Integrated Sediment Transport Modelling Using OpenMI (SWAT and SOBEK-RE) for the Blue Nile River Basin

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MSc Thesis (WSE-HI. 08-20)
September 2008
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This research is done for the partial fulfilment of the requirements of the Master of Science degree at UNESCO-IHE Institute for Water Education, Delft, the Netherlands

Delft
September 2008
The findings, interpretations and conclusions expressed in this study do neither necessarily reflect the views of the UNECSO-IHE Institute for Water Education, nor of the individual members of the MSC committee, nor of their respective employers.
Dedication

The thesis is dedicated to my father, Dubale with a lot of love who poured me the spirit of hard work and encouraged me to finish this study. Right this moment I feel that you are smiling down…may God rest your soul always in peace!
Abstract

Sediment transport, leads to degraded soil productivity and water quality deterioration that causes worldwide problems such as sedimentation in reservoirs and alternation of river morphology. These problems are pronounced in the Blue Nile basin – the main tributary of the River Nile - because of quick land use change coupled to intensive agriculture in the Ethiopian highlands. There is an urgent need to understand the process at basin level, i.e., at the source on the Upper Blue Nile, and at the receiving side in reservoirs and irrigation canals further downstream. In this study, the Soil and Water Assessment Tool (SWAT) was used to model the erosion processes and the SOBEK was used to model river dynamics and river morphology processes. Both softwares were integrated by using the Open Modelling Interface (OpenMI) software after conversion of the programmes towards OpenMI compliant models. The integrated model allows understanding of the sediment processes and quantifying sediment transport from the upper to the lower Blue Nile. As such, the model identifies sensitive regions of soil erosion and that of sediment deposition. This study involved modelling sediment yield from catchment and routing the sediment load along the river channel. However, most of softwares could not model both processes. Therefore, SWAT-SOBEK-RE integration was aimed for. The SWAT model was calibrated from 1981 to 1986 and validated from 1990 to 1996. The model performance both for calibration and validation periods have been evaluated using the Nash-Sutcliff test. The computed Nash-Sutcliff coefficient for the calibration and for the validation of daily flow found to be 0.91, and 0.81, respectively. The Nash-Sutcliff coefficient for calibration and validation of daily sediment concentration was found to be 0.72 and 0.66, respectively. This shows good performance of the SWAT model on daily time step. The Sobek-RE model was calibrated in 2000 and validated in 2003. Good fit were found between observed and simulated discharge at Roseries and Sennar dams during calibration and validation. SWAT watershed model has been modified to provide sediment output into sediment fractions (clay, silt and sand), developed into OpenMI compliant model and integrated with the OpenMI compliant SOBEK-RE River model. The OpenMI compliant models defines the input/output exchange items (clay, flow, sand, sediment, silt) and integrated at run time using OpenMI configuration Editor interface so that they exchange flow and sediment from SWAT to Sobek-RE at El Deim. The integrated modelling estimated the amount of soil erosion to be around 86 Million ton per year from Upper Blue Nile. Moreover, it is understood that sever erosion was taken place at North-East of the subbasin and followed by North of the subbasin and 19 Million m$^3$ per year of suspended sediment deposited at Roseries dam.

Keywords: Soil erosion, Sediment transport, OpenMI, SWAT, SOBEK, Blue Nile
Acknowledgments

I am thankful to the Netherlands Fellowship program (NFP) for sponsoring me to study MSc at UNESCO-IHE Institute for Water Education. I’m grateful to Deltares-WL| Delft Hydraulics for providing me comfortable working place and facility to undertake the research and International Water Management Institute (IWMI) to support me financially for data collection.

I would like express my special thanks to Dr. Ann van Griensven for her unreserved supervision, wise guidance, motivation to prepare articles, responding my question immediately and warm discussion that we had; Prof. A. Mynett for his guidance, encouragement and finding me a working place at Deltares; Dr. A. Yasir for his invaluable advice, crucial comment, and encouragement to prepare articles; Dr. I. Popescu for her immense supervision, follow-up during course work and above all facilitating my transfer to Hydroinformatics department; Ir. S. Hummel for his invaluable support and guidance in OpenMI work.

I got strong assistance to achieve the research from various people to whom I would like to express my gratitude. Among them Dr. A. Crosato, Dr. K. Sloff, Ir. S. Seyoum, Dr. G. Zeleke and Nigussu Bekele deserve thanks.

I am very pleased to express my gratitude to Hydroinformatics department staffs who shared me their many years experience and knowledge unlimitedly. Mr. Jan Luijendijk deserves many thanks for his continues effort to find me data from Sudan.

I would like to sincerely acknowledge the following organizations that provided me data for the research: Ethiopian Ministry of Water Resources, Soil Conservation Research Program (SCRP), and Hydraulic Research Station of Wad Madani, Sudan.

Last but not least, I’m indebted to my mother, Zehara who is my icon of love; my sisters (Ehtaferahu, Konjit, and Emwodish) ; my brothers (Fikre and Sisay); my friends (Betre, Ketema, Kebede, Mesert and Nigussu) for their frequent encouragement from home.
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1 Introduction

1.1 Background

Soil erosion is a process of detachment of soil particles due to raindrop energy and/or surface runoff, the transport of sediment by surface runoff and the deposition of sediments as velocity surface runoff decrease. Soil erosion causes world wide environmental problems leading to degraded soil productivity, water quality, causes sedimentation in the reservoirs and increased the probability of floods as a result of reduction of flood storage capacity. Thus sediment transport has been of interest in China since 4000 year back in time (Simons and Sentürk, 1992).

Sediment transport deals with flow of water and sediment particles. Therefore, properties and theories of both water flow and sedimentation are important. Sediment is transported in water bodies as suspended load and bed load. Bed load is defined as the sediment load which moves along the bed. Suspended load is defined as the sediment load which moves in suspension and occupies the entire flow depth above the bed load layer. According to the mechanism of suspension the suspended sediment may belong to the bed material load and the wash load. Wash load is defined as the transport of material finer than the bed material. It has no relation to the transport capacity of the stream: the rate is determined by the amount which becomes available by the erosion in the catchment area upstream. Usually a diameter $D$ with $50 \mu m < D < 70 \mu m$ is taken as a practical distinction between wash load and bed material load. The distinction between bed load and suspended load can not be defined sharply. Not only the grain size but also the flow conditions characterize the distinction (Jansen, et al., 1979).

The Blue Nile river is increasingly vital to the rapidly growing population exceeding 100 millions in Ethiopia, Egypt and Sudan, but it is facing a number of environmental problems caused by the extensive exploitation of its territory and resources (Garzanti, et al., 2006). Rapid population increase led to fast land-use change from forest to agricultural land. This changes together with steep slope topography and inappropriate land-use in upper Blue Nile has resulted severe soil erosion (Nyssen, et al., 2004).

Sediment transport process has affected the whole Blue Nile basin negatively even though it was nutrient-rich sediment source before the construction of dams in the Nile valley (Nixon, 2002). The upper Blue Nile is losing fertile topsoil which is storage of moisture and nutrient for plant growth hence, exacerbating impacts of drought. Moreover, sediment from agricultural land transports fertilizer which affects negatively the receiving water bodies such as lake and rivers are leading to serious eutrophication problems. Meanwhile multipurpose reservoirs and irrigation canal in the lower Blue Nile is affected seriously by sedimentation. The sedimentation in turn has led to hydropower head cutoff, decrease the amount of water for irrigation, for instance Gezira irrigation scheme (800,000 ha) spends half of its operation and maintenance budget on de-silting irrigation canals and increase of flood risk.
In general, there is scarcity of information on how much is the soil erosion, its impact downstream and trends in time at basin scale in Blue Nile. Therefore, there is an urgent need to understand sediment transport process for the Blue Nile basin.

1.2 Research Questions

Which sediment transport processes dominate in the Blue Nile?
- How much is the soil erosion in the Upper Blue Nile, and how this is routed up to the outlet?
- How much is the sediment routed from outlet, trapped in reservoir up to the confluence with the White Nile?

How can these be modelled in an integrated way, i.e., both soil erosion, and sediment transport?

1.3 Objectives

- To develop SWAT in to OpenMI compliant interface and integrate with SOBEK-RE.
- To understand the process and quantify soil erosion, sediment transport from upper to lower Blue Nile.
- Identify sensitive regions for erosion and deposition.

1.4 Outline of the thesis

The first chapters discuss about introduction, research questions and the objective of the study. The second chapter contains the literature review. The first section of the chapter discusses in detail about catchment soil erosion models and describes pertinent past work done in the area. The second section of the chapter discusses about river flow and morphology models and further explains relevant past work done in the area. The last section of the chapter discusses thoroughly about model integration.

Chapter three discusses about physical and hydrological resources of the study area. Chapter four describe the input data used. The fifth chapters provide insight to models description, methodology followed to setup the models, calibrate and validate the models.

The sixth chapter cover the result and discussion part of the study. Here, the model result was compared to past work either from positive or negative perspective.

The last chapter conclude about the study and provides recommendation further study.
2 Literature Review

Tremendous numbers of soil erosion and sediment transport models have been developed based on laboratory, field, analytical and numerical methods such as finite difference and finite element.
Models can be classified into different categories. Empirical models developed from regression of observed data whereas physical-based models are developed based on the physics such as conservation of mass and momentum. Deterministic model provides the same result for two equal sets of input data while stochastic model results in different output (Refsgaard, 1996). Lumped models consider a system as a black box and everything is spatially averaged as a single system. However, distributed models consider the heterogeneities by dividing the system into smaller groups.

