.8
Lishi	0.0156	0.0593	280.1	0.0537	244.2	0.0504	223.1
Suining	0.0191	0.0619	224.1	0.0543	184.3	0.0509	166.1
Anxi	0.0073	0.0632	765.8	0.0366	401.4	0.0333	356.2
Yuexi	0.0018	0.0553	2972.2	0.0483	2583.3	0.0250	1288.9

Adopted from Zhang et al. (2008a): K_{est}=the estimated k, RE = relative error in %. The units of K are in SI units.

The comparative results of the different erodibility estimators with respect to the on field observed erodibility values are plotted and shown in figure 2.2.

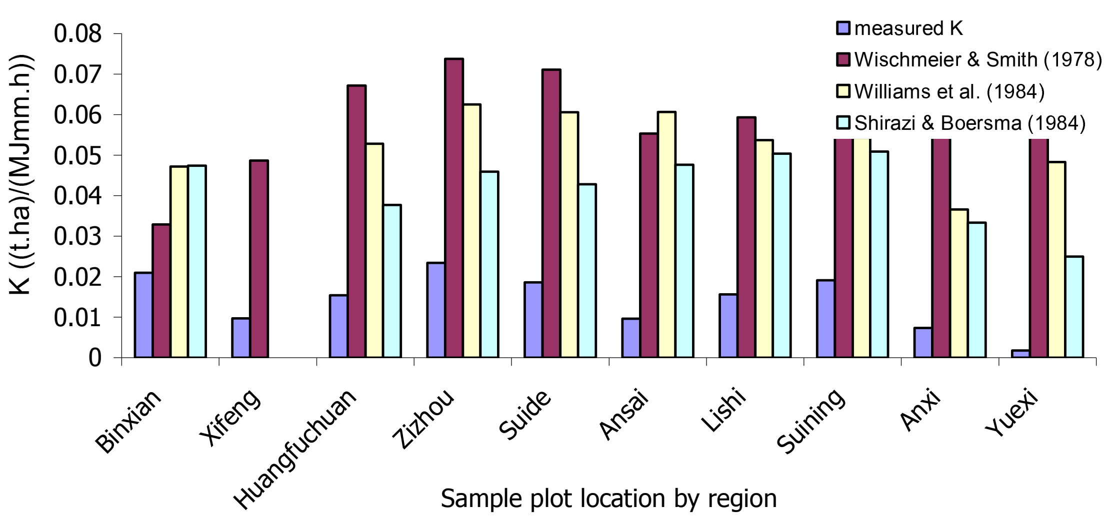


Figure 2.2: Comparison of the results of different erodibility estimation equations

For all the sites of observations except Binxian and Anasai, the relative errors are highest for K values calculated using the equation of Wischmeier and Smith (1978) and lowest using the equation of Shirazi and Boersma (1984). The equation of Williams et al. (1984) showed an intermediate relative error as compared to the two methods.

In a similar way, an investigation was conducted in Poland to evaluate the applicability of the equations of Wischmeier and Smith (1978) and Williams et al. (1984) (Wawer et al. 2005). In this research a prototype sprinkler system resembling a natural rainfall was established in the Polish Academy of Sciences' Institute of Agro physics in Lublin. The spraying of water was conducted for different time periods of: 30, 40, 45, 50 and 60 minutes. The amount and intensity of the sprinkled rain, the soil moisture, the runoff generated and the soil detached and transported as sediment were recorded. The experiment was repeated 13 times for each case. Using the parameters collected on the plot land under the established sprinkler, the soil erodibility factor (K_d) was computed from the Wischmeier and Smith (1978) equation. The computed K_d value was taken as observed soil erodibility value.

$$K_{USLE} = K_d = \frac{Sed}{1.292 EI_{USLE} \times P_{USLE} \times LS_{USLE} \times CFRG} \qquad (2.8)$$

where

Sed = sediment uptake (t/ha/day)

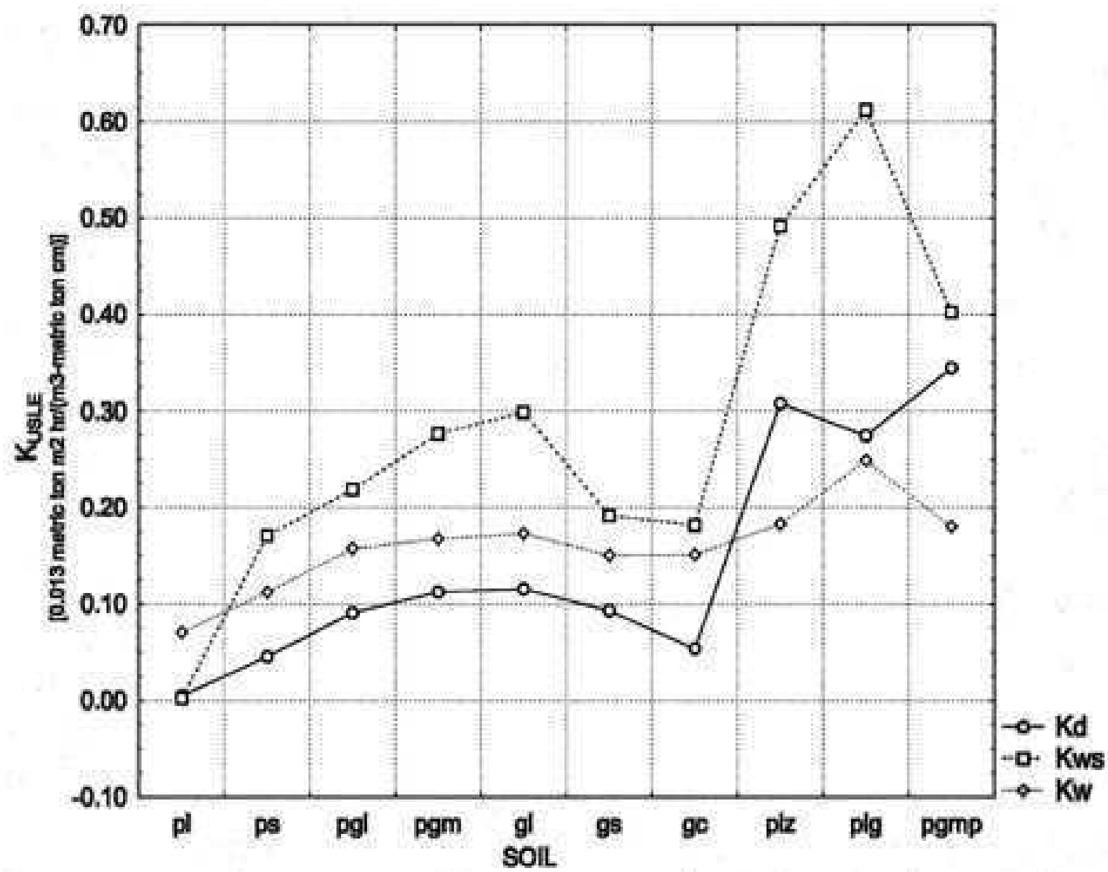
EI_{USLE} = rainfall erosion index ($0.017 Mg\ cm/m^2/h$)

K_{USLE} = USLE soil erodibility factor

P_{USLE} = support practice factor

LS_{USLE} = topographic factor

The soil erodibility factor was computed using the equation of Wischmeier and Smith (1978) (equation 2.8) and using the equation of Williams et al. (1984) (equation 2.6). The erodibility factor value computed from the measured soil loss quantity was compared with the erodibility value computed by the two empirical equations described above. The comparative assessment of the result is shown on the following figure.



Adopted from Wawer et al. (2005): Kd = computed from sprinkling, Kws = calculated from Wischmeier and Smith (1978), Kw = Calculated from Williams et al. (1984)

Figure 2.3: Estimated and field observed soil erodibility factors

As shown in figure 2.3, the Kw approaches the Kd when compared to the Kws indicating that, the equation of Williams et al. (1984) predicts the erodibility factor in a better way than the equation of Wischmeier and Smith (1978).

2.4 Discussion

Existing equations for the estimation of soil erodibility have been reviewed. The majority of the equations were developed based on limited data sets and for the conditions of a specific area (Wischmeier and Smith 1978, El-Swaify and Dangler 1977, Young and Mutchler 1977, Romkens et al. 1977). The erodibility equations of Shirazi and Boersma (1984) and Williams et al. (1984) were derived from global data sets.

Selection and application of the equations should be done wisely so that a reasonable erodibility value can be predicted. There have been few researches conducted to evaluate the applicability of the different erodibility equations under different conditions. Zhang et al. (2008a) and Wawer et al. (2005) evaluated the degree of applicability of the most popular equations with respect to the erosion data measured in the field. The investigation revealed that the erodibility equations of Wischmeier and Smith (1978), Williams et al. (1984) and Shirazi and Boersma (1984) overestimated the erodibility values. From the result, it was observed that the three methods show different range of errors. According to Zhang et al. (2008a), the equation of Shirazi and Boersma (1984) shows the least errors and the equation of Williams et al. (1984) shows intermediate errors. The equation of Wischmeier and Smith (1978) has shown the largest error as compared to the other two methods. Similarly, the investigation conducted by Wawer et al. (2005) also indicated the better performance of the equation of Williams et al. (1984) as compared to the equation of Wischmeier and Smith (1978) even though both methods overestimate the K factors.

The review of the two research results indicates that the direct application of the erodibility estimation methods provides over estimated values which can significantly influence the soil loss rate or the sediment outflow from a watershed. The overestimation of the methods could be due to the many soil parameters incorporated in the equations. The more parameters are considered, the more the error increases during data collection and analysis. Moreover, soil parameters like the organic carbon content are difficult to accurately measure and as a result a large margin of error can be introduced into the equations.

The most popular organic soil measurement is by the soil burning method. The method assumes that the loss of weight of considered soil sample is due to the burning of organic carbon content. In soils with significant clay components, the result is expected to be too erroneous. The burning method is a very approximate method which varies in accuracy depending on the clay content of the soil. The better the performance of the equation of Shirazi and Boersma (1984), which is independent of the organic carbon content can justify this comment.

In the equation of Shirazi and Boersma (1984), the geometric grain size which is a function of the particle size fraction and particle size limit may be too sensitive to small discrepancies as it was represented by an exponential function (equation 2.5). The small discrepancies in the data of particle size fraction and particle size limit can lead to large errors. To avoid such discrepancies a detailed investigation of the particle size information is required which needs many representative soil sample data and accurate laboratory analysis.

Another advantage of the erodibility equation of Williams et al. (1984) is that its input requirements can be extracted from the FAO (1998) soil database. In the absence of soil properties measured on the field, the FAO database parameters are the possible alternative sources for obtaining the soil properties that are required in equation of Williams et al. (1984). However, the demand for a great number of soil input parameters remains a major challenge for estimating erodibility factor. Minimizing the input requirement for the soil erodibility factor estimation can alleviate the difficulty of obtaining sufficient data. Therefore, assessing the possibility of an alternative approach to minimize the number of required input data and easily measurable soil parameters is mandatory. The formulation of an alternative soil erodibility estimation approach is described in chapter 4.

3. DESCRIPTION OF THE STUDY AREA

To achieve the proposed objectives (section 1.2) two river basins, namely Blue Nile and Upper Awash basins in Ethiopia have been selected. Upper Awash basin has been used for parameter identification and derivation of alternative empirical equation for sediment yield estimation. Gudar subbasin and Fincha subbasin have been used as test watersheds for evaluation of the SWAT2005 model parameters and the evaluation of the alternative sediment yield quantification equation.

3.1 Climatic zone classification

Ethiopia has three distinct climatic zones, namely Dega (humid), Wayne Dega (semiarid) and Kola (arid). The humid climate zone has been divided into three sub sections: humid, moist subhumid and dry subhumid (Lemma 1996). The humid part of the country includes areas receiving annual rainfall of greater than 1280 mm with a temperature of about 16 °C and with elevations greater than 2440 m above mean sea level (a.s.l). Semiarid parts are areas with annual rainfall between 500 mm and 1530 mm, temperatures of about 22 °C and elevations of 1830 to 2240 m a.s.l. The arid part of the country receives an annual rainfall of less than 510 mm, its temperature is about 27 °C and its elevation is less than 1830 m a.s.l. The population is concentrated in the humid and semiarid climate zones where agriculture is the base for the economy of the country. As a result, there is high anthropogenic pressure on the ecosystem especially on land and water.

There are 12 major river basins in Ethiopia: 8 are perennial river basins, one is a lake basin and three (Danakil, Aisha and Ogaden basins) are intermittent river basins with almost no or insignificant flow. Utilization of water resources of the country are focused on the 8 river basins as they are located in a climate zone favorable for human settlement. Awash basin and Blue Nile basin are the most widely utilized and are being developed for water resources projects mainly for hydropower and irrigation purposes. The Awash basin covers 70 % of the country's area for irrigated agriculture and provides hydropower with installed power of 46 Mega Watt (MW). The Koka dam located in the basin is the main source of water for irrigation and hydropower purposes. Nevertheless, the dam has lost 40 % of its storage capacity due to sedimentation problems in the 30 years of its service period (EEPC 2002). The Blue Nile basin is the largest river basin and covers about 33.2 % of the total area of the country. It contributes about 86 % of the discharge to main Nile River. The basin has 48.9 % of the hydropower potential and over 1 million hectare of land for irrigation potential. Severe degradation of the soil fertility due to erosion resulting from the combined effect of anthropogenic and natural extremes (long term drought) has been one of the characteristics of the basin. With the aim of using the available water resource in the basin, the government of Ethiopia is constructing different large scale hydropower and irrigation projects.

For sustainability of the water resources projects watershed management activities which considers erosion, river bank and reservoir sedimentation is a crucial area of interest. Based on the availability of different data sets for modeling purposes, the Upper Awash basin has been selected for the model derivation and two subbasins (Gudar and Fincha) of the Blue Nile basin have been selected for the model testing and evaluation (figure 3.1). The selection of the subbasins was made based on the availability of data and their location in different climate zones (semiarid and subhumid).

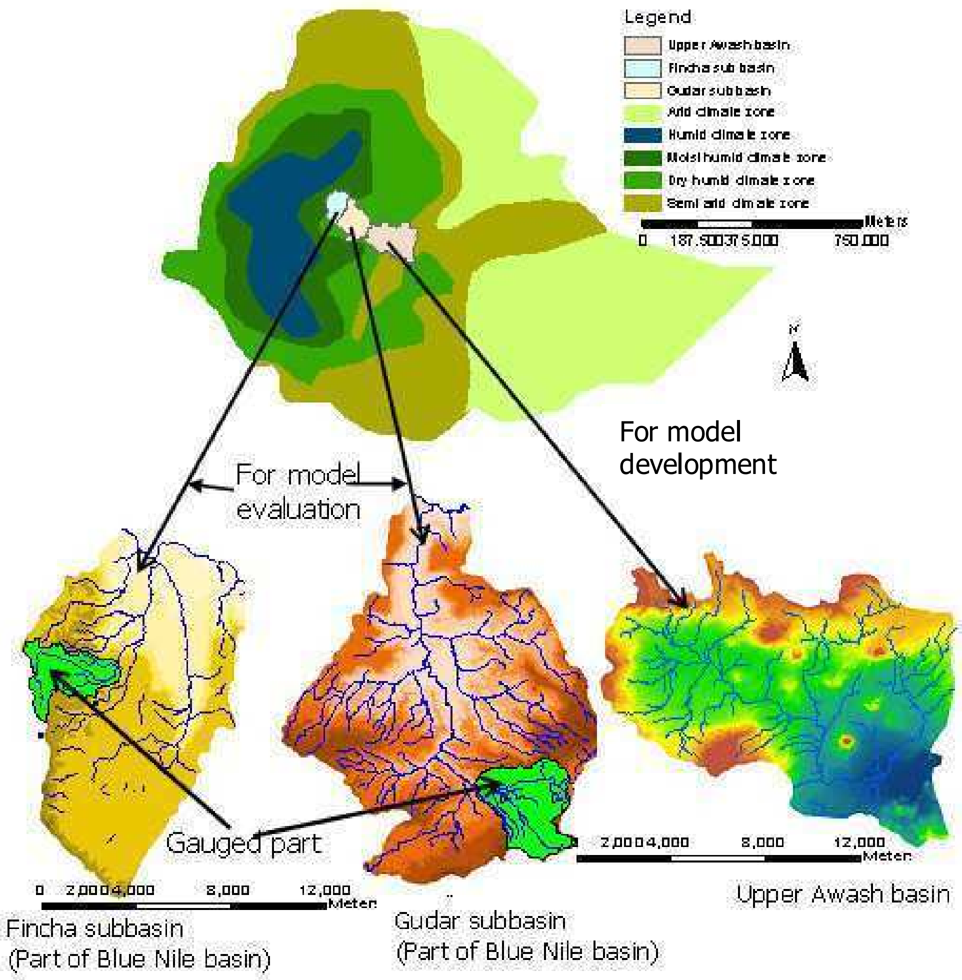


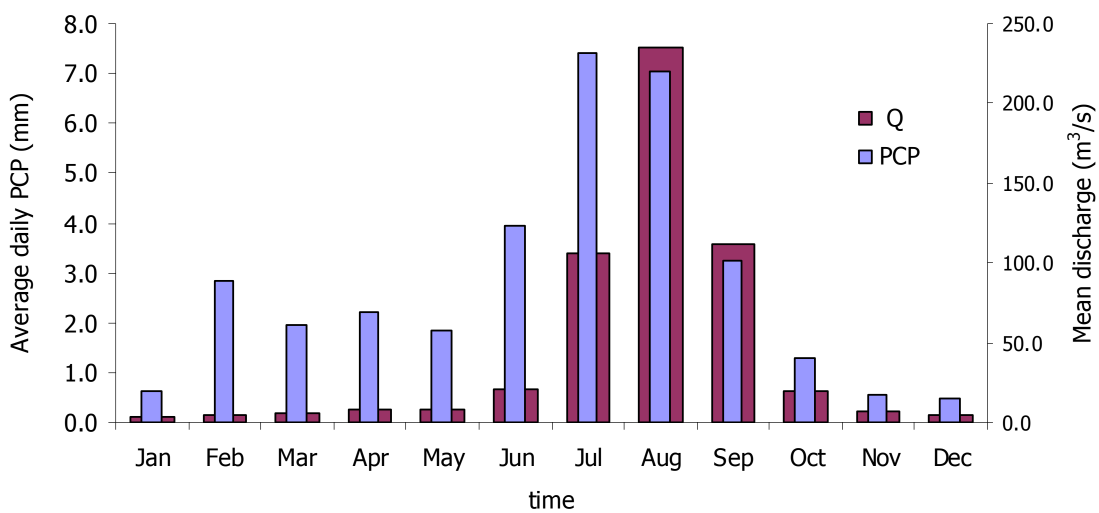
Figure 3.1: Location of the selected study areas for model development and verification

The characteristics of the selected study basins are described below.

3.1.1 Upper Awash basin

Upper Awash basin has an area of 10,540 km^2. The basin is characterized mainly by agricultural land, forest and in limited parts by urban areas, wetland and pasture. Agricultural land coverage is about 80 % and the forest land is 14 % of the area. Leptosols are the dominant soil types in the area which covers 63 % of the basin. Eutric vertisols, Chromic Cambisols, Dystric Gleysols and Dystric Nitosols are also the most common soil types. The average basin slope ranges from 0.7 % to 16.5 %.The study area has and elevation range of 1648 m a.s.l to 3642 m a.s.l.

The hydro-climatology of the basin is variable both seasonally and annually. Months from May to September are the monsoon season which contributes to the occurrence of high runoff. As a result, the peak stream flows in rivers are observed during these periods, while for the remaining months of the year, flows in the perennial rivers are contributed by base flow during dry periods. From 1990 to 2006 data records at Hombole gauging station, the average maximum and average minimum discharge was observed to be 235.5 m^3/s in August and 3.76 m^3/s in January respectively (Figure 3.2). Similarly, maximum rainfall was observed in the month of July. The observed maximum rainfall intensity was 60 mm/h.



PCP=Precipitation, Q=Discharge

Figure 3.2: Average discharge and precipitation in Upper Awash basin

3.1.2 Blue Nile basin

Similar to the Awash basin, in Blue Nile basin the maximum rainfall is attained during the months of May to September. Maximum stream flow is also observed in the same time period. The physiographic characteristics of the two subbasins (Gudar subbasin and Fincha subbasin) are described below.

3.1.2.1 Gudar subbasin

Gudar subbasin is located in the western part of Blue Nile basin and it has a total drainage area of 1,946.8 km^2 (figure 3.1). The subbasin is characterized mainly by agricultural land use and few settlements. It is located in the dryhumid climatic zone. The hydrology data and the arbitrarily measured suspended sediment data of the Gudar River are available from Federal Ministry of Water Resources of Ethiopia (FMWRE). The gauging station for the measurement of both (discharge and sediment) parameters is located at the upstream section of the river with a drainage area covering 621.94 km^2. The subbasin has an average slope range of 0.95 % to 20.6 %. Leptosols, Luvisols and Vertisols are the dominant soils in the subbasin.

3.1.2.2 Fincha subbasin

Fincha subbasin is located in the moist humid climatic zone of the Blue Nile basin. The subbasin has a total area of 2,662 km^2 out of which 299.18 km^2 is gauged. Stream flow data and randomly measured suspended sediment data on the Nesh river is available from FMWRE. The area is characterized by agricultural land use. Dystric nitisols and Haplic alisols are the dominant soils in the area.

3.2 Data availability

The Federal Ministry of Water Resources of Ethiopia (FMWRE) and the National Metrology Service Agency (NMSA) are the major sources of data required for this research. FAO (1998) soil map was another source of data utilized for the definition and characterization of the different soil properties. Moreover, primary data on soil properties, suspended sediment measurement, land cover pictures and geographic locations of the high erosion and deposition area were collected during field work. The different data types that were collected during the study period are described as follows.

3.2.1 Primary data collection

The primary data are mainly data elements which have been collected during the field work.

Suspended sediment data: Suspended sediment data has been collected from 3 tributary rivers of the Awash basin and from 2 gauging stations on the main Awash River. The suspended data was collected during the field study using DH-48 sediment sampler. DH-48 is a standard sediment sampler that has a collector bottle with a capacity of 470 ml and ¼" diameter nozzle size. The sampler weight is approximately 2 kg. It can be used in shallow water depths with medium flow velocities. Using the DH-48, suspended sediment data was collected from Holeta River, Teji River, Mojo River and at Hombole and Kunture gauging stations on the main Awash river. The samples were analyzed in FMWRE laboratory (Figure 3.3).

Figure 3.3: Collection and analysis procedures of suspended sediment data

The daily sediment load has been estimated using the related discharge and has been used for a cross check with the sediment mass predicted from the rating curves of each of the gauging stations (figure 3.4 and figure 3.6). As shown in figure 3.4 and figure 3.6 sampling was done twice on 26/11/09 for Kunture gauging station. One time sampling was done immediately after rainfall occurrence and another sampling was done 10 hours later.

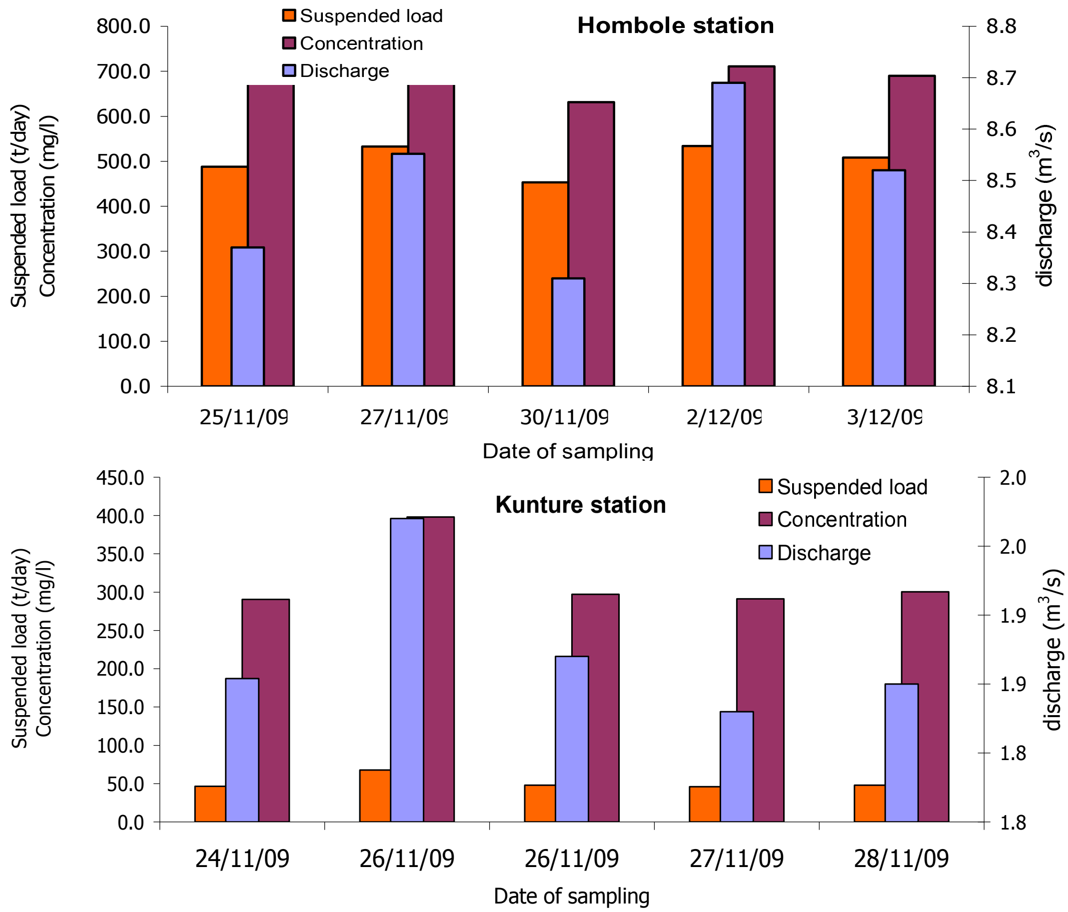


Figure 3.4: Arbitrary measured suspended sediment data

Soil sampling: Soil samples have been collected for the major soil types in the Awash basin from a 60 cm x 60 cm pit with a depth of 100 cm. The sampling has been done separately at two depth profiles: the first at a depth of 30 cm and the second at 70 cm. The collected soil samples were taken to laboratory and the textural classes have been determined through dry and wet sieve analysis (described under section 4.2).

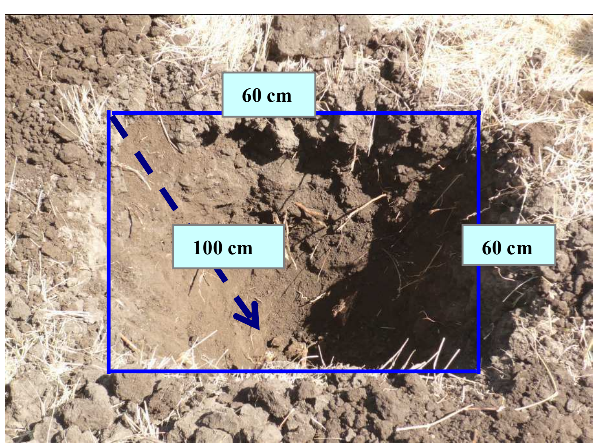


Figure 3.5: Soil sampling pit under excavation

3.2.2 Secondary data collection

A digital soil map (1:3,000,000 scale) as well as land use and land cover maps for Awash and Blue Nile basins were obtained from FMWRE. The obtained soil map was co-referenced with the FAO (1998) soil database to obtain the physical description and characteristics of the map. The digital elevation model (DEM) of 90 x 90 m resolution was downloaded from website www.srtm.csi.org. Climate data such as precipitation, temperature, relative humidity, wind speed and hours of sunshine for 10-20 years were obtained from NMSA. Stream flow data for 30 years and randomly measured suspended sediment load data have been obtained from FMWRE. For the respective gauging stations, the corresponding suspended load has been estimated using the rating curve established by the ministry office. The estimated suspended load from the established rating curve has been evaluated using the primary data collected during field work. The results from the suspended load measured in the field and estimated suspended load from rating curve are shown below (figure 3.6).

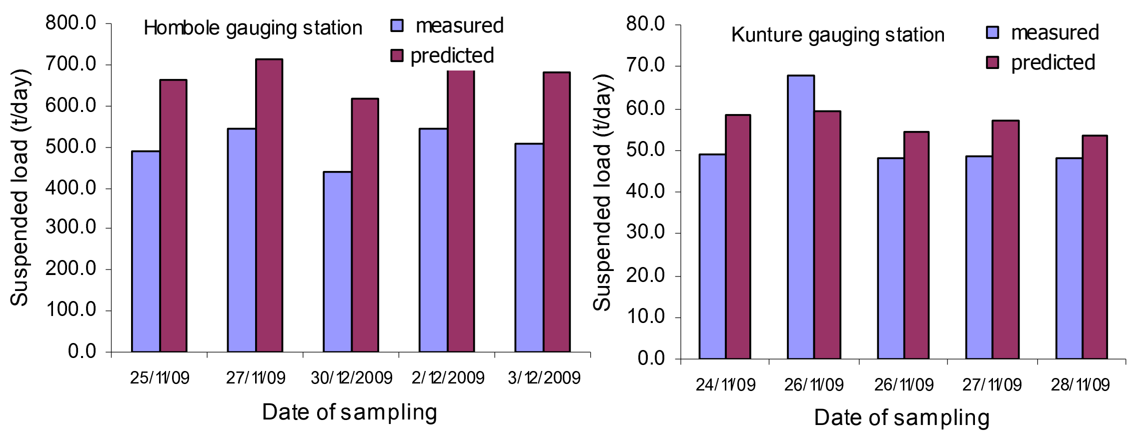


Figure 3.6: Comparison of measured suspended sediment load with the predicted value

It can be seen that the difference between the predicted suspended load values from the rating curve and the measured sediment load is comparatively small. Hence, the result from the rating curve of each gauging station has been reliably used.

4. ALTERNATIVE APPROACH FOR SOIL ERODIBILITY ESTIMATION

4.1 Background and data availability

Data availability and reliability are the primary issues that should be considered in the analysis of the soil erodibility factor. The reliability of predicting the erodibility factor depends on the quality and availability of input data. Data that is required for erodibility factor predication can be collected from in-situ or can be extracted from existing data sources. Collection of soil parameters for large areas like Upper Awash basin is costly and time consuming. The availability of FAO (1998) global soil database is the possible source of soil information for different researches and investigations related to soil erodibility prediction. In this research FAO (1998) soil database and the soil map of Upper Awash basin in Ethiopia has been considered as source of available soil data.

The Food and Agriculture Organization of the United Nations (FAO) has been preparing and updating the world soil database at different spatial scales. In 1990, a map of world soil resources was completed at a scale of 1:25,000,000 (FAO 1998). In 1998, the updated version of the soil map was adopted as the world soil database. It was from the 1998 world soil database that the soil and terrain maps of the different parts of the continents were made available. The Digital Soil and Terrain Database of North East Africa (SEA), that includes Ethiopia was prepared separately and has been available on purchase of a CD-ROM containing all soil and terrain information of the area. The soil map (figure 4.1) obtained from FMWRE has been referenced with the FAO soil database. In the FAO soil naming, the prefix or first name describes the soil's diagnostic horizon while the second name denotes the actual naming. The description of each soil property is based on the second name of the FAO soil. The definition & characterization of each FAO soil predominantly available in the study is described below.

Acrisols: Acrisols are referred to as strongly weathered acid soils with low base saturation. They have higher clay content in their sub soils than in their top soils. Acrisols exist in the hilly or undulating topography of wet tropical or subtropical climate zones. They are also characterized by their suitability for forest vegetation growth. There is a high risk of susceptibility of soil to erosion and sediment production on hilly areas.

Andosols: Andosols are common in the volcanic and silicate rich areas of humid climates. The soils cover areas of mountainous and undulating topography in regions ranging in climate from arctic to tropic. These soils are favorable for a wide range of vegetation cover. As a result, these soils have a high potential for agricultural activity because of their fertility, ease of cultivation and rootability. In areas covered by such soils, there is less probability of occurrence of erosion.

Cambisols: Cambisols show variations in color, structure, carbon and clay content along the different soil depth profiles. The soils have medium to fine textured materials that result from the decomposition of a wide range of rocks. Cambisols exist on a level to mountainous topography of all weather climates. They are favorable for a wide range of vegetation growth and have good potential for agricultural activities. Under uncontrolled agricultural activities and poor land management, there is a high potential of erosion occurrence and sediment production

Fluvisols: Fluvisols are a soil category of alluvial deposits in river banks, lacustrine and marine zones. They exist in flat topography and are the results of deposition during flood seasons. These soils are good for agricultural activities because of their high potential of fertility supplied from eroded upland areas.

Gleysols: Glycols are predominantly observed in wetland areas where there is shallow ground water. These soils are formed from a wide range of unconsolidated fluvial sediments, lacustrine and marine deposits.

Leptosols: Leptosols are very shallow soils that overlay rocky and very coarse soil textures. They are also coarse in texture size and mixed with gravel materials. These soils are available at high altitudes, with mostly dissected topography of all climates. Erosion is the greatest threat to leptosols. As a result, severe erosion problems may be observed on leptosols under high anthropogenic effects. Shallow rooted crops can be grown on such soils and so they can be considered as acceptable for agricultural activities.

Luvisols: Luvisols are characterized by their high clay content in lower soil depths. The soils originate from a wide variety of unconsolidated materials including glacial till aeolian, alluvial and colluvial deposits. Luvisols are most common on flat or gently sloped land in both cool and warm temperate climate with distinct dry and wet seasons. Most luvisols are suitable for agriculture activities with erosion control on sloped land. The risk of erosion is low for areas covered by luvisols

Nitisols: Nitosols are well drained tropical soils with more than 30% clay in their subsurface horizons. The soils are dominantly found in flat and hilly land under tropical and savanna vegetation. Nitisols are most productive soils in humid tropics. The erosion risk is high on hilly side where there are no proper land management practices.

Solonchaks: Solonchacks are characterized by high salt concentration and predominantly available in arid and semiarid climate zones and coastal regions. Agriculture should be preceded by actions like leaching the excess salt by using irrigation water for washing the soil.

Vertisols: Vertisols are heavy soils, with a high clay proportion and swelling characteristics. The soils form deep and wide cracks when drying out. Vertisols are dominant in depressions leveled to undulating topography of tropical, sub tropical, humid and semi arid to subhumid climates with an alternation of wet and dry seasons.

Xerosols: Xerosols are characterized by their accumulation of gypsum sulphate. These soils are formed from the weathering of unconsolidated alluvial, colluvial and aeolin deposits. Xerosols exist in depressions and leveled to hilly topography of arid climates. Sparse vegetation and shrubs are adapted to the soils. The soils are suitable for the production of small grain crops. The erosion threat to such soil is insignificant because in arid climates the total annual rainfall depth is considerably less.

4.2 Application of FAO soil map to the study area

The Awash basin in Ethiopia has been selected as a study area to analyze the soil erodibility factor. A digital soil map of the area has been obtained from the Federal Ministry of Water Resources of Ethiopia. The major soil types of Awash are indicated on the following figure 4.1.

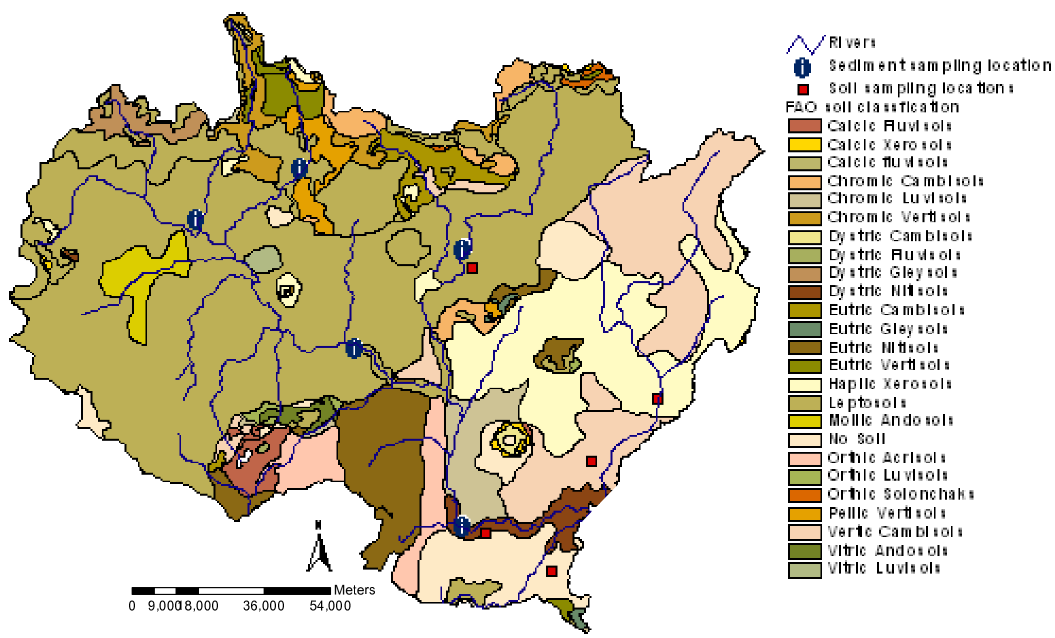


Figure 4.1: Soil map and sampling locations of the Upper Awash basin

The physical properties of the soils in Upper Awash basin have been extracted from FAO (1998) world soil database. The corresponding soil properties for each soil type are indicated in table 4.1.

Table 4.1: Soil properties extracted from FAO (1998) soil database

S.No	FAO Soil	% Org C	% clay	% silt	% sand
1	Chromic Cambisols	1.44	38.0	22.0	40.0
2	Leptosols	0.97	25.0	16.0	59.0
3	Calcic Xerosols	0.64	22.0	30.0	49.0
4	Dystric Gleysols	2.92	59.0	22.0	19.0
5	Chromic Vertisols	0.69	61.0	14.0	25.0
6	Calcic Fluvisols	0.65	20.0	40.0	40.0
7	Dystric Nitisols	1.12	52.0	18.0	40.0
8	Eutric Cambisols	1.07	27.0	37.0	36.0
9	Eutric Nitisols	0.60	21.0	11.0	68.0
10	Eutric Vertisols	0.68	61.0	14.0	25.0
11	Haplic Xerosols	0.53	14.0	10.0	76.0
12	Chromic Luvisols	0.63	24.0	12.0	64.0
13	Mollic Andosols	3.95	29.0	40.0	31.0
14	Orthic Solonchaks	0.40	32.0	25.0	43.0
15	Orthic Luvisols	0.41	14.0	10.0	76.0

To verify the reliability of the FAO world soil database characteristics, field data on physical properties of the soils have been collected for the major soils of the study area. There are five major and dominant soils in the area where for each soil type sampling has been carried out from a 60 cm x 60 cm pit with 100 cm depth (figure 3.5). The soil samples from each pit have been collected at two depth profiles, 0-30 cm and 30-100 cm and analyzed in a laboratory using the hydrometer method. The temperature correction, percentage sand, percentage silt and percentage clay computation has been done based on the Milford (1997) laboratory guideline procedures.

- Soil moisture correction

$$MCF = 1 - \left[(AD - OD)/AD \right]$$

where

$$MCF = \text{Moisture Correction Factor} \qquad (4.1)$$

AD = Air Dry weight

OD = Oven dry weight

- Determination of weight of dry soil

The weight of the dry soil is determined by multiplying the air dry weight by the moisture correction factor (MCF)

$$\text{Weight of Dry Soil} = \text{Air dry Soil} \times \text{MCF} \tag{4.2}$$

- Correcting hydrometer reading

To correct the hydrometer reading for the temperature, add 0.36 g/l for every 1 ^{o}C above 20 ^{o}C temperature, subtract 0.36 g/l for every 1 ^{o}C below 20 ^{o}C temperature.

For temperature above 20 ^{o}C:

$$HR = \text{measured reading(g/l)} + [(\text{measured temperature} - 20) \times 0.36\,\text{g/l})] \tag{4.3}$$

where

$HR = \text{hydrometer reading}$

For the temperature below 20 °C:

$$HR = \text{measured reading(g/l)} - [(\text{measured temperature} - 20) \times 0.36\,\text{g/l})] \tag{4.4}$$

- Determination of percent sand, silt and clay

$$\%\ \text{clay} = \frac{\text{Corrected 2 hour hydrometer reading} \times 100}{\text{Oven dry weight of soil sample}} \tag{4.5}$$

$$\%\ \text{silt plus clay} = \frac{\text{Corrected 40 second hydrometer reading} \times 100}{\text{Oven dry weight of soil sample}} \tag{4.6}$$

$$\%\ \text{sand} = 100 - \%\ \text{silt} - \%\ \text{clay} \tag{4.7}$$

Based on the laboratory analysis procedures, the percentages of sand, silt and clay have been determined (table 4.2 and figure 4.2).

Table 4.2: Laboratory analysis result of sampled soils

Sample ID	PT1	PT2	PT3	PT4	PT5
Weight of dry sample (g)	50	50	50	50	50
40-sec hydrometer reading (g/l)	16	19	18	16	16
Temperature	14	13	16	24	15
Corrected 40-sec reading (g/l)	18.16	21.52	19.44	14.56	17.8
2-hour hydrometer reading (g/l)	9	11	11	10	12
Temperature	16	14	19	23	19
Corrected 2-hour reading (g/l)	10.44	13.16	11.36	8.92	12.36
Percent clay	20.88	26.32	22.72	17.84	24.72
Percent silt	15.44	16.72	16.16	11.28	10.88
Percent Sand	63.68	56.96	61.12	70.88	64.4
Textural class name	SCL	SCL	SCL	SL	SL
Soil type	Leptosols	Haplic Xerosols	Vitric Cambisol	Chromic luvisols	Dystric Nitosols

*** Remark: The temperature for sample analysis of PT4 is high because the laboratory analysis was conducted in afternoon time when the water from the pipeline was too hot.

SCL = Sandy clay loam, SL = Sandy loam

The analysis results from the field data and the FAO soil database characteristics have been compared and the result is indicated by the following figure (figure 4.2).

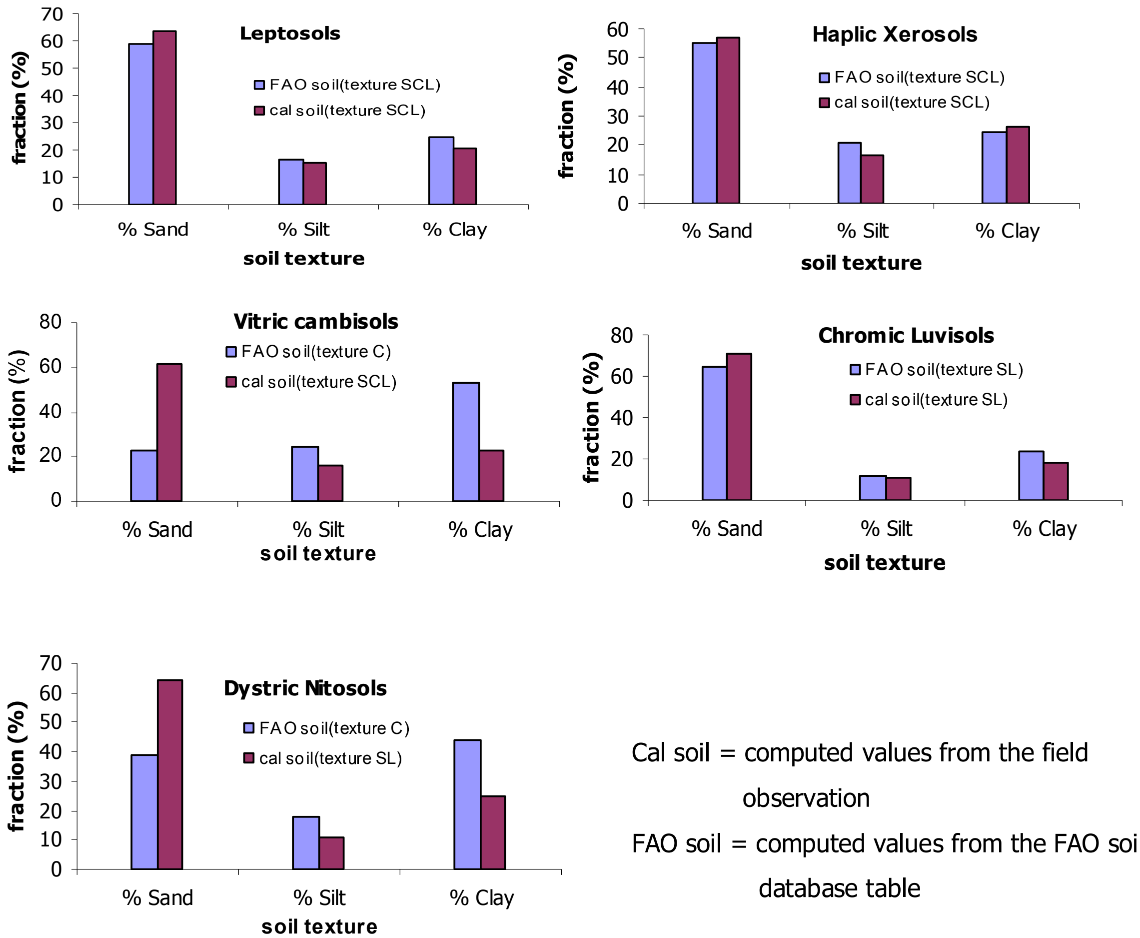


Figure 4.2: Comparison of the FAO (1998) soil properties with field measured data

The similarity and variation of the soil texture classes have been compared between the FAO (1998) soil properties and the soil properties measured in the field.