2.1 Catchment Soil Erosion Models

The Universal Soil Loss Equation (USLE) is an empirical model developed by Wischmeier and Smith (1978). Their aim was to establish an empirical model for predicting erosion on a cultivated field so that erosion control specialists could choose the kind of measures needed in order to keep erosion within acceptable limits given the climate, slope and production factors (Wischmeier and Smith, 1978). It requires input data such as annual rainfall, soil erodibility, topographic, land-cover and support practice factors. The output of the model is annual sediment yield from a given catchment. The advantage of this model is that it uses a simple equation. The limitations are that the model is not event-based and cannot identify those events that most likely result in large scale erosion. Gully erosion and mass movement are ignored and the deposition of sediment is not considered to occur in the modeled area (Merritt, et al., 2003). Further, the model requires much investment in time and money to develop database to run the model. A modified USLE evaluation provides an estimated average soil loss of 42 t/ha/yr from cropland, rising to 70 t/ha/yr from ‘unproductive’ land (not defined) and dropping to 1 t/ha/yr under forest in the Ethiopian highlands (Hurni, 1988).

The Water Erosion Prediction Project (WEPP) models expected users include all users’ of the universal Soil Loss Equation for predicting soil erosion in the United States (Flanagan and Nearing, 1995). The WEPP programs are process-based models that operate on a daily time step to estimate soil, vegetation, and surface residue conditions when a rainfall event occurs. This information is then used to predict the infiltration, runoff, erosion, and sediment loss for each individual event, and then long-term estimates are made using summations of the single event predictions (Flanagan and Nearing, 1995). The model does not consider erosion, transport and deposition processes in the main channels such as classical gullies and perennials streams (Merritt, et al., 2003). The adaptation and application of WEPP to the traditional farming system of the Ethiopian highland were studied (Zeleke, 1999). The hill slope application of WEPP was tested on cultivated plots of Anjeni Research Unit, Gojam located within the Upper Blue Nile catchment. The overall result shows that the model over predicts runoff and slightly under-predict soil losses.
The Agricultural Non-point Source model (AGNPS) is a non-point source pollution model developed by the US Department of Agriculture, Agricultural Research Service (Young, 1987). It calculates upland erosion, overland runoff volume, pollutants from point source inputs at each grid cell in the catchment and route to the next grid cell when the overland flow concentrated enough. The hydrological output includes runoff volume, peak runoff rate and the fraction of runoff generated in the cell. Sediment outputs include sediment yield, sediment concentration, sediment particle size and distribution, upland erosion, amount of deposition (%), sediment generated in the cell, enrichment ratios by particle size. The pollutant loading module computes such as sediment bound nitrogen and etc. The sediment transport module use revised universal soil loss equations (RUSLE) to estimate soil erosion and route sediment using the CCHE1D. The limitation is that sediment output highly influenced by grid size selection (Merritt, Letcher and Jakeman, 2003).

The agricultural non-point source (AGNPS) model was tested and validated in Kori gauged-watershed, south Wello zone, Ethiopia (Mohammed, et al., 2004). The model calibration resulted in model efficiencies of 0.73, 0.53 and 0.90 for surface runoff, peak runoff rate, and sediment yield, respectively. Validation results produced model efficiencies of 0.86, 0.65 and 0.88 for surface runoff, peak runoff rate and sediment yield, respectively. It can be concluded that the AGNPS model is a useful prediction tool for understanding erosion processes on the Ethiopian highlands and for locating and targeting specific areas within the watershed that have high potential for soil loss, thus helping the conservation planner to design conservation plans.

Soil and Water Assessment Tool (SWAT) is a physical process based model to simulate the process at catchment scale (Arnold, et al., 1998, Neitsch, et al., 2005) further details of SWAT model is given in section 5.1. It divides a catchment or basin in to sub-basins by hydrological response unit (HRU) based on soil type, land use and management practice. Thus, dividing the basin into HRU will simulate the hydrological process in detail. Two options exist in SWAT for estimating surface runoff from HRUs combinations of daily or subhourly rainfall and the Natural Resources Conservation Service Curve Number (CN) method (USDA, 1972) or the Green and Ampt method (Green and Ampt, 1911). Three methods for estimating potential evapotranspiration are also provided: Priestly-Taylor (Priestley and Taylor, 1972), Penman-Monteith (Monteith, 1965), and Hargreaves (Hargreaves and Riley, 1985). SWAT computes the sub-catchment sediment yield using the Modified Universal Equations (MUSLE) which uses runoff energy to detach and transport sediment (Williams and Berndt, 1978).

SWAT has been applied from a few to thousand hectares size catchment. SWAT was evaluated for the 932.5 km² Upper North Bosque River Watershed in north central Texas and found that predicted monthly sediment losses matched measured data well but daily output was found poor (Saleh, et al., 2000). The performance of SWAT was tested in Thur River basin (area 1700 km²), which is located in the Switzerland for sediment transport processes at catchment scale (Abbaspour, et al., 2007). It was found that quiet good results were obtained for sediment. Comparison of estimated and SWAT simulated average annual sediment loads for five major Texas river basin (20,593 to 569,000 km²)
lead to the conclusion that in all the river basins, SWAT simulated sediment yields compared reasonably well with estimated sediment yields obtained from the rating curves (Arnold, et al., 1999).

2.2 River flow and morphology model

SOBEK is a one-dimensional open-channel dynamic numerical modelling system, equipped with the user shell and which is capable of solving the equations that describe unsteady water flow, sediment transport and morphology and water quality. It can simulate and solve problems in river management, flood protection, design of canals, irrigation systems, water quality, navigation and dredging. Since it is equipped with sediment transport and morphological modules, it simulates sediment transport processes and the resulting changes of the river bed morphology (RIZA, 2005).

SOBEK 1 D morphological model was used to predict the sedimentation pattern in the Merowe reservoir, Sudan, and the reduction of sediment load in the downstream reach. One of the operation rules studied included flushing operations with 5 years interval. Almneh, (2005) found the parallel retreat of the bank of the river is responsible for the width change in river channel. However, in reaches where the degradation is limited due to the presence of bed rock (as is the case in the Main Nile downstream of the Merowe dam) the change in width cannot be quantified using a 1D model, but it might be substantial (Almneh, 2005).

The HEC-6 model is a one-dimensional model that predicts scour and deposition within rivers and reservoirs (US Army Corps of Engineers, 1998a). In river applications, HEC-6 simulates uniform changes in river bed elevation over the entire width of the channel which is caused by erosion and deposition over time under subcritical flow. The model has no provisions for simulating lateral channel changes, such as meander migration, or lateral changes in bed slope. The governing equations in HEC-6 include the energy equation, and conservation of mass for water and sediment. The momentum equation is not included in HEC-6, so environments with rapid fluctuations between subcritical and supercritical flow are inappropriate for modelling. In addition, HEC-6 assumes that sediment supply and demand are satisfied within each reach at each time step, and the model takes into account the effects of sediment gradation. HEC-6 is one of the most widely used and economical, commercially available sediment transport models.

GSTARS 2.0 is a stream tube model for alluvial river simulation. Backwater computations are carried out using the standard step method based on the conjunctive use of the energy and momentum equations. The model is able to deal with subcritical or supercritical flow regimes or both simultaneously. Stream tubes are used for hydraulics and sediment transport calculations to achieve a lateral variation within a cross section. Sediment routing and bed sorting and armouring computations are performed independently for each stream tube. The model has 13 transport functions for particle sizes ranging from clay to silt, sand, and gravel, including nonequilibrium transport and flows with high concentration of wash load. The model is able to predict variations in
channel width according to the theory of total stream power minimization (Yang and Simoes, 1998).

Sediment dynamics within pools of the North Fork Poudre River in Colorado as an example of the processes controlling fine sediment deposition, storage, and transport within laterally constricted pools was studied (Rathburn and Wohl, 2003). The 1996 release of $\sim 7000 \text{ m}^3$ of silt-to-gravel-sized sediment from a reservoir on the North Fork provided an opportunity to develop a field data set of fine sediment dynamics and to test the predictions of three different one- or two-dimensional sediment transport and hydraulic models against the field observations. The models were calibrated against quantitative measurements of pool scour and fill. One-dimensional HEC-6 results indicate that robust simulations yield the greatest agreement between predicted and measured pool bed elevation change. Model calibration on two pools and validation on one pool indicate that at least 58% of observed bed changes after the sediment release were predicted by HEC-6. Modeling accuracy using quasi-two-dimensional GSTARS 2.0 was considerably more variable, and no pool-wide trends were obtained. The two-dimensional model RMA2 substantially improved the representation of eddy pool hydraulics within a compound pool of the North Fork. Results from the hydraulic modeling, coupled with bed load and total load computations, delineate areas of scour and deposition which are consistent with observations in the field.

2.3 Model integration

Model integration is systematic sharing of information between models. The reason for integration is to support integrated water resources management that often requires a system approach to make decisions. Most of the times, it is impossible to make such decision using a single model while such decision could be possible through integration of various models. However, model integration demands additional efforts and resources which could be mentioned as a disadvantage. Model integration was done by many researchers (Debele, et al., 2008; Wool, et al., 1994; Dudley, et al., 2005; Leon, et al., 2003 and Seyoum, 2005).

Three possible ways of model integration may be identified as (i) loose coupling, (ii) tight coupling and (iii) fully integrated. Loose coupling integrates models with common file exchange usually in ASCII format. This type of integration requires a number of programs that exchange data from one application to another and possibly a data base management system (DBMS) and/or number of transfer files. A disadvantage of this approach is that there is no common graphical interface and the data exchange and conversion between the models can be very cumbersome. Loose coupling may also involve considerable work in changing data formats and the data structure, particularly if the models have been obtained from different sources. In tight coupling models integration is controlled by a system that provides a graphical user interface for viewing and controlling the integration. Unlike loose coupling, tight coupling does not require file conversion or editing; however, it is a complex process and requires a great deal of programming and data management plus a customised menu-driven user interface for display. In fully integrated systems, all the components are embedded in one single unit.
This requires all the models to be programmed and act as a component of the core program.

SWAT and a two-dimensional, Water Quality Model (CEQUAL-W2) are integrated to simulate the combined processes of water quantity and quality both in the upland watershed and downstream water body. Where as the SWAT model outputs water quality variables in its entirety, the CE-QUAL-W2 model requires inputs in various pools of organic matter contents. An intermediate program was developed to extract outputs from SWAT at required subbasin and reach outlets and converts them into acceptable CE-QUAL-W2 inputs. The CE-QUAL-W2 model was later calibrated for various hydrodynamic and water quality simulations in the Cedar Creek Reservoir, TX, USA. The results indicate that the two models are compatible and can be used to assess and manage water resources in complex watersheds comprised of upland watershed and downstream water bodies (Debele, et al., 2008).

Determining the sources and impacts of nutrient loadings from a watershed to a receiving waterbody can be a difficult but critical step in developing nutrient reduction strategies or waste load allocations. This assessment is typically accomplished using runoff and routing models (e.g. SWMM) to predict the non-point source loads and entering the information into hydrodynamic and water quality models of the waterbody (e.g. WASP and RIVMOD). The Linked Watershed/Waterbody model (LWWM) was developed to facilitate the model linkages. LWWM provides user friendly software that aids the user in the development of input data sets for the models and processing of the simulation results. LWMM also provides a linkage to geographical information systems (GIS) where watershed definitions and characterizations information can be obtained (Wool, et al., 1994).

A technical user interface approach based on expert system technologies that provide intelligent access to databases, models, scenarios and decision support outputs was used to integrate multi-model to a watershed management study on Lake Seymour, BC, Canada, where sediment erosion due to precipitation events or forest fires may lead to concerns of high turbidity conditions in a reservoir. First, a hydrological model (WatFlood) was used to model surface runoff in the watershed. The agricultural non-point source (AGNPS) model was then coupled with WatFlood to estimate runoff and sediment loads. A two-dimensional hydrodynamic model (Telemac-2D) was used to simulate the lake currents. Transport and dispersion models (SUBIEF and SedSim) were used to simulate the nutrient and sediment transport in the reservoir and assess the turbidity at the water supply intake. A water quality model (WQM) was then used to predict nutrient conditions in the lake. From this preliminary attempt, some insight was obtained from the integrated results readily that otherwise would have been difficult to achieve by other approaches such as simple manual approach (Leon, et al., 2003).

The Open Modelling Interface Environment (OpenMI) is used in variety of modelling linkage and proved to be satisfactory. The OpenMI was used to couple hydrological model MIKE SHE with river management model MIKE BASIN. The OpenMI simplifies the linking with a relatively small reengineering of up to a couple of hundred lines of code as compared to the thousands of lines of codes the model written. It provided the flexibility and applicability of the models are enhanced though performance issue was not
investigated (Christensen, 2004). The migrated HYMOD-RR and Ensemble Kalman Filter models into OpenMI compliant were linked using configuration class. The integrated models output was compared with batch file method and result was found same. In addition, the OpenMI linkage provided an advantage of speed and ease of customizing for other models (Seyoum, 2005).
3 Study Area

The Blue Nile River flows from Ethiopia highlands around Lake Tana about 3000 km\(^2\) (1780 m a.s.l) to Sudan (500 m) over a distance of roughly 940 km (Conway, 1997). The plateau country is not flat, but rather hilly with grassy downs, swamp valleys and scattered trees, see Figure 3.1. The highland plateau has been deeply incised by the Blue Nile and its tributaries and has a general slope to the northwest. The Didessa and Dabus, draining the southwestern of the basin contribute a third of the total flow. The upper Blue Nile characterized rapid land use change from forest to agricultural land due to rapid population growth. Vertisols is the dominant soil types through the basin. Poor land cover coupled with hilly topography led to quick concentration of runoff into outlet hence affecting the flow regime.

Climate is governed by the seasonal migration of the intertropical convergence zone from south to north and back, such that total precipitation as well as the length of the summer rain and runoff season progressively decrease northward (from > 2000 mm/a in the Baro basin, to \(\sim\) 1500 mm/a in much of the Blue Nile basin (Sutcliffe and Parks, 1999). Since the rainfall is highly seasonal, the Blue Nile possesses a highly seasonal flood regime with over 80% of annual discharge occurring in the four months from July to October, while 4% of the flow occurs during the driest period from January to April. In the basin the annual mean potential evaporation decrease with increasing elevation from 1800 mm to 1200 mm.

The river course crosses humid to semiarid climate conditions and there is usually little additional runoff North of Roseries in the Sudan except for the two tributaries, the Dinder and Rahad. These join downstream of Roseries but have their headwaters in the Ethiopian Highlands. The Blue Nile below the Roseries is mild stream with a slope of about 0.12 x 10\(^{-3}\) which is about one tenth of the torrential stream which prevails all the way from the exit of the Lake Tana to Roseires (Shahin, 1985). The reach between Roseires and Sennar gets 600 mm as an average depth of rain and 2450 mm evaporation per annum.

The Roseries dam is 1,000 m long and 68 m height concrete dam with the crest at 485.2 m. The dam was completed in 1966 to store water for irrigation and water supply and for generating hydropower. The dam contains 5 deep sluices and a gated spillway, consisting of 7 units, with a maximum discharge capacity at level 483.0m of 16,500 m\(^3\)/s. The hydroelectric potential amounts 212 MW. The volume of the reservoir was originally 3,000 M m\(^3\) at a level of 480m with a surface area of 290 km\(^2\) extending over a length of 75 km. The storage capacity has been considerably affected by siltation and is now about 30 percent less than originally. A special operation strategy, by maintaining a low reservoir level and high flow velocities during the passage of the flood, is applied to reduce siltation (delft-hydraulics, 1992).

The Sennar dam was built in the 1920’s to supply the Gezira irrigation scheme by gravity from a head works on the left bank of the river. Lately in 1966 a small hydropower station of 15 MW was built on the east side of the dam. The volume of the reservoir was originally 930 Mm\(^3\) at a level of 424.70 m, with a surface area of 160 km\(^2\). The storage
capacity has been considerably reduced by siltation and it is now around 50 percent of the original capacity. Like Roseries reservoir, the operation strategy is to keep the level minimum at 420.20 m during the rising flood to allow the minimum siltation as possible (delft-hydraulics, 1992).

Figure 3.1 Study area Blue Nile
4 Input Data

SWAT requires land use, soil, topography and weather input data to model a catchment. The following land use, soil and topography data were obtained from public sources:

- **Digital Elevation Model (DEM):** DEM from SRTM (Shuttle Radar Topography Mission available at [http://www2.jpl.nasa.gov/srtm/index.html](http://www2.jpl.nasa.gov/srtm/index.html)) with spatial resolution of 3 arc-second (approximately 90 meters) has been used for catchment and subcatchment delineation. The SRTM "finished" data meet the absolute horizontal and vertical accuracies of 20 meters and 16 meters respectively. These data are provided in mosaiced 5 deg x 5 deg tiles for easy download and use ([http://srtm.csi.cgiar.org/](http://srtm.csi.cgiar.org/)). A total of 4 tiles in ASCII format were downloaded, converted into raster (grid) and mosaiced using ARCGIS 9.2 to produce DEM that cover the study area well. Moreover, the DEM sinks was filled using ARCGIS to avoid flow to imaginary sink.

- **Digital stream network (DSN):** DSN-HYDRO1k is the USGS’ HYDRO1k stream network database is used to guide the flow accumulation layer for areas with an upstream drainage area greater than 1000 km².

- **Soil map:** The FAO, Food and Agriculture Organization of the United Nations (FAO, 1995) provides about 5000 soil types at a spatial resolution of 10 kilometres with soil properties for two layers (0-30 cm and 30-100 cm depth). Additional soil properties (e.g. particle-size distribution, bulk density, organic carbon content, available water capacity, and saturated hydraulic conductivity) were obtained from Reynolds et al. (1999) or by using pedotransfer functions implemented in the model Rosetta ([http://www.ars.usda.gov/Services/docs.htm?docid=8953](http://www.ars.usda.gov/Services/docs.htm?docid=8953)).

- **The soil database:** Soil parameter data of International Soil Reference and Information Centre (ISRIC) at 1° spatial resolution, has been obtained from ([http://islscp2.sesda.com/ISLSCP2_1/html_pages/groups/hyd/islscp2_soils_1deg.htm](http://islscp2.sesda.com/ISLSCP2_1/html_pages/groups/hyd/islscp2_soils_1deg.htm)).