From figure 4.2 it can be observed that for the most dominant soils (Leptosols, Haplic Xerosols and Chromic Luvisols), the properties of the soils extracted from FAO (1998) soil database are similar to the properties of the soils analyzed from field data. The soil texture class was found to be sandy clay loam (SCL) for Leptosols and Haplic Xerosols for both FAO soil characteristics and the on field measured soil characteristics. Similarly, for the Chromic Luvisols, the soil texture is sandy loam (SL) in both cases. Nevertheless, for Vitric Cambisols and Dystric Nitisols, there is significant variability in sand proportion which is the main reason for the variability of the soil texture class. The significant variation in sand proportion could be due to the location of the soil on an area of low land. In low land areas, there is high chance of deposition of sand which explains the deviation of the composition of the analyzed soil collected in the study area compared to FAO database. In order to improve the measurement results a higher number of samples from a deeper depth should be taken so that a representative values can be obtained at different soil profiles. In overall conclusion with regards to the reliability of the FAO (1998) soil properties, the available soil characteristics data can be confidently applied which could be proven during field data collection and analysis.

4.3 An alternative soil erodibility estimation approach

The texture of a soil plays a fundamental role in its susceptibility to erosion. The texture of soils can be expressed in terms of the percentage of sand, silt and clay fractions. On the basis of the discussion made under section 2.4, the respective soil erodibility factor (K) has been computed from the equation of Williams et al. (1984) (equation 2.6) for the Upper Awash basin. The computed K values and the major soil texture ratios are indicated in figure 4.3. The right hand side y-axis describes the different soil texture fractions (silt/sand, silt/clay and silt/ (sand and clay)) while the left hand side y-axis describes the soil erodibility factor(K) value computed from the equation of Williams et al. (1984) . The x-axis represents the different FAO soil numbering as denoted in table 4.1.

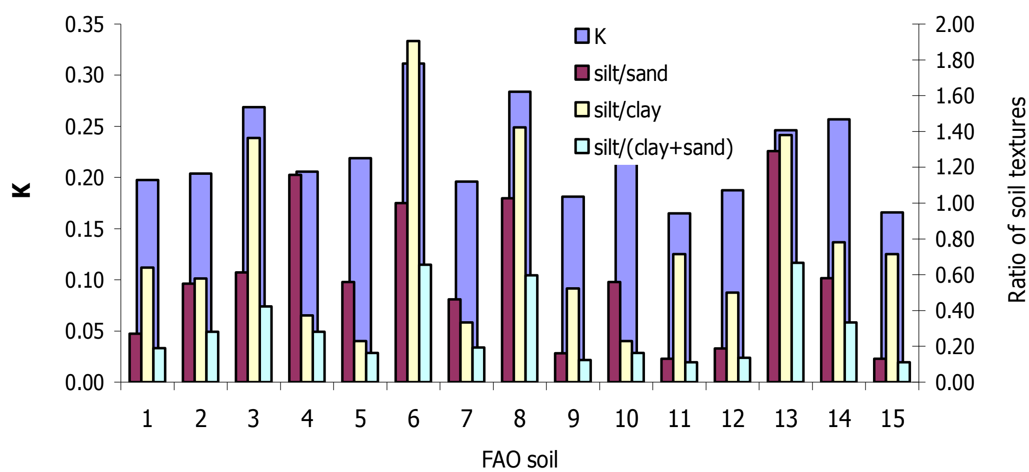


Figure 4.3: K values for Upper Awash basin

As it can be seen from figure 4.3, the K value shows a dependency pattern on different ratio of the soil textures. The K values are proportionally increasing or decreasing with the soil texture ratios. To investigate the possibility of formulating an alternative equation for soil erodibility estimation using soil textures, a partial correlation has been made with respect to

K, silt to clay ratio, silt to sand ratio, silt to sand and clay ratio. For the correlation analysis, two cases were considered: Awash basin soil and FOA/UNESCO's world soil data. The correlation coefficient of the different the K value with respect to particle size is shown on table 4.3.

Table 4.3: Correlation coefficient (r) of soil erodibility factor (K)

Ratio of soil distribution	Awash basin data	FAO (1998) soil data
% silt to % clay	0.77	0.54
% silt to % sand	0.72	0.78
% silt to % sand and clay	0.88	0.82

The ratios of silt to sand and clay reflect the highest correlation as compared to the remaining elements for both cases. Sand dominated soils are less susceptible to erodibility because they have low runoff potential which is due to the high infiltration rate. Clay soils are similarly less susceptible to erodibility due to the strong binding effect of individual particles. Thus, it can be concluded that soil erodibility is inversely proportional to the percentage of sand and the percentage of clay. In contrast, the presence of high silt content in soils increases the susceptibility to erosion. Based on the correlation results of the different soils and the result summarized in table 4.3, the silt to total clay and sand ratio has been selected for the formulation of the alternative soil erodibility estimation method.

A nonlinear regression equation has been fitted to the data of the study area. Percentage silt to the percentage of sand and the percentage of clay has been considered as an explanatory variable and the K values calculated using the equation of Williams et al. (1984) has been considered as a dependent variable. A nonlinear regression equation (equation 4.8) has been established.

$$ERFAC = a\left[\frac{\%\ silt}{\%\ sand + \%\ clay}\right]^{b} \qquad (4.8)$$

where

$ERFAC$ = proposed alternative soil erodibility factor

$\%\ sand$ = percentage of sand proportion in the soil

$\%\ silt$ = percentage of silt proportion in the soil

$\%\ clay$ = percentage of clay proportion in the soil

a = 0.32 and

b = 0.27 are factors obtained from regression coeffecients

4.4 Evaluation of the alternative soil erodibility estimation method

4.4.1 Evaluation of the ERFAC equation using Upper Awash basin soil data

The derived ERFAC equation has been applied for the computation of the soil erodibility values for soils in the study area. The result of the computation is plotted on figure 4.4, as shown below. The x-axis represents the dominant soil types (table 4.1) in the study area while the Y-axis is the value of the erodibility factor (k) calculated by the equation of Williams et al. (1984) method and the newly proposed equation (ERFAC). The secondary Y-axis indicates the relative errors.

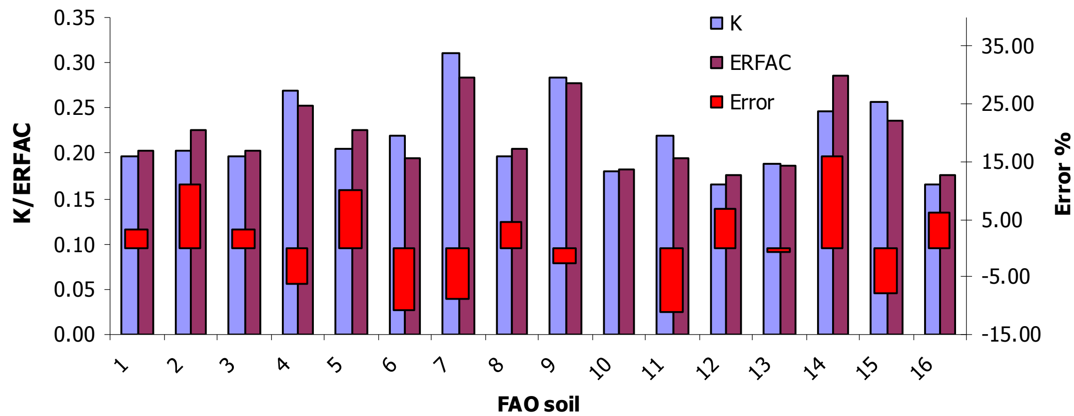


Figure 4.4: Comparative analysis of relative errors for individual soil

The derived model (equation 4.8) has been evaluated for its performance, based on the statistical indicators such as Pearson's correlation coefficient (r), coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), relative mean square error (RMSE) and individual relative errors (RE).

Coefficient of determination (R^2): Is the index of correlation of the result from ERFAC equation and the result from the equation of Williams et al. (1984). The value of R^2 ranges from 0 to 1. As the value of R^2 approaches 1, the better is the performance of the derived model and as the value of R^2 approaches 0 (less than 0.5) the bad will be the performance of the model.

Nash-Sutcliffe Efficiency (NSE): NSE is the normalized statistics which measures the relative magnitude of the residual variance as compared to the K value from the equation of Williams et al. (1984). Similar to R^2, the more the NSE approaches 1, the better will be the model performance and vice-versa.

Root mean square error observation standard deviation ratio (RSR): It is an error index indicator. RSR ranges from 0 to 1 with the lower value closer to zero indicating higher accuracy of the model performance and higher the value approaching 1 indicating poor model performance.

Percent bias (PBIAS): This measure the average tendency of the K value computed from ERFAC to be larger or smaller than the K values from the equation of Williams et al. (1984). PBIAS is expressed in percentage: the lower the absolute value of the PBIAS is the better the model performance will be.

Relative Error (RE): Relative error measures the error magnitude of ERFAC method as compared to the equation of Williams et al. (1984) method. This indicator is preferable because it can clearly show for which soil the proposed ERFAC equation can perform well.

The detail computation methods of the statistical indicators are briefly described in the later section (section 5.3.2). The following table shows the summary indicators for the evaluation of the model.

Table 4.4: Statistical indicators of the newly proposed erodibility equation

Indicator description	**Indicator values**
R^2	0.75
NSE	0.68
PBIAS	-0.14%
RMSE	0.0046
RE	-10% to 15%

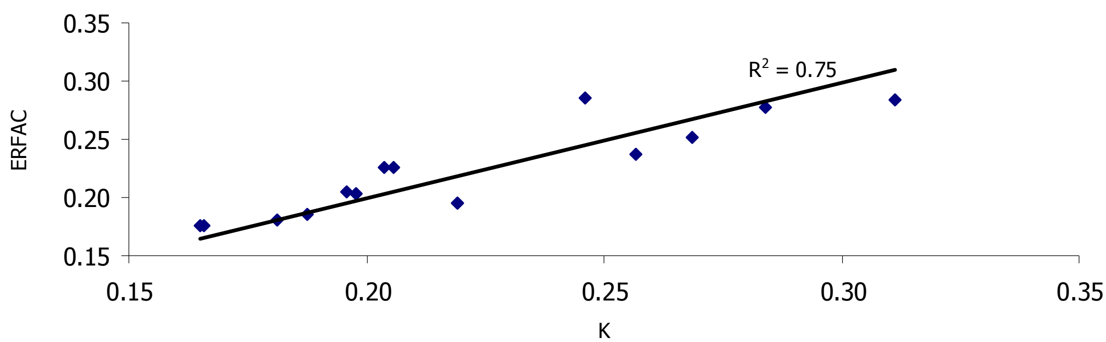
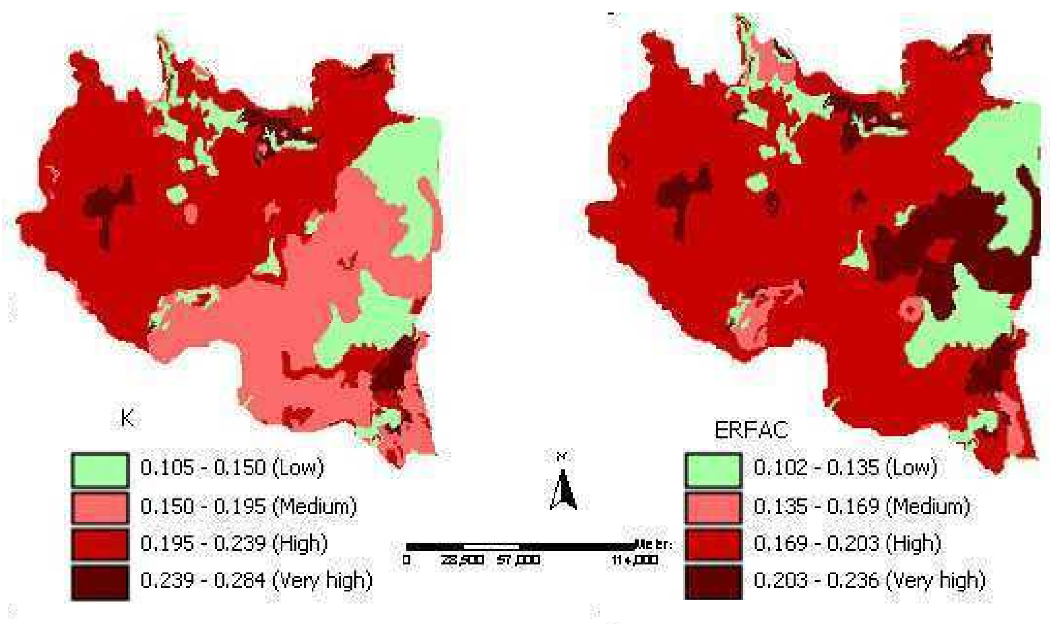


Figure 4.5: Comparison of erodibility factors estimated by ERFAC and the equation of Williams et al. (1984) method

Beside the statistical indicators (table 4.4) used for the empirical model (ERFAC) evaluation, the spatial pattern of the soil erodibility map based on both methods has been analyzed. Soil erodibility maps from the equation of Williams et al. (1984) and the newly proposed ERFAC equation has been produced in GIS (figure 4.6).The erodibility maps have been produced in such a way that the erodibility factor values were divided in to four classes: low, medium, high and very high erodibility factors. Figure 4.6a shows soil erodibility factor obtained from the equation of Williams et al. (1984) (K) and figure 4.6b shows erodibility map obtained from the newly proposed erodibility factor estimation method (ERFAC).The two maps are able to depict similar information on the spatial variability of the soil erodibility. Areas occupied by the Leptosols show identical erodibility class on both maps. The Leptosols areas fall within the high erodibility range. However, areas identified as having medium erodibility potential using the equation of Williams et al. (1984) method fall under high erodibility potential by applying the newly proposed method (ERFAC).This could be due to the organic carbon content parameter which is not taken in to account in the ERFAC equation. The areas that show variation in erodibility potential cover the low land and vegetated parts of the study area. In low land areas there is more chance of deposition and as a result the soils are rich in organic carbon content which reduces the risk of soil erodibility.



(a) K map from equation of Williams et al. (1984) (b) K map from ERFAC

Figure 4.6: Spatial pattern of soil erodibility distribution in Upper Awash basin

4.4.2 Evaluation of the ERFAC equation using FAO world soil data

The applicability of the newly proposed soil erodibility factor estimation method (ERFAC) has been evaluated using the world soil map database. During the evaluation steps, soils which had been used to establish the ERFAC equation were excluded. The ERFAC equation was applied to calculate the soil erodibility factor and to compare the results with the erodibility factors calculated by the equation of Williams et al. (1984). A total of 104 different FAO (1998) soils have been considered for the analysis. The results of the ERFAC and the equation of Williams et al. (1984) have been compared based on the computation results of the respective equations (2.6) & (4.8). The results are summarized in three groups based on their computed relative errors. Group 1 are soils which show relative errors less than 10 %, group 2 are soils which show relative errors less than 20 % and group 3 are all soils which show relative errors less than 60 % except one soil (Gleyic Podsols) whose relative error has been 90 %. The grouping of the soils is represented in figure 4.7. Figure 4.8 display the detailed results of the calculated relative errors for group 1 and 2 as well as for all FAO soils. The list of soils in each of the soil groups is attached in Annex A.

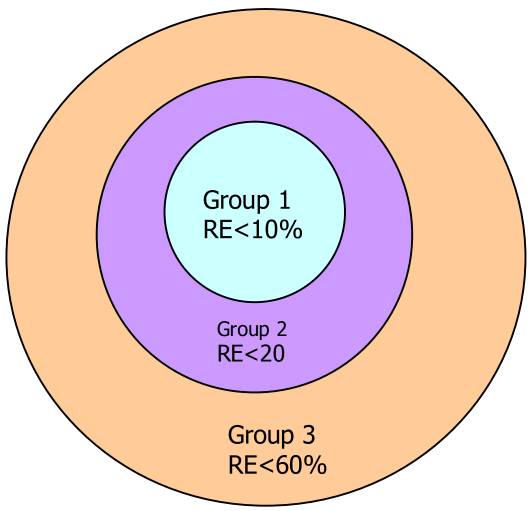


Figure 4.7: Different groupings of the soils considered in the analysis (drawn not to scale).

The percentage of soils falling into group 1 comprises 40 % of the total soils considered in the evaluation, while the percentage of soils in group 2 accounts for 80 %. The remaining 20 % of the soils show relative errors between 20 % and 60 % except Gleyic podsols soil which its relative error was found to be 90 %. The statistical indicators (R^2 and NSE) have been computed for the 3 soil groups and shown as indicated on table 4.5.

Table 4.5: Summary result of statistical indicators

Indicator	Group 1	Group 2	Group 3
R^2	0.90	0.71	0.73
NSE	0.92	0.64	0.57

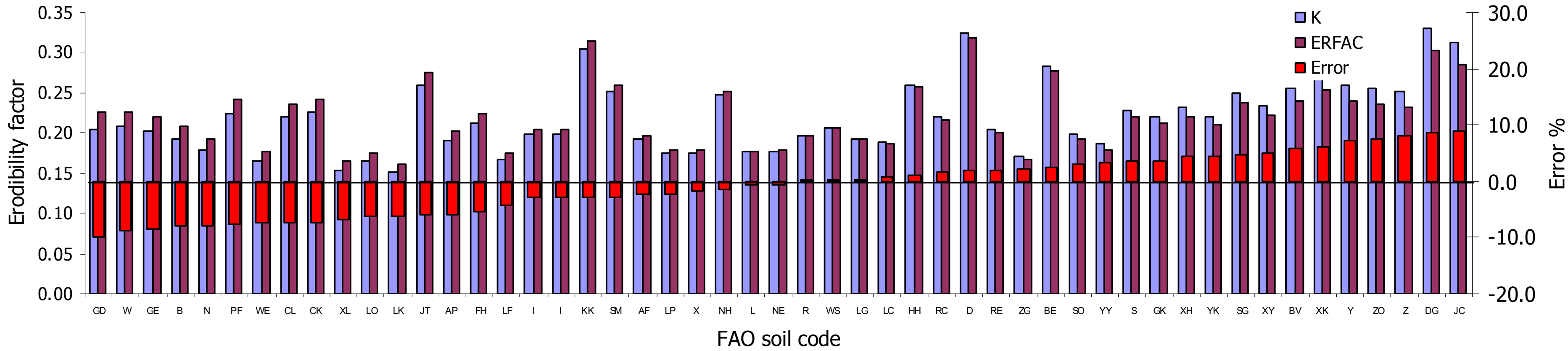


Figure 4.8a: Comparison of soil erodibility factors estimated by the equation of Williams et al. (1984) and the ERFAC for soils of group 1

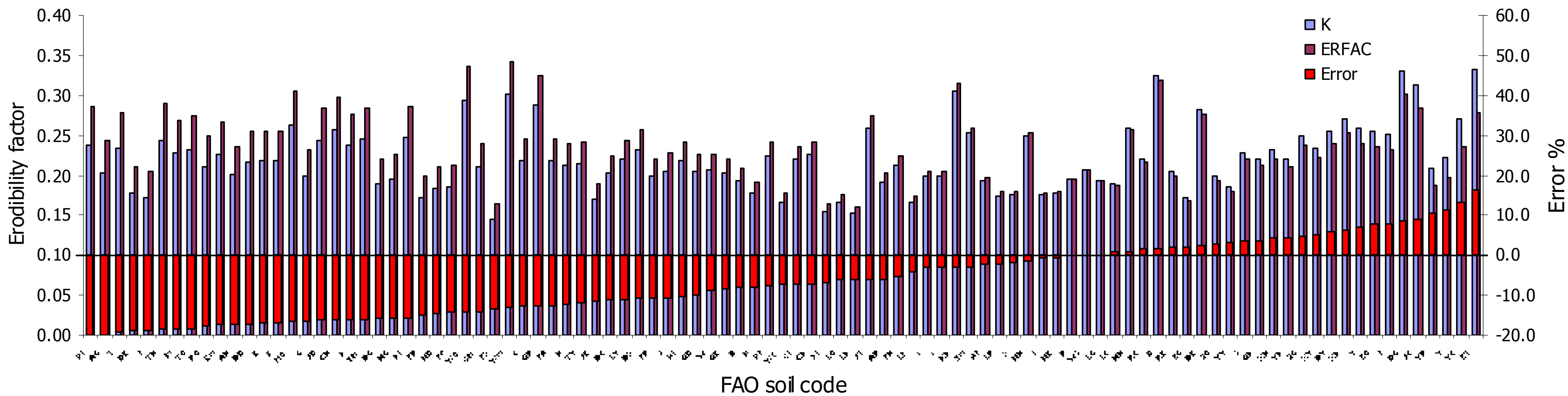


Figure 4.8b: Comparison of soil erodibility factors estimated by the equation of Williams et al. (1984) and the ERFAC for soils of group 2

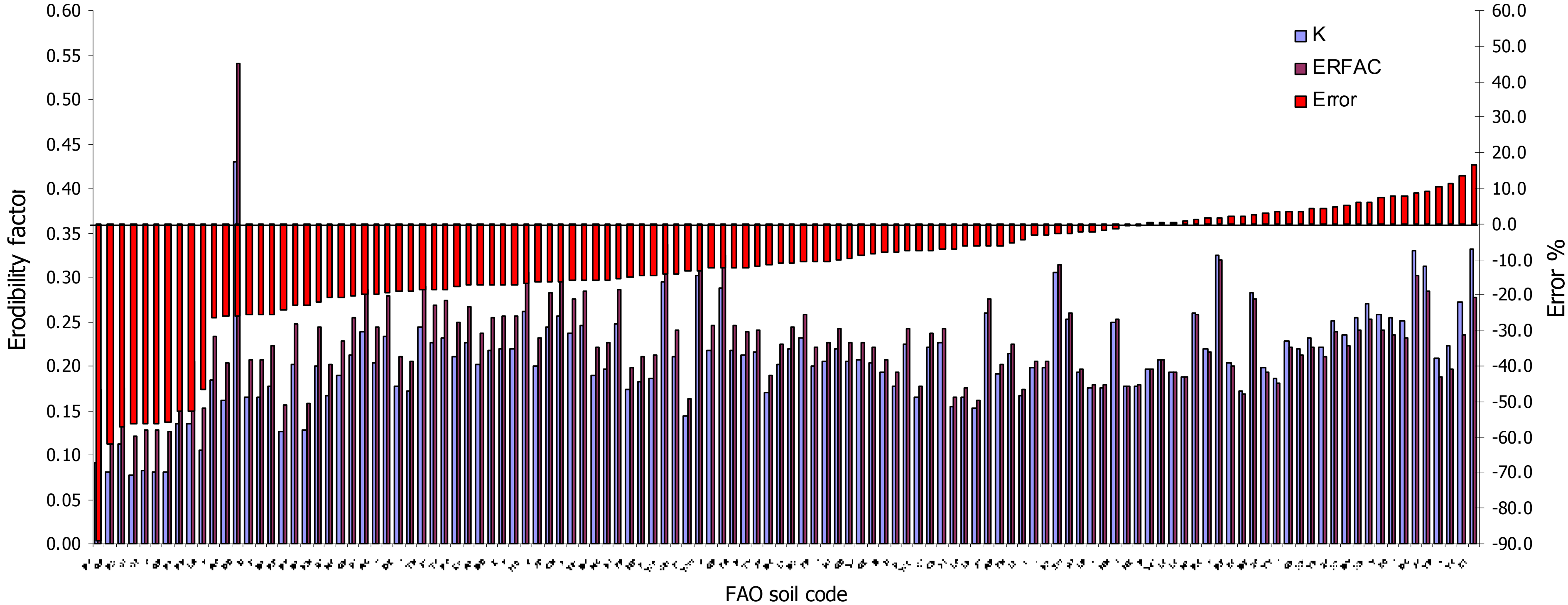


Figure 4.8c: Comparison of soil erodibility factors estimated by the equation of Williams et al. (1984) and the ERFAC for all FAO (1998)

Figure 4.8 Comparison of erodibility factors estimated by the equation of Williams (1984) and the equation of ERFAC

4.5 Discussion

Two empirical relations namely, the equation of Williams et al. (1984) and the newly developed ERFAC equations have been applied for a quantification of the soil erodibility factor. A soil map from FMWRE and the FAO (1998) soil characteristics database were the main sources for the input parameters of the equations. Both empirical models were applied to the Awash basin soil data and the world soil data. Awash basin soil data has been used for derivation of the ERFAC equation, while the world FAO soil data has been used for the evaluation of applicability and reliability of the equation.

The ratio of silt content to clay content, the ratio of silt content to sand content, and the ratio of silt content to sand and clay contents have been computed and their correlation to the soil erodibility factor has been calculated. Higher correlation coefficients (CC equal to 0.88) of the erodibility factor have been observed with percentage silt to total percentage clay and percentage sand ratio. In a similar way, correlation coefficients of 0.77 for silt to clay contents and correlation coefficients of 0.72 for silt to sand content ratio have been observed. Likewise, with a partial correlation analysis, a correlation coefficient was estimated for FAO world soil data. The CC values of 0.54, 0.82 and 0.78 have been computed for silt content to clay content ratio, silt content to sand and clay contents ratio, and silt content to sand content ratio respectively. Here, it is worthy to mention that, the correlation coefficient of the erodibility is the highest in both cases (Awash soil data and FAO soil data) for silt content to sand and clay contents ratio. It is an indication of the erodibility of a soil to depend on different combinations of soil textures. From the analysis result, it can be observed that soils with high silt content as compared to sand and clay content are more likely vulnerable to erosion. The higher the clay content in the soil decreases the soil erodibility, because of the strong bounding effect of the soil particles. The clay component strongly binds the individual soil particles and as a result they are not easily detached by the splashes of rainfall. Moreover, the soil transportability by surface runoff is less probable due to the same effect of the clay soil behaviour. In contrary, sand dominated soils are coarse in size and the particles are loosely bound together. As a result the rainfall that occurs on the surface soil infiltrates to the deep profiles and not capable to transport the soil particles. Silt dominated soils have intermediate particle sizes and as a result they are not tightly bound together and not coarse enough to infiltrate the rainfall depth.

The occurrence of rainfall can easily detach the soil particles and transport to river networks by the surface runoff and stream discharges.

Based on the correlation coefficient of silt to total sand and clay content ratio of Upper Awash basin soils, the soil erodibility factor using Williams et al. (1984) has been used as a dependent variable to fit the equation in a regression analysis. The results obtained using ERFAC equation have been compared with the results of the soil erodibility factor obtained by using the equation of Williams et al. (1984) and were found to have relative errors of less than 10 % for soils in the study area. Moreover, the ERFAC equation has been evaluated for its applicability to soils that are different from the soils of the Awash basin. As described in section 4.3.2, FAO (1998) world soil data has been considered for the evaluation of the ERFAC equation. The individual soil erodibility, obtained by ERFAC has been analyzed with respect to the Williams equation erodibility values. The equation of Williams et al. (1984) has been selected as a reference for derivation of the ERFAC equation based on the evaluation result of the existing soil erodibility estimation methods described in chapter 2.

Three soil groups have been identified based on their relative errors computed between ERFAC and the equation of Williams et al. (1984). 40 % of the world soil types have shown relative errors of less than 10 %. The majority of soils in this group are characterized by less clay content (less than 30 %). The textural classes of such soils range from silt loam to sand textures. For the second group of soils, which account for about 80 % of the total soil considered in the evaluation, the relative errors between the erodibility estimation method of Williams et al. (1984) and the ERFAC equation have been computed as less than 20 %. Such soils have clay proportions of between 20 % and 40 % which increased the textural range from slit clay to sandy soil textures as compared to the textures of the group 1 soils. The third soil group have shown relative errors of less than 60 %. It is worthy to mention that the soils which have shown relative errors less than 10 % are poor in organic carbon content. Silt and sand dominated soils contain less organic carbon content. As the clay proportion in the soil increases, the relative error has been similarly increased. The analysis and evaluation of the applicability of the ERFAC equation confirms that soil erodibility factor can be predicted with a minimum error for silt dominated soils and an acceptable error range for silty clay soils.

ERFAC equation is reasonably applicable for soils with textural range of silty clay to sandy soils which account for 80 % (group 1 and group 2) of world soil database.

The advantage of the ERFAC equation is that, it doesn't require organic carbon content and it is based on properties of a soil that can be easily measurable. The organic carbon content of a soil is mostly determined by burning the soil samples which its accuracy is always under question. The omission of organic carbon content from ERFAC equation is advantageous because the propagation of error from sampling and estimating the carbon content can be avoided. The soil properties that are required by the ERFAC equation can be easily obtained in laboratory through dry and wet sieve analysis techniques. The free availability of the FAO (1998) world soil database is another advantage of applying the equation for preliminary analysis of soil erosion. In ERFAC equation the regression coefficients denoted as a and b have been fixed based on the soil data sets in Awash basin. As has been noticed in section 4.4.2 and the discussions made in the above paragraphs, the equation predicts soil erodibility value as reasonable as the equation of Williams et al. (1984) does. This implies that the coefficients a and b can be adopted for all soils in group 1 and group 2 soil classes.

Therefore, ERFAC is an alternative soil erodibility prediction equation that simplifies the cost and time invested in collecting huge data sets from field works. Additionally, there is less error propagation from the input data sets as it is based on few and easily measurable soil characteristics.

5. APPLICATION OF SWAT2005 MODEL

5.1 Review of watershed models

Comprehensive and physically based watershed models have the capability of simulating hydrologic, sediment and water quality processes at a watershed scale. For watershed sediment modeling, careful attention should be given to select the appropriate model. Model capability to compute the sediment yield, good model documentation and model support and proven record of application is a minimum criterion for model selection (Kalin and Mohammed 2003). Different comprehensive watershed models have been developed to assess non point source pollutants including watershed sediment yield. In reference to Borah and Bera (2003), different types of watershed models are summarized below differentiating between models representing long term simulation (continuous time step) and single event based simulation.

5.1.1 Continuous time step simulation models

Continuous time step models are characterized by their capability of simulating stream flow and sediment fluxes on a long term time basis. In the following, some of the most popular continuous time step simulation models are explained briefly.

AnnAGNPS (Annualized Agricultural Nonpoint Source): In the model, a watershed is represented based on homogeneity of land areas, river reaches and impoundments. The model can simulate hydrology, sediment transport and nutrients transport on a long term, daily or sub daily time steps.

Overland flow is computed by the runoff curve number method and the peak flow by the soil conservation service (SCS) TR-55 method, while subsurface flow is computed from Darcy's equation or Hooghoudt's equation. Manning's equation, with a trapezoidal cross section is used for the computation of runoff in channels for peak flow estimation by TR-55 method.

Overland sediment transport is estimated from sheet and rill erosion generated by using the RUSLE equation. The rate of sediment deposition is based on the distribution of particle size and fall velocity. The sediment transport in a channel is estimated using the modified Einstein equation and the transport capacity of flow.

ANSWERS (Areal NonPoint Source Watershed Environment Response Simulation): This model has sediment detachment and sediment transport components. It is capable to simulate long term processes based on daily time steps. The watershed is defined based on a square grid with uniform hydrologic characteristics. Manning's and continuity equations are used to calculate the overland runoff of each grid cell. The subsurface flow is determined using Darcy's gravity flow equation. In a similar way to the overland flow, Manning's equation and the continuity equation are used to determine the runoff in the channels.

Overland sediment flow is determined from the raindrop detachment, soil erosion and a sediment transport equation. The raindrop detachment is computed from rainfall intensity and the USLE factors. Soil erosion is determined by unit width flow and the USLE factors whereas transport and deposition of sediments are computed using Yalin's equation. However, the model doesn't simulate channel sediment separately.

HSPF (Hydrologic Simulation Program Fortran): This model is intended to simulate the water quantity and its quality in a watershed. In HSPF, a watershed is represented by pervious (agriculture) and impervious (urban) land areas. This model has the capability to simulate stream flow and sediment transport on a long term based for hourly time steps.

The overland flow is computed using the empirical outflow depth to the detention storage relation and the Chezy-Manning's equation. Interflow, percolation and ground water flow are computed from different empirical relations. Channel flow is computed based on the continuity equation with the assumption that all flows enter the channel at one point in the upstream section. The outflow is determined based on the reach volume or user supplied demand.

Overland sediment is estimated from the transport capacity function which is based on rainfall splash detachment and wash off processes.

SWAT 2005 (Soil Water Assessment Tool): SWAT is also a nonpoint source pollution model with the capability of simulating hydrology, missing weather elements, sediment and pollutants transport. Temporally, it can simulate long term and daily time steps. It is capable to simulate long term processes based on daily time steps.

Overland flow is computed using the curve number method and the modified rational formula. The curve number approach is used to determine the runoff volume and SCS TR-55 or the modified rational method is used for peak flow computation. In case of subsurface flow which joins the river before reaching the ground water, the Kinematic storage model (Sloan et al. 1983) is used, whereas for ground water flow empirical relations are used. Flow in a channel is determined using Manning's equation and routed based either on the variable storage coefficient method or the Muskingum method.

Overland sediment movement is estimated using MUSLE (Williams and Berndt 1977). The sediment transport in channels is determined from the combination of stream power concept of Bagnold (Bagnold 1977) and the soil erodibility factor from USLE (Wischmeier and Smith 1978).

WEPP (Water Erosion Prediction Project): WEPP is a process based soil erosion estimation model. It incorporates the spatial variability of the topographic conditions, soil characteristics and different land management activities. The model can be used for estimation of sediment yield for small watersheds. Moreover, interrill and rill erosion are considered. Interrill erosion is the result of rainfall impact mainly the rainfall intensity and the sediment transport in the rill channels is as a result of interrill runoff. For watershed sediment yield prediction, the model assumes that sediments are transportable if the channel flow shear stress exceeds the critical shear stress and the sediment supply to the channel doesn't exceed the channel sediment transport capacity. The spatially varied flow equation is used for computation of the flow shear stress in channels.

5.1.2 Single event based simulation models

The common single event based simulation models are described below.

AGNPS (Agricultural NonPoint Source): This model has the capability to simulate hydrology, land erosion and sediment transport. It simulates single storm events. The watershed is analyzed based on a uniform square area. The runoff curve number method is used to compute overland and channel flow. Nevertheless, the model does not simulate subsurface flow. Overland sediment transport, including channel sediment transport is computed using the USLE.

CASC2D (CASCade of planes in 2-dimensions): The model can be used to analyze the flow and the sediment of a storm event as well as on a long term basis. Similarly, to the other models, CASC2D has the capability of simulating hydrology and sediment transport at a watershed scale using spatially varying input parameters. Watershed is represented by 2-D square grids for the overland flow and 1-D for the channel flow. The 2-D diffusive wave equation solved by the finite difference method is used to compute overland flow.

Overland sediment transport is estimated using the modified Kilinc-Richardson equation with USLE factors and conservation of mass. Yang's unit stream power equation is used for computation of instream sediment transport.

KINEROS (Kinematic Runoff and Erosion Model): In this model, the watershed is represented as planes for surface runoff and conduits or channels. Overland and channel sediment is computed based on the raindrop detachment and scour, while deposition of sediment is based on the sediment transport capacity and a mass balance equation.

PRMS (Precipitation Runoff Modeling System): The model developed to evaluate the watershed response to various parameters: for example, precipitation, climate and land use. The watershed is represented as flow planes and channel segments. The Green-Ampt equation is used for computing the excess of rainfall and the kinematic wave equation is used for the overland and channel flow calculation.

Overland sediment transport is determined from a combination of rainfall intensity, overland flow detachment and the sediment continuity equation. Sediment transport in channels is calculated based on the sediment delivery from the upland without considering detachment and deposition.

As mentioned in the above section, there are different kinds of watershed models. However, the selection of the model is based on its applicability, which depends on the intended purpose of the study and the available data for the model setup. Watershed sediment yield modeling, model comprehensiveness and its capability to include major natural processes need prior attention. In addition, the availability of input data, good model documentation and application and success history are other points to be considered. Among the above described models, the SWAT2005 model has wide applicability in different parts of the world. As a result, it has a comprehensive success history. The capability of the SWAT2005 model to generate the missing weather elements makes it more preferable to be applicable in data limited areas. The model capability to compute watershed geomorphologic parameters like watershed area, watershed and river slopes as well as watershed and river lengths in the watershed configuration component of the model is another advantage. The result of this watershed configuration is useful input parameters for statistical analysis and formulation of the alternative empirical model to be proposed for sediment yield estimation. Therefore with a due consideration to the above described reasons SWAT2005 has been selected to be calibrated and used for the extraction of basic watershed parameters, surface runoff depth, stream flow, soil loss rate and total sediment yield.

5.2 Overview of SWAT2005 model

SWAT (Soil Water Assessment Tool) is a physically based, long term, computationally efficient watershed model. To model hydrology, sediment or nutrients transport, the watershed is divided into subbasins. The land areas in the subbasins are divided into one or more land units, possessing similar land use, soil type and applied management strategies. These similar land units, in land use, management and soil attributes are called Hydrologic Response Units (HRUs). The HRUs are helpful for a better estimation of the loadings (flow, sediment, pollutants) from the subbasins. Hydrology and sediment transport are the main components of the SWAT2005 model.

5.2.1 Hydrology component

The water balance is the backbone of the hydrologic and hydraulic modeling in a watershed. In SWAT, the water balance is computed from the soil water content which is described by the following equation.

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}\right) \qquad (5.1)$$

where

SW_t = final soil water content (mm)
SW_0 = initial soil water content (mm)
t = time (days)
R_{day} = amount of precipitation (mm)
Q_{surf} = amount of surface runoff (mm)
E_a = amout of evapotranspiration (mm)
W_{seep} = amount of water entering vadose zone (mm)
Q_{gw} = amount of return flow day (mm)

The amount of precipitation is one of the input parameter amongst other weather parameters which are required to set up the model. For the evapotranspiration component of the water balance, the model has three options for calculating potential evapotranspiration, namely the Hargreaves method, Priestley-Taylor method and Penman-Monteith method. The surface runoff component of the water balance is determined from the SCS method described as below.

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \quad (5.2)$$

$$I_a \cong 0.2S \quad (5.2a)$$

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \quad (5.2b)$$

Hence $$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)} \quad (5.2c)$$

where

I = initial abstraction (mm)

S = retention parameter (mm)

CN = curve number

To compute the surface runoff depth using the above stated equation (equation 5.2), CN is the major parameter to be used in the SWAT2005 model. The SCS curve number is a function of soil permeability, land use and antecedent moisture condition. The soil permeability and the soil available water content are provided for the model through soil database input components. The provided soil available water content is used to estimate the antecedent soil moisture condition. Similarly, the curve number (CN) is estimated for the respective area of land use pattern and different hydrologic soil groups. The land use map and soil maps along with their corresponding database are provided as an input for the model.

5.2.2 Hydraulic component

In SWAT model, the open channel cross section is assumed as trapezoidal with side slope of 2:1 (figure 5.1). Manning's equation is used for the computation of channel flow velocity. The channel Manning's roughness coefficient is entered as an input data. The channel cross section and longitudinal slope are computed from the digital elevation model (DEM). Flow is routed through the channel network using the variable storage routing method or Muskingum routing methods (Chow et al. 1988).

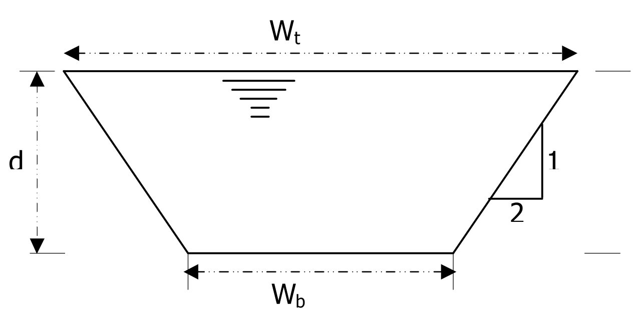


Figure 5.1: Trapezoidal channel dimensions

5.2.3 Sediment component

The sediment supply from the individual HRUs is computed by the modified universal soil loss equation.

$$Sed = 11.8(Q_{surf} \times q_{peak} \times area_{hru})^{0.56} K_{USLE} \times C_{USLE} \times P_{USLE} \times LS_{USLE} \times CFRG \qquad (5.3)$$

where

Sed = sediment yield (t/day)

Q_{surf} = surface runoff volume (mm)

q_{peak} = peak runoff rate (m^3/s)

$area_{hr}$ = area of HRU (ha)

K_{USLE} = USLE erodibility factor

C_{USLE} = USLE cover and managment factor

P_{USLE} = USLE support practice factor

LS_{USLE} = USLE topographic factor

CFRG = coarse fragment factor

The peak runoff is an indicator of the erosive power of a storm event and is used to estimate the sediment yield in the MUSLE equation. The modified rational equation is used to calculate the peak runoff. The method assumes that if a rainfall of certain intensity i begins at time t=0 and continues indefinitely, the rate of runoff increases until the time of concentration $t=t_{conc,}$ and the entire subbasin area is contributing to the flow at the outlet. The corresponding equation is:

$$q_{peak} = \frac{C \times i \times A}{3.6} \qquad (5.4)$$

where

q_{peak} = peak runoff rate (m^3/s)

C = runoff coefficient

i = rainfall intensity (mm/h)

A = subbasin area (km^2)

The formula can be further described in terms of surface runoff depth and time of concentration: coefficient

$$q_{peak} = \frac{\alpha_{tc} \times Q_{surf} \times A}{3.6\, t_{conc}} \tag{5.5}$$

$$\alpha_{tc} = 1 - \exp[2.t_{conc}.\ln(1 - \alpha_{0.5})]$$

where

t_{conc} = time of concentration for the subbasin (h)

$\alpha_{0.5}$ = fraction of daily rainfall falling in half hour highest intensity rainfall

Sediment routing

The sediment supplied from the HRUs is routed to the downstream section of river networks to compute the net sediment flux. In the SWAT model, the Bagnold's equation as a function of maximum channel velocity is used to determine sediment transport, re-entrainment and deposition. The maximum amount of sediment that can be transported out of the reach is expressed as:

$$Conc_{sed} = C_{sp} \times V_{ch.pk}^{Spex} \tag{5.6}$$

where

$Conc_{sed}$ = maximum sediment that can be transported (t/m^3)

C_{sp} = linear parameter for maximum sediment reentrainment

$V_{ch,pk}$ = peak channel velocity

Spex = exponential parameter for maximum sediment reentrainment

The model considers 33 different watershed parameters for sediment yield modeling. However, not all parameters play an equal role in the sediment yield of the subbasins. Hence, the identification of the most and least flow and sediment governing parameters is a priority for the model calibration and validation. The parameter identification can be done by using a sensitivity analysis. Sensitivity analysis in SWAT2005 is carried out based on the combined robust Latin Hypercube One at a Time (LH-OAT) method (Griensven et al. 2006).