- **Landuse map:** The USGS Global Land Cover Characterization (GLCC) database ([http://edcsns17.cr.usgs.gov/glcc/glcc.html](http://edcsns17.cr.usgs.gov/glcc/glcc.html)) with a spatial resolution of 1 kilometre and 24 classes of landuse representation has been used in the model. The parameterization of the landuse classes (e.g. leaf area index, maximum stomatal conductance, maximum root depth, optimal and minimum temperature for plant growth) is based on the available SWAT landuse classes and literature research (Schuol and Abbaspour, 2007).

- **Weather, flow and sediment:** Measured ground temperature and rainfall data at stations within the Upper Blue Nile, were used to run the model. Most of stations either established recently or had many missing data. Therefore, a weather generator based on monthly statistics was used to fill in the gaps. Solar radiation and wind speed was generated by the weather generator. The observed flow data and sediment
concentration generated using sediment rating curves at El Deim, outlet of the basin was used for calibration and validation.

- **Sediment rating curve:**
  A sediment rating curve describes the average relation between discharge and suspended sediment concentration for a certain location (Asselman, 2000). The sediment rating curve is usually expressed as a power function of discharge (see equation 4.1).

  \[ Q_s = aQ^b \]  

  Where \( Q_s \) is suspended sediment transport (M tons/day)  
  \( Q \) is water discharge (m\(^3\)/s)  
  \( a \) and \( b \) are regression coefficient and exponent, respectively

The NBCBN/ River Morphology Research Cluster has developed sediment rating curve at El Deim (see Figure 4.1 and Figure 4.2) using available solid and liquid paired data. The suspended sediment was measured by bottling sampling taken once a day from the channel bank (NBCBN-RM, 2005).

![Figure 4.1 Suspended sediment rating curve for El Deim gauging station, rising flood stage](image)

Figure 4.1 and Figure 4.2 show sediment rating curve for the rising (July and August) and falling (September and October) flood stage that was quiet right. The reason was that the Blue Nile flood is highly seasonal so does the sediment transport rate. Although from the two figures it seems a linear least squares fit of the logarithms of the data points used, rather they used eye fitting to avoid the erroneous result that may be caused from the considerable scatter (NBCBN-RM, 2005).
Equations 4.2 and 4.3 show sediment rating curve for the rising and falling flood stage. It can be seen that they used b is equal to 1.0 for the rising flood stage and b is equal to 2.0 for falling flood stage.

\[
Q_s = 4.286 \times 10^{-4} Q^{1.0} \\
\]

\[
Q_s = 1.837 \times 10^{-9} Q^{2.0} \\
\]

We could not able to use the sediment load estimated from the above rating curve to calibrate the SWAT since the sediment load of a river is likely to be underestimated when concentrations are estimated from water discharge using least squares regression of log-transformed variables (Crowder, et al., 2007, Singh and Durgunoglu, 1989). Moreover, we were not able to estimate the concentration since the b values are constant and gave us constant concentration which is unrealistic. Therefore, it was necessary to develop new rating curve which could be used for the study. We got two years data for 1992 and 1993 flood season from Wad Madani Hydraulic Research Station, Sudan.

\[
Q_s = 1 \times 10^{-4} Q^{1.142} \\
\]
We constructed sediment rating curve using linear least squares fit of the logarithms. Figure 4.3 shows the sediment rating curve and equation 4.4 describes the function for the rising flood stage. While, Figure 4.4 shows the sediment rating curve and equation 4.5 describes the function for falling flood stage.

Model efficiency was measured using the Nash-Sutcliffe (NS) statistical test for sediment rating curve models developed by NBCBN and us. It was obtained that NS of 0.31 and 0.56 for equation 4.2 and 4.4, respectively during the rising flood stage. While Ns of 0.62 and 0.75 was obtained for equations 4.3 and 4.5 models, respectively during the falling flood stage. Therefore, the rating curve developed by us was found better because not only it addresses our interest but also perform better.

\[ Q_s = 7 \times 10^{-10} Q^{2.4643} \]

**Figure 4.3** Suspended sediment rating curve for El Deim gauging station, rising flood stage
Figure 4.4 Suspended sediment rating curve for El Deim gauging station, falling flood stage
5 Methodology

To model the erosion and sediment transport in the Blue Nile, SWAT and SOBEK have been linked to each other. The selection criteria for SWAT and SOBEK are pointed below:

- Capability of modelling rainfall runoff, soil erosion and sediment transport.
- Good model documentation and model support.
- Proven record of application with sufficient history.
- A few data requirements.
- Linkage capability and adaptability.
- Model availability and cost.

Figure 5.1 Models application to the study area
Most of the models do not model both erosion/deposition from catchment and channel, often they model channel erosion, transportation and deposition. Despite SWAT models sediment transport both at catchment and river channel, the sediment routing routine has relatively simplistic equations that do not catch the process that happen in long river reach. The equations do not consider sediment transport characteristics, such as bottom shear stress and also very limited description of channel morphology, which determines whether erosion or deposition will occur, given flow velocities (Benaman, et al., 2005). Moreover, it does not enable to model the backwater effect on sediment deposition caused by hydraulic structures which is the case of the study area. For instance, some adaptations to channel processes were suggested that improves mass balance, flow velocity, and in-stream water processes (Van Griensven, et al., 2006). Therefore, there was a need to couple SWAT with model that better route sediment in long river reach such as SOBEK-RE.

The SWAT model was used to model the upper Blue Nile till the outlet El Deim. SOBEK was used to route the flow as well as the sediment together from the El Deem to Khartoum, see figure 5.1. The OpenMI interface was used to link the two models at the boarder.

### 5.1 SWAT model

#### 5.1.1 SWAT model description

Soil and Water Assessment Tool (SWAT) is a physical process based model developed by Dr. Jeff Arnold in Texas to simulate the process at catchment scale on daily time step (Neittsch et al., 2005). The objective of SWAT model development was to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, landuse and management conditions over long periods of time. It divides a catchment or basin in to sub-basins by hydrological response unit (HRU) based on soil type, land use and management practice. Thus, dividing the basin into HRU will simulate the hydrological process in detail. SWAT simulates the hydrology of a watershed in to two phases, the land and water or routing phases of the hydrologic cycle. The land phase of the hydrologic cycle controls the amount of water, sediment, nutrient and pesticide loadings to the main channel. The routing phase of the hydrologic cycle defines the transport of water, sediment, nutrient and pesticide through the channel to the outlet of the subbasin.

SWAT simulates the hydrologic cycle of the subbasin using water balance equation:

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

where $SW_t$ is the final water content (mm), $SW_0$ is the initial water content on day $i$ (mm), $t$ is time (day), $R_{\text{day}}$ is amount of precipitation on day $i$ (mm), $Q_{\text{surf}}$ is the amount of runoff on day $i$ (mm), $E_a$ is the amount of evapotranspiration on day $i$ (mm), $w_{\text{seep}}$ is the amount of water entering of the vadose zone from the soil profile on day $i$ (mm), and $Q_{gw}$ is the amount of return flow on day $i$ (mm).
The hydrologic cycle in SWAT simulation involves the storage of precipitation by canopy and soil. The canopy held the precipitation made available directly for evaporation. The precipitation infiltrates into the soil, stored in the soil profile and once the precipitation ceased redistribution occurs because of water content differences in the soil profile. As the infiltration capacity of the soil decreases gradually surface runoff is generated. Percolation occurs when the field capacity of the soil is exceeded and the layer below is not saturated. SWAT predicts the canopy as well as soil storage using the curve number or the Green & Ampt infiltration method based on the daily or subdaily precipitation data used, respectively. The main components of water balance are discussed below but the detail description of the hydrologic cycle could be seen in Arnold et al., (1998) and Neittsch et al., (2005).

Surface runoff volume is computed using the modified SCS curve number method (USDA, 1972) or the Green & Ampt infiltration method (Green and Ampt, 1911). In this study the curve number method was used because daily precipitation use (see equation 5.4).

\[
Q_{surf} = \frac{(R_{day} - I_{a})^2}{(R_{day} - I_{a} + S)}
\]

where \(Q_{surf}\) is the accumulated runoff or rainfall excess (mm), \(R_{day}\) is the rainfall depth (mm), \(I_{a}\) is the initial abstractions which includes surface storage, interception and infiltration prior to runoff (mm) and \(S\) is the retention parameter (mm). The retention parameter defined as:

\[
S = 25.4 \left( \frac{1000}{CN} - 10 \right)
\]

where \(CN\) is curve number of the day. The initial abstractions usually approximated as \(0.2S\) and equation 5.2 becomes:

\[
Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)}
\]

Peak runoff rate predictions are made using the modified rational method, see equation 5.5.

\[
q_{peak} = \frac{\alpha_c \cdot Q_{surf} \cdot \text{Area}}{3.6 t_{conc}}
\]

where \(q_{peak}\) is the peak runoff rate \((\text{m}^3\text{s}^{-1})\), \(\alpha_c\) is the fraction of daily rainfall that occurs during the time of concentration, \(Q_{surf}\) is the surface runoff (mm), Area is the subbasin area \((\text{km}^2)\), and \(t_c\) is the time of concentration for the subbasin (hr).

The model provides three methods for estimating potential evapotranspiration: Priestly-Taylor (Priestley and Taylor, 1972), Penman-Monteith (Monteith, 1965), and Hargreaves (Hargreaves and Riley, 1985). The Penman-Monteith method requires solar radiation, air temperature, wind speed and relative humidity. If wind speed, relative humidity, and
solar radiation are not available Priestly-Taylor and Hargreaves provides options. The SWAT computes evapotranspiration from soils and plant separately.

The percolation is calculated for each soil layer. The percolation component uses a storage routing technique combined with crack flow model to predict flow in each soil layer. The volume of water available for percolation in the soil layer is calculated using equations 5.6 and 5.7:

\[
SW_{ly, excess} = SW_{ly} - FC_{ly} \quad \text{if} \quad SW_{ly} > FC_{ly}
\]

\[
SW_{ly, excess} = 0 \quad \text{if} \quad SW_{ly} \leq FC_{ly}
\]

where \(SW_{ly, excess}\) is the drainable volume of water in the soil layers in a given day (mm), \(SW_{ly}\) is the water content of the soil layer in a given day (mm), and \(FC_{ly}\) is the water content of the soil layer at field capacity (mm). The amount of water that moves from one layer to the other calculated using the storage routing technique, equation 5.8:

\[
w_{ly, excess} = SW_{ly} \left(1 - \exp \left[-\frac{-\Delta t}{TT_{perc}}\right]\right)
\]

where \(w_{ly, excess}\) is the amount of water percolating to the underlying soil layer on a given day (mm), \(SW_{ly, excess}\) is the drainable volume of water in the soil layers in a given day (mm), \(\Delta t\) is the length of the time step (hrs), and \(TT_{perc}\) is the travel time for percolation (hrs). The travel time for percolation computed for each soil layer using the linear storage, equation 5.9.

\[
TT_{perc} = \frac{SAT_{ly} - FC_{ly}}{K_{sat}}
\]

Groundwater flow contribution to the total stream flow is simulated by creating shallow aquifer storage. The water balance for shallow aquifer is computed with equation 5.10.

\[
aq_{sh,i} = aq_{sh,i-1} + w_{rechrg,sh} - Q_{gw} - w_{revap} - w_{pump,sh}
\]

where \(aq_{sh,i}\) is the amount of water stored in shallow aquifer on day \(i\) (mm), \(aq_{sh,i-1}\) is the amount of water stored in shallow aquifer on day \(i-1\)(mm), \(w_{revap}\) is the amount of water moving into the soil zone in response to water deficiencies on day \(i\) (mm), \(w_{rechrg,sh}\) is the amount of recharge entering shallow aquifer on day \(i\) (mm), and \(Q_{gw}\) is groundwater flow or base flow on day \(i\) (mm). Groundwater flow from shallow aquifer to stream is estimated with equations 5.11 and 5.12.
\[ Q_{gw,i} = Q_{gw,i-1} \exp\left(-\alpha_{gw} \Delta t\right) + w_{rechrg,sh} \left(1 - \exp\left(-\alpha_{gw} \Delta t\right)\right) \quad \text{if} \quad aq_{sh} > aq_{shthl,q} \quad 5.11 \]

\[ Q_{gw,i} = 0 \quad \text{if} \quad aq_{sh} < aq_{shthl,q} \quad 5.12 \]

where \( Q_{gw,i} \) is groundwater flow or base flow in to the main channel on day \( i \) (mm), \( Q_{gw,i-1} \) is groundwater flow or base flow in to the main channel on day \( i-1 \) (mm), \( \alpha_{gw} \) is baseflow recession constant, \( \Delta t \) is the time-step (day), \( w_{rechrg,sh} \) is the amount of recharge entering shallow aquifer on day \( i \) (mm), \( aq_{sh} \) is the amount of water stored in shallow aquifer at the beginning of the day \( i \) (mm), \( aq_{shthl,q} \) is the threshold water level in the aquifer for groundwater contribution to the main channel to occur (mm).

SWAT routs flood in the channel using kinematic wave model variations i.e., Variable Storage routing method or Muskingum river routing method.

SWAT computes the subcatchment sediment yield using the Modified Universal Equations (MUSLE) which uses runoff energy to detach and transport sediment (Williams, 1978). The modified universal soil loss equation is:

\[ sed = 11.8 \cdot (Q_{surf} \cdot q_{peak} \cdot area_{hr},)^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG \quad 5.13 \]

where, \( sed \) is the sediment yield on a given day (metric tons), \( Q_{surf} \) is surface runoff volume (mm \( H_2O / ha \)), \( q_{peak} \) is peak runoff rate (m\(^3\)/s), \( area_{hr}, \) is area of HRU (ha), \( K_{USLE} \) is USLE soil erodibility factor (0.013 metric ton m\(^2\) hr/(m\(^3\)-metric ton cm)), \( C_{USLE} \) is USLE cover and management factor, \( P_{USLE} \) is USLE support practice factor, \( LS_{USLE} \) is USLE topographic factor, \( CFRG \) is coarse fragment factor.

Once the sediment load in the surface runoff calculated, the amount of sediment released to the main channel is calculated (Neitsch et al, 2005):

\[ sed = \left(sed^i + sed_{stor,j-1}\right) \cdot \left(1 - \exp\left[ - surflag \Delta t \right]\right) \quad 5.14 \]

where, \( sed \) is the amount of sediment discharged to the main channel on a given day (metric tons), \( sed^i \) is the amount of sediment load generated in the HRU on a given day (metric tons), \( sed_{stor,j-1} \) is the sediment stored or lagged from previous day (metric tons), \( surflag \) is the surface runoff lag coefficient, \( t_{conc} \) is the time of concentration for the HRU (hrs).

Sediment is routed using stream power to predict degradation and fall velocity to estimate deposition in the channel (Arnold et al, 1995). However, SWAT version 2005 the equations were simplified and the maximum amount of sediment that can be transported from a reach segment is a function of peak channel velocity. The peak channel velocity, \( V_{ch,pk} \), is calculated (Neitsch et al, 2005):

\[ V_{ch,pk} = \frac{q_{ch,pk}}{A_{ch}} \quad 5.15 \]

where, \( q_{ch,pk} \) is the peak flow rate (m\(^3\)/s) and \( A_{ch} \) is the cross sectional area of the flow in the channel (m\(^2\)). The peak flow rate is defined as:
\[ q_{ch,pk} = \text{prf} \cdot q_{ch} \]  
5.16

where, \text{prf} is the peak rate of adjustment factor, and \( q_{ch} \) is the average rate of flow (m\(^3\)/s).

The maximum amount of sediment that can be transported from a reach segment is calculated:

\[ \text{Conc}_{\text{sed},ch,max} = C_{sp}V_{ch,pk} \]  
5.17

where \( \text{Conc}_{\text{sed},ch,max} \) is the maximum concentration of sediment that can be transported by the water (ton/m\(^3\) or Kg/L), \( C_{sp} \) is a coefficient defined by the user, \( V_{ch,pk} \) is the peak channel velocity (m/s) and \( \text{spexp} \) is an exponent defined by the user (varies between 1.0 and 2.0).

To determine deposition or degradation, the calculated maximum sediment concentration will be compared to the concentration of sediment in the reach at the beginning of the time step, \( \text{Conc}_{\text{sed},ch,i} \). If the \( \text{Conc}_{\text{sed},ch,i} > \text{Conc}_{\text{sed},ch,max} \) deposition is the dominant process in the reach segment and the net amount of deposited is calculated:

\[ \text{Sed}_{\text{dep}} = (\text{Conc}_{\text{sed},ch,i} - \text{Conc}_{\text{sed},ch,max}) \cdot V_{ch} \]  
5.18

where \( \text{Sed}_{\text{dep}} \) is the amount of sediment deposited in the reach segment (metric tons), \( \text{Conc}_{\text{sed},ch,i} \) is the initial sediment concentration in the reach (Kg/L or ton/m\(^3\)), \( \text{Conc}_{\text{sed},ch,max} \) is the maximum concentration of sediment that can be transported by the water (ton/m\(^3\) or Kg/L), \( V_{ch} \) is the volume of water in the reach segment (m\(^3\) H\(_2\)O).

If the \( \text{Conc}_{\text{sed},ch,i} < \text{Conc}_{\text{sed},ch,max} \) degradation is the dominant process in the reach segment and the net amount of sediment reentrained is calculated:

\[ \text{Sed}_{\text{deg}} = (\text{Conc}_{\text{sed},ch,max} - \text{Conc}_{\text{sed},ch,i}) \cdot V_{ch} \cdot K_{CH} \cdot C_{CH} \]  
5.19

where \( K_{CH} \) is the channel erodability factor (cm/hr/Pa) and \( C_{CH} \) is the channel cover factor.

Once the amount of deposition and degradation has been calculated, the final amount of sediment in the reach is determined:

\[ \text{Sed}_{ch} = \text{sed}_{ch} - \text{sed}_{\text{deg}} + \text{sed}_{\text{dep}} \]  
5.20

where \( \text{sed}_{ch} \) is the amount of suspended sediment in the reach (metric ton), \( \text{sed}_{\text{dep}} \) is the amount of sediment deposited in the reach segment (metric ton), \( \text{sed}_{\text{deg}} \) is the amount of sediment reentrained in the reach segment (metric tons). The amount of the sediment transported out of the reach is calculated:

\[ \text{Sed}_{out} = \text{sed}_{ch} \cdot \frac{V_{out}}{V_{ch}} \]  
5.21

where, \( \text{Sed}_{out} \) is the amount of sediment transported out of the reach (metric tons), \( \text{sed}_{ch} \) is the amount of suspended sediment in the reach (metric tons), \( V_{out} \) is the volume of
outflow during the time step (m\(^3\) H\(_2\)O), \(V_{ch}\) is the volume of water in the reach segment (m\(^3\) H\(_2\)O). Moreover, channel down cutting computed by updating channel dimension when the volume of water in the reach exceeds 1.4 \(\times\) 10\(^6\) m\(^3\).