5.3 Application of SWAT2005 model to Upper Awash Basin

5.3.1 Model input description

5.3.1.1 Weather generator

The weather generator is one of the main components of the SWAT model. It helps to estimate the values of the missing data for the climatic parameters of the study area. The missing values of climate elements like rainfall, temperature, wind speed, relative humidity and sunshine hours are generated by the weather generator component. The weather generator component requires statistical parameters, such as a standard deviation for the maximum and minimum temperature, daily precipitation, average daily solar radiation, average amount of precipitation falling in a month, probability of wet day followed by dry day, probability of wet day followed by wet day and average dew point temperature. The statistical parameters are computed using the computer program developed by Liersch (2003). This program requires time series data of precipitation and temperature and provides all input parameters pertaining to the weather generator component in SWAT2005. For the Upper Awash basin, three meteorology stations (Addis Ababa, Debre Ziet, Wolliso) have been analyzed and used to establish the weather generator database (figure 5.2).

5.3.1.2 Climate data

The meteorological data elements such as daily precipitation, maximum and minimum temperature, daily wind speed, daily sunshine hours and daily relative humidity are basic climatic elements to set up the SWAT2005 model. The climatic information can be provided as measured input data or can be generated by the model using the weather generator. The data for the weather elements should be provided on a daily basis. For Awash basin, 8 meteorological data stations are available within and nearby the study area. The stations record daily precipitation data since 17 years (1990-2006) and the daily maximum and minimum temperature values for 10 years (1997-2006). The following figure indicates the geographic location of the meteorology and river gauging stations.

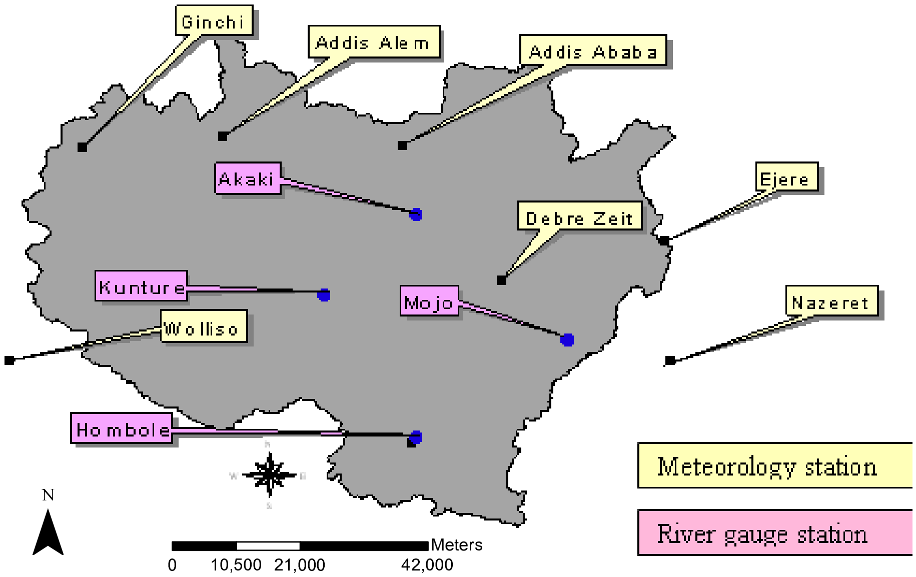


Figure 5.2: Hydro-metrological gauging stations in Upper Awash basin

The average rainfall depth recorded at each meteorological station is shown in figure 5.3 below. In all the stations, the maximum rainfall has been observed in months of July and August while the minimum rainfall has been observed in months of November to January. The maximum rainfall occurs at Addis Ababa meteorological station. Addis Ababa, Addis Alem, Debre Zeit and Wolliso are located at the highest elevation of the basin and as a result, they receive high rainfall depth. However, at Hombole meteorological station minimum rainfall occurs as the places are in low land area of the basin.

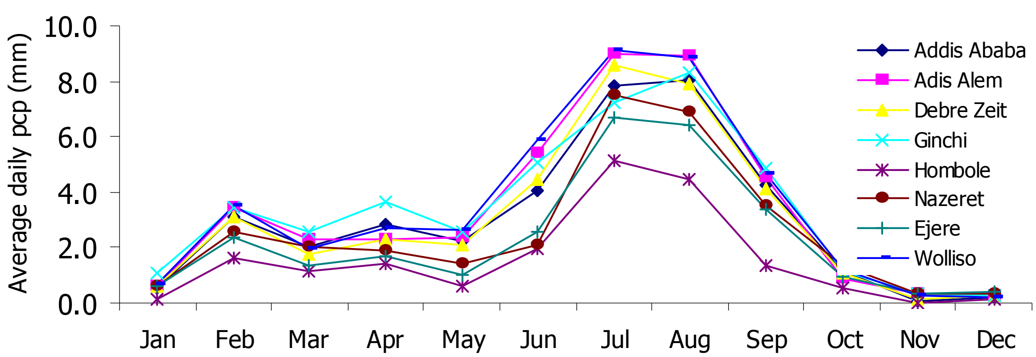


Figure 5.3: Average precipitation depth observed in Upper Awash basin (1990-2006)

The temperatures of three meteorological stations in the study area are shown on figure 5.4 below. The temperature in the study area ranges from 8.1 ^{o}C to 24.7 ^{o}C. From the graph the spatial variability of the temperatures is not so significant.

However, at low land areas of the basin where there is no data available, especially near Hombole and Nazeret meteorological stations, the temperatures are much higher than what is observed at the stations indicated on figure 5.4.

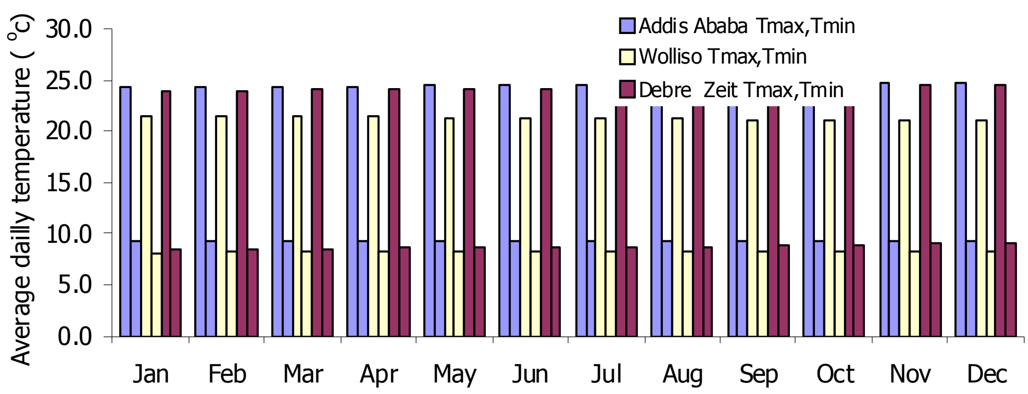


Figure 5.4: Average temperature observed in Upper Awash basin (1997-2006)

5.3.1.3 GIS data

The spatial variability of the basin's physiographic factors can be extracted from different digital maps which are the main building blocks of watershed configuration parameters in SWAT model. Data for 90 m X 90 m digital elevation model (DEM), land use map, land cover maps and soil maps (1:3,000,000 scale) obtained from Federal Ministry of Water Resources of Ethiopia (FMWRE) have been used as an input for the model setup. Prior to the application of the maps in the model, pre-processing work was carried out. The available DEM data were put together and the missing values were interpolated with a help of 3D visualization software. Similarly, the land use map has been re-classified into SWAT land use classes. The soil map has been referenced with FAO (1998) world soil database to obtain the physical properties of the individual soils. The properties of the soils are mainly parameters related to soil texture and grain size percentage composition which is helpful to compute other necessary physical soil characteristics. Apart from the properties of the soils obtained from FAO (1998) soil map, additional soil characteristics are required to set up SWAT2005 model. Soil saturated hydraulic conductivity, bulk density, soil available water and texture class at different soil depths are crucial for modeling with SWAT. Therefore, these soil characteristics were computed from the Soil Plant Air Water (SPAW) model which is described below.

SPAW Model

SPAW (Saxton and Rawis 1986) is a model capable of simulating daily hydrologic water budgets of agricultural landscapes. The model has soil water characteristics as one of its components. The soil water characteristics, soil texture (percentage of sand and percentage of clay) and percentage of organic carbon content is used as input for the model. The basic mathematical background of the model is the equation of Saxton and Rawis (1986) developed from extensive laboratory analysis on the national soil characterization database of the United States Department of Agriculture (USDA). The following figure shows a print screen of the SPAW model.

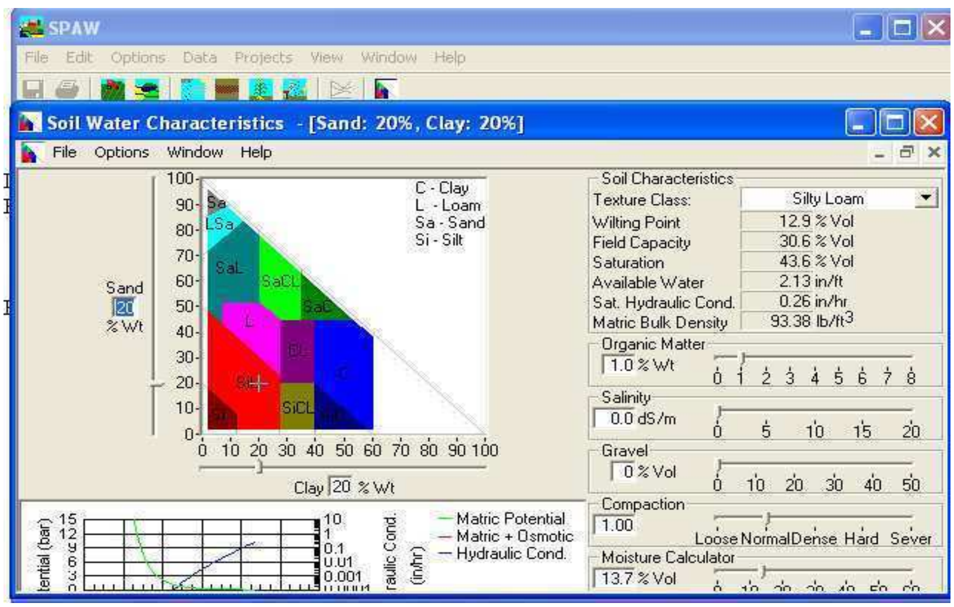


Figure 5.5: Print screen of the SPAW model

The model computes the soil characteristics such as texture class, wilting point, field capacity and saturation in percent by volume, available soil water, saturated hydraulic conductivity and bulk density. For each soil type observed in the Awash basin, their respective characteristics were computed in SPAW and the output has been used as input for SWAT soil parameterization. Overland and channel flow roughness values were adopted from Engman (1986) and Chow (1959). Similarly, the hydraulic conductivity of the channel bed material was adopted from Lane (1983) [*cited from Srininvasan 2008]*. The parameters of the RUSLE were adjusted at the beginning of the model simulation considering the specific situation of land use and soil type in the study area. The initial parameters for the practice factor P and cover factor C were adopted from Renard et al. (1997). The soil erodibility K factor has been calculated using the equation of Williams et al. (1984) (Section 5.2.3).

5.3.1.4 Hydrology and suspended load data

The time series data of discharge and suspended load concentration is required for the model calibration and validation. Daily data on stream flow measured for 30 years has been obtained from FMWRE. There are four gauging stations in the study area (figure 5.2) which are named as Akaki, Kunture, Hombole and Mojo gauging station where suspended load concentration was measured randomly at different time periods. For each gauging station, FMWRE established a sediment rating curve whose accuracy has been checked during the field work phase of this research (section 3.2.1). The established rating curve equations have been used to generate total sediment transport data for the available stations for the time period of 1990-2006. As SWAT simulates total sediment load including bed load, it is necessary to include the bed load component on the suspended load to have total sediment load for the model calibration and validation. However, there is no measured data on bed load material. In most rivers, bed load to suspended load is in the range of 1:5 to 1:50 (Csermark and Rakoczi 1987). Hence, 10 % of the suspended load has been added as bed load to the suspended load obtained from the rating curve.

5.3.2 Calibration and validation of SWAT2005 Model

The sediment outflow from each HRU and subbasin is primarily governed by soil, hydrologic and hydraulic parameters such as soil erodibility, surface runoff, stream discharge and stream flow velocity. Therefore, prior to sediment calibration, surface runoff and stream flow should be calibrated. As SWAT2005 model considers many parameters, it is mandatory to identify which of the basin parameters are most important to govern runoff, stream flow, and sediment yield. For both calibration of stream flow and sediment yield, governing parameters should be prioritized according to their order of influence. Prioritization of the parameters has been done using the robust Latin Hypercube One at a Time sensitivity analysis method. The entire study area has been divided into 21 subbasins. For each subbasin, the parameters have been ranked according to their order of influence. The frequency of each parameter in the first 5 top rank orders has been calculated. The computation result of the sensitivity analysis for stream flow and sediment yield is indicated in table 5.1.

Table 5.1: Ranks of most sensitive parameters of the watersheds

Parameters	Description	ranks		Parameter range
		flow	sediment	
ALPHA_BF	Base flow recession constant	3	6	0.0-1.0
CANMAX	Maximum canopy storage	6	--	0.0-100.0
CN_2	Initial SCS CN II value	1	1	0.0-100.0
CH_K	Channel hydraulic conductivity	9	8	0.0-150.0
ESCO	Soil evaporation compensation factor	4	9	0.0-1.00
SURLAG	Surface lug	8	2	1.0-12.0
SOIL_Z	Soil depth	5	--	0.0-3500.0
Soil_k	Saturate soil hydraulic conductivity	7	--	0.0-2000.0
SOL_AWC	Available water capacity	2	4	0.0-1.00
SLOPE	Average slope steepness	--	3	0.0-60
SPCON	Parameter for sediment routing	--	5	0.0001-0.01
USLE_P	Cover factor	--	7	0.1-1.0

The parameters shown in table 5.1 have been given special attention for both stream flow and sediment calibration. CN_2, SOL_AWC, ALPHA_BF, ESCO and SOIL_Z have been considered for stream flow calibration, while CN_2, SURLAG, SLOPE, SOL_AWC and SPCON have been considered for sediment calibration. The remaining parameters have been considered in calibration according to their order of importance. The automatic calibration tool using parametric solution (PARASOL) algorithm (Griensven et al. 2006) imbedded in SWAT2005 model has been used to calibrate the stream flow.

The model has been calibrated to the measured data of the 3 gauging stations, namely Hombole, Kunture and Akaki stations (figure 5.6). Seventeen years data records of stream flow and corresponding suspended data computed from the respective rating curve have been used for model calibration and validation. The entire period of record has been divided into two, i.e. from 1990 - 2000 data has been used for model calibration, while the data from 2001 - 2006 have been used for model validation. The calibration and validation results of the model are shown in figure 5.7 to figure 5.12.

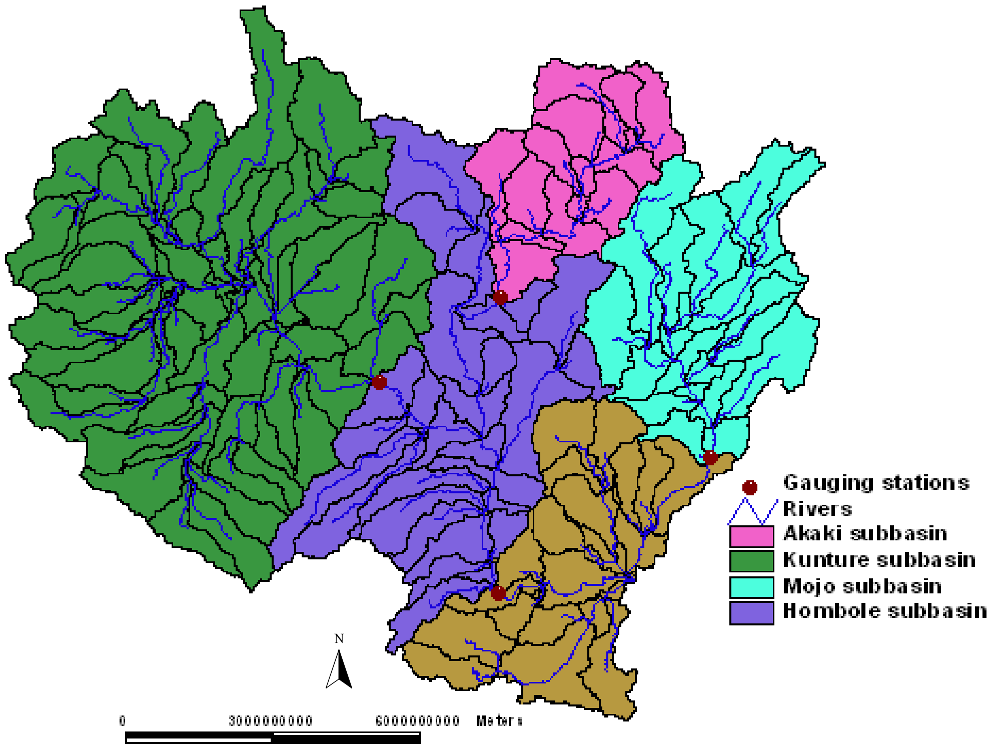


Figure 5.6: Map of Upper Awash basin classified according to gauges location

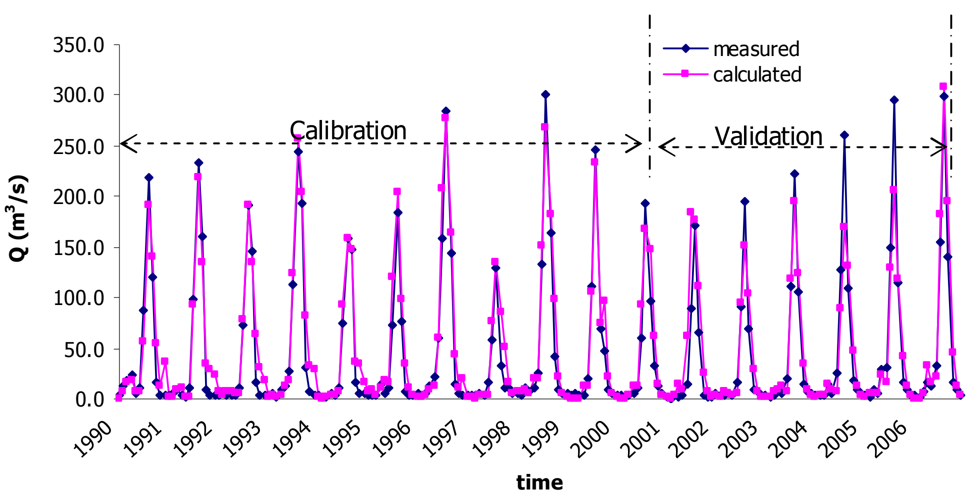


Figure 5.7: Stream flow calibration and validation at Hombole gauging station

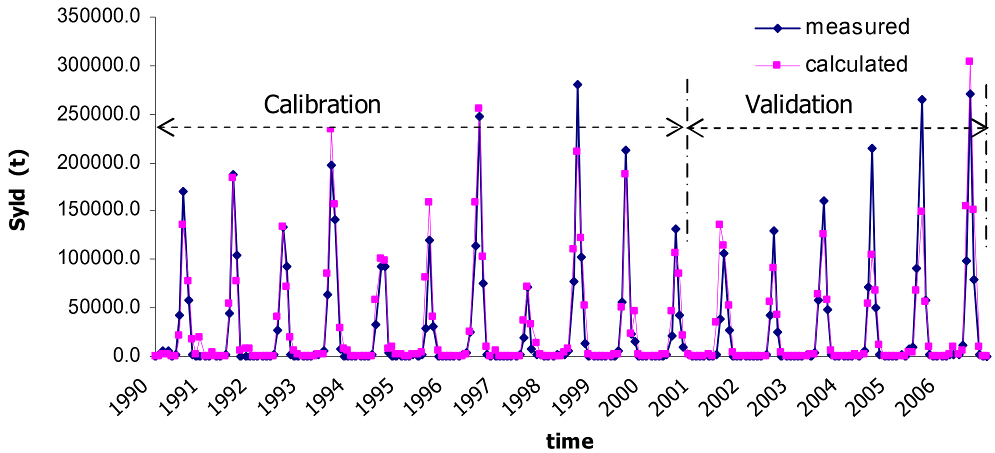


Figure 5.8: Sediment yield calibration and validation at Hombole gauging station

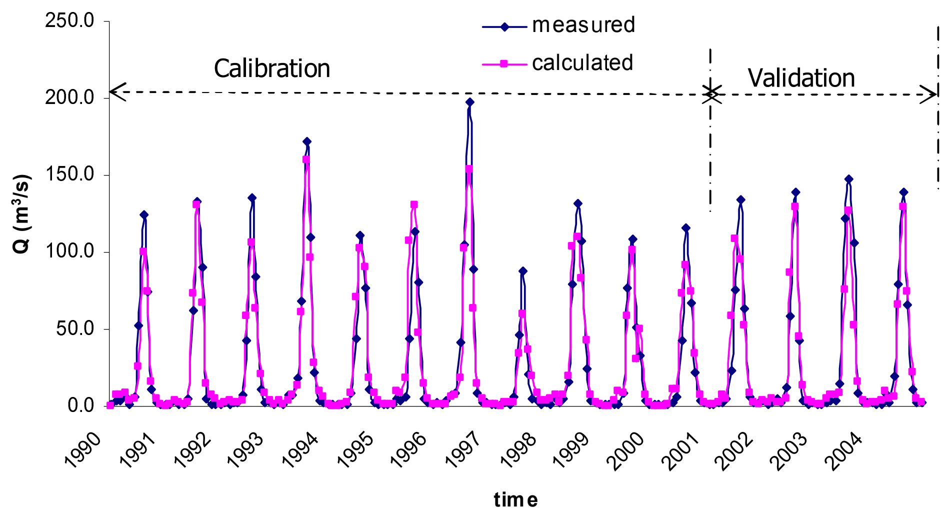


Figure 5.9: Stream flow calibration and validation at Kunture gauging station

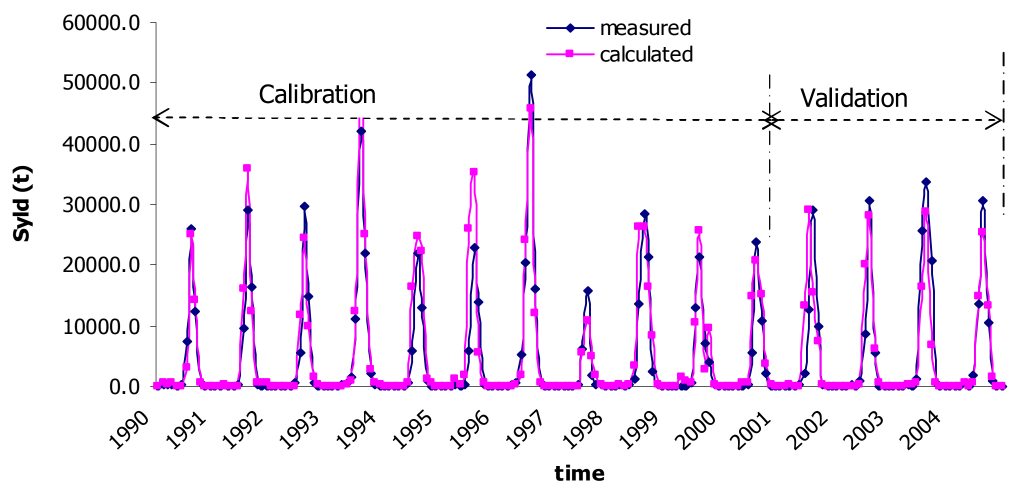


Figure 5.10: Sediment yield calibration and validation at Kunture gauging station

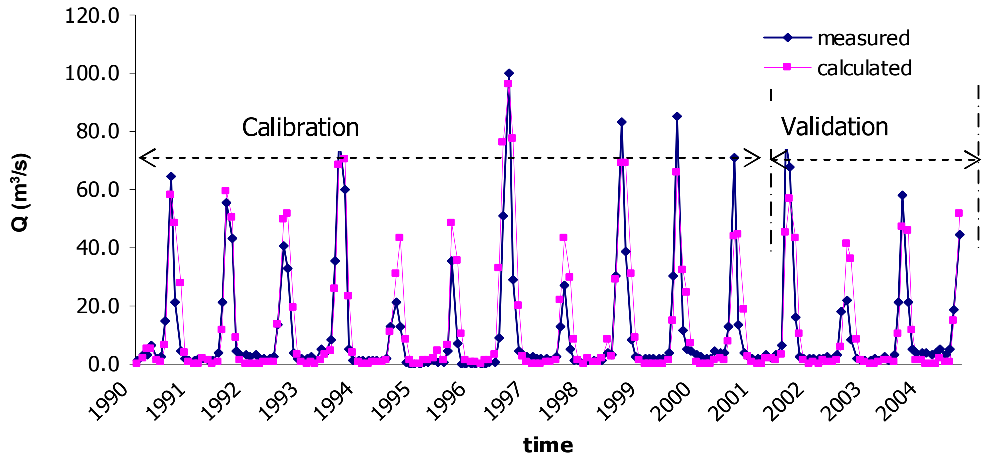


Figure 5.11: Stream flow calibration and validation at Akaki gauging station

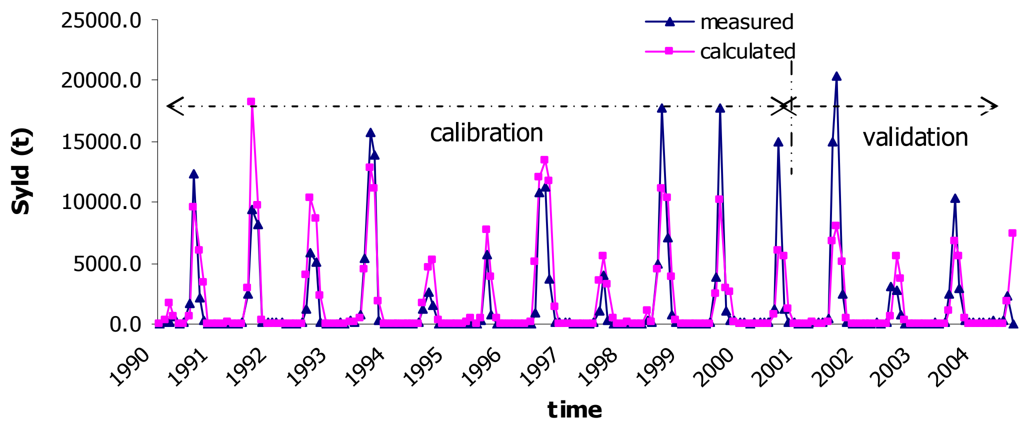


Figure 5.12: Sediment yield calibration and validation at Akaki gauging station

To evaluate the accuracy of the overall model calibration and validation, different statistical indicators like coefficient of determination (R^2), Nash-Sutcliffe modeling efficiency (NSE), Root mean square error observation standard deviation ratio (RSR) and percent bias (PBIAS) have been used.

The statistical indicators used for SWAT2005 model calibration and validation in Awash basin have been calculated using the following empirical relations.

Coefficient of determination (R^2): Is the index of correlation of measured and simulated values. The value of R^2 ranges from 0 to 1. The more the value of R^2 approaches 1, the better is the performance of the model and the values of R^2 less than 0.5 indicate a poor performance of the model.

$$R^2 = \left[\frac{\sum_{i=1}^{n} (O_i - \bar{O})(S_i - \bar{S})}{\sqrt{\sum_{i=1}^{n} (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^{n} (S_i - \bar{S})^2}} \right] \quad (5.7)$$

where

Oi = Observed stream flow

Si = Simulated stream flow

$\bar{o}$ = Mean observed stream flow

$\bar{S}$ = Mean simulated streamflow

n = Number of observation

Nash-Sutcliffe Efficiency (NSE): NSE is the normalized statistics which measures the relative magnitude of the residual variance as compared to measured data variance. Similar to R^2, the more the NSE approaches 1, the better will be the model performance and vice versa.

$$NSE = 1 - \frac{\sum_{i=1}^{n} (Si - Oi)^2}{\sum_{i=1}^{n} (Oi - \bar{O})^2} \quad (5.8)$$

Root mean square error observation standard deviation ratio (RSR): It is an error index indicator. RSR ranges from 0 to 1, with the lower value closer to zero indicating higher accuracy of the model performance. Values approaching 1 indicate a poor model performance.

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n} (O_i - S_i)^2} \right]}{\left[\sqrt{\sum_{i=1}^{n} (O_i - \bar{S})^2} \right]} \quad (5.9)$$

Percent bias (PBIAS): This measures the average tendency of the simulated data to be larger or smaller than the observed values. PBIAS is expressed in percentage; the lower the absolute value of the PBIAS is the better will be the model performance.

$$PBIAS = \left[\frac{\sum_{i=1}^{n} (O_i - S_i) * (100)}{\sum_{i=1}^{n} (O_i)} \right] \quad (5.10)$$

Hence, equations 5.7 to 5.10 have been used to compute the statistical indicators. The calculated values of R^2, RSR, NSE and PBIAS are as indicated in table 5.2.

Table 5.2: Model performance evaluation indicators: calibration / validation

Indicators	Gauging stations					
	Hombole		Kunture		Akaki	
	Flow	Sediment	Flow	Sediment	Flow	Sediment
R^2	0.93/0.81	0.83/0.83	0.90/0.89	0.77/0.80	0.72/0.71	0.92/0.94
NSE	0.93/0.80	0.82/0.90	0.89/0.77	0.75/0.62	0.79/0.79	0.67/0.55
RSR	0.26/0.43	0.41/0.42	0.33/0.48	0.50/0.60	0.46/0.46	0.58/0.61
PBIAS	-9.5/-7.5	-24/-47	2.54/-0.88	-19.6/-45.1	-0.16/-0.01	-14.57/-9.3

The calibration of the model at Akaki gauging station has shown very poor performance, especially during peak flow seasons (figure 5.12). This could be due to the fact that, the SWAT model simulates sediment yield based on MUSLE equation. MUSLE was basically derived for agricultural catchments, whereas the areas upstream of the Akaki gauging station are dominantly occupied by settlements.

Based on the computed indicators, the performance of the model has been evaluated. The evaluation of the model accuracy has been based on performance ratings: very good, good, satisfactory and unsatisfactory. Moriasi et al. (2007) suggested SWAT2005 model performance evaluation criteria (table 5.3).

Table 5.3: Model performance rating criteria (adopted from Moriasi et al. 2007)

Rating	RSR	NSE	PBIAS		
			flow	Sediment	N,P
Very good	0.00 to 0.50	0.75 to 1	<10	<15	<25
Good	0.50 to 0.60	0.65 to 0.75	10 to 15	15 to 30	25 to 40
Satisfactory	0.60 to 0.70	0.50 to 0.65	15 to 25	30 to 55	40 to 70
Unsatisfactory	> 0.70	< 0.50	> 25	> 55	> 70

N = Nitrogen, P = Phosphorus

In reference to the summary of the model performance rating records (table 5.3), the calibration and validation results of the SWAT2005 model for the Upper Awash basin with the available data at Hombole, Kunture and Akaki stations have been evaluated.

5.3.2.1 Evaluation of the stream flow calibration and validation

The performance of the model to simulate the stream flow during the calibration and the validation periods has been evaluated based on the computed results of the indicators and the suggested model performance rating standards. The computed statistical indicators shown in table 5.2 range from 0.93 to 0.72 for R^2, 0.93 to 0.79 for NSE, 0.26 to 0.46 for RSR and -9.5 % to 2.54 % for PBIAS at the three gauging stations during the calibration period. The values of all statistical indicators fall in the range of very good model performance in accordance with Moriasi et al. (2007) recommendations. Likewise, the model was evaluated for the performance of the validation period. The computed statistical indicators range from 0.89 to 0.71 for R^2, 0.90 to 0.77 for NSE, 0.43 to 0.48 for RSR and -7.5 to -0.01 for PBIAS at the three gauging stations during the validation period. Similar to the calibration period, the model performance rating was evaluated in terms of Moriasi et al. (2007) model performance evaluation criteria and was found to be a very good performing model.

5.3.2.2 Evaluation of the sediment yield calibration and validation

The performance of the model for the sediment yield modeling differs for the calibration and the validation periods. Therefore, the following discussion of the results is separately made for both periods. The performance of the results of the model has been evaluated in a similar way as for the stream flow. The computed statistical indicators range from 0.92 to 0.77 for R^2, 0.82 to 0.67 for NSE, 0.41 to 0.58 for RSR and -24.0 to -19.6 for PBIAS at Hombole, Kunture and Akaki gauging stations during the calibration periods. The indicators have been found to be within the range of a very good and good performance level. Similarly, for the validation period, the computed statistical indicators have been computed as 0.83 to 0.80 for R^2, 0.90 to 0.62 for NSE, and 0.42 to 0.6 for RSR and -45 to -47 for PBIAS. These values of the statistical indicators are in the good and very good model performance range except for the PBIAS value which is in the range of satisfactory criteria. As the indicator results are predominantly in the range of very good and good model rating, the overall model calibration and validation result can be rated as good model performance.

As has been observed during the model calibration and validation for stream flow and sediment yield, different ranges of the model performance can be recognized. The model performance was very good for stream flow and good for sediment yield modeling. This could be due to the quality of the stream flow and sediment data quality and reliability. For the gauging stations considered for model calibration, the stream flow was measured continuously and the data has been in a good quality as compared to the suspended sediment yield data that has been measured arbitrarily. The sediment data has been generated from the sediment rating curves and it can not be said that the value of the generated sediment yield data is as reliable as the stream flow data. Therefore, it can be noted that the more reliable and relatively accurate the input data for model calibration is, the better is the model performance. However, the model performance for sediment yield in Upper Awash basin is in good performance range and the model result can be a basis for further analysis or can be used as a guideline for sediment management at watershed scale. After successful calibration and validation of the model, the adjusted parameters are summarized in table 5.4.

Table 5.4: Adjusted parameter after SWAT2005 calibration and validation

Parameter	Description	Adjusted value	range
ALPHA_BF	Base flow recession constant	0.09	0.0-1.0
CANMAX	Maximum canopy storage	10 %	0.0-100.0
CN_2	Initial SCS CN II value	36-96	0.0-100.0
Ch_k	Channel hydraulic conductivity	10mm/h	0.0-150.0
ESCO	Soil evaporation compensation factor	0.75	0.0-1.00
SURLAG	Surface lag	4 days	1.0-12.0
SOIL_Z	Soil depth	300mm	0.0-3500.0
Soil_k	Saturate soil hydraulic conductivity	0.1-41mm/h	0.0-2000.0
SOL_AWC	Available water capacity	0.07-0.22	0.0-1.00
SLOPE	Average slope steepness	0.7 %-16.5 %	0.0-60
SPCON	Parameter for sediment routing	0.002	0.0001-0.01
USLE_P	Cover factor	0.3-0.7	0.1-1.0

5.3.3 Basin sediment balance

Following the successful calibration of the sediment yield at different gauge locations, the soil loss rate from the upland area of the watersheds can be computed. In Upper Awash basin, the annual soil loss rate and its spatial distribution have been analyzed in SWAT2005 model. Similarly, the sediment outflow from each of the tributaries and the main river section has been modeled. The calculated soil loss rate ranges from 0.73 t/ha/yr to 224.1 t/ha/yr. Similar findings have been reported as the maximum soil loss rate which is in range of 200-300 t/ha/yr (PDRE, 1989). Based on Hudson (1981) who state that soil loss rates in the range of less than 10 t/ha/yr are tolerable, the soil erosion risk map of the Upper Awash basin have been prepared from the SWAT2005 model output (figure 5.13).

The spatial pattern of the soil loss rate has been analyzed in terms of tolerable and non tolerable. Areas with a soil loss rate of less than 10 t/ha/yr have been equally divided into two soil loss classes (very low and low). Similarly, an area of the study area with a soil loss rate greater than 10 t/ha/yr has been equally divided into three soil loss classes (medium, high and very high). Thus, the entire study area has been divided into five soil loss classes namely very low (0.73 - 4.6 t/ha/yr), low (4.6 - 10.0 t/ha/yr), medium (10.0 - 71.37 t/ha/yr), high (71.37 - 142.73 t/ha/yr) and very high (142.73 - 224.1 t/ha/yr). According to the research results, 44 % of the study area coverage is in the range of tolerable soil loss rate while the 56 % of the area is within the non tolerable range.

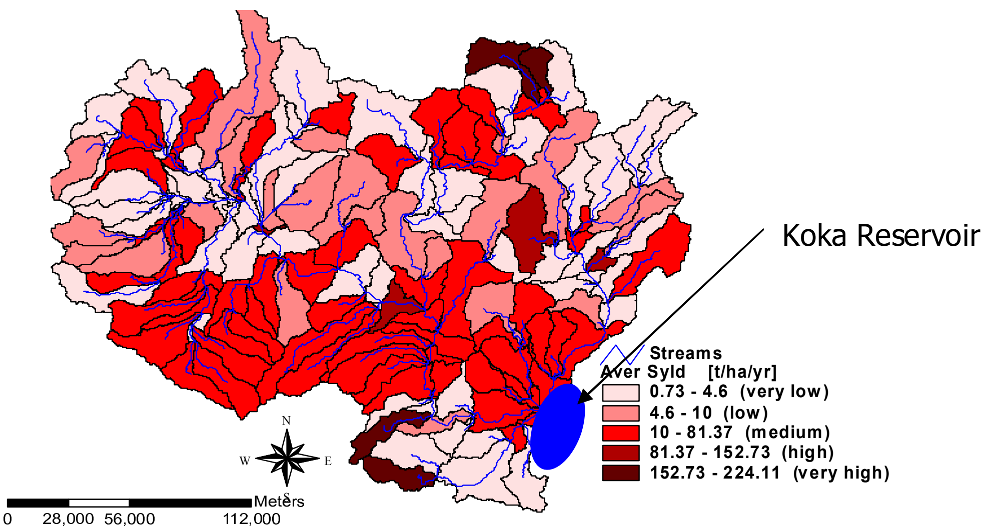


Figure 5.13: Spatial patterns of soil loss rate in Upper Awash basin

The temporal distribution of the sediment outflow characteristics of the entire basin has been computed with SWAT2005 model. At the outlet of the basin, Koka dam is located (figure 5.13). Since the dam construction in 1959 three bathymetric surveys were carried out. In figure 5.14 the data from FMWRE is displayed giving an indication of the loss of storage volume due to siltation of sediments eroded from Upper Awash basin.

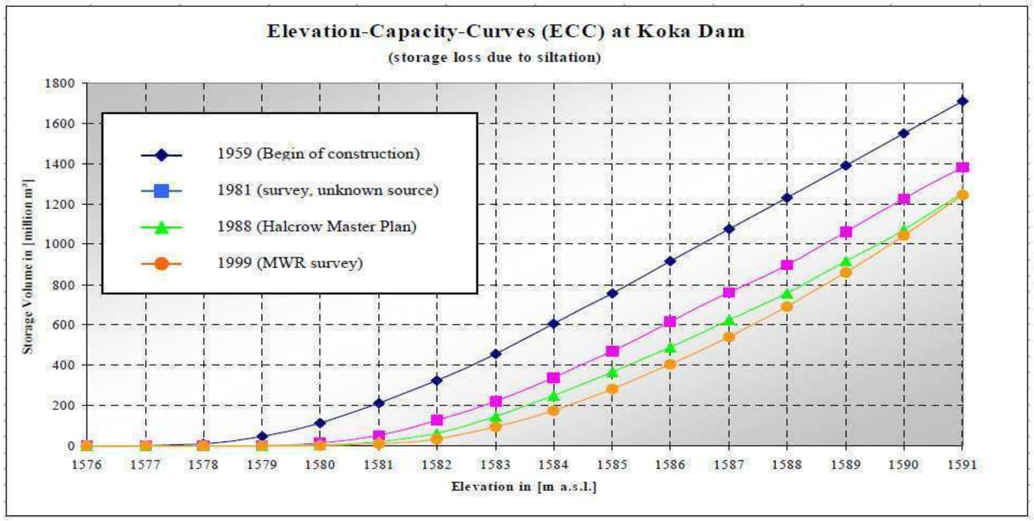


Figure 5.14: Bathymetric survey chart of Koka reservoir (FMWRE report 1999)

Based on the bathymetric survey result, the annual rate of sediment deposition has been estimated to be about 12×10^6 m^3. The sediment outflow from the reservoir has been computed by deducting the 12×10^6 m^3 rate of deposition from the respective annual sediment inflow. The computation result is indicated in the figure 5.13.

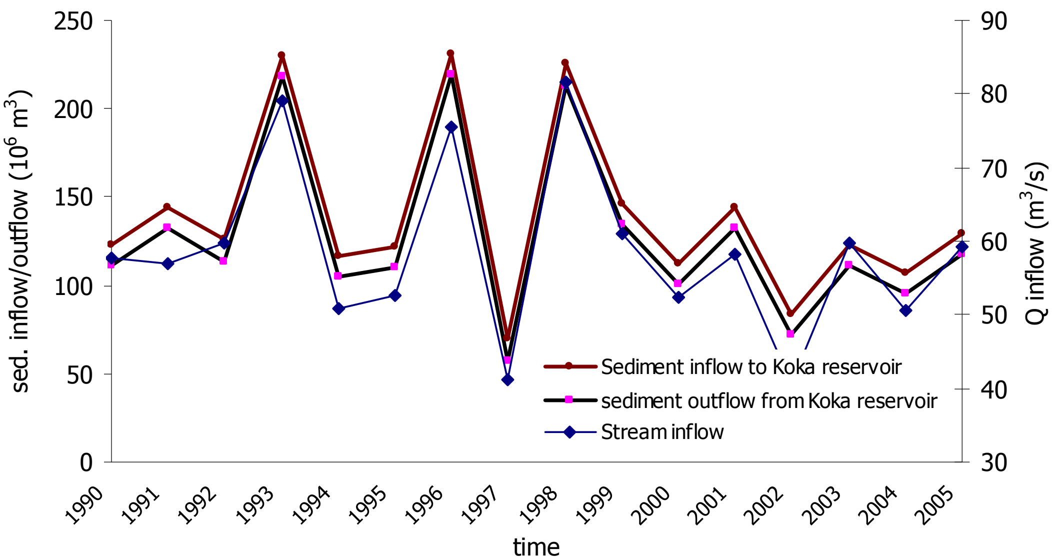


Figure 5.15: Temporal pattern of sediment balance in Koka reservoir

As can be seen from the above figure, the sediment inflow into the reservoir has been decreasing tremendously. The decrease in the sediment supply is due to the decrease in the stream flow of the basin as it has been observed that the discharge is also decreasing in a similar trend.

The performance of the identified sensitive parameters in SWA2005 model has been evaluated for its applicability on Blue Nile basin (Section 2.1.2). Two study areas from Blue Nile basin namely Gudar and Fincha subbasins have been considered for the application of the model.

5.4 Application of SWAT2005 model to Gudar subbasin

Gudar subbasin of the Blue Nile basin described under section 2.1.2 has been selected for SWAT2005 model application. The measured stream flow and suspended sediment data was available on Gudar River. Based on the available data of the river gauging station, SWAT has been set up and calibrated for the stream flow and the sediment yield. Data from rainfall stations (Ginchi, Gudar, Ambo, Asgori) have been used in the model. Figure 5.16 shows the gauged part of the subbasin. The temperature and other climatic elements were generated from the weather generator component. The weather generator component for Gudar subbasin has been transferred from Awash basin due to the geographical proximity of both study areas. After having established the required database, similar procedures applied to Awash basin have been repeated for Gudar subbasin. The duration of data record at the gauging station was limited to 10 years (1990-2000). Therefore, the SWAT model could not be validated for Gudar subbasin.

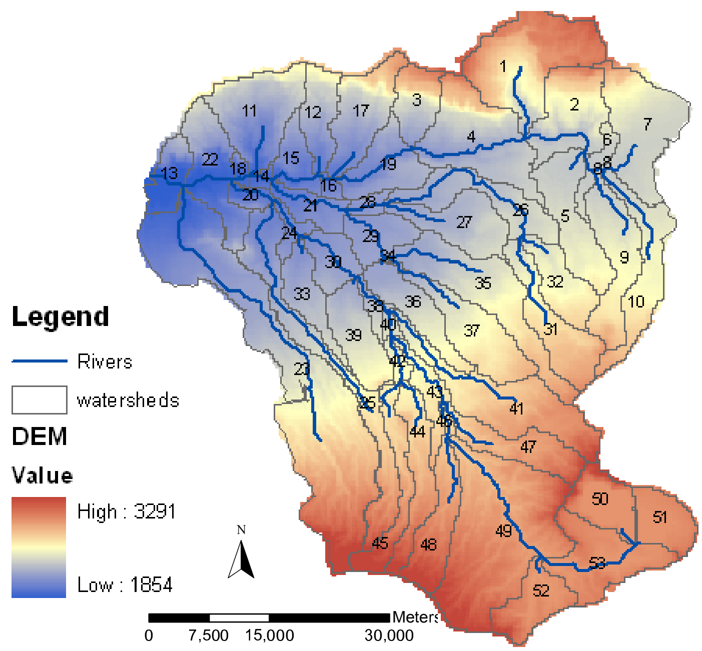


Figure 5.16: Map of Gudar subbasin used for model evaluation

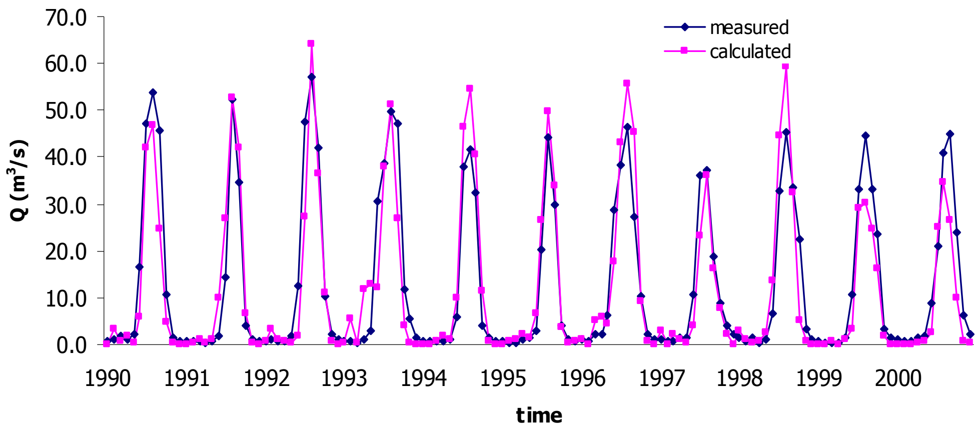


Figure 5.17: Stream flow calibration at Gudar gauging station

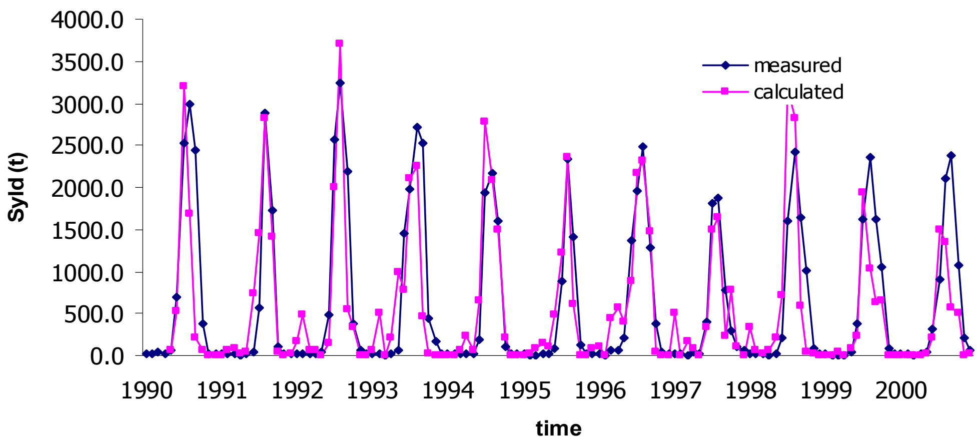


Figure 5.18: Sediment yield calibration at Gudar gauging station

Based on the calibration result, the model performance has been evaluated in terms of the statistical indicators (table 5.5). The statistical indicators have been computed to evaluate the performance of the model calibration on Gudar subbasin. Similar indicators described in section 5.3.2 have been used to evaluate the model performance.

Table 5.5: Computed statistical indicators for Gudar subbasin

Description	Stream flow	Sediment yield
R^2	0.85	0.78
NSE	0.84	0.77
PBIAS	6.89	0.76
RSR	0.39	0.48

From the computed statistical indicators and the model performance evaluation criteria (Moriasi et al. 2007), the Gudar subbasin model calibration result was rated as very good. After the successful calibration of the model, the adjusted model parameters were selected and are described in table 5.6.

Table 5.6: Adjusted parameters for Gudar subbasin

Parameters	Parameter description	Adjusted parameter	Parameter range
ALPHA_BF	Base flow recession constant	0.08	0.0 - 1.0
CANMAX	Maximum canopy storage	0.00	0.0 - 100.0
CN2	Initial SCS curve II value	80 - 92	0.0 - 100.0
Ch_k	Channel hydraulic conductivity	4	0.0 - 150.0
ESCO	Soil evaporation factor	0.75	0.0 - 1.0
SURLAG	Surface lag	4	1.0 - 12.0
Sol_Z	Soil depth	1000	0.0 - 3500.0
Soil_K	Soil hydraulic conductivity	10 - 30	0.0 - 2000.0
SOL_AWC	Soil water available capacity	0.09 - 0.17	0.0 - 1.0
SPCON	Linear adjustment factor for sed.	0.0025	0.0001 - 0.01
USLE_P	USLE_cover factor	0.85	0.1 - 1.0

The spatial pattern of soil loss rates has been analyzed for Gudar subbasin (figure 5.17). Similar to the Upper Awash case, the soil loss map of the subbasin has been divided into five soil loss classes namely very low, low, medium, high and very high. The low and very low soil loss classes are areas of the subbasin with a soil loss rate of less than 10 t/ha/yr. Such areas are rated as tolerable soil loss rate which implies that there is no significant impact on the soil productivity of the area. In contrast, areas of the subbasin with a soil loss rate greater than that of 10 t/ha/yr falls into the range of non-tolerable soil loss rate (figure 5.19). In Gudar subbasin 93.7 % of the area shows a non tolerable soil loss rate indicating that there is fast soil depletion and as a result there is high sediment supply to the adjoining rivers.

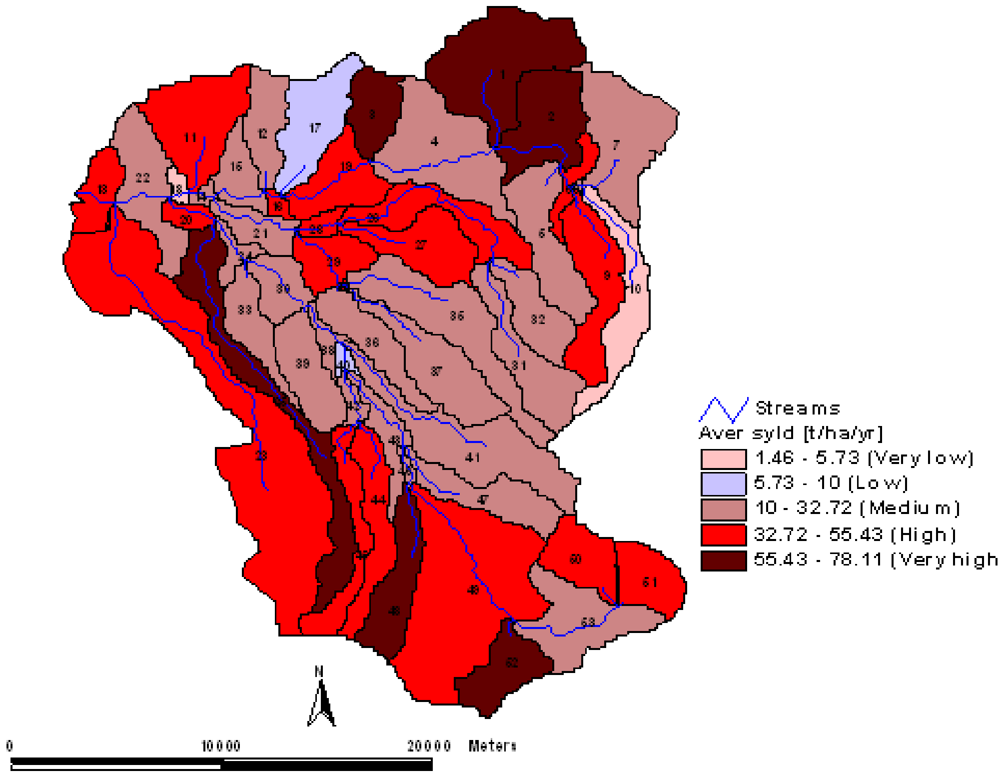


Figure 5.19: Spatial distribution pattern of the soil loss rate in Gudar subbasin

5.5 Application of SWAT2005 model to Fincha subbasin

Fincha subbasin (section 2.1.2) of the Blue Nile basin has been selected for SWAT2005 model application in moist humid climate zone. The subbasin has a total drainage area of 3917.8 km^2 out of which 299.18 km^2 is gauged. The gauged part of the subbasin which is located on Neshi River is shown in figure 5.20. The Neshi River has measured data of stream flow and suspended sediment for 9 years (1998 - 2006).

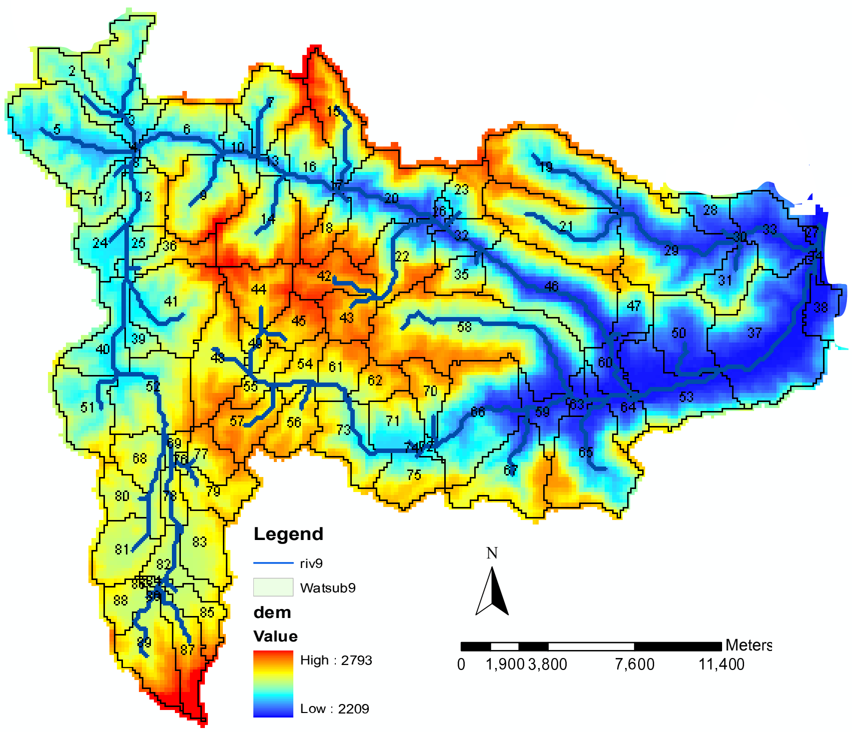


Figure 5.20: Fincha subbasin (Neshi River) used for SWAT2005 model calibration

Three meteorological stations namely Neshi, Alibo and Shambu are available in the vicinity. The weather generator component has been established from Neshi meteorological station. With the availability of the mentioned data for climate elements, stream flow and sediment yield calculation in the SWAT2005 model have been calibrated for Neshi watershed. The calibration result is shown in figures 5.21 and 5.22.

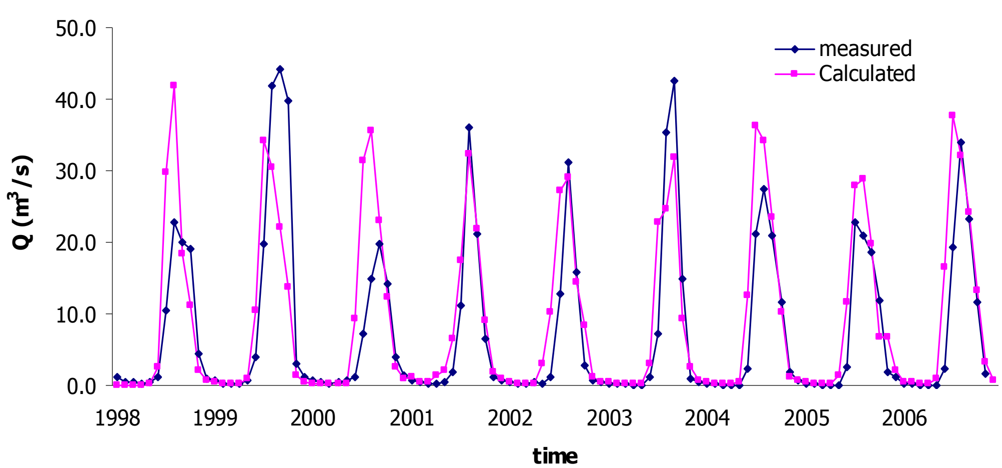


Figure 5.21: Stream flow calibration at Neshi gauging station

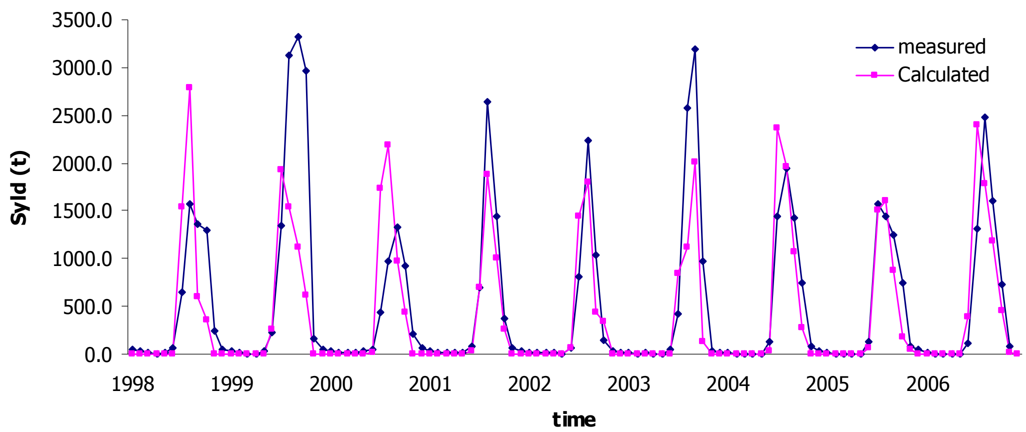


Figure 5.22: Sediment yield calibration at Neshi gauging station

The statistical indicators for the model performance have been computed (table 5.7).

Table 5.7: Computed statistical indicators for Fincha subbasin

Description	Stream flow	Sediment yield
R^2	0.70	0.68
NSE	0.69	0.72
PBIAS	-23.3%	19.8
RSE	0.54	0.52

From the computed statistical indicators and the model performance evaluation criteria (Moriasi et al. 2007), the Fincha subbasin model calibration result has been rated as a well performing model. After the successful calibration of the model, the adjusted parameters have been selected and described in table 5.8.

Table 5.8: Adjusted parameters for Fincha subbasin

Parameters	Parameter description	Adjusted parameter	Parameter range
ALPHA_BF	Base flow recession constant	0.098	0.0-1.0
CANMAX	Maximum canopy storage	0.00	0.0-100.0
CN2	Initial SCS curve II value	86	0.0-100.0
Ch_k	Channel hydraulic conductivity	80	0.0-150.0
ESCO	Soil evaporation factor	0.95	0.0-1.0
SURLAG	Surface lag	3	1.0-12.0
Sol_Z	Soil depth	1828	0.0-3500.0
Soil_K	Soil hydraulic conductivity	9.42-30	0.0-2000.0
SOL_AWC	Soil water available capacity	0.06-0.16	0.0-1.0
SLOPE	Average slope steepness	3.1-27.8	0.0-60.0
SPCON	Linear adjustment factor for sed.	0.0062	0.0001-0.01
USLE_P	USLE_cover factor	0.6	0.1-1.0

Similar to the Awash basin and the Gudar subbasin, the spatial pattern of the soil loss rate in Fincha subbasin has been analyzed (figure 5.23). According to the analysis, 99 percent of the area shows a non-tolerable soil loss rate. Similar finding were reported from an investigation conducted by Olana B. in 2006, which states that the highest erosion rate has been predicted on croplands that ranged from 0.0 to 45.4 kg/m^2/yr for the entire Fincha subbasin (Olana 2006). This magnitude of soil loss is equivalent to 0.0 to 454 t/ha/yr.

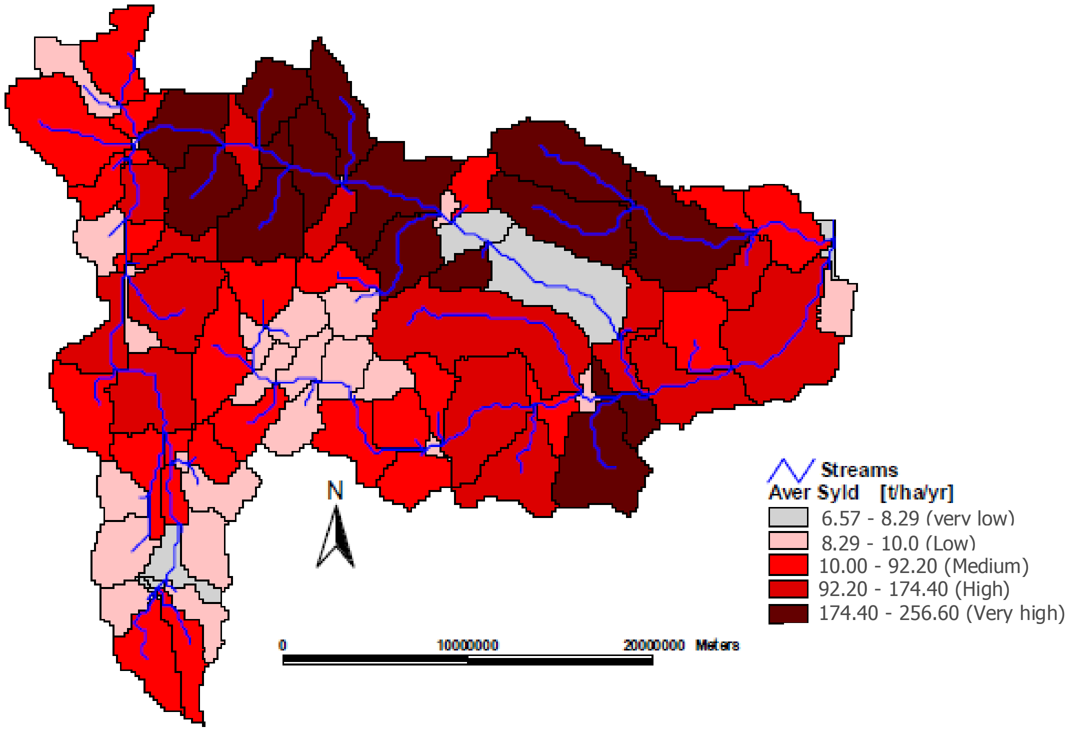


Figure 5.23: Spatial distribution pattern of soil loss rate in Fincha (Neshi) subbasin

5.6 Discussion

The watershed parameters identified by the sensitivity analysis (table 5.1) have been used for the calibration of the SWAT2005 model to get a reasonable model output on stream flow and sediment yield. The sensitivity result shows the curve number is the major parameter to govern stream flow and sediment yield. Curve number is a watershed parameter related to land cover condition and soil characteristics. Watersheds with sparse vegetation cover and less permeable soil types generate high runoff from the rainfall events. This happens because unprotected land and less permeable soils are fast to get saturation level and at saturation condition of the soil, the curve number parameter approaches to 100. Consequently, the generation of high runoff depth results for high sediment generation and transport.

Watershed slope is another parameter to play a fundamental role for sediment yield from the upland watershed. Similarly, the slope of the bed of the river is another parameter to govern sediment transport in stream section. The sediment transport is favored by the availability of sufficient kinetic energy. This kinetic energy is available in the presence of sufficient gradient. The available soil water content and the base flow recession constant are another significant factor to govern stream flow. The available soil water content determines the initial moisture condition of the soil and it is the basis for computation of the soil moisture balance and hence determines the excess runoff on land surface. The base flow recession constant is a ground water index which determines the amount of base flow contribution to the rivers during the dry seasons (no rain). It depends on the response of the ground water flow with respect to change in recharge.

The model calibration has been done for the data sets of years of record from 1990 - 2000 for the Upper Awash basin using the sensitive parameters. After the optimum parameters were obtained from the calibration result, the performance of the model has been evaluated based on the different statistical indicators discussed under section 5.3.1.4.The calibration of SWAT2005 model on Upper Awash basin was rated as a very good model performance for stream flow and good for sediment yield.

The model has been validated using the adjusted parameters in calibration period. The measured data on stream flow and sediment yield for the year 2001 - 2006 has been used for the model validation. In a similar way, as described in the above paragraph, the performance of the model during the validation period has been evaluated and rated as very good model performance for stream flow and good for sediment yield. Nevertheless, during the validation period for Hombole gauging station (figure 5.7 and 5.8) the peak values for stream flow and sediment yield are underestimated for the years 2003 to 2006.This happens due to the precipitation data quality used for the modeling. The rainfall data from Nazeret, Debre Zeit and Hombole meteorological stations has many missing values. The missing values of the data were generated from the weather generator component of the SWAT2005. So the underestimation of the stream flow and the sediment yield could be due to the underestimation of the missing rainfall data from the weather generator component.

The successful calibration and validation of the SWAT2005 model is a helpful tool when analyzing the spatial distribution pattern of soil erosion and sediment yield in the basin. As indicated in figure 5.13, catchments with high erosion hazards were identified. More than 50 % of the total area of the study area shows non-tolerable soil loss rate. Non-tolerable soil rate areas need immediate attention for mitigation activity. The selection of the appropriate action to be taken depends on the economy and effectiveness of the different erosion methods such as agricultural or engineering soil and water conservation practices.

Similarly, the model also predicted the temporal patterns of the sediment outflow from the individual watersheds and the net sediment outflow from the entire basin. The predicted sediment outflow from the individual catchments provides useful information for planning and designing of hydraulic structures on the respective rivers of the watersheds. Watersheds with high sediment-laden flows should be given special consideration when designing dams or weirs so that effective sediment control or sediment flushing components can be provided.

The predicted temporal pattern of the sediment outflow from the entire basin indicates the seasonal and annual variability of the sediment outflow. The Koka reservoir located at the outlet of the basin has been receiving the sediment supply from the entire basin. The high sediment inflow to the dam from Upper Awash basin has created sedimentation problem which has resulted in a 40 % loss of storage capacity. From this study, the annual sediment storage and the sediment flux from the reservoir have been estimated (section 5.3.2). The prediction of the sediment inflow and outflow into and out of the reservoir provides preliminary information on reservoir sediment management.

The SWAT2005 model calibration has been successfully carried out on the Gudar and Fincha subbasins. For the calibration of the model on the subbasins which are located in different climatic zones, the same parameters identified in sensitivity analysis for Upper Awash basin have been applied. The successful calibration of the model indicates that with similar parameters, SWAT2005 model can be calibrated on different river basins in moist subhumid to arid climatic zones. The sensitive parameters such as CN_2, Surlag, Slope and SPCON are major sediment calibration parameters in SWAT2005 model and can be implemented for the sediment modeling on basins located in semiarid, arid and humid climate zones.

The spatial patterns of the soil loss rate in Gudar and Fincha subbasins has been analyzed and more than 90% of the subbasins' area has been found to be in the range of non tolerable soil loss range. As compared to the Upper Awash basin soil loss rate, the two subbasins experience more erosion risk and consequently a higher sediment concentration. In Gudar subbasin, the maximum soil loss rate has been estimated to be 78 t/ha/yr while in Fincha subbasin the maximum soil loss rate has been estimated to be 256 t/ha/yr. In comparative assessment, the area coverage of non tolerable soil loss rate is highest in Fincha subbasin. This could be probably due to the highest rainfall depth and the steep topography. Moreover, the large agriculture practice in the area is another factor for the high soil depletion rate. In contrary in Upper Awash basin, the area coverage of non tolerable soil loss rate is relatively low which could be due to the presence of forest cover and better land management practice on the agricultural fields. Therefore it can said that soils of areas with intensive agricultural practice on steep slopes and less land management practices are more vulnerable to soil erosion hazards. Consequently, the sediment loads in the adjoining rivers are proportionally high due to suspended load supply from the upstream watersheds.

6. WATERSHED PARAMETERIZATION

6.1 Introduction

The erosion of soil from upland areas and deposition of sediment in low land and river banks is primarily governed by the hydrology and geomorphology of a watershed. The spatial variability of the topographic and the geomorphologic characteristics of watershed attributes to the variability of soil loss in the upland areas, and of sediment yield at the outlets of watersheds. Understanding the way in which topographic and geomorphologic factors, as well as hydrologic factors influence sediment yield is helpful in orchestrating the wise handling of sediment models and watershed management activities. Due to the fact that each watershed has its own distinct characteristics, the geomorphology and hydrology of one watershed varies from the other. Watersheds with a large drainage area and steep slopes are more likely to produce high sediment outflow as compared to the large sized watersheds with flat slopes. Additionally, the land cover situation of the watershed is another key factor. Watersheds with dense vegetation cover are more protected against erosion and sediment production. Similarly the hydrology of a watershed mainly rainfall characteristics, runoff and stream discharge is another fundamental factor to govern sediment production. The role of the different watershed factors in sediment production is interrelated with each other. For example, a watershed with a large drainage area, steep slopes and dense vegetation cover may generate less sediment yield as compared to a watershed with the same drainage area, flat slopes but less vegetation cover. In such case, the contribution from the variation of the slope and the vegetation condition determines the amount of the watershed's sediment supply. Because of the interdependency of parameters of a watershed, it is difficult to directly pinpoint a single parameter as the most governing factor for the amount of sediment yield. Certain statistical methods, such as correlation analysis need to be applied to study the interdependency of the different factors and to screen out the most sediment governing parameters.

In this specific study, the Upper Awash basin has been considered for a watershed parameterization through the application of a correlation technique.

6.1.1 Hydrologic parameters

Hydrologic parameters are the main driving force behind the production and transportation of sediment load. Rainfall depth, intensity, surface runoff and stream flow are the major hydrologic factors that play a fundamental role in erosion generation and sediment transport. Rainfall initiates soil detachment and transportation, while surface runoff and peak flow transport the eroded soil as sediment load. Surface runoff and peak flow are estimated from available empirical formulae, while the stream flow component is measured physically. Nevertheless, for large basins with many river networks there is a limited amount of measured stream flow data available for each tributary and main river section. Therefore, physically based models like SWAT2005 and other hydrologic models can help to simulate the surface runoff, peak flow and stream discharges, which can then be used as primary input for sediment modeling.

6.1.2. Geomorphologic parameter

The geomorphology of a watershed refers to its physical characteristics. The main geomorphologic factors are: area, elongation ratio, circularity ratio, drainage length, shape factor, slope, relief ratio, elevation difference and hypsometric integral. The definition and description of the common watershed geomorphologic factors are described below.

I. Area (A): A is the size of a watershed above the outlet point where the stream flow and sediment yield measurement is taken. It is one of the major geomorphologic factors to govern the amount of sediment yield from a watershed. Generally larger areas contribute high sediment load to the downstream rivers.

II. Elevation difference (HD): HD is the difference between the maximum elevation and the minimum elevation of the considered watershed. It is the geomorphologic parameter that determines the probability of deposition and transportation of sediments on land surfaces. Watersheds with a higher HD value and a small drainage area have a higher capability to transport eroded soils as sediment load.

$$HD = H_{max} - H_{min} \tag{6.1}$$

III. Hypsometric integral (HI): HI describes the ratio of HD and the difference of mean elevation and minimum elevation in a watershed. Similar to HD, HI determines the probability of sediment deposition and transportability.

$$HI = \frac{H_{max} - H_{min}}{H_{mean} - H_{min}} \tag{6.2}$$

where

H_{mean} = mean elevation of the watershed

H_{min} = minimum elevation of the watershed

H_{max} = maximum elevation of the watershed

IV. Elongation Ratio (ER): ER is the ratio of the diameter of a circle having the same area as a considered watershed and the maximum length of the watershed. It is a parameter to describe the shape of the watershed. The more elongated the watershed is the more likely the rate of sediment deposition occurs if sufficient gradient is not available to drive the sediment load to the river networks.

$$E_r = \frac{D_c}{L} \tag{6.3}$$

where

D_c = diameter of a circle having same area as the watershed

L = maximum length of the watershed

V. Slope (S): The ratio of the change in elevation between the furthest point of watershed outlet and the watershed length is the slope. The slope of a watershed is one of the major geomorphologic factors to govern sediment transport. Higher slope results in high sediment delivery to downstream section.

$$S = \frac{\Delta H}{L} \tag{6.4}$$

where

ΔH = change in elevation

L = length of the watershed

VI. Shape factor (S_f): S_f is the ratio of the square of the maximum length of the watershed to the area of the watershed.

$$S_f = \frac{L^2}{A} \tag{6.5}$$

where

L = length of the watershed

A = area of the watershedshed

VII. Drainage length (DL): DL defines the length of a stream reach in the watershed. Drainage length and shape factor are the geomorphologic parameters whose influence on sediment transport can be reflected in the other parameters like the watershed area and the elongation ratio. However, for more information on the different role of geomorphologic factors, both DL and S_f can be considered for supplementary information in watershed parameterization.

6.2 Ranking and prioritization of parameters governing sediment yield

Watershed sediment yield can be described as a function of the different parameters namely: hydrologic, geomorphologic and topographic factors. The parameters can be statistically related to the respective watershed's sediment outflow. However, there are limited data available with regard to field measured sediments. Physically based models can help in obtaining the sediment yield of a basin. Physically based models are capable to discretisize the entire study area (basin) into smaller watersheds (subbasins). The SWAT2005 model selected for this research can be taken as a good example of a physically based model. With the availability of measured stream flow and sediment data at least on two gauging stations, the model can be calibrated for various watersheds located upstream of the gauging stations. After calibration, the model results from each watershed can be used as part of the statistical analysis to further investigate the relationship of the different watershed parameters and the sediment outflow. For this specific study, SWAT2005 has been calibrated and validated for Upper Awash basin (section 5.3). With the availability of data from the calibrated SWAT2005 model, the watershed factors which govern the sediment yield have been identified.

The computation of different watershed parameters has been conducted using the SWAT2005 and GIS tools. For the parameters that could not be determined with the SWAT2005, GIS spatial analysis tools have been used. The elevation values of each watershed have been determined from the DEM data available for the study area. This was carried out with GIS spatial analysis tools by generating a contours map and extracting the respective elevations, maximum, minimum as well as average elevation for each watershed. The extracted elevation values have been used to compute elevation differences (HD) and hypsometric integrals (HI), while area, slope and watershed length parameters were obtained from the watershed configuration output data in SWAT2005. Subbasin shape factors (S_f) and subbasin elongation ratios (ER) have been calculated by their respective formulas. Stream flow and sediment yield were extracted from SWAT2005 after model calibration. With the availability of the parameters and the sediment yield from the SWAT2005 model calibration, statistical analysis has been carried out to evaluate the level of dependence of the watershed sediment yield on the hydrologic and geomorphologic factors. The degree to which watershed sediment yield is dependent on watershed parameters (hydrologic and geomorphologic) parameters has been evaluated by correlation analysis. There are three types of correlation analysis methods. These are Pearson's correlation, Kendall rank correlation and Spearman correlation. Pearson's correlation is the most widely used technique to analyze the degree of association between two or more variables where as Kendall rank and Spearman are applicable when misleading results are obtained from Pearson's method. Therefore, for this specific study Pearson's correlation method is applied.

6.2.1 Pearson's correlation

Correlation is the degree of association between two variables. A correlation can be positive or negative depending on the type of association (direct or inverse). The higher the correlation coefficient of the variables irrespective of its sign (+,-), the stronger is the resulting degree of association. Pearson's coefficient of correlation measures the degree of association between two variables being considered. For two observed variables X and Y with n number of observation data sets, the Pearson's coefficient of correlation can be expressed as:

$$r = \frac{\sum XY - \sum X \sum Y}{\sqrt{\left[\sum X^2 - \frac{(\sum X)^2}{n}\right]\left[\sum Y^2 - \frac{(\sum Y)^2}{n}\right]}} \tag{6.6}$$

When the degree of association for more than two variables is being evaluated, a correlation matrix is applied. So a correlation matrix can be used to measure the dependency of sediment yield on the watershed's hydrologic and geomorphologic parameters.

6.2.2 Application of Pearson's correlation technique

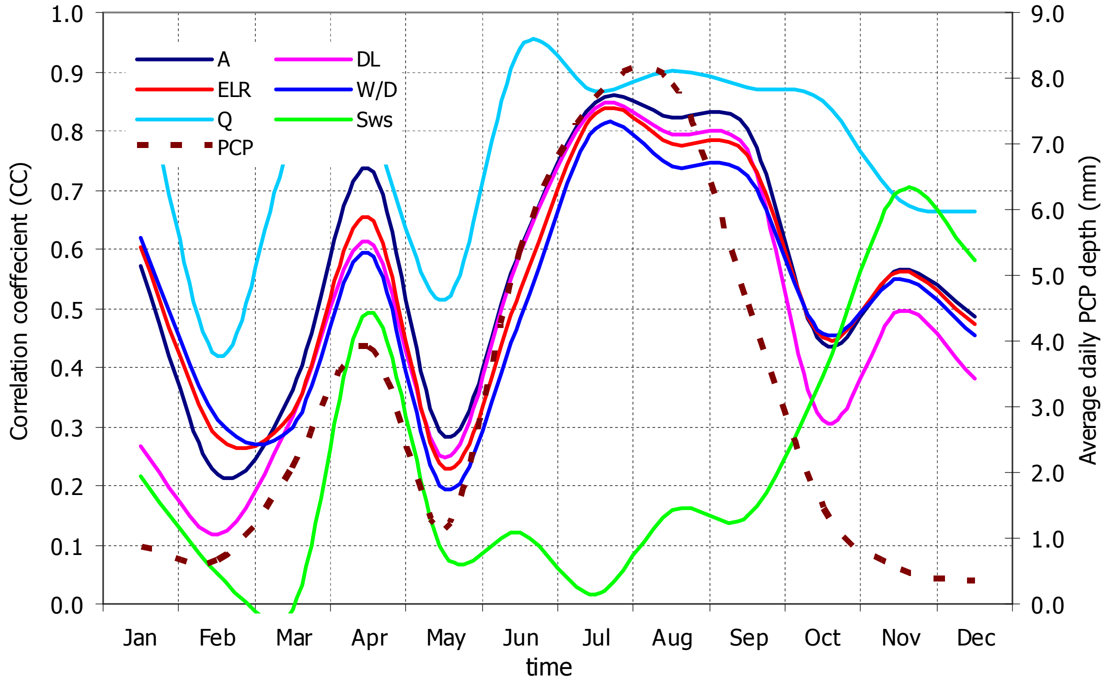
From SWAT's watershed configuration, 43 independent watersheds located upstream of Kunture gauging station (figure 5.6) in Upper Awash basin were selected. The levels of their dependency on the geomorphologic and hydrologic factors as well as the correlation of sediment yield in relation to the different watershed factors were analyzed. The correlations of the factors both in relation to each other and in relation to the sediment yield have been computed using Statplot software. The sample correlation matrix computed for each month of the year 2001 is indicated in table 6.1. Factors with a correlation coefficient (CC) of more than 0.70 are marked in bold. The correlation matrix clearly depicts the interdependence of the different parameters. It also clearly shows the degree of correlation between sediment yield to both stream flow and geomorphologic parameters.

The variation of the degree of association of sediment yield to the different watershed parameters has also been evaluated. The monthly precipitation of the different years occurring in the study area has been superimposed with the degree of association (correlation coefficient) between the major watershed parameters. The analysis result for the year 2001 has been shown on figure 6.1. Watershed area (A), watershed length (DL), elongation ratio (ELR), channel width to depth ratio (W/D), stream discharge (Q), average watershed slope (Sws) have been selected and plotted for the months of the year. The response of the watershed factors with respect to the seasonal variability of the rainfall over the study area has also been examined.

Table 6.1: Sample sediment correlation matrix with different parameters for month of August 2001

	A	DL	MAL	MIL	MEL	HDw	HI(m)	ELR	SHF	Sws	Sr	Wr	Dr	Wr/Dr	HDr	Q
A	1.00															
DL	**0.92**	1.00														
MAL	0.21	0.12	1.00													
MIL	-0.13	-0.22	0.38	1.00												
MEL	0.25	0.18	0.66	**0.73**	1.00											
HDw	0.26	0.20	**0.95**	0.09	0.48	1.00										
HI(m)	0.26	0.29	-0.15	0.24	0.53	-0.24	1.00									
ER	**0.98**	**0.89**	0.23	-0.11	0.26	0.28	0.24	1.00								
Sf	0.20	0.55	-0.12	-0.21	-0.03	-0.06	0.18	0.15	1.00							
Sws	0.23	0.07	0.38	0.43	0.56	0.27	0.28	0.24	-0.25	1.00						
Sr	-0.19	-0.30	0.37	0.30	0.29	0.30	-0.08	-0.17	-0.33	0.68	1.00					
Wr	**0.99**	**0.90**	0.23	-0.11	0.26	0.28	0.25	**0.99**	0.16	0.24	-0.17	1.00				
Dr	**0.97**	**0.89**	0.23	-0.10	0.25	0.29	0.24	**0.99**	0.14	0.24	-0.17	**0.99**	1.00			
Wr/Dr	**0.96**	**0.87**	0.24	-0.09	0.25	0.29	0.23	**0.99**	0.11	0.24	-0.16	**0.99**	**0.99**	1.00		
HDr	0.15	0.28	0.04	-0.04	0.05	0.06	0.03	0.18	0.33	0.15	-0.15	0.17	0.18	0.19	1.00	
Q	**0.90**	**0.83**	0.02	-0.28	0.09	0.11	0.27	**0.85**	0.21	0.20	-0.19	**0.86**	**0.84**	**0.81**	0.17	1.00
Syld	**0.82**	**0.79**	0.06	-0.35	0.06	0.17	0.15	**0.78**	0.23	0.16	-0.23	**0.79**	**0.77**	**0.74**	0.26	**0.90**

A=Watershed area(ha),**DL**=Drainage length(m),**MIL**=Minimum Elevation(m),**MEL**=Mean Elevation(m),**MAL**=Maximum Elevation(m),**HDw**=Max. elevation difference in the watershed, **HI**=Hypsometric Integral, **ER**=Elongation ratio, **S_f**=Shape factor, **Sws**=Watershed slope, **Sr**=River bed slope, **Wr**=Average river bank full width, **Dr**=Average river bank full depth, **Wr/Dr**=Width to Depth ratio, **HDr**=Max. elevation difference in the river(m), **Q**=Stream flow (m^3/s), **Syld**=Sediment yield(t/day).



A=Watershed area (ha), DL=Drainage length (m), ER=Elongation ratio, Sws=Watershed slope, W/D=Width to Depth ratio, Q=Stream flow (m^3/s), PCP=Average precipitation (mm)

Figure 6.1: Temporal pattern of parameters correlation coefficients

The correlation coefficient varies from season to season (figure 6.1). In general, a higher correlation has been observed in the months of April, July and August, while minimum correlation coefficients have been observed during the months of February, May and October. The slope parameters have shown an inverse correlation to the peak rainy season.

6.3 Discussion

The hydrological and geomorphologic parameters of watersheds have been selected for the analysis with a statistical method to determine the correlation of the parameters in relation to each other and in relation to the sediment yield. A strong correlation has been observed between several geomorphologic elements such as area, watershed length, elongation ratio and channel width to depth ratio. By considering one of the interdependent parameters, redundancy of information required for sediment modeling can be avoided. All other geomorphologic factors can also be included when considering watershed areas as it has demonstrated a higher correlation coefficient with regards to the remaining geomorphologic parameters.

The geomorphologic parameters: area, drainage length, channel width to depth ratio and elongation ratio show a significant correlation to sediment yield. As the watershed area has a positive correlation to channel width to depth ratio, watershed length and elongation ratio, it is reasonable to consider the watershed area as the main geomorphologic factor in determining the sediment yield governing parameter. Other similar results have also been recorded as catchment area is positively correlated with sediment yield (Tamene et al. 2006).

Figure 6.1 depicts the monthly correlation coefficient of watershed slope with respect to sediment yield. It is clear that the correlation between watershed slope and sediment yield is very weak during high monsoon seasons, but is significant during low rainfall periods (autumn and spring seasons). During the monsoon seasons, the ground is completely covered by vegetation inhibiting the erosion of surface soil. However, during autumn and late periods of spring seasons, the precipitation is not sufficient for complete plant growth: as a result of this the land surface is not covered by vegetation. This circumstance enhances the impact of slope factor on the amount of soil erosion. Additionally, during the late months of the autumn season, the rainfall depth is small but the correlation of slope is still significant. This could be due to the preceding months' rainfall effect and the sediment generated from the land surfaces can be transported in great concentration. The effect of the slope is significant during such seasons. Therefore, watershed slope can be taken as one of the fundamental parameters impacting on sediment yield as there are seasons when its correlation is strong enough to be significant. Likewise, the stream flow shows a significant correlation to sediment yield. This is due to the stream flow which is the cumulative effect of the surface runoff and the base flows are the main driving force for sediment transport from the upland and instream sections.

In general, the statistical analysis indicates that the geomorphologic factors of watershed area and slope, and the hydrologic factor of stream discharge play a fundamental role in sediment outflow. Therefore, these watershed parameters can be taken as some of the main variables which cause sediment yield at watershed scale.

7. ALTERNATIVE APPROACH FOR WATERSHED SEDIMENT YIELD ESTIMATION

7.1 Statistical approach

Empirically based models are the analytical result of statistical methods. The dependent variable to be computed is derived from certain data sets that establish the most suitable equation. Establishment of the best fit equation can be achieved through regression analysis. A regression is a statistical tool used to investigate a relationship between variables. Depending on the type of the relational functions of the variables, a regression model can be classified into the groups of linear regression model or nonlinear regression models.

7.1.1 Linear regression model

A linear regression model associates the relationship between two variables by fitting a linear equation to the observed data. In a linear regression, one or more variables are considered to be explaining the dependent variable. The explanatory variable has a straight line relation to the dependent variable.

7.1.2 Nonlinear regression model

Nonlinear regression is a form of regression analysis in which the dependent variables are associated to one or more independent (explanatory) variables in a nonlinear relationship. The regression is fitted to a nonlinear form of a mathematical equation. Nonlinear regression can be expressed in the form of logarithmic, exponential or power functions. Watershed sediment yield has been expressed nonlinearly to different parameters. The resulting regression equations have been the basis for establishing empirical models for watershed sediment modeling.

7.2 Empirical approach for sediment modeling

Sediment transport can be modeled on an upland watershed scale or in river networks. In both cases, the sediment generation and transport mechanisms are different. Hence sediment modeling can be classified into two different modeling approaches: the upland watershed sediment modeling approach and the instream sediment modeling approach. The upland watershed model predicts the sediment supply to the river, while the instream sediment transport model predicts the amount of sediment that can be transported within the river system.

7.2.1 Upland watershed models

The upland watershed factors such as average slope, land use and land cover, soil property and hydro-climatic factors are the basis for formulating empirical models which can be used to estimate sediment yield on a watershed scale. Empirical models are developed with the help of statistical techniques based on parameters observed in the field. Such models are easily applicable but often criticized for their spatial and temporal flexibility limitations. The models can only predict the erosion and sediment yield for the areas in which they were developed and for the specific time period considered for their formulation. For the specific situations of different parts of the world, different sediment yield quantification equations have been proposed.