5.1.2 SWAT model Setup

5.1.3 Watershed delineation

Watershed delineation is needed to divide the watershed into hydrologically connected subwatershed. The DEM was processed from the CGIAR-CSI GeoPortal that provides SRTM 90m Digital Elevation Data for the entire world. The SRTM data is available as 3 arc second (approx. 90m resolution) DEMs. The vertical error of the DEM's is reported to be less than 16m. This data are provided in mosaiced 5 deg x 5 deg tiles for easy download and use (http://srtm.csi.cgiar.org/). A total of 4 tiles in ASCII format were downloaded, converted into raster (grid) and mosaiced using ARCGIS 9.2 to produce DEM that cover the study area well. Moreover, the DEM sinks was filled using ARCGIS to avoid flow to imaginary sink.

DEM Setup
To delineate the watershed Digital Elevation Map (DEM) grid, mask grid and digitized stream network files were loaded using the watershed delineation tool. Topographic information was obtained from DEM which has projection. The masking was done to focus catchment area because DEM covers more area than the watershed to be modelled. Stream network was used to improve hydrographic segmentation and subwatershed boundary delineation (Biesbrouck, et al., 2002).

Stream Definition
The threshold area refers to the upstream drainage area required to define the beginning of the stream (Biesbrouk et al., 2002). The default threshold area calculated was replaced with realistic value that can well simulate both flow and sediment. (Jha, et al., 2004) studied appropriate level of subwatershed division for simulating flow, sediment, and nutrients. They found out that stream flow is not significantly affected by increasing the number of subwatersheds. However, the threshold drainage area of the subwatersheds, at which point the predicted sediment yields stabilized, was found to range between 2 and 6 percent of the total drainage area, with a median value of 3 percent. Accordingly, the default value replaced with 1,000,000 ha (5.6 % of total area) which is greater than 3 % total drainage area, which they proposed as the threshold area for adequate and efficient simulation of sediment yield for a given watershed. Then AVSWAT calculates the outlet of each subbasin and the outlet for the whole catchment was done manually, see Figure 5.2.
Landuse and Soil Definition

Landuse and soil define the characteristics of land cover and soil distribution of the basin. Grid landuse map with resolution of 1 km and soil map of FAO with resolution of 10 km with same projection as DEM were used, see figure 5.3 and 5.4. Then the landuse and soil map were overlayed to provide a unique combination of landuse and soil, hydrologic response unit (HRU).
HRU Distribution
The subbasins are divided into multiple HRUs. The numbers of HRUs in the subbasin are determined by user specified landuse and soil class threshold. In this study, 5% landuse over subbasin area and soil class over landuse area threshold were used. That means, landuse and soil class which has less than 5% coverage in the subbasins was eliminated. Therefore, 5% threshold reduced the numbers of HRUs from 610 to 110. After elimination, the remaining landuse and soil class was redistributed to cover the whole subbasin.

Weather Data
Observed rain gages and temperatures data were used as an input. However, the data that were used had missing data that should be filled. Thus, a total of 10 weather generator stations were prepared from those stations which has reasonable good quality data. For the remaining weather parameters, such as solar radiation, wind speed and relative humidity, model simulation data were used, see figure 5.2.

Building Input Data
Input for SWAT defined at watershed, subbasin or HRU levels. Unique features such as reservoir and point sources must have input data provided for each individual feature included in the watershed simulations. Watershed level inputs are parameters valid for the entire basin, e.g. to indicate model processes throughout the watershed, for instance a
method used to estimate evapotranspiration subbasin data. Subbasin level inputs define values for all HRUs within a certain subbasin such as for example rainfall and temperature information. HRU level inputs are inputs that can be set to unique values for each HRU in the watershed, an example could be the management scenario simulated in HRU (Neitsch et al., 2005).

After the input files generated, SWAT is ready to start simulation. Thus the simulation period starts January, 1980 and ends December 2003.

5.1.4 Sensitivity Analysis
Sensitivity analysis is an instrument for the assessment of the impact of the input parameters with the respect to the model output. This is useful not only for model development, but also for model validation and reduction of uncertainty (Hamby, 1994). The sensitivity analysis is done by varying parameters value and checking how the model reacts. If small change on a given parameter value results on a remarkable change on the model output, the parameter is said to be sensitive to the model.

SWAT 2005 has a routine to conduct automatic sensitivity analysis; LH-OAT sensitivity analysis has been used. The LH/OAT (Latin-Hypercube/One-factor-At-a-Time) sensitivity analysis method combines the robustness of the Latin Hypercube sampling that ensures that the full range of all parameters has been sampled with the precision of an OAT designs assuring that the changes in the output in each model run can be unambiguously attributed to the input changed in such a simulation leading to a robust and efficient sensitivity analysis method (van Griensven, et al., 2006). The concept of the Latin-Hypercube Simulation is based on the Monte Carlo Simulation but uses a stratified sampling approach that allows efficient estimation of the output statistics. The OAT design is an integration of local to global sensitivity method where each run has only one parameter changed, so the changes in the output in each model run can be unambiguously attributed to the input parameter changed. Thus, automatic sensitivity analysis was carried out and those parameters that influence the predicted outputs were used for model calibration.

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

SWAT model can be calibrated both manually and automatically. The manual calibration is most widely used calibration and involves visual comparison of observed and simulated data. It uses trial and error to adjust the parameters and closeness is evaluated with several criteria. Automatic calibration involves statistical test such as root mean square error (RMSE) or automatic optimization such as Shuffled Complex Evolution to achieve objective functions. Automatic optimization is algorithms that optimize an
objective function by systematically searching the parameter space according to fixed set of rules.

Parasol (Parameter Solutions method) is a method to perform automatic calibration which has been implemented in SWAT 2005. Parasol undertakes both optimization and uncertainty analysis in a single (Van Griensven et al., 2006). The automatic calibration procedure in Parasol is based on the Shuffled Complex Evolution algorithm. It combines the direct search method of the simplex procedure with the concept of a controlled random search of (Nelder and Mead, 1965), a systematic evolution of points in the direction of global improvement, competitive evolution (Holland, 1995) and the concept of complex shuffling., a systematic evolution of points in the direction of global improvement, competitive evolution and the concept of complex shuffling.

5.2 River flow and morphology modelling

5.2.1 SOBEK-RE model description

SOBEK is a one-dimensional open-channel dynamic numerical modelling system, equipped with the user shell and which is capable of solving the equations that describe unsteady water flow, sediment transport, morphology and water quality. It can simulate and solve problems in river management, flood protection, design of canals, irrigation systems, water quality, navigation and dredging. Since it is equipped with sediment transport and morphological modules, it simulates sediment transport processes and the resulting changes of the river bed morphology (RIZA, 2005).

The flow in one dimension is described by two equations: the momentum equation and the continuity equation. The sediment includes the continuity equation of sediment and the formula of sediment load (Sloff, 2006).

\[
\frac{\partial A}{\partial t} + \frac{\partial Q \nu}{\partial X} = 0
\]  

5.22

\[
\frac{\partial Q}{\partial t} + \frac{\partial}{\partial X} \left( \alpha_B \frac{Q^2}{A_f} \right) + g A_f \frac{\partial h}{\partial X} + \frac{gQ|Q|}{C^2 R A_f} = 0
\]  

5.23

in which:
- \( Q \) is discharge \([m^3/s]\)
- \( t \) is time \([s]\)
- \( x \) is distance \([m]\)
- \( \alpha_B \) is Boussinesq coefficient [-]
- \( A_f \) is cross section with flow \([m^2]\)
- \( A_t \) is total cross section \([m^2]\)
g is acceleration due to gravity [m/s²]

h is water level [m]

C is Chézy coefficient [m¹/²/s]

R is hydraulic radius [m]

W is flow width [m]

In a situation with steady-uniform flow the water depth approaches the normal depth value. The normal depth follows from equation 5.24 by eliminating the acceleration and convection terms, and replacing the surface slope \( \frac{\partial h}{\partial X} \) by the bed slope \( i \) [m/m]:

\[
h_n = \sqrt[4]{\frac{Q^2}{W^2 C^2 i}}
\]

The flow velocity \( u \) then follows from the continuity equation: \( Q = Wu h_n \)

A sediment transport formula can be selected, for instance Engelund-Hansen or Meyer-Peter-Müller. Often sediment transport formulas can be rewritten as a power law of the flow velocity:

\[
s = au^b
\]

in which:

- \( s \) is sediment transport per unit width, excluding pores [m²/s]
- \( a \) is coefficient \([m^{2-b}/s^{1-b}]\)
- \( b \) is exponent representing the degree of nonlinearity [-]
- \( u \) is current velocity [m/s]

In transport formulae in SOBEK the Shields parameter is often the governing parameter. It is defined as:

\[
\theta = \frac{u^2}{C^2 \Delta D} - \frac{h \cdot i}{\Delta D}
\]

in which:

- \( D \) is characteristic grain size of bed material [m]
- \( D_{50} \) is relative density of sediment (for sand \( \Delta = 1.65 \) [-])
- \( \theta \) is Shields parameter [-]

The formula of Engelund and Hansen can be written (for transport without pores) as:

\[
s = 0.05 \sqrt{\frac{g \Delta D_{50}}{g}} \frac{C^2}{g} \theta^{5/2} = 0.05 \frac{u^5}{\sqrt{g C^3 \Delta^2 D_{50}}}.
\]

in which:

- \( u^* \) is shear velocity = \( (u \cdot \sqrt{g})/C \) [m/s]
- \( D_{50} \) is median grain size of bed material [m]

Engelund and Hansen is valid for situations in which \( w_s/u^* < 1, 0.19 < D_{50} < 0.93 \text{ mm}, \) and \( 0.07 < \theta < 6 \) (in which \( w_s \) is the fall velocity).
The formula of Meyer-Peter and Müller is defined as:

\[ s = 8 \cdot D_m^3 \sqrt{g \Delta (\mu \theta - 0.047)^{3/2}} \]  \hspace{1cm} 5.27

in which:
- \( D_m \) is mean grain size of bed [m]
- \( \mu \) is ripple factor = \( (C/C_{90})^{3/2} \) [-]
- \( C_{90} \) is grain roughness = \( 18 \cdot \log (12h/D_{90}) \)

It is valid for situations in which \( ws/u^* > 1 \), \( D_m > 0.4 \) mm, and \( \mu \theta < 0.2 \).