Williams (1975) derived the modified universal soil loss equation (MUSLE), which can be used for sediment yield estimation in a catchment. By incorporating a runoff factor instead of the rainfall energy factor as a governing factor in the USLE (Wischmeier and Smith 1978), the erosion/sediment yield prediction capacity of the equation was improved (Williams 1975, Williams and Berndt 1977, Erskine et al. 2002, Sadeghi et al. 2007). The equation was developed from storm data pertaining to 18 basins in Texas and Nebraska. It was validated in 102 different basins using runoff data generated from the model "Simulation for Water Resource for Rural Basin" (SWRRB). The general form of the equation is expressed as:

$$Y = 11.8(Q \times q_p)^{0.56} \times K \times LS \times CP \qquad (7.1)$$

where

Y = Sediment yield from a catchment (t)

Q = Runoff volume (m^3)

q_p = Peak flow rate (m^3/s)

K = Soil erodibility factor

LS = Slope length and gradient factor

C = Crop factor

P = Practice factor

The MUSLE has been applied for sediment yield investigation in many parts of the world. Moreover, the equation has been used as a basis for the development of physically based models like SWAT2005 (Arnold et al. 1998). Because of the suitability of the different input data types, the equation has been integrated with Geographic Information Systems (ArcMUSLE) (Zhang et al. 2008b). The advantage of the MUSLE is its simplicity and its ability to incorporate the soil factor, topographic factor, practice and hydrologic factors though it's empirical nature remains its weak point. Nevertheless, this model has been popularly applied in many parts of the world for watershed sediment yield modeling.

Tamene et al. (2006) analyzed factors determining sediment yield variability in North Ethiopia. In their study, the attributes of different catchment characteristics for reservoir sedimentation in mountainous watersheds were analyzed. Eleven catchments were considered to have the desired geomorphologic factors and based on the extracted factors, sediment yield was estimated from the reservoir deposition data. The sediment deposition in the reservoirs was estimated based on data collected from pits and bathymetric surveys. The pit based surveys were conducted on dry reservoirs while the bathymetric surveys were conducted on full reservoirs. Pits were dug in the floor of the reservoirs to depth of the deposited sediment which was assumed as thickness of the deposition. The thickness of the deposited sediment was multiplied by the area of influence for each pit, which was computed by Theissen polygon method. The total volume of deposition was calculated by the sum of the volume of deposits associated to each pit. The bathymetric survey was used to calculate the capacities of each reservoir and then to compare this result with the original capacity of each reservoir before sedimentation had taken place. The difference between the reservoir capacities estimated from the bathymetric survey and the original capacity was taken to be the volume of sediment deposition for each reservoir.

The geomorphologic properties of the catchment for each reservoir were computed including the rainfall depth and different land use factors. Multivariate statistical techniques, Pearson's correlation and principal component analysis were applied to evaluate the interdependency of geomorphologic factors, rainfall depth and sediment yield. According to the study, sediment yield has a strong correlation to standardized bank collapse and gully erosion, catchment area, elevation difference and hypsometric integral. However, the annual sediment yield had a weak correlation with different land use and land cover factors. Multiple regression analysis was applied to relate an area specific annual sediment yield to the principal components obtained by principal component analysis (PCA) technique.

$$\text{LogSSY} = 0.007 \times \text{SBCBR} + 0.003 \times \text{EL} + 0.002 \times \text{RG} - 0.007 \times \text{BUSH} + 2.33 \qquad (7.2)$$

where

SSY = Area specific sediment yield ($t/km^2/yr$)

SBCR = Standardized bank collapse and gully erosion

EL = Proportion of erodible lithology (%)

RG = Surface ruggedness

BUSH = Proportion of Bush/Shrub cover(%)

As shown by the derived equation, the climate parameter was not explicitly included, although it is one of the major components of factors governing the watershed erosion and sediment delivery. Therefore, further investigation is crucial to include weather components such as the rainfall depth, rainfall intensity and surface runoff. In the discussion part of the investigation, Tamene et al. (2006) points out the need for further and detailed analysis with regard to obtaining good sediment prediction models. Detailed analysis for a larger number of sites is required to establish a robust prediction model for annual sediment yield (Tamene et al. 2006).

Grauso et al. (2008) tested the possibility of estimating suspended sediment yield using geomorphologic parameters in a regression analysis. The study was conducted on 20 watersheds located in Italy to test a regression equation developed by Ciccacci et al. (1987). The aim of developing the regression equation was to be able to relate annual suspended sediment yield (SSY) to geomorphologic factors as drainage density (Dd) and hierarchical anomaly index (Δa). Hierarchical anomaly index is the ratio of the minimum number of first order streams necessary for the drainage network to the number of first order channels actually occurring in the drainage network Dd is the total length of rivers divided by the total area of the drainage area. The Ciccacci et al. (1987) equation has the following form:

$$SSY = 10^{0.33Dd+0.10\,\Delta a+1.45} \qquad (7.3)$$

The regression equation was applied to non gauged catchments of the Tavo River and was found to underpredict the SSY by 10 % as compared to conceptual and empirical erosion models (Ciccacci et al. 1987). However, the result obtained from the equation was reasonably acceptable indicating the possibility of applying such empirical models to estimate the sediment yield on a watershed scale. This approach is potentially useful in order to obtain information about the sediment sources for watersheds in the absence of more detailed information that is required in order to apply a physically based approach (Grauso et al. 2008).

Restrepo et al. (2006) studied factors controlling sediment yield in the Magdalena River basin in South America. In his study, geomorphologic, hydrologic and climatic factors were related to the sediment yield of 32 watersheds in the Magdalena River basin. To explore the factors controlling sediment yield, Pearson's correlation coefficient was calculated for each of the different variables considered in the basin. The correlation matrix shows that sediment yield is strongly correlated to the annual maximum water discharge and mean annual runoff volume. However, the annual sediment load of the basin showed a weak correlation to geomorphologic factors. After analyzing the correlation between the parameters, statistical methods were applied to derive a linear multiple regression model for the different sections of the entire basin using maximum water discharge and mean annual runoff as variables. The coefficient of determination for the regression model ranges from 0.31 to 0.89 which implies that further improvements should be made by analyzing watershed parameters. Extended data sets on sediment yield and the inclusion of a more sophisticated analysis of land use are necessary to evaluate the model (Restrepo et al. 2006).

Liebault et al. (2002) analyzed the relationship between watershed variability and its characteristics influence on channel features and intensity of channel changes. The study was conducted on the Eygues River in Southern France. Morphometric and relief, lithology and surficial deposits and land use were the main watershed variables considered for this analysis. The multivariate statistical method was applied to achieve a clear idea of the correlation among the different variables as well as channel changes. The channel change was considered in terms of depth and width of flow. Mean channel degradation of 1.51 m was observed in three decades (Liebault et al. 2002). Drainage density and the percentage of agricultural land in the watershed were found to be the main variables explaining the channel narrowing due to sedimentation and widening. However, it was stated that further research is required on the connection between surface erosion and change in geometry of a channel. Further research is needed on the disconnection between geometry of channels and erosion processes on hill slopes, as it appears that these factors exert major control on the morphology and the evolution of active channels (Liebault et al. 2002).

Verstraeten and Poesen (2001) conducted research on factors controlling sediment yield from intensively cultivated catchments in a temperate and humid climate. The cause for variation of sediment yield in the 26 catchments of the study area was investigated. The parameters such as, catchment area (A), Hypsometric integral (HI), drainage length (DL) and horizontal distance between the outlet and most remote point of the catchment (D) were selected for the analysis of the correlation of parameters with respect to sediment yield. Based on the analysis result, multiple regression models as a function of A, HI, DL and D were developed to predict sediment yield. The empirical equations developed from the investigation are indicated below.

$$\ln \mathrm{SSY} = 3.72\,\mathrm{A} - 0.84\ln \mathrm{HI} + 0.11\ln \mathrm{DL} \qquad (7.4)$$

$$\mathrm{SY} = 0.21\mathrm{D} + 22.2\mathrm{HD} - 988\,\mathrm{HI} \qquad (7.5)$$

where

SSY = area specific sediment yield (t/ha/yr)

SY = total sediment yield (t/yr)

The two empirical models were validated by excluding one catchment at a time and recalculating the sediment yield for the remaining sample of catchments. During the validation, R^2 was calculated as 0.75 and 0.82 for SSY and SY, respectively. Nevertheless, it was mentioned in the conclusion part of the study that, the variation in sediment yield might be due to the slope steepness and land escape which were not incorporated into the model development. Beside this, it is worth mentioning that the absence of climatic and hydrologic parameters in the prediction model limits the scope of reliability on the model application.

7.2.2 Instream sediment transport

7.2.2.1 Instream sediment components

The eroded soils that are supplied to the rivers from upland catchments or river banks are transported in the form of suspended and/or bed load. The sediment from the upland watershed that is very fine in size is mainly transported as suspended load, whereas the sediment which is coarser in size is transported as bed load. This is clearly defined by Einstein (1964) as: "Every sediment particle which passes a particular section of the stream must satisfy the following two conditions: (1) It must have been eroded from somewhere in the watershed above the cross section. (2) It must have been transported by the flow, from the place of erosion to the river cross section. Both of these conditions may limit the sediment rate at the river cross section depending on the relative magnitude of the two control factors which are: the availability of the material in the watershed and transporting ability of the stream". In most streams the finer part of the sediment load which the flow can easily carry in large quantities is limited by its availability in the watershed. This part of the suspended load is designated as wash load. The coarser part of the load which is not so easily transported by flowing water is designated as bed material load and is limited in its rate by the transporting ability of the flow between the source and the section (figure 7.1).

The suspended load material transported by water is mainly clay, silt, and fine sand. Wash load is mainly very fine clay that is washed from upland catchments and transported in river networks. Depending on the hydraulic conditions, suspended particles may settle down and may be deposited on river beds and banks or floodplain areas. Bed material is transported along the river bed in form of rolling, sliding or saltation. In rivers, main part of sediments is transported as suspended material. The ratio of bed load to suspended load can range from 1:5 to 1:50 (Csermark and Rakoczi, 1987).

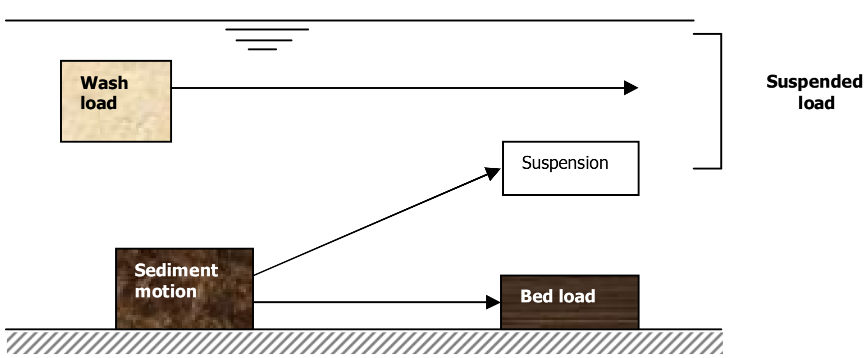


Figure 7.1: Forms of sediment transport in rivers

The concentration of sediment in rivers varies at different flow depths depending on the type of sediment load (figure 7.2). Generally, the concentration of sediment is at its highest near the river bed.

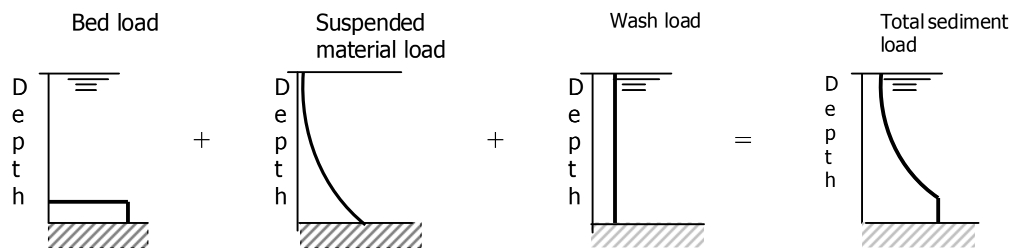


Figure 7.2: Schematic diagram of the vertical distribution of sediment concentration (Gordon and Brain 2004)

Several interrelated natural processes govern the transport of sediment in watershed and river systems. The geomorphology, hydrology and hydraulics of the river are amongst the major interrelated variables governing sediment transport processes. The sediment flow in a river is influenced by two major factors: firstly the quantity of the sediment supplied from the upland area and secondly, the transport capacity of the receiving river. If the supply of sediment from the upland area is greater than the transport capacity of the stream, aggradations (deposition) will take place. Conversely, if the sediment supply is less than the river transport capacity, degradation (erosion) takes place.

7.2.2.2 Sediment transport equations

Different sediment transport equations have been developed for different specific situation of river systems. Einstein's (1950) equation for sand bed rivers, Colby's (1964) equation for sand bed rivers with a depth of less than 10 ft, Yang's 1984 equation for the transportation of gravel with bed material in the range of 2 mm to 10 mm sediment transport equations can be mentioned [Chanson 1999]. Most existing sediment transport equations are formulated for sand beds, artificial channels and flumes. In addition to that, the channel flow conditions are assumed to be steady and uniform. The equations were derived based on certain assumptions and hypotheses. Mainly the stream discharge, stream velocity, channel slope and shear stresses are the major variables taken into consideration. Both bed load and suspended load have been estimated using different equations formulated by different investigators.

Bed load transport equations

Numerous bed load transport equations have been proposed based upon the data from laboratory experiments relating shear stress or tractive force, flow condition and composition of bed material. The bed load equations are expressed as a function of the shear stress and sediment properties. In reference to Chanson 1999, the commonly used bed load equations are described below.

Du Boys (1879) proposed a bed load transport model based on the assumption that the movement of sediment takes place as a sliding layer. His formulation was based on the bed shear stress and critical shear stress as main parameters derived from laboratory experiments with a uniform grain size composed of various kinds of sand and porcelain.

$$q_s = \lambda \tau_o (\tau_0 - (\tau)_c \qquad (7.6)$$

where

$$\lambda = \frac{0.54}{(\rho_s - \rho)g}$$

τ_o = River bed shear stress

τ_c = Critical shear stress for initiation of motion

ρ_s = Density of bed material particle

ρ = Density of the water

q_s = Bedload

Shields (1936) formulated an equation for estimating the volumetric sediment discharge per unit width (q_s) as a function of shear stress, τ_0 and critical shear stress, $(\tau_0)_c$.

$$\frac{q_s}{q} = 10 \frac{\sin\theta}{s} \frac{\tau - (\tau_o)_c}{\rho g(s-1)d_s} \qquad (7.7)$$

q_s = volumetric sediment transport

$$S = \frac{\rho_s - \rho}{\rho}$$

$1.06 < s < 4.20$ mm, s is the bed material specific gravity

$1.56 < ds < 2.47$ mm, d_s is the grain size diameter

Einstein (1942) developed a similar equation with a similar parameter to that of Shield's method. The d_s is approximated to d_{35} to d_{45}.

$$\frac{q_s}{\sqrt{(s-1)gd_s^3}} = 2.15 \exp(-0.391 \frac{\rho(s-1)gd_s}{\tau_o} \qquad (7.8)$$

if $$\frac{q_s}{\sqrt{(s-1)gd_s^3}} < 0.4$$

$1.25 < s < 4.25$

$0.315 < d_s < 28.6$ mm

Meyer-Peter (1949, 1951) developed a mechanism for estimating mass sediment flow rate (m_s) in terms of mass water flow rate (m) for uniform grain size and volumetric sediment discharge per unit width (q_s) for particle mixtures.

$$\frac{m^{2/3}}{d_s} - 9.57\,(\rho\rho g(-1)^{10/9} = 0.462\,(s-1)\frac{\rho g((m_s)^2)^{2/3}}{d_s}, 1.25 < s < 4.2 \tag{7.9}$$

$$\frac{q_s}{\sqrt{(s-1)gd^3}} = \left(\frac{4\tau_o}{\rho(s-1)gd_s} - 0.188\right)^{3/2}, d_s \approx d_{50} \tag{7.10}$$

Schoklitsch (1950) also developed a bed load estimation equation based on laboratory experiments and field measurements taken from the Danube and Aare rivers.

$$m_s = 2500\,(\sin\theta)^{3/2}(q - q_c) \tag{7.11}$$

where

$$q_c = 0.26\,(s-1)^{5/3} d_{40}^{3/2} (\sin\theta)^{-7/6} \tag{7.12}$$

Suspended sediment load

The sediment load in a river is kept in suspension because of the turbulence in the flow. Most sediment joining the stream from the upland area is transported as suspended sediment load. The concentration of the sediment distribution is higher on the bed of the river, while it is lower at the surface which is an inverse relation to the velocity distribution (figure 7.3).

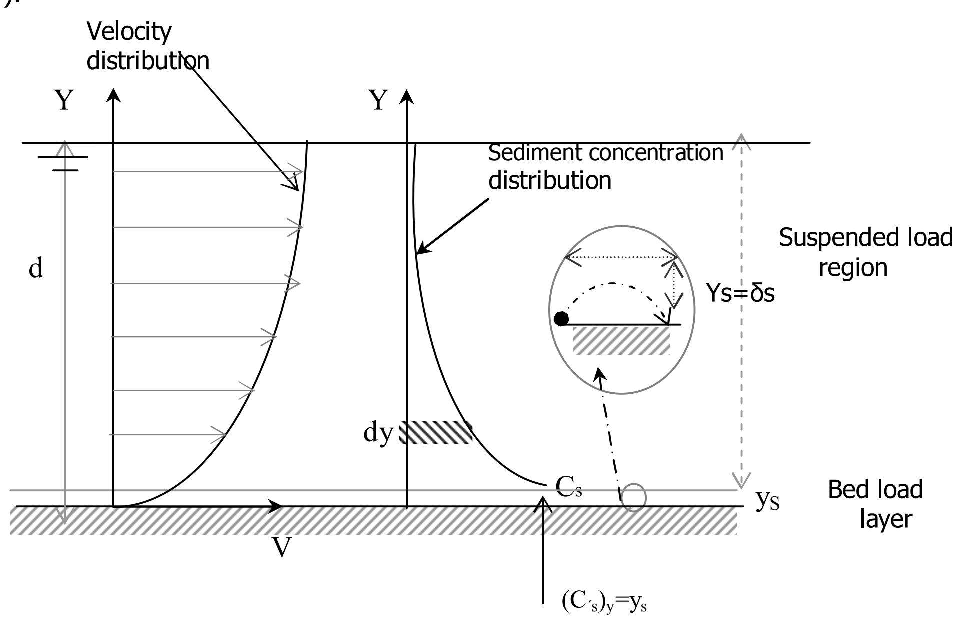


Figure 7.3: Sediment concentration pattern in streams (Chanson 1999)

The suspended sediment load is expressed as the concentration of sediment at a reference depth of the stream. Considering a unit width of river cross section for an elemental depth of flow dy as indicated in figure 7.3, the volumetric suspended load transport rate can be mathematically represented as follows:

$$q_s = \int_{\sigma_s}^{d} C_s V dy \qquad (7.13)$$

where

q_s = volumetric suspended sediment transport rate per unit width

C_s = sediment concentration to be estimated as

$$C_s = (C_s)_{Y=Y_S} \left(\frac{\frac{d}{y} - 1}{\frac{d}{Y_S} - 1} \right)^{W_o/(KV_*)}$$

$(C_s)_{y=y_s}$ = the sediment concentration at $y = y_s$

C_s = valid if $y > y_{s,}$ at $y = y_s$, it predicts an infinite bed concentration

d = the depth of flow

w_o = particle fall velocity

K = Karman constant (k = 0.4)

w_o/KV_* = Rouse number(Julien1995)

V = local velocity at a distance y

V_* = Shear velocity

Total sediment load

The total sediment load (q_s) instream is the sum of bed load ($(q_s)_b$) and suspended load($(q_s)_s$). The bed load component and the suspended load component can be estimated by any of the equations described in section 7.2.2.2 .Thus the equation for total sediment load can be expressed as;

$$q_s = (q_s)_b + (q_s)_s \qquad (7.14)$$

Hence, once the bed load and suspended load are computed separately by the respective equations, the total sediment load of a river can be expressed by using equation 7.14. The computed value of the sediment transport at any river cross section is the net resultant of the supplied sediment from the upland and instream erosion as well as deposition processes. The applicability of the existing sediment yield equations is limited to available data in the respective areas. In areas where data is limited, the estimation of sediment yield using existing equations has been a big challenge. Therefore, in this research an alternative sediment yield estimation mechanism has been formulated and is described in detail in the following sections.

7.3 Derivation of an alternative empirical model

7.3.1 Watershed sediment yield estimation equation

Multiple regression models are constructed when more than one independent predictor variable is used to describe a single dependent variable (Bazoffi et al. 1996, Neil and Mazari 1993, Flaxman 1972, Onstad 1984). This is also applicable for the description of sediment yield of a watershed. The selection of the multiple regression model type depends on the linearity and nonlinearity relation of the variables to the sediment yield. If at least one of the watershed variables has a nonlinear relationship to sediment yield, nonlinear multiple regression models are preferred. In most of the researches conducted so far, sediment yield has been expressed as nonlinear relation with both discharge and watershed area (William and Berndt 1977, Phillips 1991, Verstraeten and Poesen 2001 Tamene et al. 2006, Sharma et al. 2007). In this section of the research work, the results of the geomorphologic and hydrologic factors described under section 6.2 have been used to formulate a simplified and alternative model for estimating watershed sediment yield.

The SWAT2005 model was used to divide the entire Upper Awash basin into 166 subbasins or watersheds. 93 independent watersheds located at upstream of Kunture gauging station were extracted. Such watersheds have no sediment supply from the upstream part. The areas of the extracted watersheds range in size from 4.86 ha to 28,945.35 ha and have average slopes of between 0.4 % and 16 %. Based on the results of the watershed parameterization (section 6.2), the sediment governing parameters were extracted and calculated for each of the 93 independent watersheds. The watershed slope and the river slope were considered separately as it is assumed that sediment outflow is the result of contribution of the upland watershed parameters and the instream parameters. Similarly, the stream flow and the peak surface flow have been computed separately. The watershed area, watershed slope, river discharge and river slope are the result of the SWAT2005 model. The soil erodibility value is computed by the newly developed erodibility estimation equation (section 4.2) and the peak runoff rate is computed using the modified rational formula.

The time of concentration that is required for the peak runoff rate is computed from the formula of Kirpich (1940). The Kirpich's equation can be expressed as:

$$t_c = 0.019 . L^{0.77} \times S^{-0.385} \qquad (7.15)$$

where

t_c = time of concentration (min)

L = length of main river (m)

S = average channel slope (m / m)

From equation 5.5 and equation 7.15, the peak flow rate is computed for each watershed being considered. Based on the parameters of the independent watersheds the regression equation is established. The Datafit 9.0.59 statistical model (Oakdale Engineering, USA) is applied for the regression formulation.

Datafit model

Datafit is a science and engineering tool that simplifies the task of plotting data, regression and statistical analysis. The software has built in mathematical models which generate regression equations. Moreover, the user can define the type of regression equation to be used in the model. For this specific research, a nonlinear regression model (equation 7.16) is established for the sets of input parameters which are defined in the previous sections (section 6.3 and section 7.3.1.1).The established empirical model is described below.

$$\text{Syld} = aq_{pk}^{X} \times A \times S_1 \times K + Q^{b} \times S_2 \qquad (7.16)$$

where

Syld = watershed sediment yield(t/month)

q_{PK} = peak surface flow (m^3/s)

A = area of the watershed (ha)

S_1 = average slope of the watershed (m/m)

K = soil erodibility factor computed from ERFAC

Q = stream flow (m^3/s)

S_2 = average slope of the river (m/m)

a = 0.000121

b = 1.61 – 2.63

X = peak flow adjustment factor (0.75 – 1.00)

The equation is based on the assumption that the net sediment flux at the watershed outlet is the resultant sediment supply from the upland area and the local sediment production from banks and river bed. The watershed slope, area, peak surface runoff and soil erodibility are the major upland watershed factors considered for the formulation of the equation. The average river slope and the stream flow are the two factors for the instream sediment component of the equation.

The exponent b varies with the seasonal fluctuation of the river flow. A value of 1.61 is applicable for the driest period of the year, whereas a value of 2.63 can be applied during the rainy season. For the remaining times of the year, a value of 2.1 can be assumed. In the derived empirical model, the exponent X was introduced as the peak flow adjustment factor. The value of X ranges from 0.75 to 1.0 depending on the geomorphology of the watershed.

The watershed's river lengths as compared to the maximum watershed length together with slope and elongation ratio are the main geomorphologic factors which determine the value of the exponent X. The value of X can be expressed in terms of the ratio of the river length to watershed length and the ratio of river slope to watershed slope. The two variables, the slope ratio and the length ratio have been combined to provide a single variable. The expression used to estimate the value of the X is illustrated below.

$$X_c = 0.745 R^{-0.070} \tag{7.17}$$

Where

X_c = exponent term for the peak runoff component

R = product of the length ratio and slope ratio

$$R = \frac{L_R}{L_{WS}} \frac{S_R}{S_{WS}} \tag{7.17a}$$

L_R = length of the river

L_{WS} = length of the watershed

S_R = average slope of the river

S_{WS} = average slope of the watershed

Depending on variations in the watershed shape factor and the slope ratio, the value of X_c can be further adjusted. Shape factor (S_f) is described by the ratio of the squared value of the length of the watershed and the area of the watershed. X_c is adjusted in such a way that if the slope ratio is greater than 15 % and the shape factor is between 2 and 4, the value of X_c should be increased by 10 %, which means the actual X value will be 1.1 times the computed X_c value. If the slope ratio is less than 15 % and the S_f is less than 2, the X value will be reduced by 10 % which means that the actual X value will be 0.9 times the computed X_c value. This proposed relation shows that the higher the shape factor and the steeper the average slope of the watershed, the higher will be the amount of sediment yield. If the shape factor is higher, but the average slope steepness is lower, the less will be the amount of sediment yield. Mathematically, the adjusted X value can be expressed as:

$$X = 1.1 X_C \quad \text{if } 2 < S_f < 4 \text{ and } S_R > 15\ \% \tag{7.17b}$$

$$X = 0.9 X_c \quad \text{if } S_f < 2 \text{ and } S_R < 15\ \% \tag{7.17c}$$

Else $X = X_c$

After applying appropriate adjustments for the respective watersheds using equations 7.17 to 7.17c, the sediment yield has been computed and the sample computation result is shown below (figure 7.4).

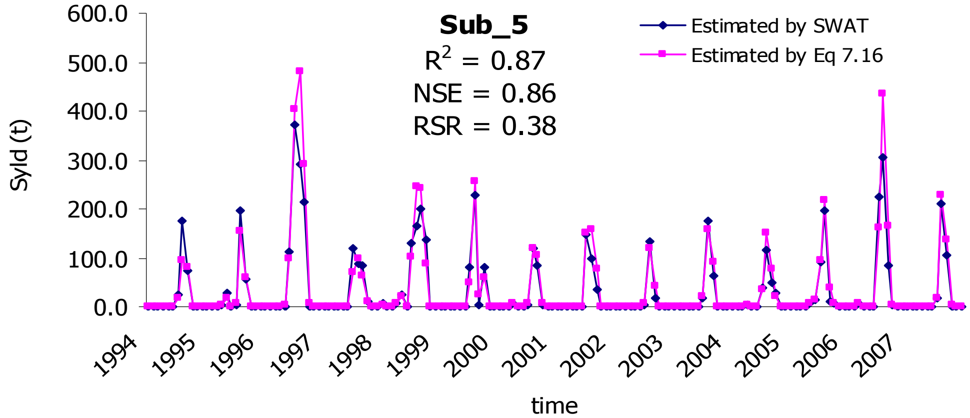


Figure 7.4a: Results from the alternative formula and SWAT2005 for watershed sub-5

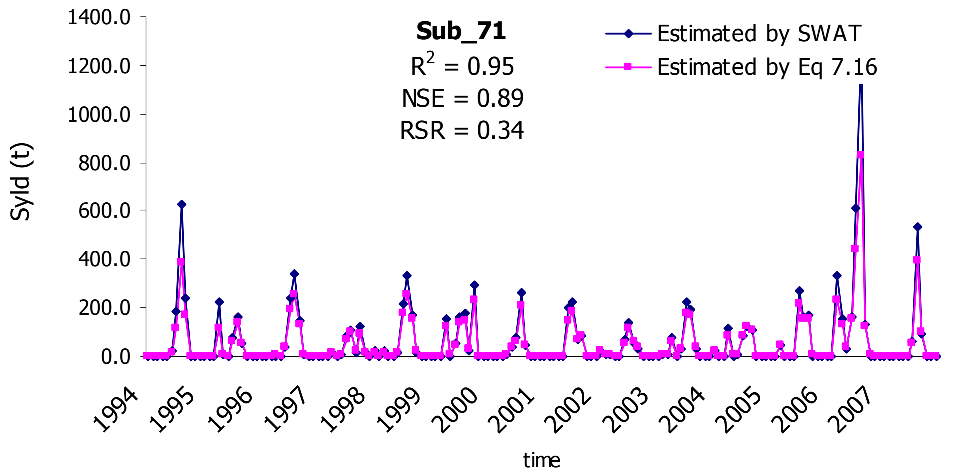


Figure 7.4b: Results from the alternative formula and SWAT2005 for watershed sub-71

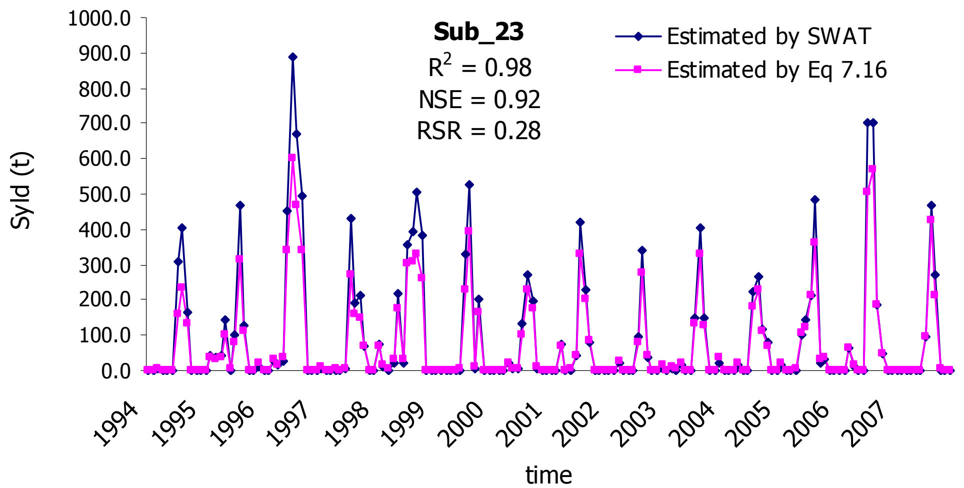


Figure 7.4c: Results from the alternative formula and SWAT2005 for watershed sub-23

Figure 7.4: Results of the derived empirical model compared with the SWAT2005 for sample watersheds selected from Upper Awash basin

7.3.2 Formulation of sediment routing equation

The sediment supply from the independent watersheds reaches the basin outlet through the river networks. After the sediment is supplied to the river network, some part may be deposited or transported depending on flow conditions. The sediment in a river is transported as long as the sediment load is kept in suspension by the flow velocity. As a result of this the transport capacity of a river is proportional to the stream flow velocity.

For the purpose of this investigation, it was assumed that the rate of change in flow velocity and change in channel bed width between two adjoining river sections determines the sediment transport capacity of the river sections. The higher the velocity of the supplying river section and the greater the width of the receiving river section, the higher is the resulting sediment transport capacity. This proportional representation is described as the ratio of velocity and the average bed-width of the channel (figure 7.5);

$$\text{sedout} \quad \alpha \quad \frac{v_1}{v_2}$$

$$\text{sedout} \quad \alpha \quad \frac{B_2}{B_1}$$

α means proporational to

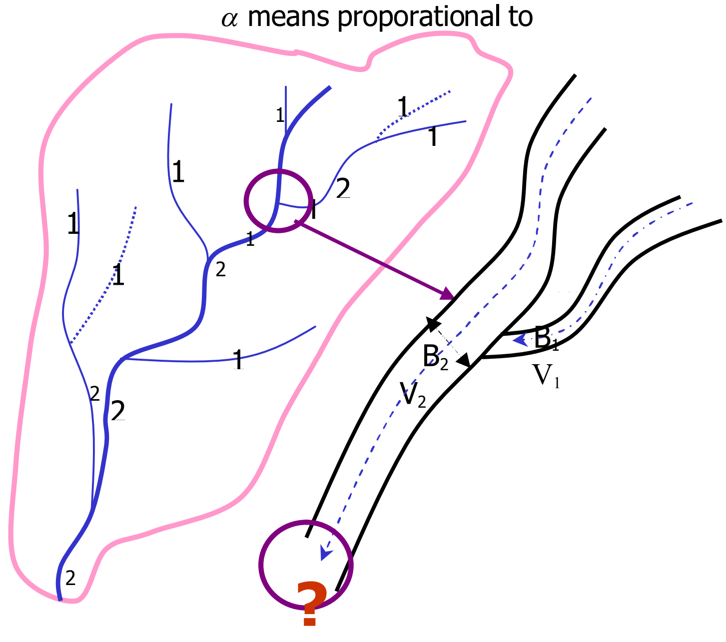


Figure 7.5: Conceptual river network system in a river basin

Based on the assumption of the proportional relationships, referenced above, the following equation is proposed:

$$sed_{out} = \left[\frac{V_1}{V_2} \times \frac{B_2}{B_1} \times Sed_{in} \right] + Sed_{ws} \qquad (7.18)$$

where

Sed_{out}	=	Net sediment outflow from the river reach under consideration (t/month)
Sed_{in}	=	Sediment supplied to the reach from the upstream reaches (t/month)
Sed_{ws}	=	Sediment supplied from the watershed under consideration (t/month)
B_2 & B_1	=	Average river width of the recieving and supplying river reaches (m)
V_2 & V_1	=	Flow velocity of recieving & supplying stream reaches respectively (m/s)

After the sediment yield from each watershed in the basin has been computed it was then routed to any point of interest in the river network by introducing the routing mechanism proposed in equation 7.18. The routing equation introduced as a function of the channel bed width and flow velocity ratio has been applied to the sediment outflow from networked rivers. The sample river sections receiving sediment load from the upland watersheds are shown in figure 7.6 below.

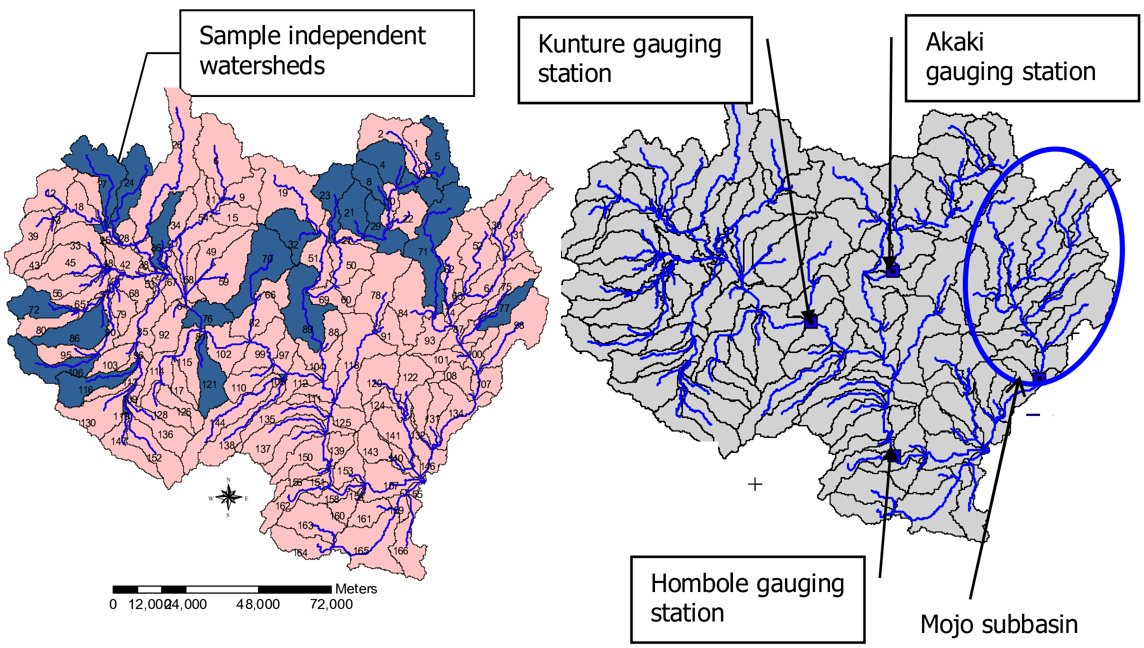
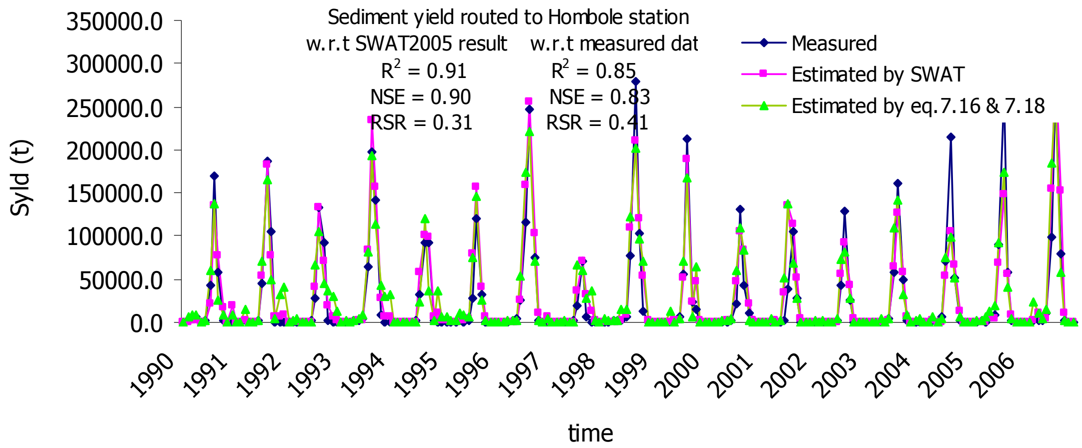
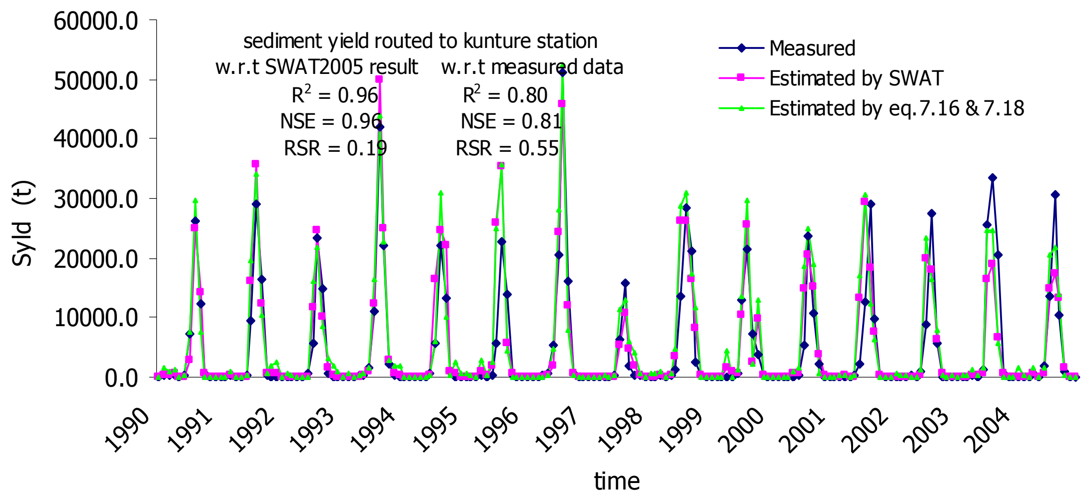


Figure 7.6: Selected sample watersheds for model validation

The suggested sediment routing equation (eq. 7.18) has been evaluated at three locations (Akaki, Hombole and Kunture gauging stations) in the basin, where flow and sediment measuring stations are present. The stations are those used for calibration and validation of the SWAT2005 model. The results of the analysis from the routing equation, SWAT2005 model and the measured values of the sediment outflow at gauging stations of the basin are shown in figure 7.7. Additional river sections used to evaluate the routing equation are described in annex D.



w.r.t= with respect to



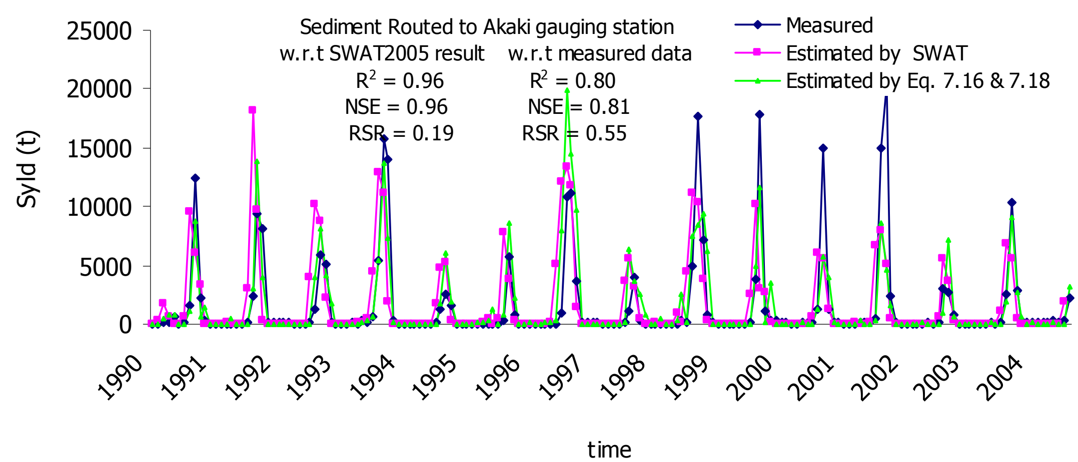


Figure 7.7: Results of the proposed routing equation compared with SWAT2005 result and the measured sediment load

7.4 Evaluation of the developed empirical model

The degree of acceptability of a certain model result depends on its performance under different scenarios and conditions. The performance of the developed empirical model has been evaluated for its applicability under different climatic conditions. As stated in section 3.1, Ethiopia has four main climatic zones one of which the humid zone has three sub divisions. The three main climatic zones are humid, subhumid, semiarid and arid. The humid climatic zone is then subdivided into three sub climatic zones namely: humid, moist subhumid and dry subhumid. The developed empirical model (equations 7.16 and 7.18) has been formulated based on data from Upper Awash basin watersheds located in the dry subhumid climate zone. The performance of the developed model has been evaluated for its applicability on watersheds located in different climatic zones.

7.4.1 Model performance evaluation for semiarid climate zone

The downstream section of the Upper Awash basin is located within the semiarid climate zone. The majority of the watersheds in Mojo subbasins (figure 7.6) are located in semiarid climatic zone. The watersheds in this zone were not incorporated in the model derivation. Such watersheds can be used as test watersheds to evaluate the model performance for the semiarid zones. Different watersheds were extracted from SWAT2005 model for areas within the semiarid zone (Mojo subbasin) (figure 7.6). Figure 7.7 shows the model performance for the sample watershed. The performance of the empirical model was evaluated based on the common statistical indicators: R^2, NSE and RSR. The corresponding statistical indicators are shown on the respective watersheds sediment outflow graphs (figure 7.8). The computed R^2 and the NSE are greater than 0.9 and the RSR ranges between 0.13 and 0.24.

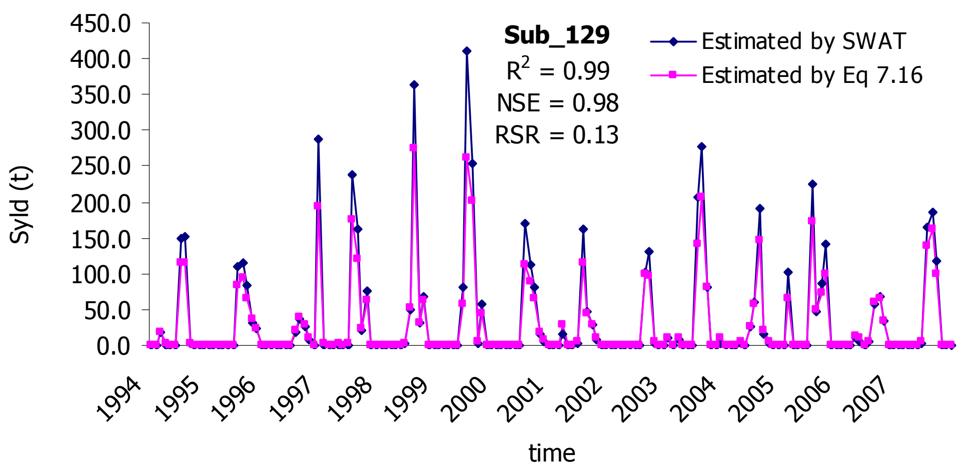


Figure 7.8a: Model performance evaluation for sample watershed sub-129

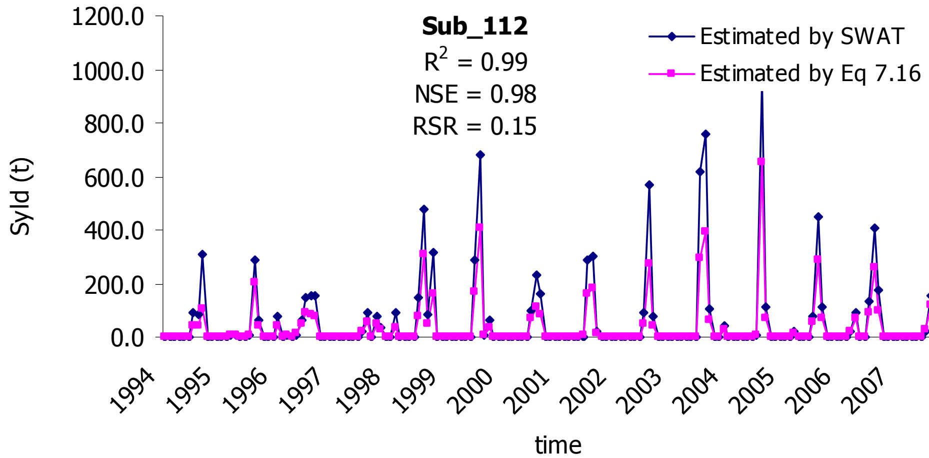


Figure 7.8b: Model performance evaluation for sample watershed sub-112

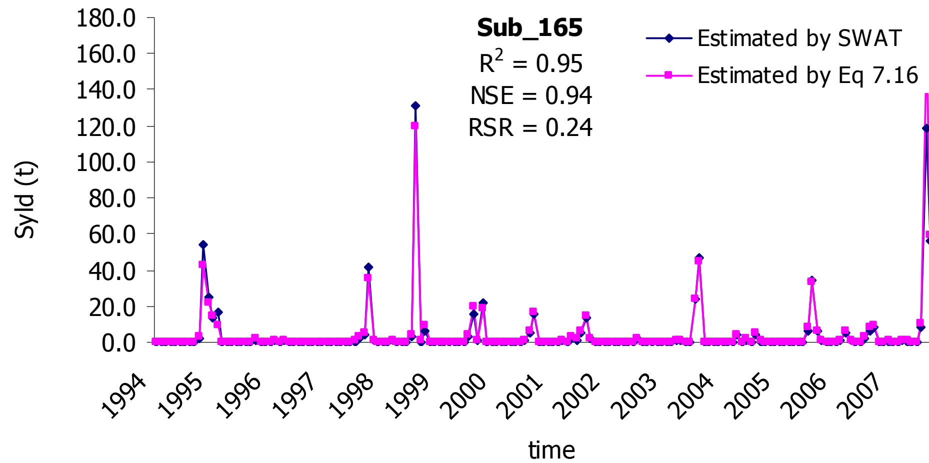


Figure 7.8c: Model performance evaluation for sample watershed sub-165

Figure 7.8: Model performance evaluation for sample watersheds in Mojo subbasin

7.4.2 Model performance evaluation for dry subhumid climatic zone

The Gudar subbasin in the Blue Nile basin (described in section 2.1.2) was used to evaluate the model performance in a dry subhumid climate zone. The upper part of the subbasin which covers 62,194 ha is gauged. The gauging station is located on Gudar River. The subbasin was divided in to 53 watersheds and the SWAT model has been calibrated with respect to the stream flow and sediment yield data recorded at Gudar gauging station. The watersheds have a drainage area of between 853.8 ha and 4940.4 ha and an average slope of between 4.15 % and 20.6 %. The developed empirical model has been used to compute the sediment outflow from each watershed into the subbasin. The results were compared with the output from SWAT2005. The computation result from the sample watersheds (subbasins) (figure 5.16) are shown in figure 7.9. The calculation results of more watersheds are summarized in annex B.

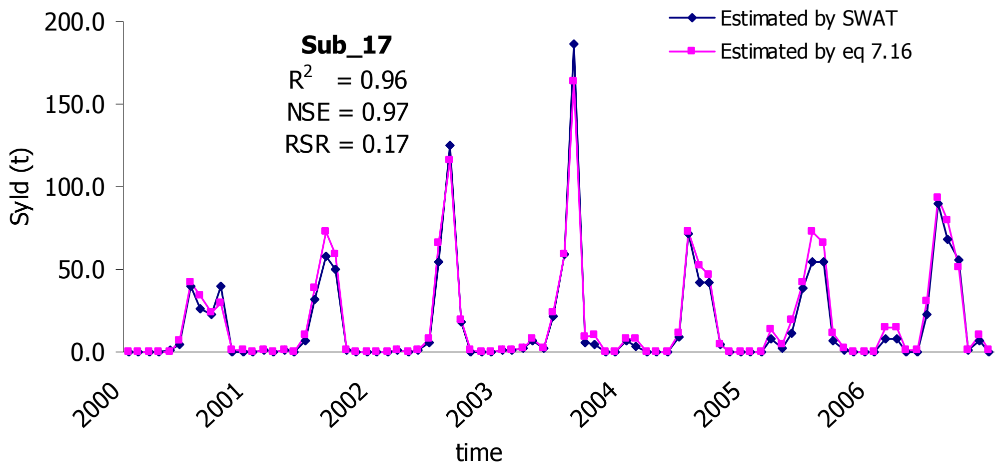


Figure 7.9a: Model performance evaluation for sample watershed sub-17

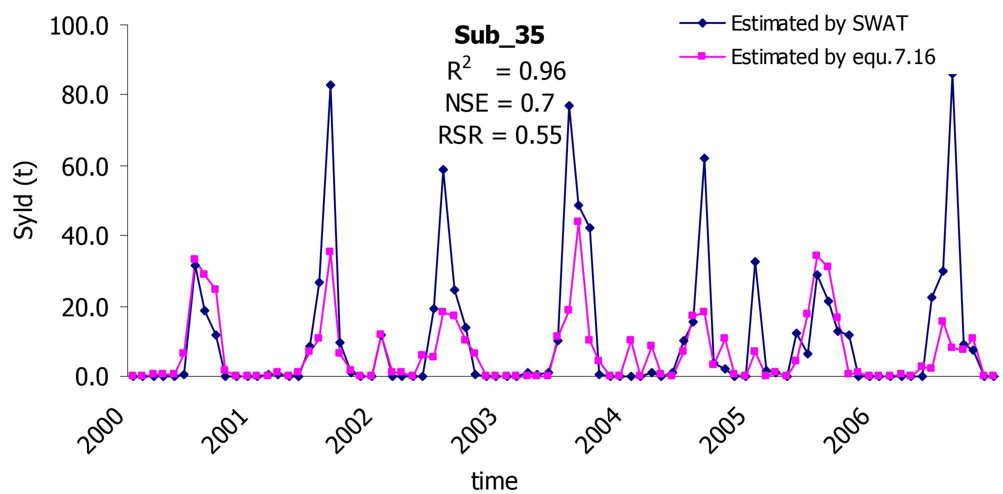


Figure 7.9b: Model performance evaluation for sample watershed sub-35

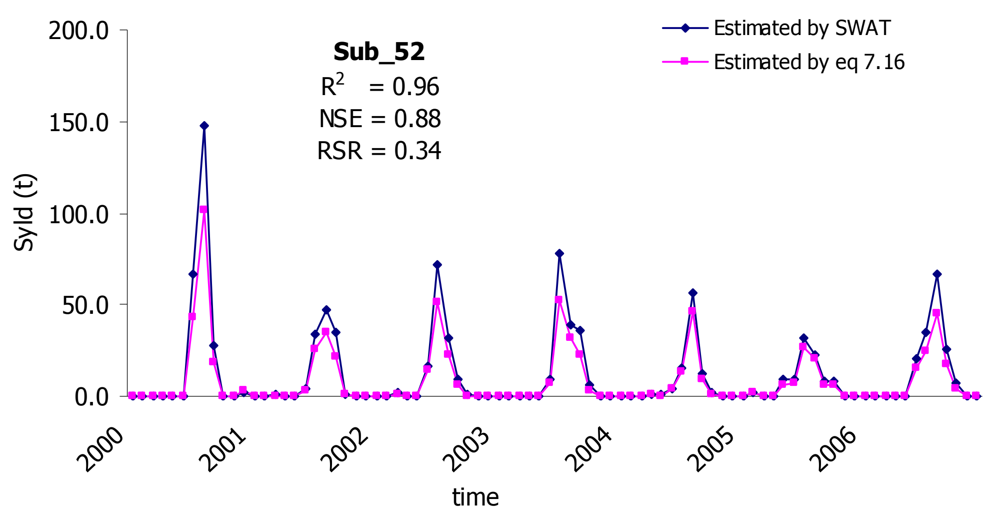
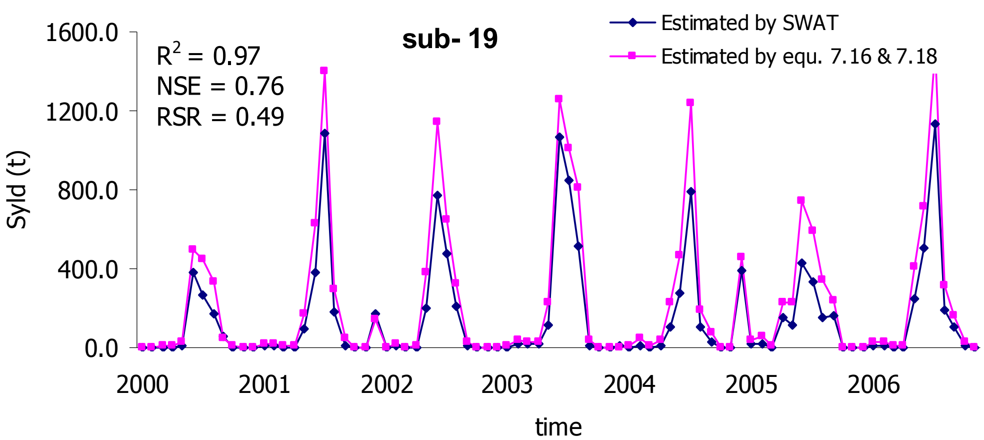


Figure 7.9c: Model performance evaluation for sample watershed sub-52

Figure 7.9: Model evaluation for sample watersheds in Gudar subbasin

For some of the watersheds (for example sub-35) the proposed equation under estimates the peak value as compared to the SWAT2005 model. The proposed alternative equation has the exponent X for the peak flow rate. The presence of the exponent term (X) makes the equation too sensitive for high peak flow rate and hence, careful attention should be paid in computing the value of X. The slope variability within the watershed under consideration is a crucial factor for the computation of X value. To avoid exaggerated errors in estimation of the average slope of the watershed the basin under consideration can be divided into many and small size watersheds. The division of the basin into many watersheds can increase the accuracy of estimating representative watershed slopes.

The sediment routing equation for the networked rivers in multi watersheds have been applied to Gudar subbasin. The computation result from selected river sections is shown in figure 7.10 and in annex F.



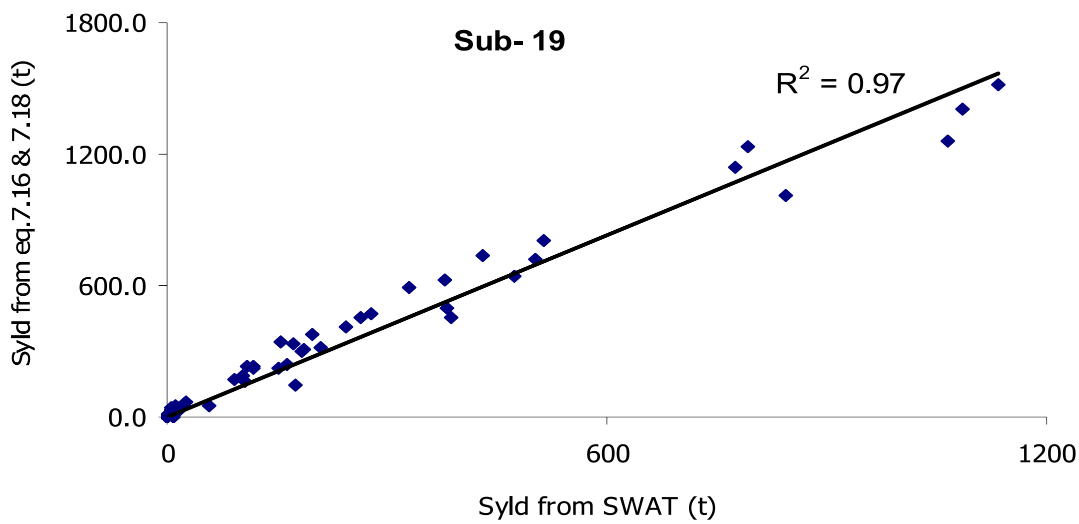
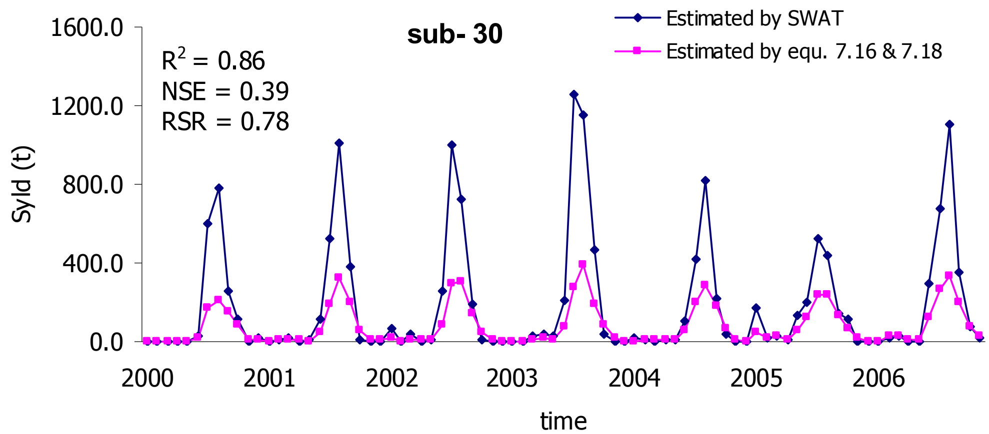


Figure 7.10a: Model performance evaluation in watershed sub-19



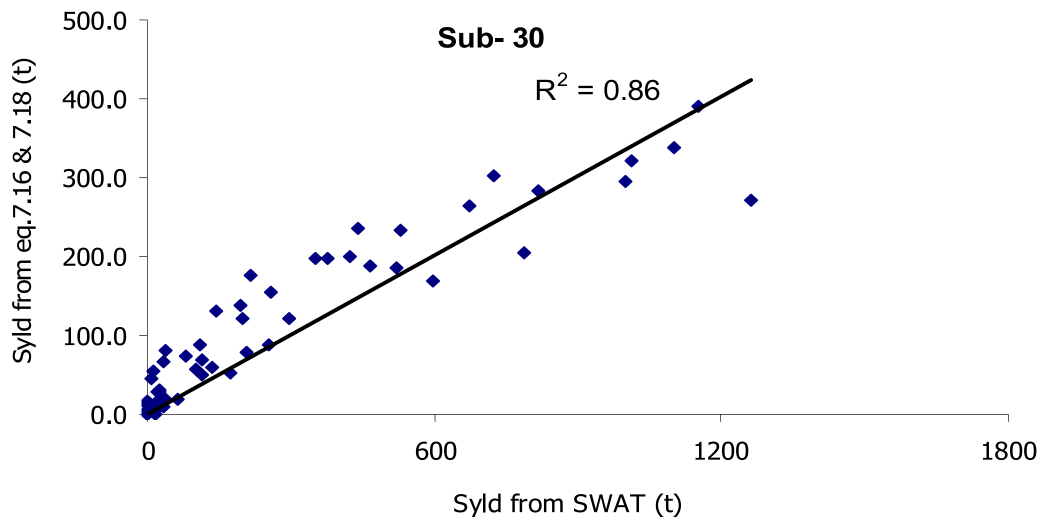
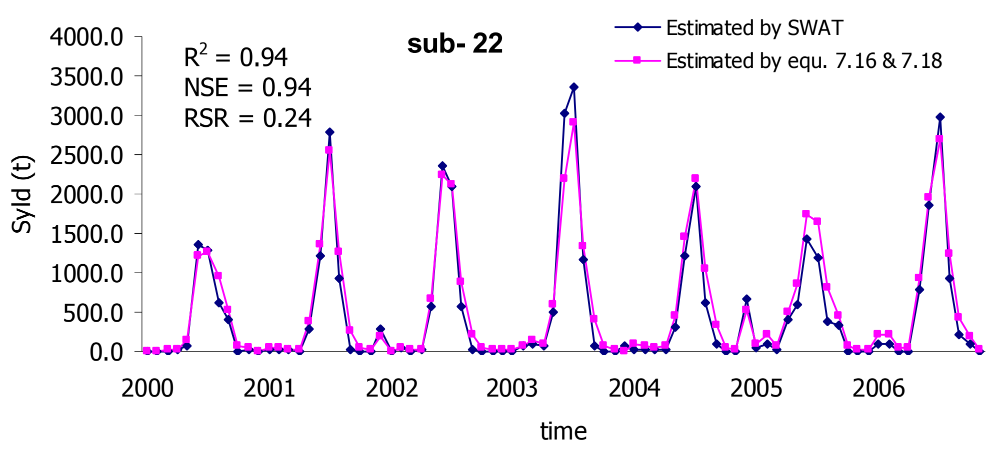


Figure 7.10b: Model performance evaluation in watershed sub-30



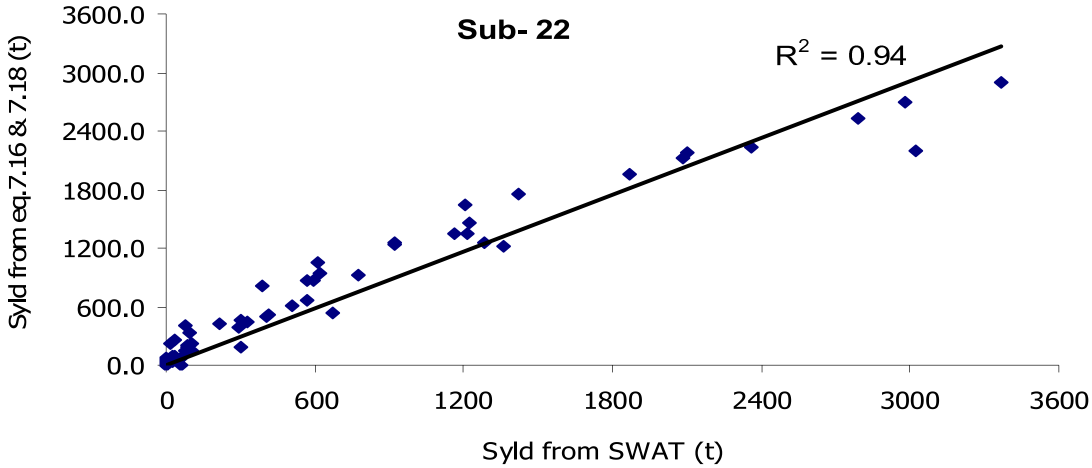


Figure 7.10c: Model performance evaluation in watershed sub-22

Figure 7.10: Evaluation of the sediment routing model for Gudar subasin.

The peak values of the sediment outflow from some of the networked watersheds (for example sub-30) are highly underestimated as compared to the SWAT2005 model result. The channel width and slope are fundamental factors to determine the prediction of the net sediment flux. The over estimation or underestimation of the slope and the channel width may result in poor prediction capability of the sediment routing equation. There might be two reasons for the poor prediction capability of the equation for some of the watersheds: the insufficient channel width to accommodate all the supplied sediment supply to the receiving river section or the less flow velocity of the supplying river section to keep all the sediments in suspension. In both cases, deposition occurs in the river mouth and as a result less sediment will be supplied to the downstream section. In contrary, if flow velocity of the supplying river section is at the stage of scouring velocity and the receiving river section has the sufficient width to accommodate the supplied sediment without deposition, the net sediment outflow from the reach under consideration is higher than the actual sediment yield observed in the river. From the applicability aspect of the formulated routing equation (equation 7.17), careful attention should be given in estimating the channel dimension and computation of the flow velocity. Reasonable and more reliable channel width can be obtained if finer resolution DEM data can be used for interpolation of the river width at different reaches or on field measured channel dimensions are available.

7.4.3 Model performance evaluation for moist subhumid climate zone

The Fincha subbasin (described in section 2.1.2) was selected to evaluate the performance of the developed empirical model in a moist subhumid climate zone. The SWAT2005 model has been calibrated with respect to the available data of flow and sediment yield in the Neshi

River. The Neshi River has a total drainage area of 29,918 ha which has been divided into 89 sub watersheds each of which has an area ranging between 199.84 and 1543.5 ha. The watersheds have an average slope of between 11.3 % and 27.8%. The derived empirical model was used to compute the sediment yield from each of the independent watersheds. The results of the empirical model have been compared to the SWAT2005 model output. The comparison of the results for the selected watersheds (subbasin) (figure 5.20) is shown in figure 7.11 and in annex C.

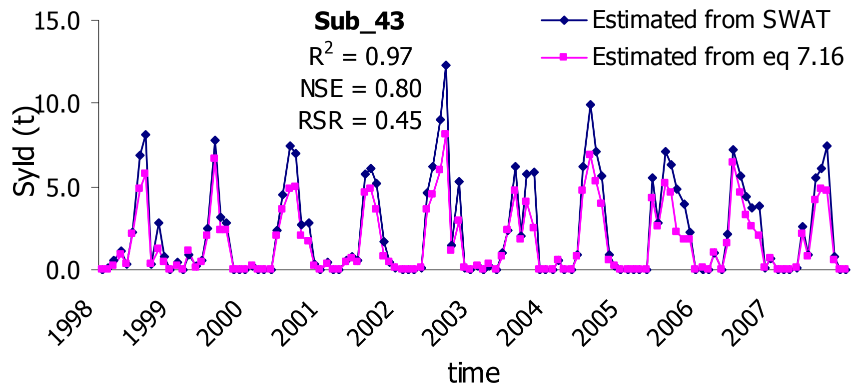


Figure 7.11a: Model performance evaluation for sample watershed sub-43

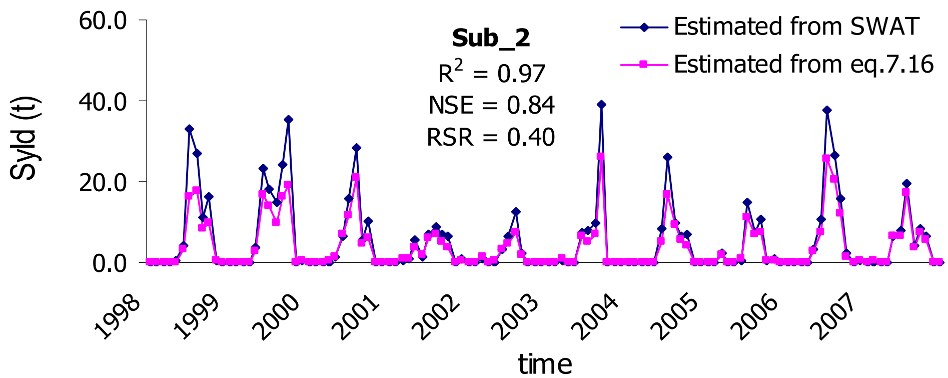


Figure 7.11b: Model performance evaluation for sample watershed sub-2

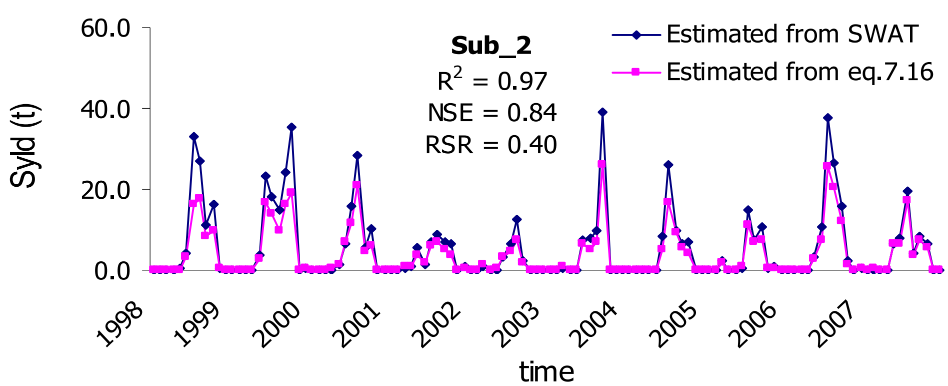


Figure 7.11c: model performance evaluation for sample watershed sub-1

Figure 7.11: Model evaluation for sample watersheds in Fincha subbasin

The proposed sediment routing equation within river networks has been evaluated on watersheds in the Fincha subbasin. The parameters required for the routing coefficients were extracted from SWAT2005 model after calibration. The velocity and channel width ratios of the receiving and supplying channels were calculated. Based on the suggested routing equation (equation 7.18), the sediment outflow from networked rivers (figure 5.20) has been calculated. The sample computation result is indicated in figure 7.12 below and in annex E.

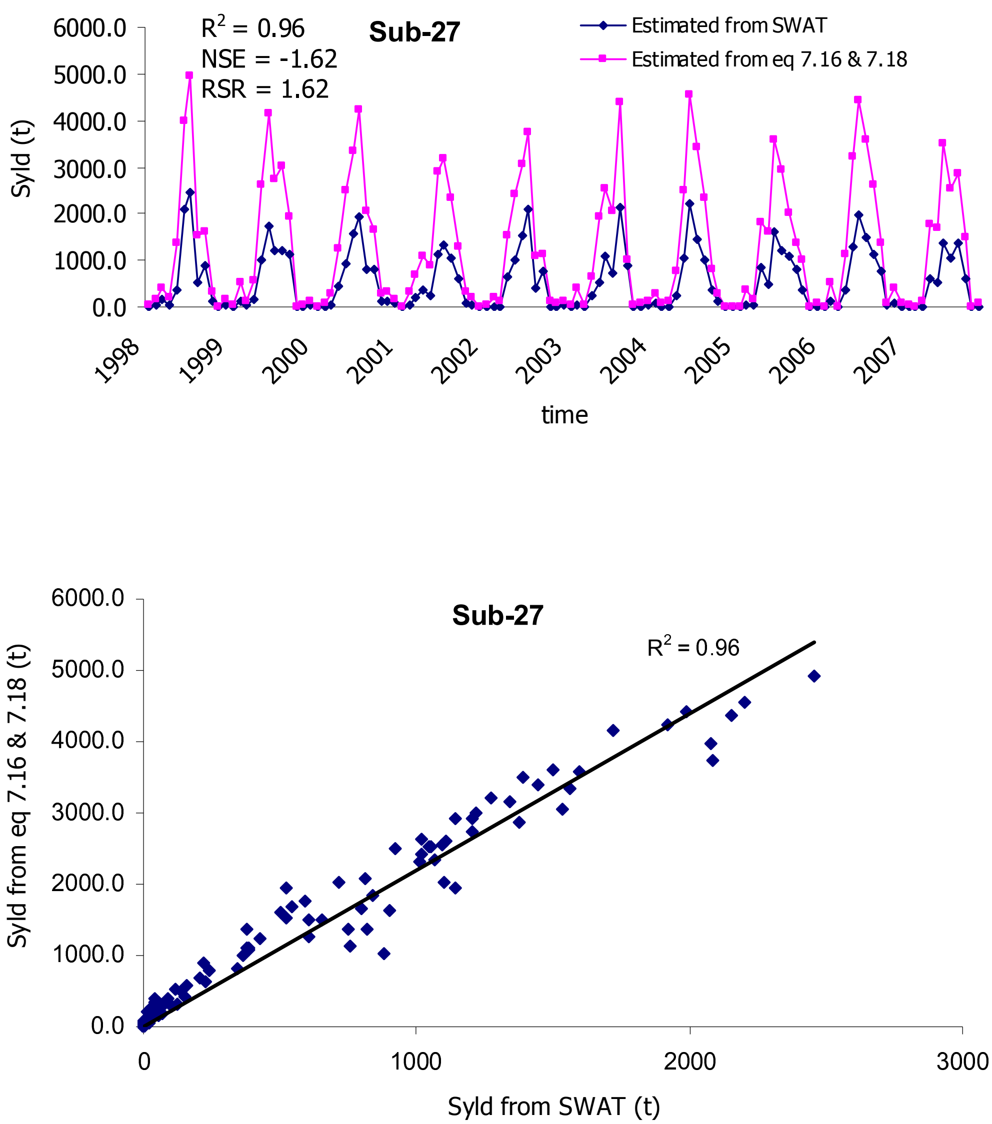
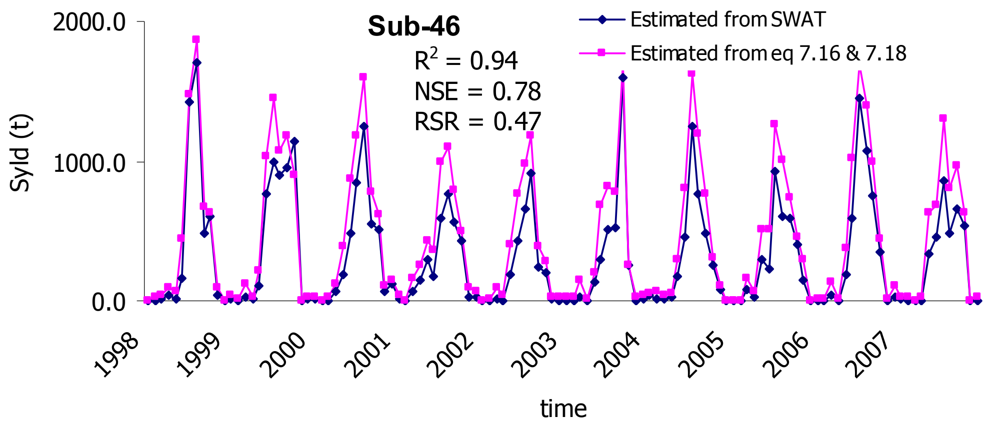


Figure 7.12a: Model performance evaluation in watershed sub-27



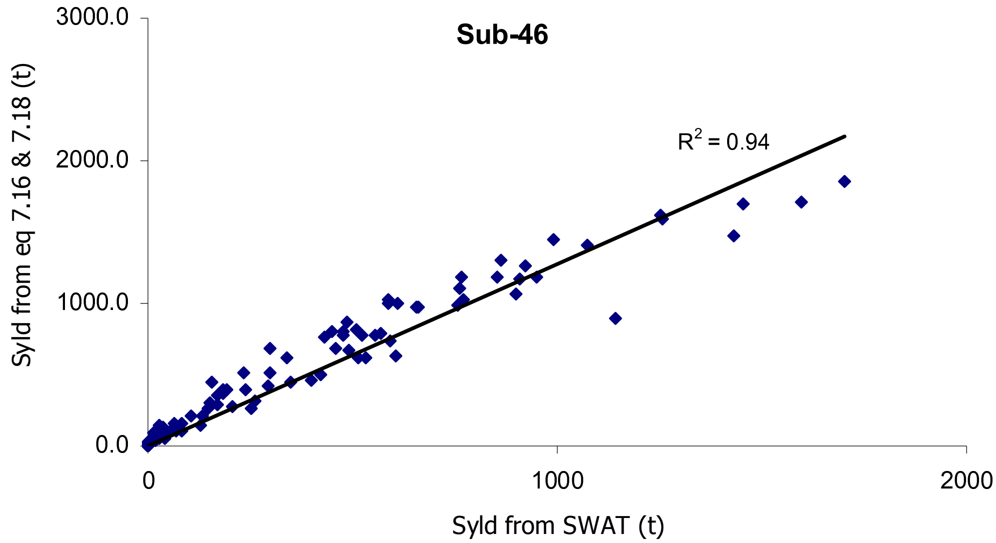
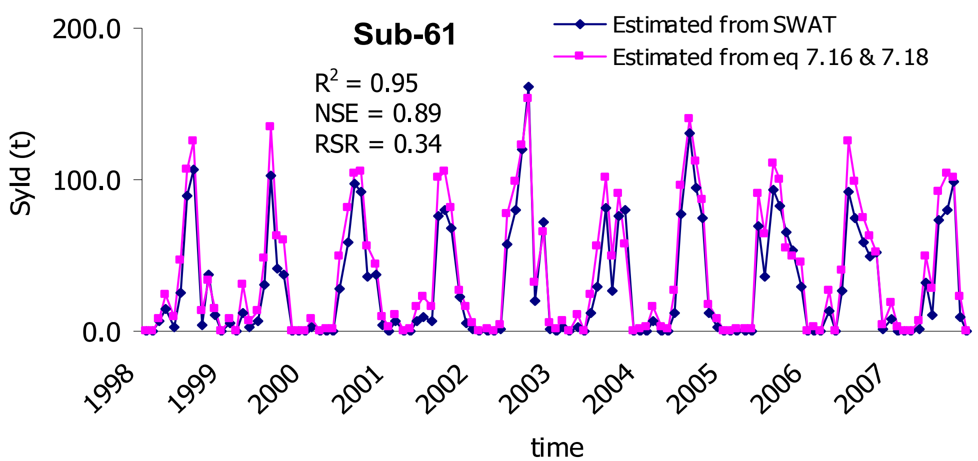


Figure 7.12b: Model performance evaluation in watershed sub-46



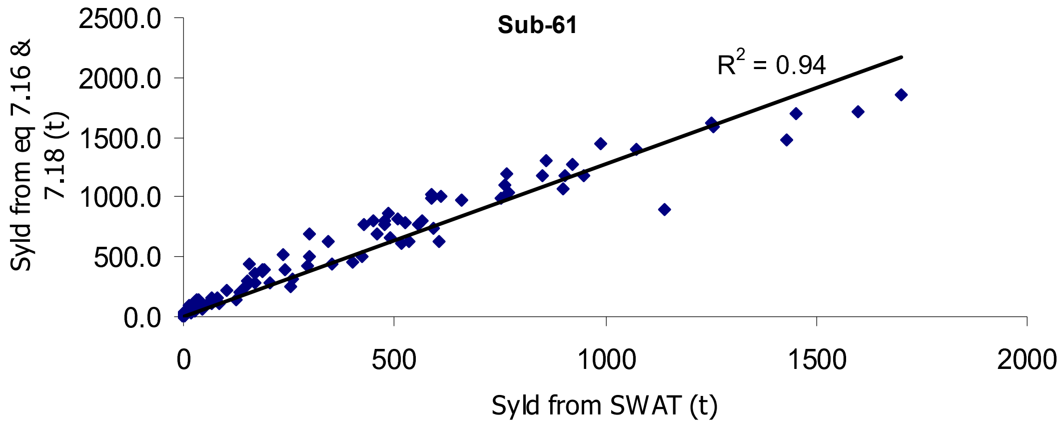


Figure 7.12c: Model performance evaluation in watershed sub-61

Figure 7.11: Sediment routing model performance evaluations for Fincha subbasin

Similar to the Gudar subbasin case, in watersheds of the Fincha subbasin, overestimation or under estimation of the routing equation has been observed for most of the sample watersheds (figure 7.12 and annex E). The underestimation or overestimation of the equation is most likely due to the same reasons described under section 7.4.2. Moreover, the river in this subbasin is meandering river course with alluvial banks. The alluvial river banks are easily susceptible to change in morphology and as a result the width of the river changes abruptly. Such abrupt change of river width consequences in change of flow velocity in short reaches of the river. The abrupt change in river width and velocity is more likely to result in the high or low routing factor introduced into equation 7.18. As a result the net sediment outflow from the river networks may be under estimated or over estimated.

7.5 Discussion

To formulate an alternative watershed sediment yield estimation equation, the geomorphologic, hydrologic and hydraulic parameters identified in section 6.2 have been applied as sediment governing parameters. For the development of the model, it has been assumed that the sediment supply at the outlet of a watershed originates from the upland watershed area and the instream section of the river sections. The upland sediment supply component has been formulated based on peak surface runoff, watershed area, watershed slope and the soil erodibility factor, while the instream sediment transport component has been taken as a function of stream flow and the average river slope. The soil erodibility factor has been computed from the newly proposed soil erodibility estimation method in section 4.2.

The geomorphologic parameters are the major factors observed to vary from one watershed to another. The variability in the geomorphology of the watershed and its hydrological characteristics are the main reasons for the variability of sediment yield. Taking into account the variability of the different watershed geomorphologic factors, the X factor has been introduced into the derived empirical model (equation 7.17), as exponent for the peak runoff. The X factor ranges from 0.75 to 1.0 depending on the relative proportion of the river length to watershed length and the proportion of river slope to the watershed slope. The mathematical expression described in equation 7.17 provides the approximate value of X, which needs to be adjusted according to the watershed shape factor. Further adjustment for the computed X value were carried out based on the shape factor and the ratio of the average river slope to watershed slope (section 7.2.3).

The adjustment of factor X is a key parameter for the flexibility of the derived alternative equation for sediment yield estimation and thus the applicability of the equation is not limited to the selected study area (Upper Awash basin) unlike most empirical equations. This has been proved on the model applicability evaluation in Gudar and Fincha subasins which are located in different river basins and different climatic zones. Moreover, a physical interpretation for the sediment yield dependency on the geomorphology of a watershed can be given. Watersheds that are elongated and have a steep slope are more likely to produce more peak runoff from the upland surfaces. In such cases the X value becomes high and the net sediment flux in the river shall be proportionally high. Inversely, if the watershed is long and the slope is flat, there is less probability of occurrence of peak surface flow. As a result, the sediment generation from the upland and its delivery to river networks shall be proportionally low. In such cases the X value becomes less than unity and the sediment yield value will be low. The boundary condition for the X value to be greater than or less than unity is described in section 7.3.2.

The derived alternative sediment estimation equation has been tested for its applicability to various watersheds located in different climatic zones. The performance of the developed empirical model has been evaluated based on the statistical indicators (R^2, NSE, and RSR) for different watersheds of the Fincha and Gudar subbasins. The computed R^2 and NSE have been found to be greater than 0.9 and 0.8 respectively. Moreover, the RSR has been estimated to be less than 0.45. According to the analysis result, the equation can depict as accurate a sediment yield as the physically based SWAT2005 model does. In applying the SWAT2005 model for sediment yield estimation at different watersheds, there should be a measured sediment yield data available for the model calibration and validation which limits the model applicability for areas with no sediment data. The newly proposed equation for sediment yield estimation can solve such limitation. Once the hydrology component of the

SWAT2005 model is calibrated successfully, the sediment yield can be reasonably estimated by the proposed equation.

The newly proposed equation for sediment yield estimation has another advantage beside its flexibility to any watershed geomorphologic and hydrologic parameter. The existing empirical models developed by the past researchers are mostly on yearly time step which doesn't give information for the monthly or daily time step. In this research, it has been attempted to derive an alternative equation which can predict sediment yield in monthly time steps and successful result have been achieved.

In the derived alternative equation, the practice and cover factor are not included which makes the equation easier to apply to any areas with no sufficient data on land use and cover pattern. Actually the peak runoff which is the main driving force for sediment yield depends on the cover and practice factor. For example, watershed with dense vegetation or erosion mitigation measures like terraces, bunds and contoured trenches reduce the occurrence of peak surface flow. As a result, less soil will be eroded and less sediment load will be supplied to rivers. In contrary, if the watershed is covered by bare land or sparse vegetation and more erodible soils, the sediment generation from the watershed and its delivery to river network is proportionally high. The incorporation of peak runoff as one of the sediment yield governing factors indirectly includes the land cover and land use related parameters of a watershed.

The sediment outflow from a multiple watershed (networked watersheds) is transported in river networks where it may be deposited or fully transported, depending on the flow condition and channel characteristics. The sediment routing factors, which have been assumed to be dependent on the change in flow velocity and channel bed width of the supplying and receiving rivers, have been used to estimate the net sediment outflow. The routing equation was proposed on the assumption that, the sediment transport capacity of rivers is mainly governed by the change in flow velocity and the geometry of the channel cross section. The performance of the proposed routing equation has been evaluated for its applicability to different river reaches in Fincha and Gudar subbasins and satisfactory results have been observed. The reasonable prediction capability of the routing equation confirms that change in flow velocity and bed width between any two sections of a river play a major role in sediment transport capacity. If there is high sediment load from the upstream part of the river and the receiving river section is not capable to transport the sediment supply, deposition will happen and the river flow regime may change. The change in flow regime of the river may result in inundation and flooding of flood plains and adjacent areas which can lead to loss of life and property. If sediment supply from the upper reaches is known, the amount of the sediment to be transported out of the receiving river section can be fixed by proportioning the channel dimension and the flow velocity.

During the evaluation of the applicability of the proposed routing equation, overestimation and underestimation has been observed for some of the watersheds (figure 7.10 and figure 7.12). The overestimation or the underestimation of the routing factor results in an erroneous sediment outflow from the entire river network. The slight overestimation and underestimation of the routing factor for the test river section considered in figure 7.10 (subbasin 30) and figure 7.12 (subbasin 27) could result from the coarse DEM (90mx90m) resolution. In this research the river cross section is taken from the SWAT2005 model configuration. In application of the SWAT2005 model, DEM (90mx90m) has been used. This DEM resolution may not be sufficiently accurate to interpolate river cross sections especially for small tributaries and narrow river sections. During the analysis it has been observed that the width of the river changes abruptly (10 to 20 times) in few hundred meters of the considered river stretch which is not true in real situation. It is at such sections that exaggerated overestimation or underestimation has been observed. To overcome such problem more finer DEM resolution is recommended to be used for the interpolation of river sections. In the absence of a finer resolution of DEM data, it is advisable to study different reaches of the river at the upstream and downstream section to get better information on the channel width pattern. With such information on the pattern of the river width, necessary adjustments can be.

As a general remark, the proposed alternative sediment yield estimation equation (equation 7.16) can be successfully applied to predict sediment outflow on a watershed scale. Similarly, it can be said that satisfactory results have been obtained from the proposed sediment routing equation (equation 7.18). In the absence of sufficient data for calibration and validation of the physically based models, the proposed alternative sediment prediction equations (equations 7.16 & 7.18) can be applied, as it has been proved on various watersheds of Ethiopia River basins located in different climatic zones.