To obtain the sediment-transport rate including pores, it is necessary to multiply the equations above with a factor \( 1/(1-\epsilon_p) \) in which \( \epsilon_p \) is the porosity of the bed (in the order of 0.4). Output of sediment-transport rates from SOBEK-RE is presented as transport including pores.

For the bed level, the sediment transport balance in SOBEK is used for the total cross section:

\[ \frac{1}{1-\epsilon_p} \frac{\partial A}{\partial t} + \frac{\partial S}{\partial X} = 0 \]  \hspace{1cm} 5.28

in which:
- \( A \) is area of cross section [m\(^2\)]
- \( S \) is sediment transport through a cross section [m\(^3\)/s]
- \( \epsilon_p \) is fraction of pores [-]

For a constant width, this equation reduces to:

\[ \frac{1}{1-\epsilon_p} \frac{\partial Z_b}{\partial t} + \frac{\partial s}{\partial X} = 0 \]  \hspace{1cm} 5.29

in which:
- \( Z_b \) is bed level [m]
- \( s \) is sediment transport per unit width, excluding pores [m\(^2\)/s]

The simulations in SOBEK are carried out following a decoupled approach. In this approach the flow, sediment and morphology simulation are decoupled in a way that they are sequentially called at every time step. Decoupling of the equations is only valid for flows with Froude numbers which are not close to unity.

The numerical scheme used by SOBEK for computing the morphology is a Lax-Wendroff type of scheme (Lax and Wendroff, 1960, 1964 and Hirsch, 1990). It is so-called explicit scheme which means that the solutions for bed-levels at a next time level are computed from known values from the preceding time level. The time-step used by this scheme can only be limited to prevent instability. This scheme differs from the Preissmann scheme which is used for solving the flow equations. The Preissmann scheme is an ‘implicit scheme’ which implies that it includes the unknown values for the next time level with the known values from the previous time level in the equations which have to be solved. The method allows for large time steps, but results in a large number of equations which have to be solved (using matrix solvers).
From the basic equations for flow and morphology, i.e. the partial differential equations expressing conservation of momentum and mass of fluid and sediment, certain mathematical and physical properties can be deduced. Most relevant for understanding the system are the characteristic celerities of the model which follow from the system (e.g., Jansen 1979, de Vries 1965). These celerities express the propagation speed of small disturbances (infinitely small waves) on the water surface or on the bed. For the equations used in the SOBEK model three celerities can be deduced:

- a negative and a positive celerity \( c_{1,2} \) associated to the propagation of long waves on the water surface \((\approx u \pm \sqrt{gh})\)
- a positive celerity associated to the propagation of small bed-waves, with a value:

\[
C_3 = \left( \frac{u_m \Psi}{1 - Fr^2} \right)
\]

where, \( \Psi = \left( \frac{\partial s}{\partial u} \right) \approx n \frac{s}{q} \) and \( C_3 \) in [m/s]

In which \( Fr = \) Froude number of the main-channel flow, \( h = \) average water depth in main channel, \( q = \) main-channel discharge per unit of width, \( s = \) sediment-transport rate per unit of width, \( u_m = \) flow velocity in main channel, \( n = \) power of the transport formula (if \( s = mu^n \)).

In the validity region of SOBEK-Rivers (Froude numbers less than unity, and particularly less than 0.6 to 0.8) the celerity for bed waves is significantly smaller than those for flow. This means that dynamic morphological processes occur on a much larger time-scale than the dynamic flow processes. Under this assumption quasi-steady water movement may be assumed. This means that at each morphological time step the flow is computed as a steady-state situation (e.g., a backwater-curve), implying that \( c_{1,2} \rightarrow \pm \infty \) compared to \( c_3 \) or that the terms \( \partial Q/\partial t \) in the momentum equation for flow and \( \partial A/\partial t \) in the continuity equation for flow can be neglected with respect to the other terms in their equations. This quasi-steady approach allows for changing flow conditions during the morphological simulation, where at each morphological time step the prevailing conditions are used to compute the corresponding steady flow field.

The use of a quasi-steady approach is often recommendable since it allows for much larger computational time steps than a fully unsteady flow simulation. In SOBEK simulation the computational time step is limited by the CFL-condition (after Courant, Friedrichs and Lewy) for stability of the numerical morphology scheme, or by restrictions of the numerical flow scheme with respect to the accuracy. The stability condition (CFL condition) for morphological simulations is expressed by the following relation:

\[
\sigma = \alpha_c c_3 \frac{\Delta t}{\Delta x} < 1
\]

Where

- \( c_3 \) is celerity of bed disturbances, equation (3)
- \( \Delta t \) is (morphological) time step
\[ \Delta x \quad \text{is} \quad \text{space step} \]
\[ \alpha_c \quad \text{is} \quad \text{stability factor preventing non-linear stability (e.g., 1.01)} \]
\[ \sigma \quad \text{is} \quad \text{dimensionless Courant number} \]

This condition can be used to estimate an appropriate time step for quasi-steady morphological simulations. If this condition is not met, the morphological time step is reduced automatically in such way, that the original time step is divided into the smallest number of equal sub-time steps required to satisfy this condition.

For simulations with unsteady flow the time step is not limited by stability criteria for the flow computation (only for morphological computation the CFL condition is applied). However, the use of a Courant number \( \sigma = c_1 \cdot \Delta t / \Delta x \) much larger than the order of 10 is not recommended due to limited accuracy. At large Courant numbers the flow simulation can give rise to small oscillations. Sometimes some extra damping can be introduced in computation by taking the Preissmann coefficient \( \theta = 1.0 \) instead of 0.55.

### 5.2.2 SOBEK-RE Model Setup

The output SWAT model both the flow and sediment was routed using the one dimensional model SOBEK-RE. Thus the model was changed from Flow module to Morphology by selecting morphology from physical aspect and for the model area river was selected. The model geographic area was defined \( x \) minimum equal 0 and \( x \) maximum 5000000 m and \( y \) minimum equal to 0 and maximum 500000 m.

**Cross-section**

The data for the cross section was used found from ministry of irrigation of the Sudan; it was surveyed in early 1990. There are 40 cross-sections with average distance of 20 km between Khartoum and Sinner, 36 cross-sections with average distance of 10 km between Sinner to Rosaries and 5 cross-sections at average distance of 20 km near the Rosaries dam and one cross-section was assumed at El Diem using Google Earth and the gauging station depth. However, some of the data were not used because they were not between the ranges and look suspicious. Figure 5.5 shows the mean bed level the study area.
Structures

Compound structure was made from General structures and Weir to model the dam that is at the study areas. The general structure was used to model 5 deep sluices that are used to flush the sediment and the broad weir used to model the 6 spill ways. Moreover, time controller was used to model the reservoir operation program. The time controller was used at Roseries and Sennar dams to regulate the water level upstream of the dam. The reason for the selection of such controller is that it requires only time series water level.

Friction

For friction a Chezy coefficient of 50 both for positive and negative flow was used.

Boundary and Initial conditions

Time series discharge hydrograph was used as upstream boundary conditions at El Deem and water level at Khartoum was used as downstream boundary conditions, see figures 5.6 and 5.7. The backwater effect goes to the till distance 53 km from Roseries dam. Thus, to avoid the backwater effect the upstream condition was used at El Diem station 105 km away the dam, see equation 5.32.

\[
dx = \frac{dh}{i} \left( \frac{1 - \left( \frac{h_n}{h} \right)^3}{1 - \left( \frac{h_n}{h} \right)^{3/2}} \right) \text{.........................................................5.32}
\]
Where $dx$ is horizontal change
$dh$ is vertical change, 5.3 m
$h_c$ is critical depth, 3.23 m
$h_n$ is normal depth, 10.98 m
$h$ is average depth, 15 m
$i$ is slope, 0.1 m/km

For morphology, time series sediment inflow of was used as an upstream boundary conditions (figure 5.8) at El Deem and bed level of 368 m at Khartoum for downstream conditions.
A discharge of 2000, 1000 and 600 m$^3$/s was defined at 0, 105 and 379 km as flow initial conditions and a water level of 486, 481 and 420 at 0, 105 and 379 km, respectively.