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8. CONCLUSION AND RECOMMENDATIONS

8.1 Conclusion and summary of the research findings

- The proposed alternative erodibility estimation equation (ERFAC) can predict the erodibility factor as accurately as the equation of Williams et al. (1984). ERFAC has a simplified form and uses easily measurable physical soil properties such as percentages of sand, silt and clay.
- To calibrate the SWAT2005 model, the identification of sensitive parameters helps to reduce the number of model parameters. For the Upper Awash basin, the sensitive parameters have been identified. These are CN_2, ALPHA_BF, SOL_AWC, ESCO and SOL_Z for runoff and stream flow. Similarly, CN_2, SURLAG, ALPHA_BF and SPCON were the major parameters that govern the sediment yield. The sensitive parameters identified in Upper Awash basin have been applied for the SWAT model calibration in Fincha and Gudar subbasins and successful results have been obtained. Thus, the described parameters can be used for the model calibration and validation for basins in tropics and temperate zones, where the runoff and stream flow of the area is mainly determined by rainfall.
- For the specific case of the Upper Awash basin, the spatial patterns of soil loss rate and sediment yield have been modeled by the SWAT2005 model. Steep topography and agricultural areas result in a high rate of soil loss. Conversely, flat areas and vegetated areas show low to medium soil loss rates. Quantitatively, areas of the basin with a non tolerable soil loss rate account for about 56 %, while a tolerable rate of soil loss accounts for 44 %. Therefore, there is high and rapid depletion of the top soil from the areas of the basin. It is due to such soil loss rate from the upland areas and sediment supply to the river networks that the Koka dam located at the outlet of the Upper Awash basin has been experiencing serious sedimentation problems. The reservoir has lost 40 % of its storage capacity in its 30 years service time.
- The high rate of soil loss from agriculture land is a probable reason for the transportation of agricultural chemicals into the reservoirs and as a result the deterioration of the water quality has taken place in the Koka reservoir. The deterioration of the water quality resulted in the formation of toxic substances in the reservoir, causing a significant loss of life to both humans and cattle (Al Jazera report, February 21, 2009). Therefore, the spatial distribution of the soil loss rate obtained from this investigation is helpful in prioritizing areas that need immediate mitigation measures to reduce soil erosion. Moreover, preliminary information on the probable agricultural chemical loading can be obtained from the soil loss rate and the

spatial sediment yield distribution map, which can be used for further detailed analysis of non point source pollutant modeling using the same SWAT2005 model.

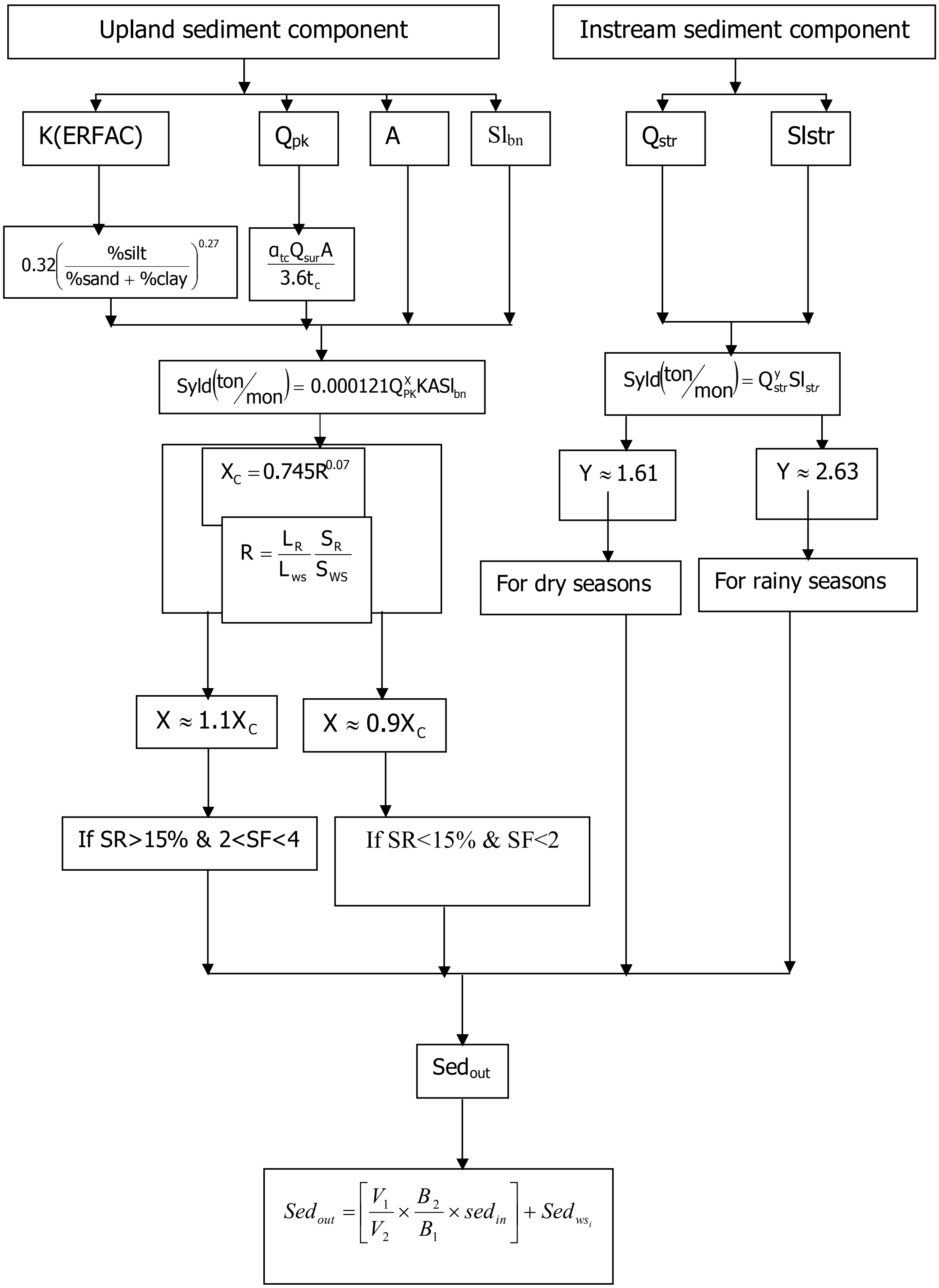
- The spatial pattern of the soil loss rate which results in higher sediment yield has been computed for Gudar and Fincha subbasins. In both subbasins, the rate of soil depletion is higher than in the Awash basin. More than 90% of the subbasins` areas have been within the non tolerable soil loss range.
- The geomorphologic and hydrologic parameters of a watershed are the fundamental factors governing its sediment delivery. Average watershed area and average slope as geomorphologic factors and stream flow and peak surface flow as hydrologic factors have been identified as the major parameters governing sediment yield in the Upper Awash basin. The identified parameters have been applied to sediment yield modeling for various watersheds in different basins and in different climatic zones and a successful result has been obtained. Hence, the described watershed parameters can be taken as main watershed factors governing sediment yield on a watershed scale.
- The alternative empirical sediment yield estimation model has been developed based on the independent watersheds in the Upper Awash basin. The applicability of the empirical model has been tested on watersheds within different hydro climatic zones. The evaluation of the model at Fincha and Gudar subbasins demonstrated successful model applicability. Therefore, the derived alternative sediment yield estimation model can be used to estimate sediment yield from watersheds of different geomorphologic characteristics. In areas without measured sediment data, the proposed alternative empirical sediment model can be applied for determining the sediment component in order to calibrate and validate physically based model like SWAT2005. The X factor, introduced into the alternative equation as power term of the peak flow plays a big role in the flexibility of the equation making it applicable to different watersheds with different geomorphologic characteristics.
- The alternative equation (ERFAC), which was proposed for the estimation of the soil erodibility factor, has been introduced into the alternative watershed sediment estimation equation (equation 7.16). The erodibility value used in the SWAT2005 model was based on the computational result of the equation of Williams et al. (1984). The comparison of the sediment outflow from a watershed derived from the proposed alternative sediment equation with the SWAT2005 model has demonstrated a good model performance. The sediment yield modeling by SWAT2005 and the alternative sediment yield estimation equation use different approaches of the soil erodibility factor. Nevertheless, the results from both models show good agreement.

This is additional evidence for the good soil erodibility prediction capability of the ERFAC equation, because in the alternative sediment yield estimation empirical model, the soil erodibility was computed from ERFAC while in SWAT2005 model, the soil erodibility factor was computed from the equation of Williams et al. (1984).

- The sediment outflow from a nested watershed or the sediment load at different reaches of a river section has been estimated from the proposed sediment routing equation. The sediment routing equation (equation 7.18) was formulated based on the change in velocity and the change in channel bed width of the supplying and receiving river sections. The sediment yield from each watershed reaches the river network. Therefore, its transport within the river network can be successfully determined by the proposed routing equation.

As overall summary and conclusion, the target of developing an alternative sediment modeling option for data scarce areas under the suggested hypothesis was successfully achieved. Moreover, the hypothesis of the investigation has been proved at different stages of the research work mainly during the formulation of the ERFAC equation, the analysis of basin sediment yield, computation of the soil loss rate using SWAT2005 model and the derivation of an alternative sediment yield estimation model. The summarizing flow chart of the research result is shown on the following figure.

Summary flow chart of the developed alternative sediment model



The proposed alternative approaches for erodibility estimation and sediment yield prediction empirical models has not been validated for measured data for different scenarios like watershed with different land use, geomorphologic characteristics and soil characteristics variation .The proposed alternatives models were evaluated with respect to simulated results from existing models. Therefore, following recommendations are put forward as continuation of the future prospect of this research result.

8.2 Recommendations for the research perspective

With the achievement of the formulated research objectives, there is still further recommendation for future direction of the research

- The available FAO (1998) soil data was the basis for the derivation and evaluation of the alternative soil erodibility estimation method. Though the ERFAC equation can predict the soil erodibility factor as the equation of Williams et al. (1984), verification of the model performance from actually on ground erosion data is necessary. In this specific research the ERFAC equation has not been verified with respect to on ground measured soil erodibility value. Hence, a standard plot needs to be established at field scale on different soil types. On each plot sufficient erosion related parameters (RUSLE factors) are required to be gathered to compute the erodibility factor from a primary data.
- The alternative sediment yield estimation model has been developed to replace the difficulty of sediment calibration for the physically based model SWAT2005 model in situations of limited data availability. The proposed equation Verification of the model performance from primary sediment data for different watershed characteristics will remain one of the research perspectives. After the model verification for different conditions of watershed characteristics, the developed empirical model can be linked into SWAT2005 model to model sediment yield without any measured data that is need for model calibration.

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Annexes

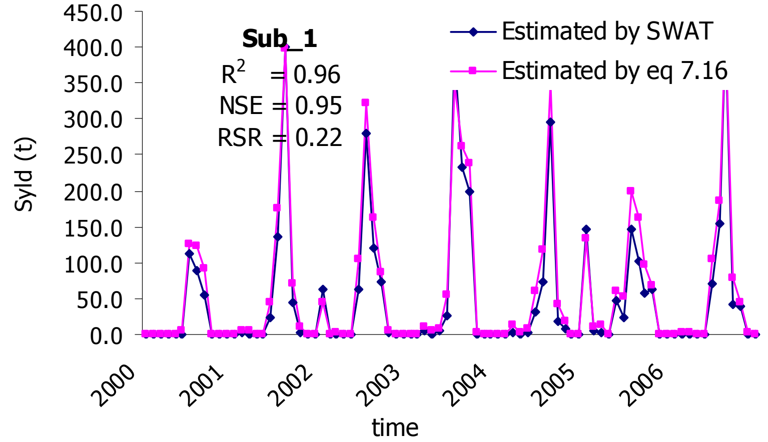
Annex A: FAO soil category classified in to different groups based on the accuracy of the ERFAC estimation methods

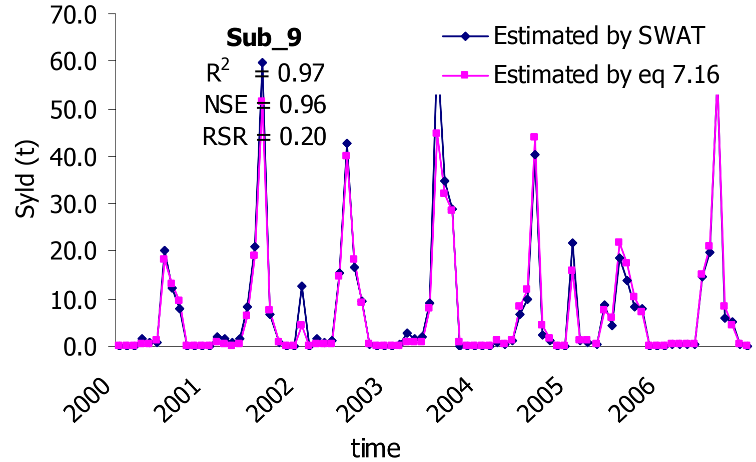
Group1	
Soil code	**FAO Soil**
Pg	Gleyic Podsols
Ph	Humic Podsols
Pl	Leptic Podsols
Po	Orthic Podsols
Pp	Placic Podsols
Qa	Albic Arenosols
Qc	Cambic Arenosols
Qf	Ferralic Arenosols
Ql	Luvic Arenosols
Rc	Calcaric Regosols
Rd	Dystric Regosols
Re	Eutric Regosols
RK	Rock Debris
Rx	Gelic Regosols
S	SOLONETZ
ST	Salt Flats
t	Takyric Solonchaks
Th	Humic Andosols
Tm	Mollic Andosols
To	Ochric Andosols
Tv	Vitric Andosols
U	RANKERS
V	VERTISOLS
Vc	Chromic Vertisols
Vp	Pellic Vertisols
W	PLANOSOLS
Wd	Dystric Planosols
We	Eutric Planosols
Wh	Humic Planosols
Wm	Mollic Planosols
WR	Water Bodies
Ws	Solodic Planosols
X	XEROSOLS
Xh	Haplic Xerosols
Xk	Calcic Xerosols
Xl	Luvic Xerosols
Xy	Gypsic Xerosols
Y	YERMOSOLS
Yh	Haplic Yermosols
Yk	Calcic Yermosols
Yl	Luvic Yermosols
Yt	Takyric Yermosols
Yy	Gypsic Yermosols
Zg	SOLONCHAKS
Zg	Gleyic Solonchaks

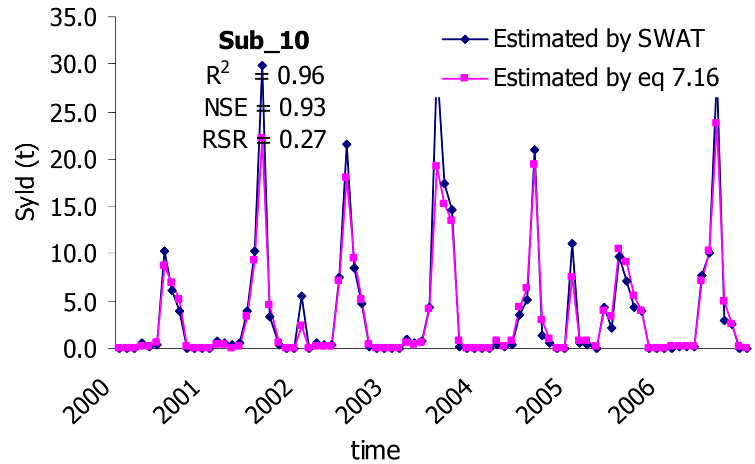
Group 2		Group 2		Group 2	
Soil code	**FAO Soil**	**Soil code**	**FAO Soil**	**Soil code**	**FAO Soil**
Cl	Luvic Chernozems	Mg	Gleyic Greyzems	Xl	Luvic Xerosols
Dd	Dystric Podzoluvisols	Mo	Orthic Greyzems	Xy	Gypsic Xerosols
De	Eutric Podzoluvisols	Nd	Distric Nitosols	Y	YERMOSOLS
Dg	Gleyic Podzoluvisols	ND	No data	Yh	Haplic Yermosols
DS	Dunes / Shifting Sand	Ne	Eutric Nitosols	Yk	Calcic Yermosols
E	RENDZINAS	Nh	Humic Nitosols	Yl	Luvic Yermosols
Fa	Acric Ferrlsols	O	HISTOSOLS	Yt	Takyric Yermosols
Fh	Humic Ferralsols	o	Orthic Solonchaks	Yy	Gypsic Yermosols
Fo	Orthic Ferralsols	o	Orthic Solonetz	Zg	SOLONCHAKS
Fp	Plinthic Ferralsols	Od	Dystric Histosols	Zg	Gleyic Solonchaks
Fr	Rhodic Ferralsols	Oe	Eutric Histosols		
Fx	Xanthic Ferralsols	Ox	Gelic Histosols		
G	GLEYSOLS	Pg	Gleyic Podzols		
g	Gleyic Solonetz	Ph	Humic Podzols		
Gc	Calcaric Gleysols	Pl	Leptic Podzols		
Gd	Dystric Gleysols	Po	Orthic Podzols		
Ge	Eutric Gleysols	Pp	Placic Podzols		
Gh	Humic Gleysols	Qa	Albic Arenosols		
GL	Glaciers	Qc	Cambic Arenosols		
Gm	Mollic Gleysols	Qf	Ferralic Arenosols		
Gp	Plinthic Gleysols	Ql	Luvic Arenosols		
Gx	Gelic Gleysols	Rc	Calcaric Regosols		
Hc	Calcaric Phaeozems	Rd	Dystric Regosols		
Hg	Gleyic Phaeozems	Re	Eutric Regosols		
Hh	Haplic Phaeozems	RK	Rock Debris		
Hl	Luvic Phaeozems	Rx	Gelic Regosols		
I	LITHOSOLS	S	SOLONETZ		
J	LUVISOLS	ST	Salt Flats		
Jc	Calcaric Fluvisols	t	Takyric Solonchaks		
Jd	Dystric Fluvisols	Th	Humic Andosols		
Je	Eutric Fluvisols	Tm	Mollic Andosols		
Jt	Thionic Fluvisols	To	Ochric Andosols		
K	KASTAZNOZEMS	Tv	Vitric Andosols		
Kh	Haplic Kastanozems	U	RANKERS		
Kk	Calcic Kastanozems	V	VERTISOLS		
Kl	Luvic Kastanozems	Vc	Chromic Vertisols		
L	LUVISOLS	Vp	Pellic Vertisols		
La	Albic Luvisols	W	PLANOSOLS		
Lc	Chromic Luvisols	Wd	Dystric Planosols		
Lf	Ferric Luvisols	We	Eutric Planosols		
Lg	Gleyic Luvisols	Wh	Humic Planosols		
Lk	Calcic Luvisols	Wm	Mollic Planosols		
Lo	Orthic Luvisols	WR	Water Bodies		
Lp	Plinthic Luvisols	Ws	Solodic Planosols		
Lv	Vertic Luvisols	X	XEROSOLS		
M	Mollic Solonchaks	Xh	Haplic Xerosols		
M	Mollic Solonetz	Xk	Calcic Xerosols		

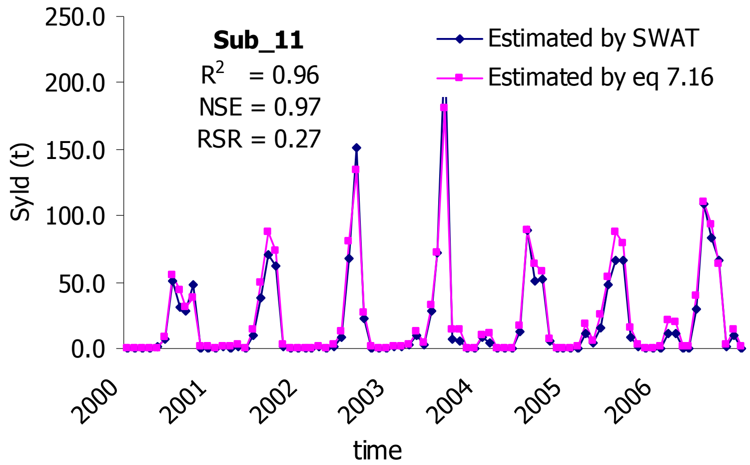
Group 3		Group 3		Group 3	
Soil code	**FAO Soil**	**Soil code**	**FAO Soil**	**Soil code**	**FAO Soil**
R	REGOSOLS	Jt	Thionic Fluvisols	To	Ochric Andosols
Af	Ferric Acrisols	K	KASTAZNOZEMS	Tv	Vitric Andosols
Ag	Gleyic Acrisols	Kh	Haplic Kastanozems	U	RANKERS
Ah	Humic Acrisols	Kk	Calcic Kastanozems	V	VERTISOLS
Ao	Orthic Acrisols	Kl	Luvic Kastanozems	Vc	Chromic Vertisols
Ap	Plinthic Acrisols	L	LUVISOLS	Vp	Pellic Vertisols
Bc	Chromic Cambisols	La	Albic Luvisols	W	PLANOSOLS
Bd	Dystric Cambisols	Lc	Chromic Luvisols	Wd	Dystric Planosols
Be	Eutric Cambisols	Lf	Ferric Luvisols	We	Eutric Planosols
Bf	Ferralic Cambisols	Lg	Gleyic Luvisols	Wh	Humic Planosols
Bg	Gleyic Cambisols	Lk	Calcic Luvisols	Wm	Mollic Planosols
Bh	Humic Cambisols	Lo	Orthic Luvisols	WR	Water Bodies
Bk	Calcic Cambisols	Lp	Plinthic Luvisols	Ws	Solodic Planosols
Bv	Vertic Cambisols	Lv	Vertic Luvisols	X	XEROSOLS
Bx	Gelic Cambisols	M	Mollic Solonchaks	Xh	Haplic Xerosols
C	CHERNOZEMS	M	Mollic Solonetz	Xk	Calcic Xerosols
Cg	Glossic Chernozems	Mg	Gleyic Greyzems	Xl	Luvic Xerosols
Ch	Haplic Chernozems	Mo	Orthic Greyzems	Xy	Gypsic Xerosols
Ck	Calcic Chernozems	Nd	Distric Nitosols	Y	YERMOSOLS
Cl	Luvic Chernozems	ND	No data	Yh	Haplic Yermosols
Dd	Dystric Podzoluvisols	Ne	Eutric Nitosols	Yk	Calcic Yermosols
De	Eutric Podzoluvisols	Nh	Humic Nitosols	Yl	Luvic Yermosols
Dg	Gleyic Podzoluvisols	O	HISTOSOLS	Yt	Takyric Yermosols
DS	Dunes / Shifting Sand	o	Orthic Solonchaks	Yy	Gypsic Yermosols
E	RENDZINAS	o	Orthic Solonetz	Zg	SOLONCHAKS
Fa	Acric Ferrlsols	Od	Dystric Histosols	Zg	Gleyic Solonchaks
Fh	Humic Ferralsols	Oe	Eutric Histosols	Jc	Calcaric Fluvisols
Fo	Orthic Ferralsols	Ox	Gelic Histosols	Jd	Dystric Fluvisols
Fp	Plinthic Ferralsols	Pg	Gleyic Podzols	Je	Eutric Fluvisols
Fr	Rhodic Ferralsols	Ph	Humic Podzols		
Fx	Xanthic Ferralsols	Pl	Leptic Podzols		
G	GLEYSOLS	Po	Orthic Podzols		
g	Gleyic Solonetz	Pp	Placic Podzols		
Gc	Calcaric Gleysols	Qa	Albic Arenosols		
Gd	Dystric Gleysols	Qc	Cambic Arenosols		
Ge	Eutric Gleysols	Qf	Ferralic Arenosols		
Gh	Humic Gleysols	Ql	Luvic Arenosols		
GL	Glaciers	Rc	Calcaric Regosols		
Gm	Mollic Gleysols	Rd	Dystric Regosols		
Gp	Plinthic Gleysols	Re	Eutric Regosols		
Gx	Gelic Gleysols	RK	Rock Debris		
Hc	Calcaric Phaeozems	Rx	Gelic Regosols		
Hg	Gleyic Phaeozems	S	SOLONETZ		
Hh	Haplic Phaeozems	ST	Salt Flats		
Hl	Luvic Phaeozems	t	Takyric Solonchaks		
I	LITHOSOLS	Th	Humic Andosols		
J	LUVISOLS	Tm	Mollic Andosols		

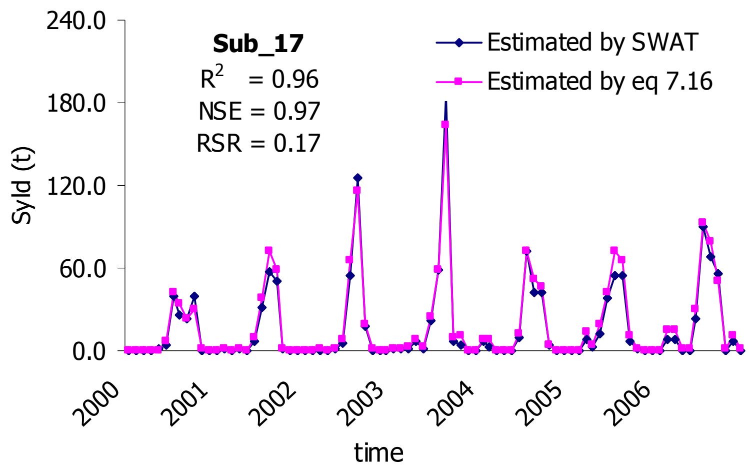
Annex B: SWAT2005 model result and the alternative equation result comparison for Gudar subbasin

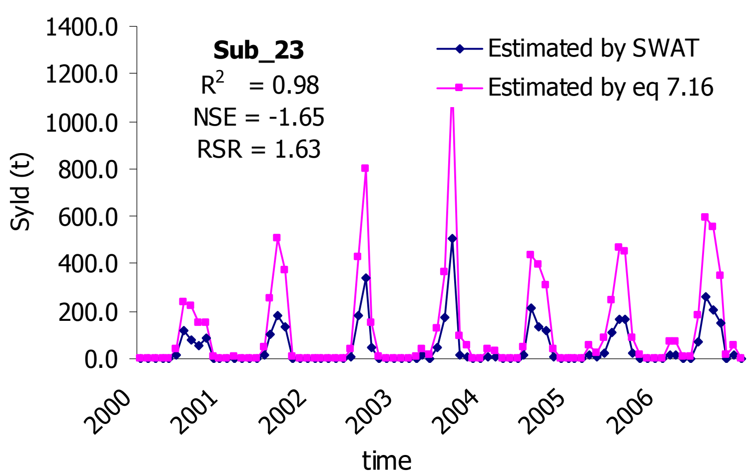


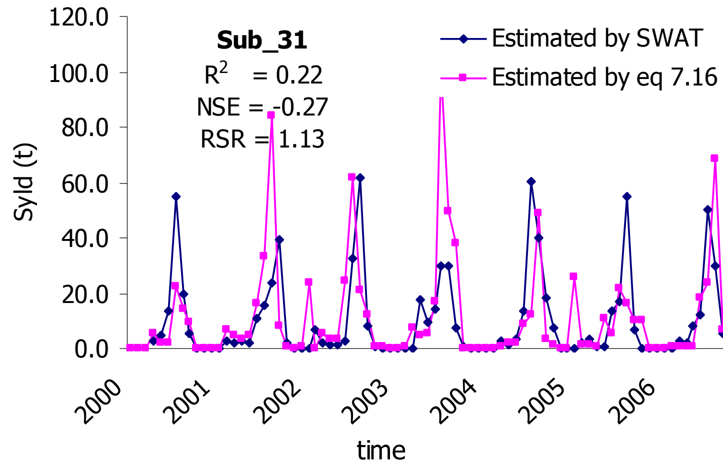


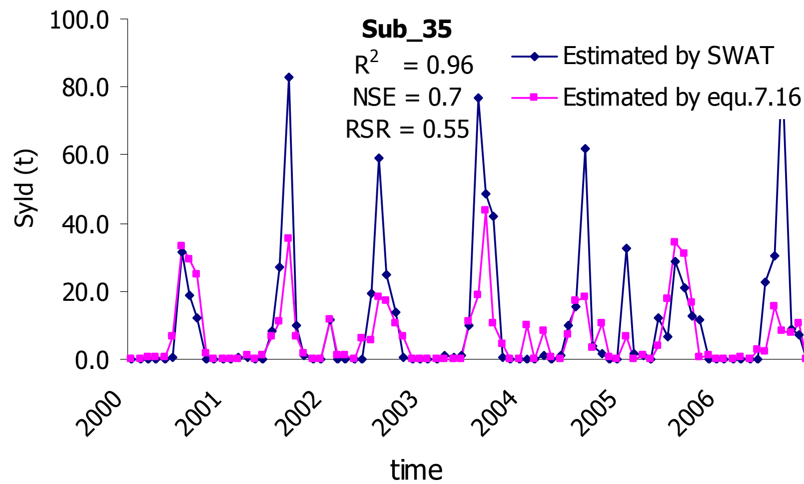


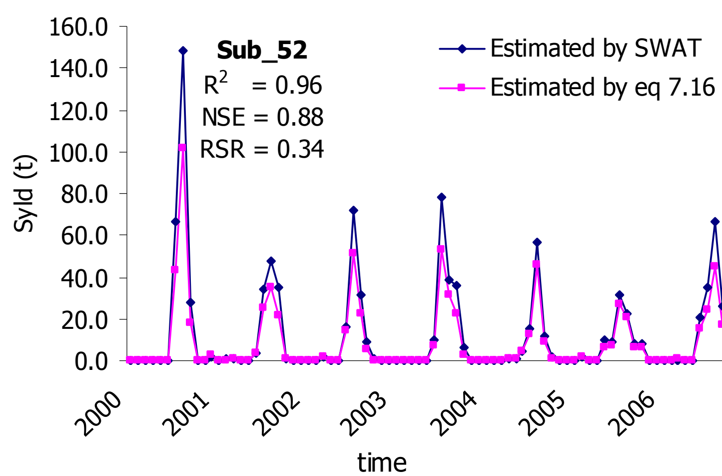

Sub_11
R2 = 0.96
NSE = 0.97
RSR = 0.27
Estimated by SWAT
Estimated by eq 7.16
Syld (t)
time
250.0
200.0
150.0
100.0
50.0
0.0
2000
2001
2002
2003
2004
2005
2006


Sub_17
R2 = 0.96
NSE = 0.97
RSR = 0.17
Estimated by SWAT
Estimated by eq 7.16
Syld (t)
time
240.0
180.0
120.0
60.0
0.0
2000
2001
2002
2003
2004
2005
2006

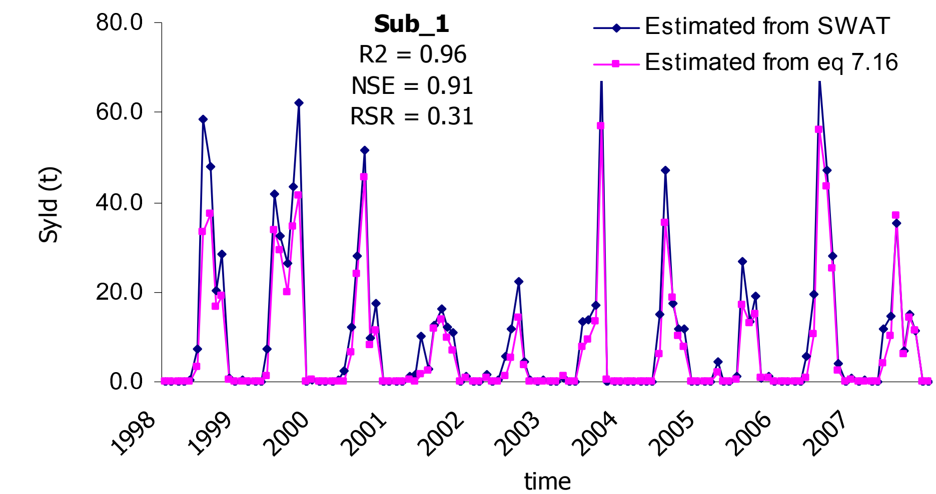

Sub_23
R2 = 0.98
NSE = -1.65
RSR = 1.63
Estimated by SWAT
Estimated by eq 7.16
Syld (t)
time
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
2000
2001
2002
2003
2004
2005
2006

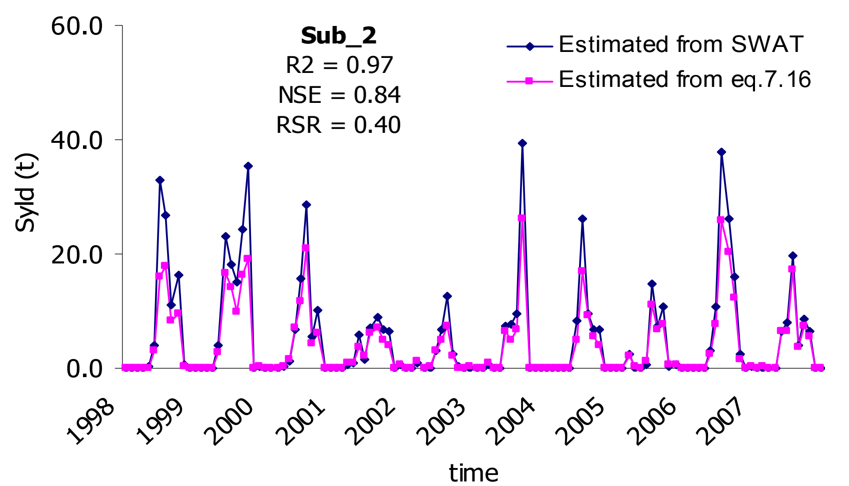

Sub_31
R^2 = 0.22
NSE = -0.27
RSR = 1.13
Estimated by SWAT
Estimated by eq 7.16
Syld (t)
time
120.0
100.0
80.0
60.0
40.0
20.0
0.0
2000
2001
2002
2003
2004
2005
2006

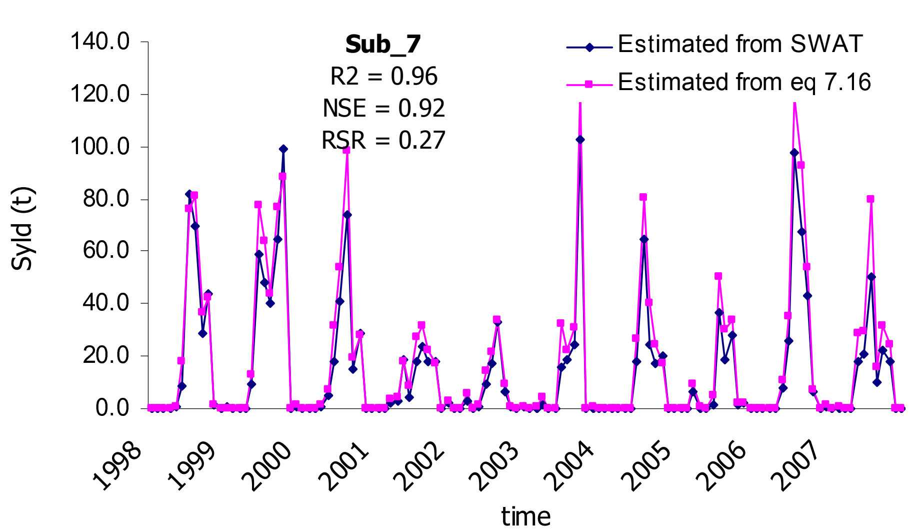

Sub_35
R^2 = 0.96
NSE = 0.7
RSR = 0.55
Estimated by SWAT
Estimated by equ.7.16
Syld (t)
time
100.0
80.0
60.0
40.0
20.0
0.0
2000
2001
2002
2003
2004
2005
2006

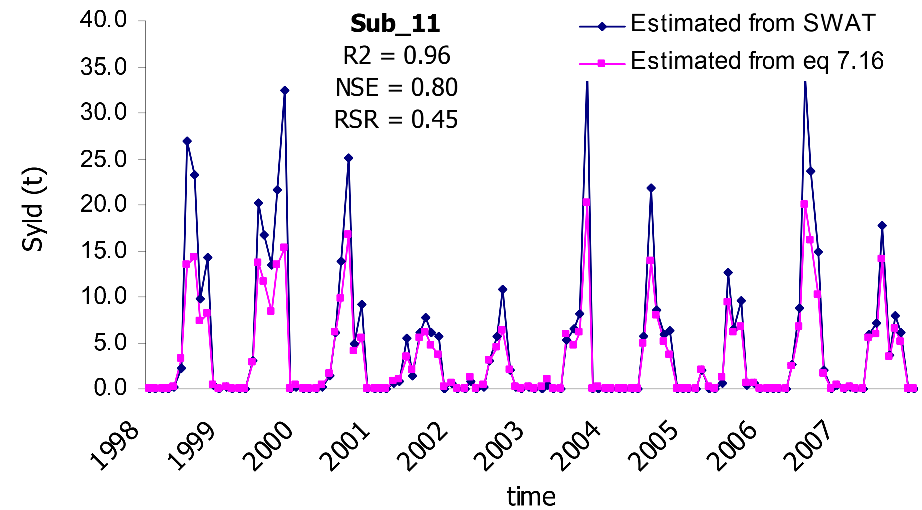

Sub_52
R^2 = 0.96
NSE = 0.88
RSR = 0.34
Estimated by SWAT
Estimated by eq 7.16
Syld (t)
time
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
2000
2001
2002
2003
2004
2005
2006

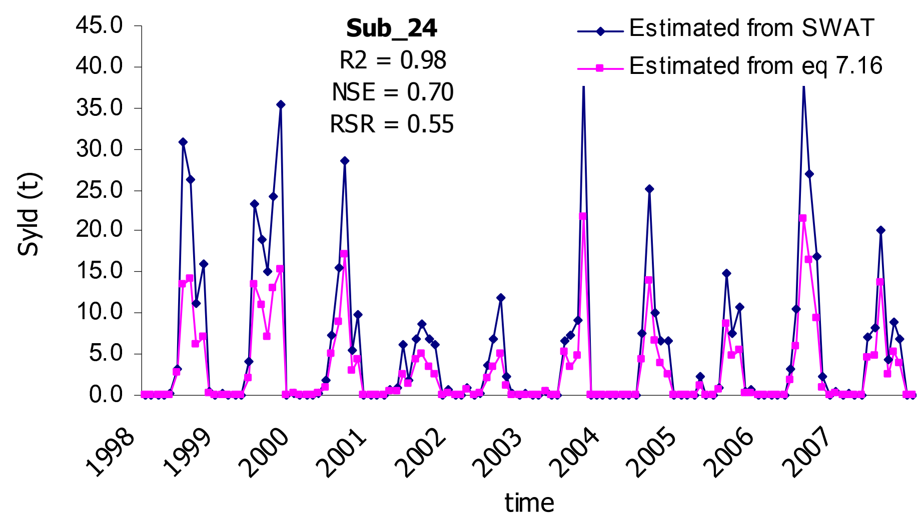
Annex C: SWAT2005 model result and the alternative equation result comparison for Fincha subbasin

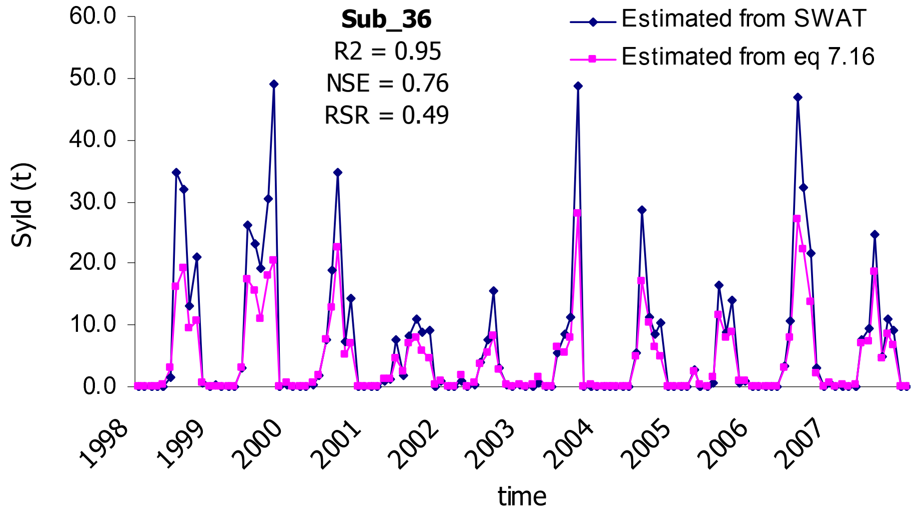


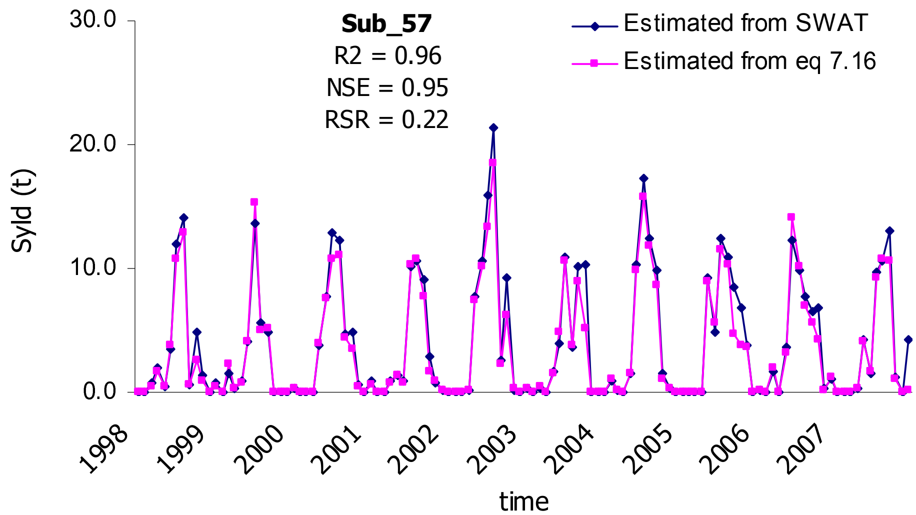


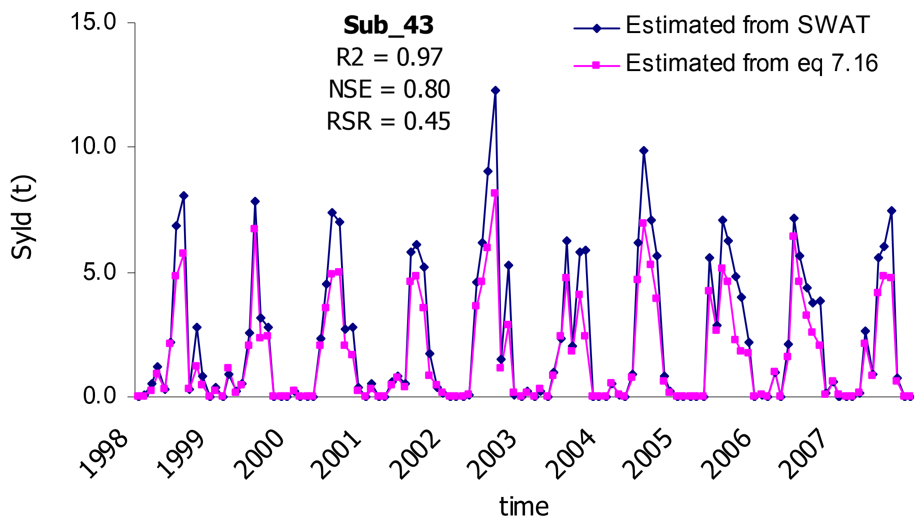


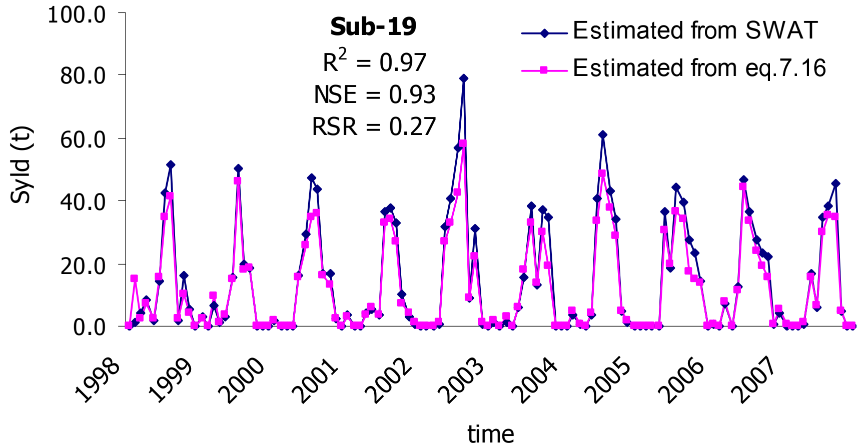

Sub_11
R2 = 0.96
NSE = 0.80
RSR = 0.45
Estimated from SWAT
Estimated from eq 7.16
Syld (t)
time
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007

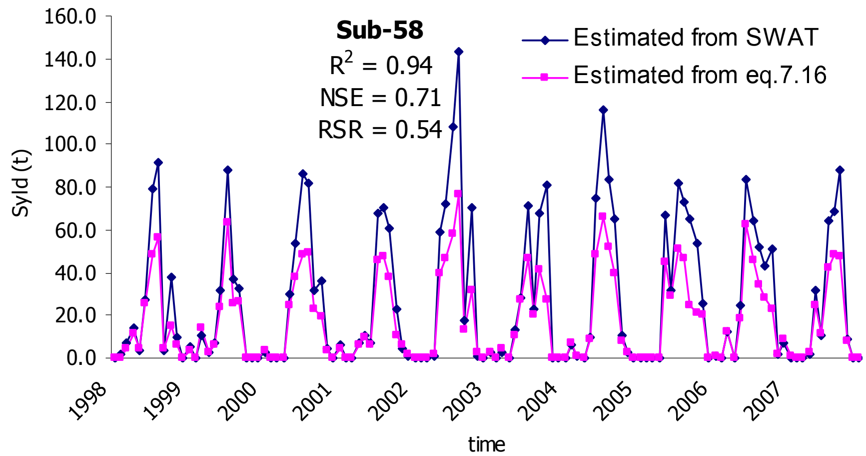

Sub_24
R2 = 0.98
NSE = 0.70
RSR = 0.55
Estimated from SWAT
Estimated from eq 7.16
Syld (t)
time
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007

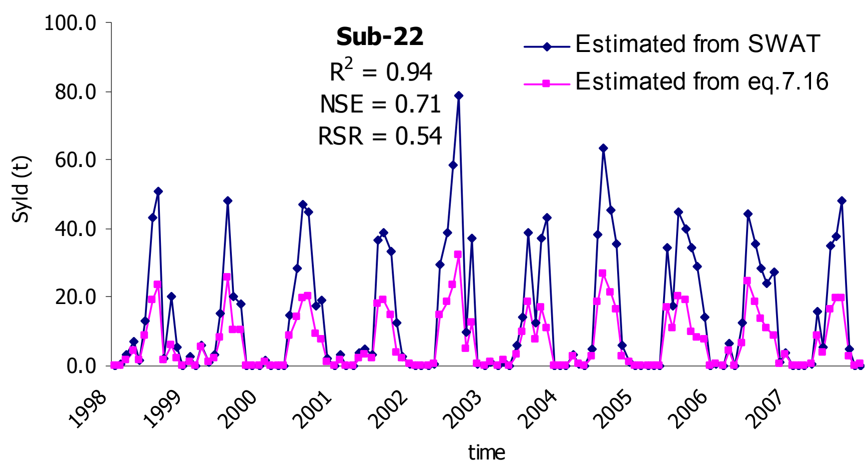

Sub_36
R2 = 0.95
NSE = 0.76
RSR = 0.49
Estimated from SWAT
Estimated from eq 7.16
Syld (t)
time
60.0
50.0
40.0
30.0
20.0
10.0
0.0
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007

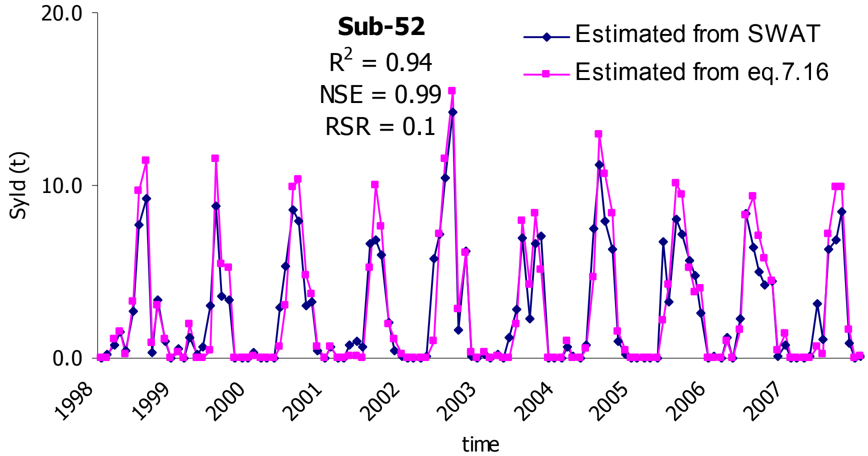

Sub_57
R2 = 0.96
NSE = 0.95
RSR = 0.22
Estimated from SWAT
Estimated from eq 7.16
Syld (t)
time
30.0
20.0
10.0
0.0
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007

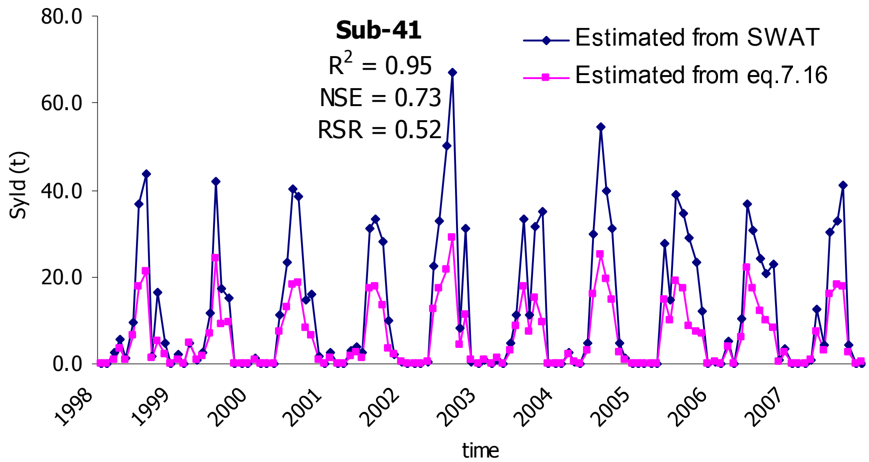

Sub_43
R2 = 0.97
NSE = 0.80
RSR = 0.45
Estimated from SWAT
Estimated from eq 7.16
Syld (t)
time
15.0
10.0
5.0
0.0
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007

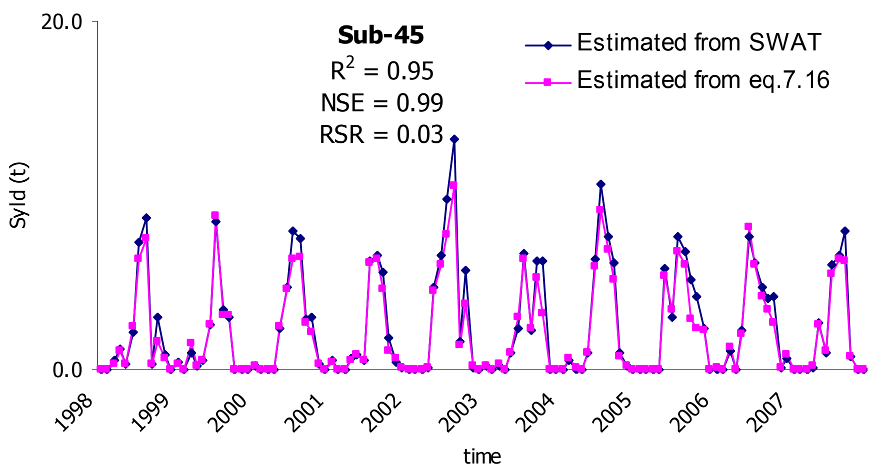

Sub-19
R2 = 0.97
NSE = 0.93
RSR = 0.27
Estimated from SWAT
Estimated from eq.7.16
Syld (t)
time
100.0
80.0
60.0
40.0
20.0
0.0
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007


Sub-58
R2 = 0.94
NSE = 0.71
RSR = 0.54
Estimated from SWAT
Estimated from eq.7.16
Syld (t)
time
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007

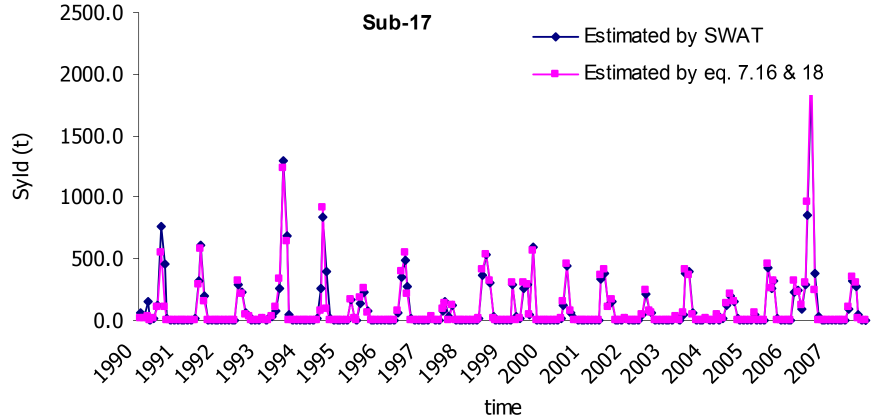

Sub-22
R2 = 0.94
NSE = 0.71
RSR = 0.54
Estimated from SWAT
Estimated from eq.7.16
Syld (t)
time
100.0
80.0
60.0
40.0
20.0
0.0
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007

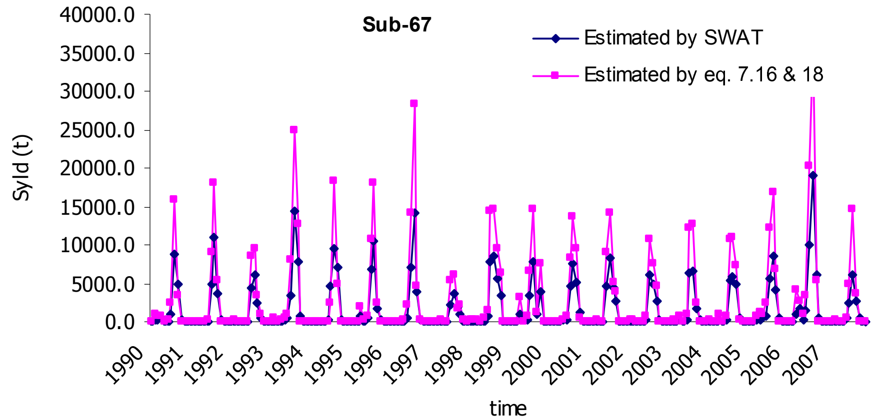

Sub-52
R^2 = 0.94
NSE = 0.99
RSR = 0.1
Estimated from SWAT
Estimated from eq.7.16
20.0
10.0
0.0
Syld (t)
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
time

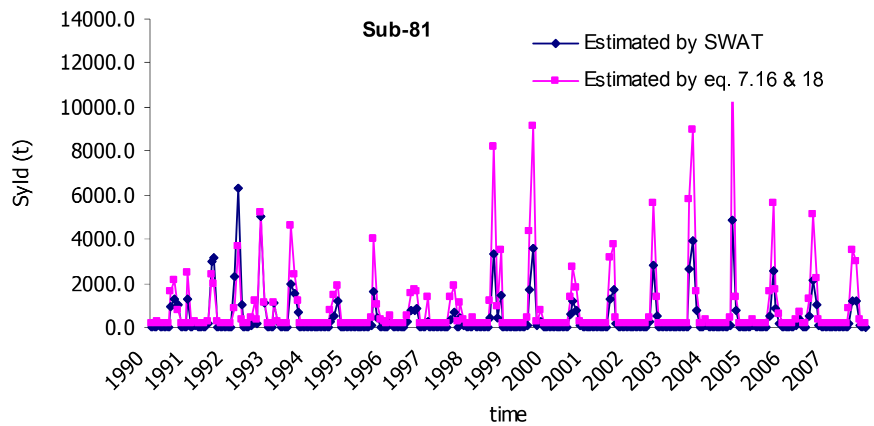

Sub-41
R^2 = 0.95
NSE = 0.73
RSR = 0.52
Estimated from SWAT
Estimated from eq.7.16
80.0
60.0
40.0
20.0
0.0
Syld (t)
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
time

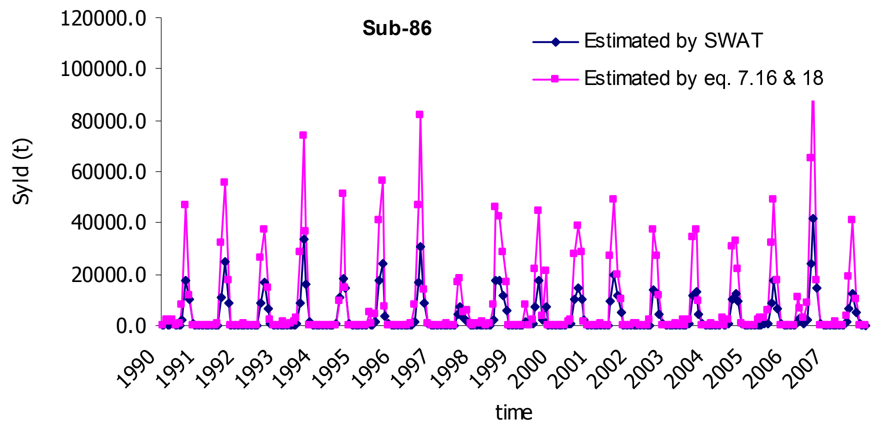

Sub-45
R^2 = 0.95
NSE = 0.99
RSR = 0.03
Estimated from SWAT
Estimated from eq.7.16
20.0
0.0
Syld (t)
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
time

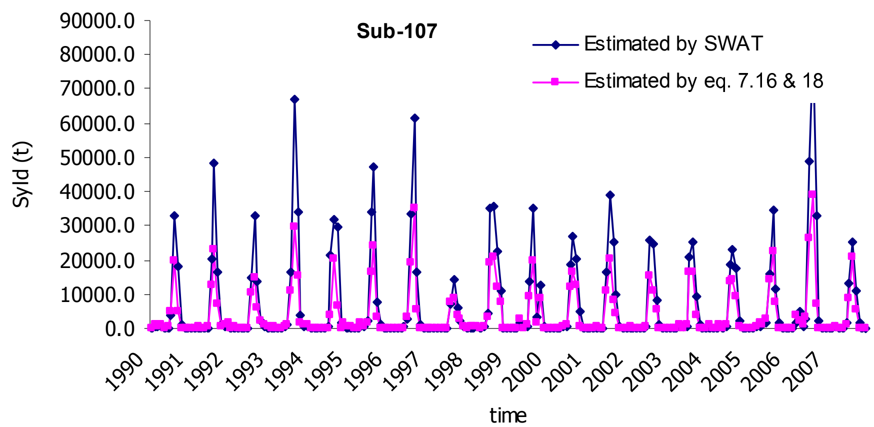
Annex D: Sediment routing result in Upper Awash basin interconnected rivers








Sub-86
Estimated by SWAT
Estimated by eq. 7.16 & 18
Syld (t)
120000.0
100000.0
80000.0
60000.0
40000.0
20000.0
0.0
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
time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40000.0
30000.0
20000.0
10000.0
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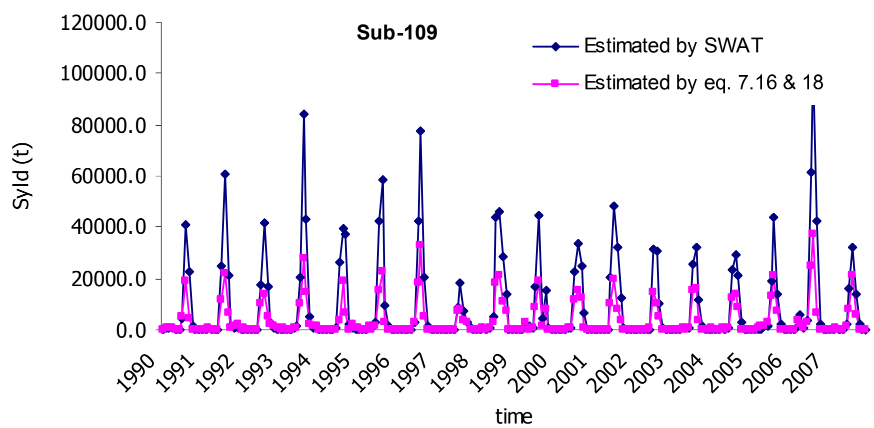
time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20000.0
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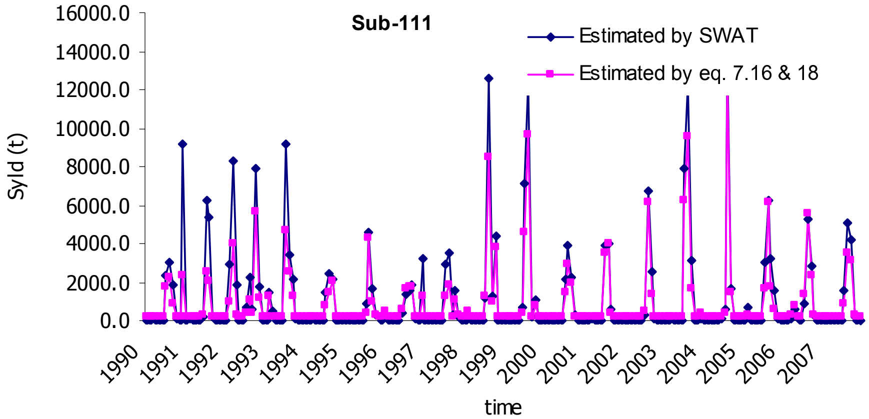
time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4000.0
2000.0
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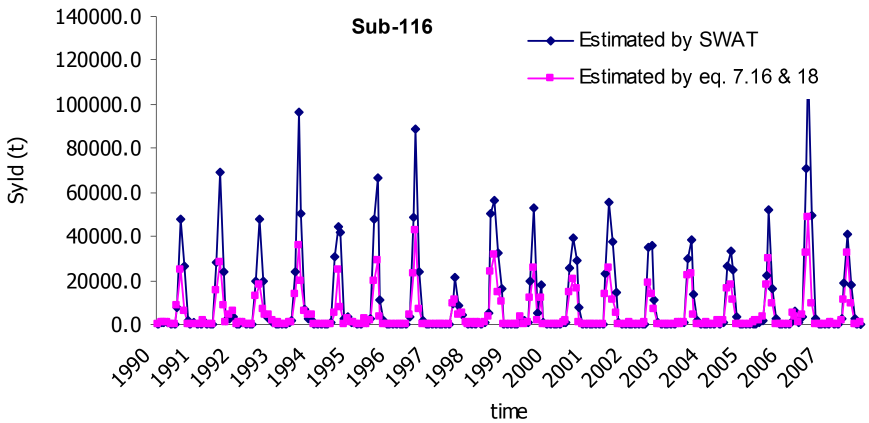
2007


Sub-116
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Estimated by eq. 7.16 & 18
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100000.0
80000.0
60000.0
40000.0
20000.0
0.0
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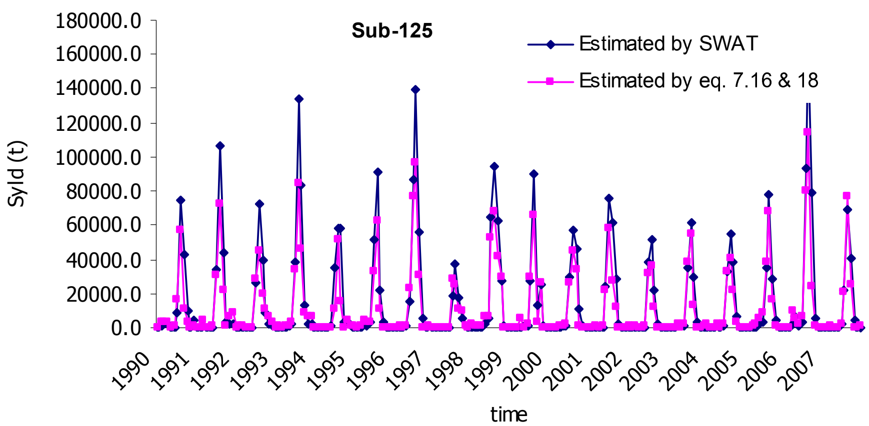
Sub-125
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100000.0
80000.0
60000.0
40000.0
20000.0
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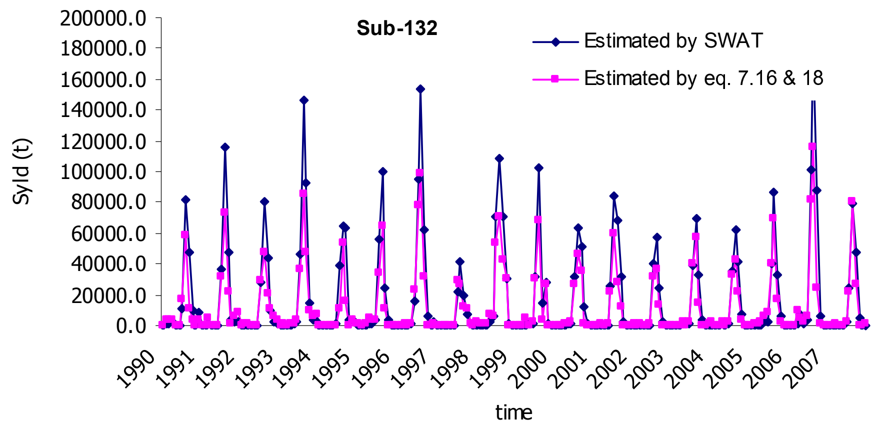
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120000.0
100000.0
80000.0
60000.0
40000.0
20000.0
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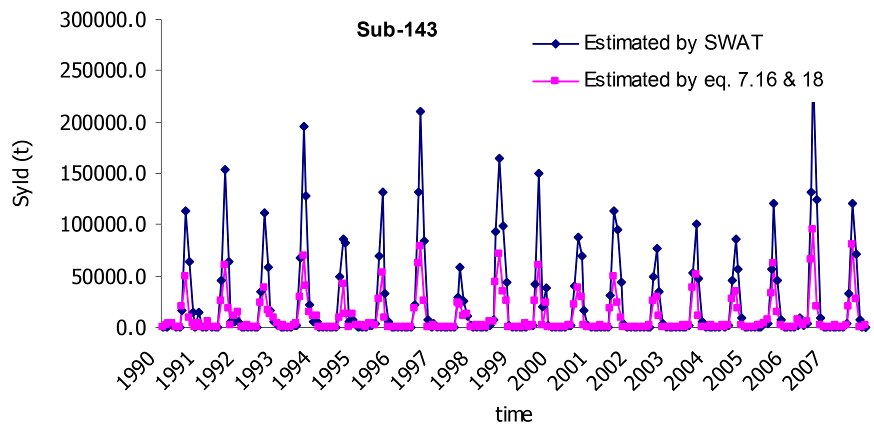
Sub-143
Estimated by SWAT
Estimated by eq. 7.16 & 18
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250000.0
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100000.0
50000.0
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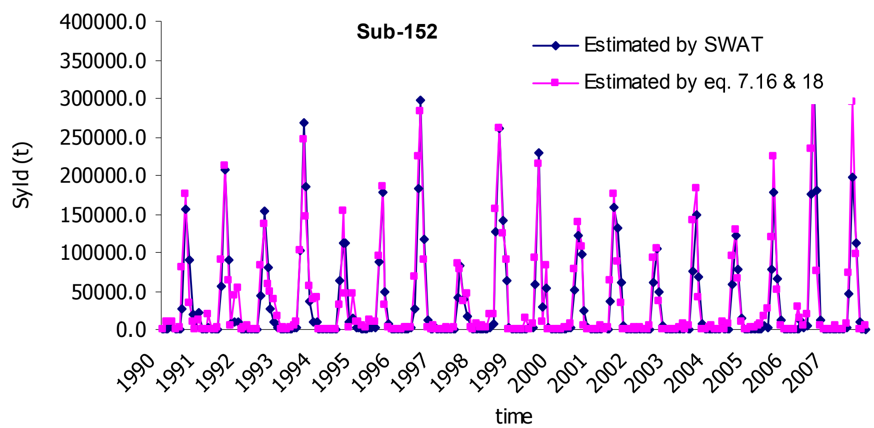
Sub-152
Estimated by SWAT
Estimated by eq. 7.16 & 18
Syld (t)
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350000.0
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250000.0
200000.0
150000.0
100000.0
50000.0
0.0
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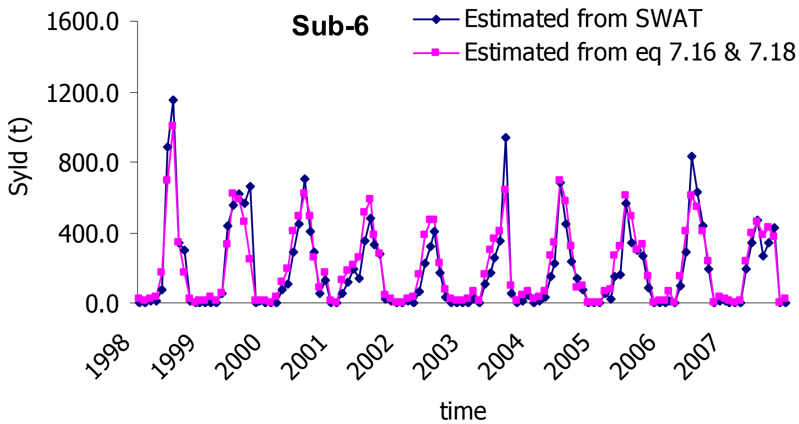
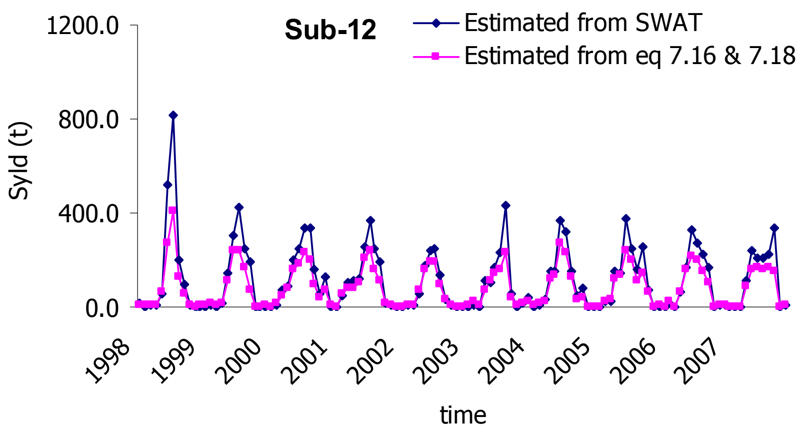
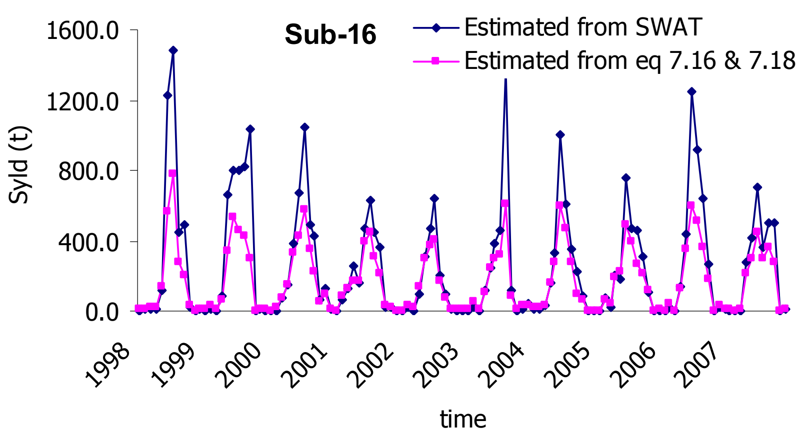
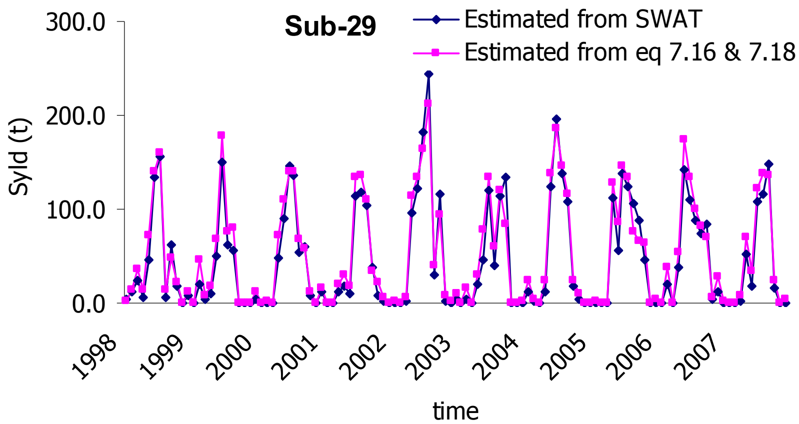
Annex E: Sediment routing result in Fincha subbasin interconnected rivers








Sub-29
Estimated from SWAT
Estimated from eq 7.16 & 7.18
Syld (t)
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200.0
100.0
0.0
1998
1999
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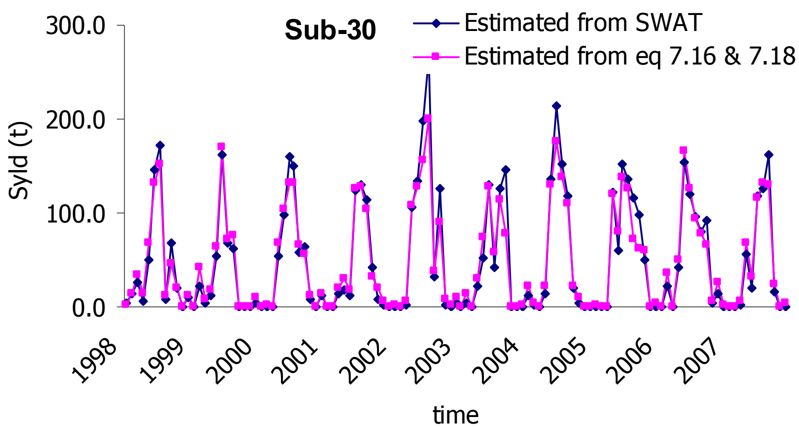
2001
2002
2003
2004
2005
2006
2007
time


Sub-30
Estimated from SWAT
Estimated from eq 7.16 & 7.18
Syld (t)
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200.0
100.0
0.0
1998
1999
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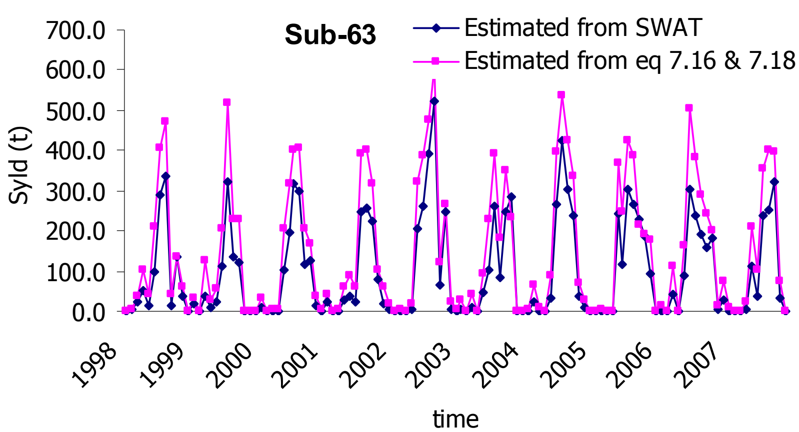
2004
2005
2006
2007
time


Sub-63
Estimated from SWAT
Estimated from eq 7.16 & 7.18
Syld (t)
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600.0
500.0
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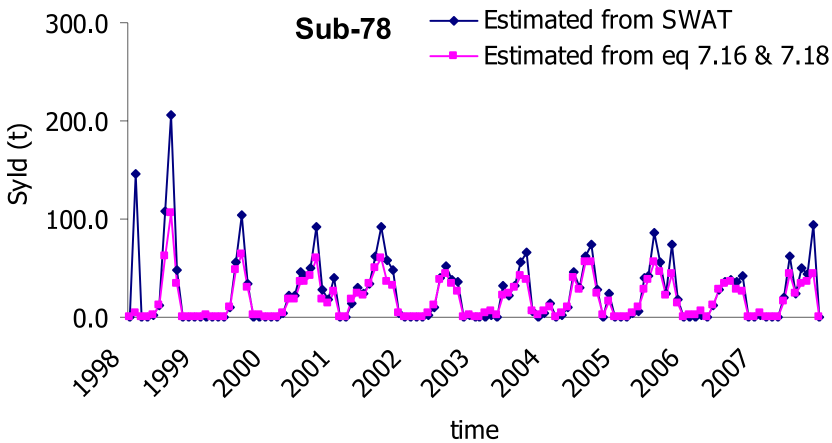
2004
2005
2006
2007
time


Sub-78
Estimated from SWAT
Estimated from eq 7.16 & 7.18
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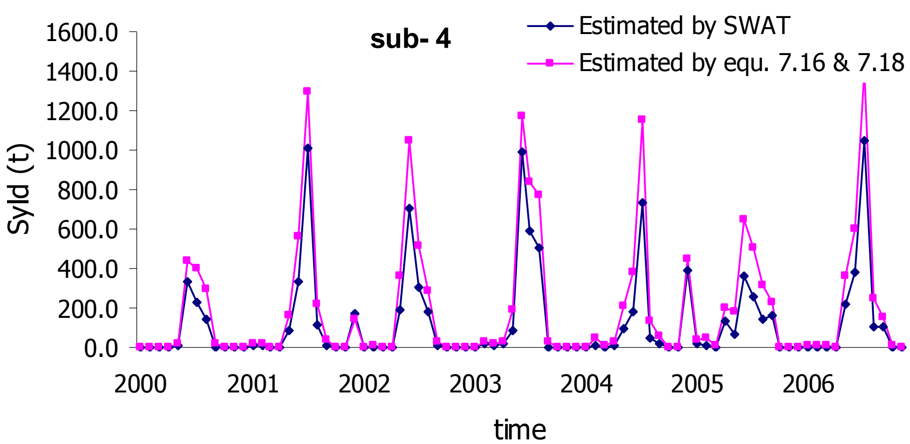
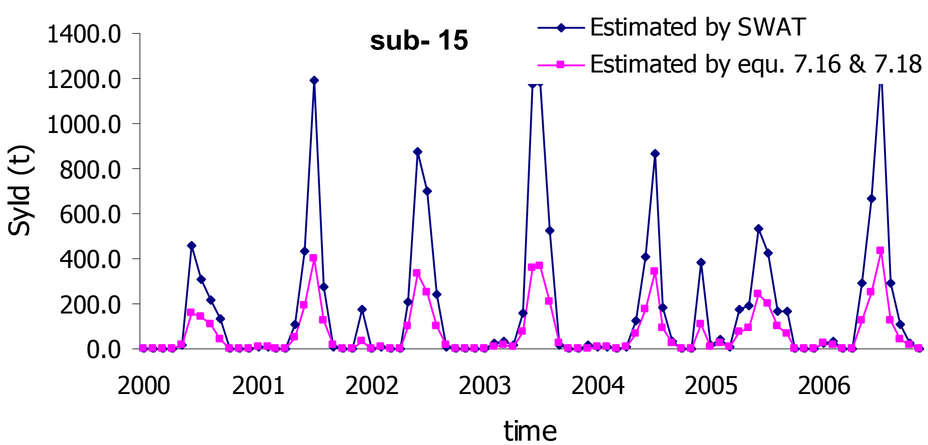
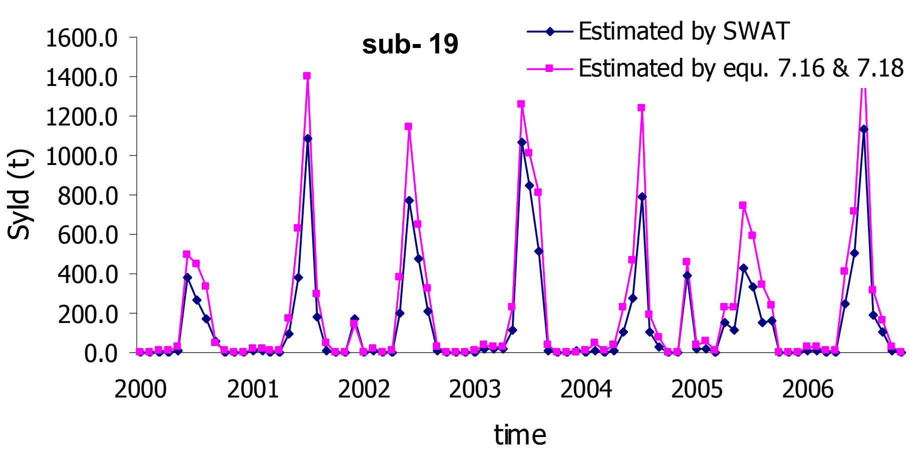
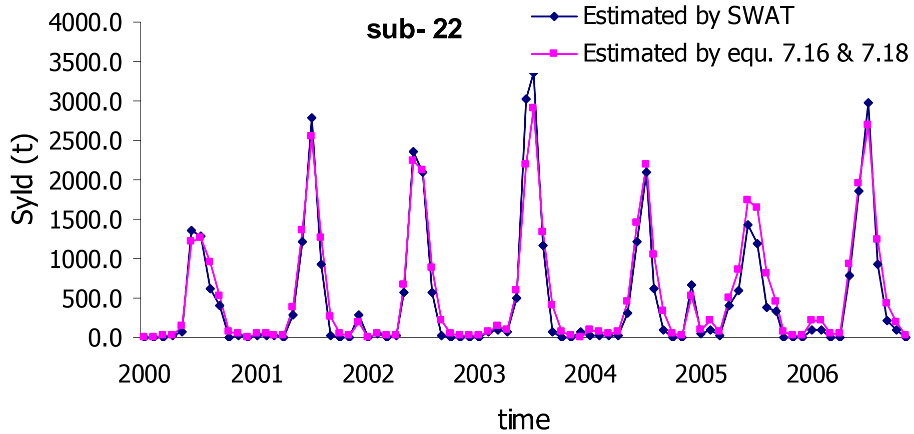
200.0
100.0
0.0
Syld (t)
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
time

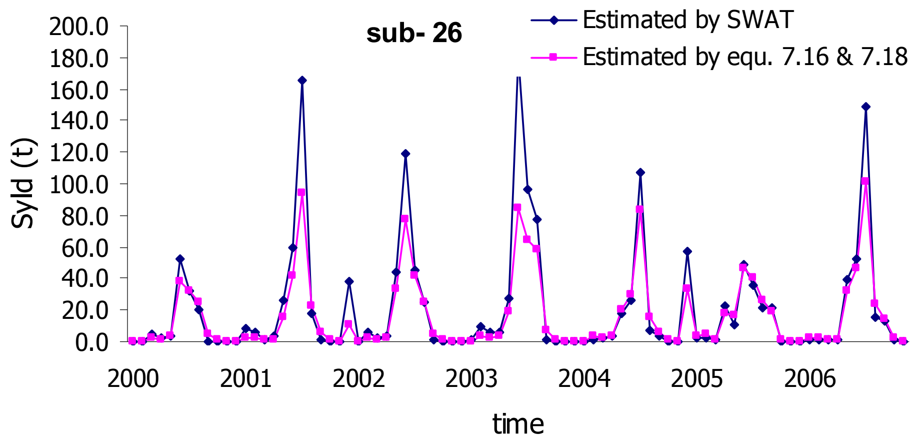
Annex F: Sediment routing result in Gudar subbasin interconnected rivers

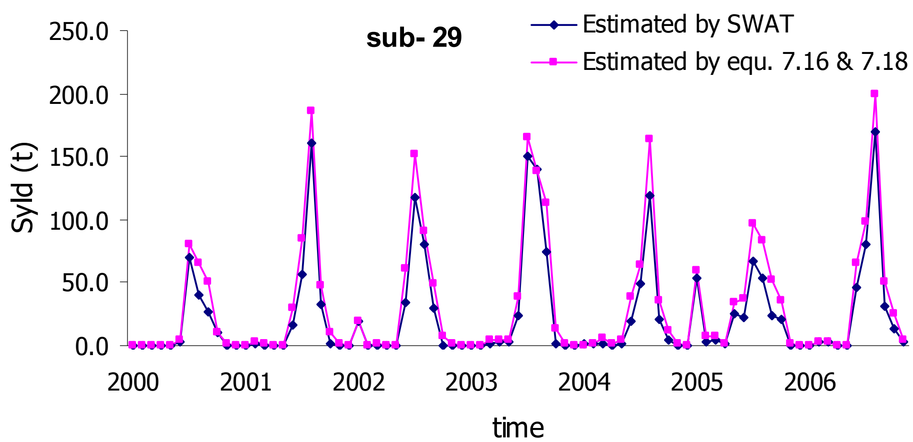


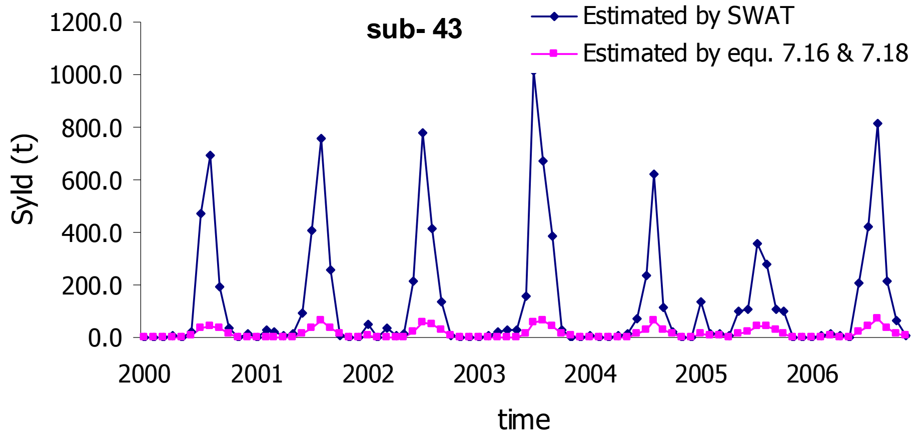





sub- 22
Estimated by SWAT
Estimated by equ. 7.16 & 7.18
Syld (t)
time


sub- 26
Estimated by SWAT
Estimated by equ. 7.16 & 7.18
Syld (t)
time


sub- 29
Estimated by SWAT
Estimated by equ. 7.16 & 7.18
Syld (t)
time


sub- 43
Estimated by SWAT
Estimated by equ. 7.16 & 7.18
Syld (t)
1200.0
1000.0
800.0
600.0
400.0
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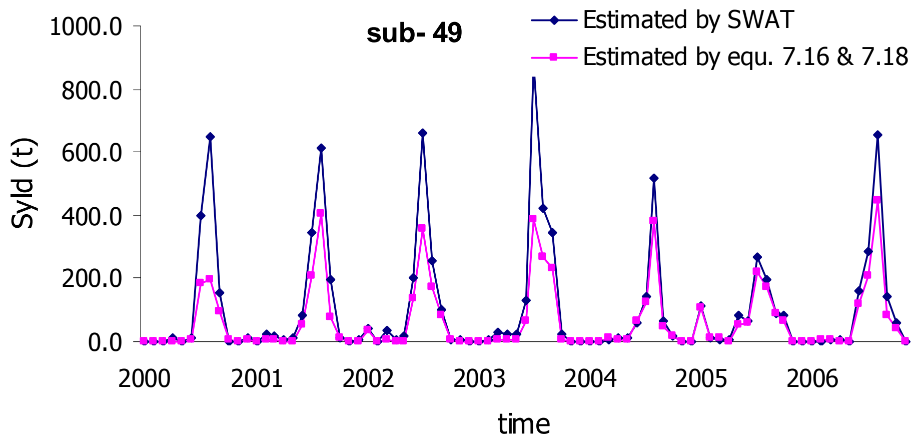
2003
2004
2005
2006
time


sub- 49
Estimated by SWAT
Estimated by equ. 7.16 & 7.18
Syld (t)
1000.0
800.0
600.0
400.0
200.0
0.0
2000
2001
2002
2003
2004
2005
2006
time

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E-Mail: iws@iws.uni-stuttgart.de
http://www.iws.uni-stuttgart.de

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