Figure 5.6 Upstream flow boundary condition at El Deem.
Figure 5.7 Downstream water level boundary condition at Khartoum.

Figure 5.8 Sediment upstream boundary condition at El Deem

**Numerical Parameter**

The selection of temporal and spatial parameter is important for the model satiability and accuracy especially for morphological simulation. Thus distance step of 1000 m was used.
In SOBEK-RE, the simulation of hydrodynamic module should be successful before proceeding to the morphology module. SOBEK simulate the hydrodynamics with implicit models. The Courant condition for stability does not have to be fulfilled in order to assure the stability of the calculations in implicit models, but it will influence the accuracy of the solution.

The value of the time step given by the Courant condition will be calculated as a reference:

The celerity of the flood waves is given by

\[ c = \frac{dQ}{B_s \, dh} \]  

5.33

Where \( c \) is celerity of flood wave (m/s)

\( B_s \) is storage width (m) = B in this case

\( dQ \) is maximum change in discharge (m³/s) in the rising limb

\( dh \) is change in water level for the corresponding discharges (m)

**Table 1** Parameters for hydrodynamic computation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>550 m</td>
</tr>
<tr>
<td>dQ</td>
<td>6000 m³/s</td>
</tr>
<tr>
<td>dh</td>
<td>5.3 m</td>
</tr>
<tr>
<td>c</td>
<td>2.06 m/s</td>
</tr>
<tr>
<td>ΔX</td>
<td>1000 m</td>
</tr>
<tr>
<td>Δt=ΔX/c</td>
<td>485.43 s</td>
</tr>
<tr>
<td>Δt</td>
<td>8.09 min</td>
</tr>
</tbody>
</table>

Since hydrodynamic module use implicit scheme the CFR should not necessarily satisfied. Hence, it is possible to increase the time step to 4 hours. In SOBEK-RE, the morphological time step is initially equal to the defined time step for the flow module, but the user has to specify the maximum number of reductions to take place in case that the stability condition is not met. The bed celerity is calculated with following equations:

\[ C_3 = \left( \frac{\Psi}{1 - Fr^2} \right) \]  

5.34

Where, \( \Psi = \left( \frac{\partial s}{\partial u} \right) \) = \( n \cdot \frac{s}{q} \) and \( C_3 \) in [m/s]

In which \( Fr = \) Froude number of the main-channel flow, \( h = \) average water depth in main channel, \( q = \) main-channel discharge per unit of width, \( s = \) sediment-transport rate per unit of width, \( u_m = \) flow velocity in main channel, \( n = \) power of the transport formula (if \( s = mu^n \)).
### Table 2 Parameters for morphological computation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Magnitude</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q(max)</td>
<td>10802.43</td>
<td>m³/s</td>
</tr>
<tr>
<td>dQ</td>
<td>6000</td>
<td>m³/s</td>
</tr>
<tr>
<td>q</td>
<td>10.91</td>
<td>m³/s.m</td>
</tr>
<tr>
<td>h</td>
<td>15</td>
<td>m</td>
</tr>
<tr>
<td>dh</td>
<td>5.3</td>
<td>m</td>
</tr>
<tr>
<td>g</td>
<td>9.81</td>
<td>m/s²</td>
</tr>
<tr>
<td>αc</td>
<td>1.01</td>
<td>-</td>
</tr>
<tr>
<td>n</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>i</td>
<td>0.0001</td>
<td>-</td>
</tr>
<tr>
<td>Δx</td>
<td>1000</td>
<td>m</td>
</tr>
<tr>
<td>S</td>
<td>10</td>
<td>m³/s</td>
</tr>
<tr>
<td>s</td>
<td>0.0182</td>
<td>m³/s.m</td>
</tr>
<tr>
<td>μm</td>
<td>1.60</td>
<td>m/s</td>
</tr>
<tr>
<td>Ψ</td>
<td>0.00834</td>
<td>-</td>
</tr>
<tr>
<td>Fr</td>
<td>0.154</td>
<td>-</td>
</tr>
<tr>
<td>c₃</td>
<td>0.01366</td>
<td>m/s</td>
</tr>
<tr>
<td>Δt</td>
<td>14400</td>
<td>s</td>
</tr>
<tr>
<td>Δt</td>
<td>0.167</td>
<td>day</td>
</tr>
<tr>
<td>σ</td>
<td>0.197</td>
<td>-</td>
</tr>
</tbody>
</table>

Most of the above parameters value estimated from available data.

### 5.3 OpenMI

#### 5.3.1 Introduction

The concept of integrated catchment management has arisen because managing environmental processes independently does not always produce sensible decisions in a wider view. For instance, soil erosion at catchment process level involves soil erosion from upstream, transport and deposition at the downstream. Therefore it becomes important to be able to model not only the individual processes such as the soil erosion or deposition etc. but also their interactions. However, most existing models tend to address only single issues. Thus the HarmonIT project has developed the open modelling interface (OpenMI) that facilitates easy linking of existing and new models (Gregersen, et al., 2005).
There are many variations of the model application pattern but most important from the OpenMI perspective is the distinction between model application, engine, model, engine component, and model component.

Model application is the entire model software system that you install on your computer. Normally a model application consists of a user interface and an engine. The engine is where the calculations take place. The user supplies information through the user interface upon which the user interface generates input files for the engine. The user can run the model simulation e.g. by pressing a button in the user interface, which will deploy the engine (see Figure 5.9). The engine will read the input files and perform calculations and finally the results are written to output files. When an engine has read its input files it becomes a model. In other words a model is an engine populated with data. If an engine can be instantiated separately and has a well defined interface it becomes an engine component. An engine component populated with data is a model component (Gregersen, et al., 2005).

![Figure 5.9 Model Application Pattern](image)

### 5.3.2 OpenMI Architecture

The OpenMI standard is a software component interface definition for the computational core (the engine) of the hydrological and hydraulic models (Gregersen, et al., 2007). It relies entirely on a “pull-based” principle where communicating components (source and target components) which exchange data in a predefined way and in a predefined format, see Figure 5.10. Basically, a model can be regarded as an entity that can provide data and/or accept data. Most models receive data by reading input files and provide data by writing output files. However, the approach for OpenMI is to access the model directly at run time and not to use files for data exchange. In order to make this possible, the engine needs to be turned into an engine component and the engine component needs to implement an interface through which the data inside the component is accessible. OpenMI defines a standard interface for engine components that OpenMI compliant engine components must implement. When an engine component implements this
interface it becomes a linkable component. A similar pattern can be applied for databases or other kinds of data sources. By turning them into components and implementing the OpenMI interface they become linkable components that provide direct access to its data at run time (Gijsbers, et al., 2005).

Figure 5.10 Data Exchange between Model [Source: adopted from Gijsbers, 2006]

OpenMI compliant model has to implement the following OpenMI standard interfaces; the detail can be found in (Gijsbers, 2004); (Gergersen, et al., 2005) and (Gijsbers, et al., 2005):

Data definition interfaces:

Data exchange requires information on what the values represent, where they apply, when they apply and how they should be processed for every data passed over link. IQuantity interface describes what a value represents while its unit is expressed by IUnit interface and IValueSet interface represents an ordered list of values in their respective elements (see Figure 5.11). The IElementSet interface describes where values are to be applied and their spatial references represented by ISpatialReference interface. Time is described either using Timestamp interfaces if it is instantaneous or ITimeSpan interface
if it is simulation period. Data operation is represented by IDataOperation and their respective argument by IArgument interface.

Meta-data interfaces:
To link components, information is needed on the existence of components and the data they can exchange. Linkable components data exchange either as input or output items defined by IInputExchangeItem or IOutputExchangeItem of IExchangeItem interfaces (see Figure 5.12).

Interface to define the link:
ILink interface captures information between two linkable components (see Figure 5.12). Thus every link contains quantity to be exchanged from SourceElementSet to TargetElementSet. Data exchanged by the GetValue method call. In case data operation required, it can be found from the link by the GetDataOperation method.

Interfaces for component access:
OpenMI-component has to implement the ILinkableComponent interface which defines the generic access to the component to become OpenMI compliant (see Figure 5.12). ILinkableComponent interface has functionalities to:
- Initialize computational core
- Accommodate inspection of the component, its content and exchangeable data
- Establish and validate the links
- Runtime section such as preparation, computation/data transfer/retrieval, completion
- Dispose the component

There are two optional interfaces that have been defined to extend its functionality with discrete time information and state management. IDiscreteTimes interface provides a list of time stamps as it is available in the source component (see Figure 5.12). While IManageState interface provides functionality to store and retrieve data in case the process does iteration or require feedback.

IEvent interface has to be implemented by linkable components to throw exception when irresolvable internal error happens (see Figure 5.12). Its purpose is pass messages such as stack tracing, progress monitoring and to flag status changes which might trigger other components to request for data via a GetValues() call.

After the OpenMI standard implemented by the OpenMI compliant components, OMI file is required to locate software units. The OMI file is an XML file of a predefined XSD format which contains information about the class to instantiate, information about the assembly hosting the class and the arguments needed for initialization.
Figure 5.11 org.OpenMI.Standard interfaces [adopted: Gijsbers, et al., 2005]
Figure 5.12 org.OpenMI.Standard interfaces [adopted: Gijsbers, et al., 2005]
5.3.3 Migrating SWAT into OpenMI

The key requirements to migrate legacy model into OpenMI compliant is the computational core has to be structured into initialize, compute and finalize procedures and the model has to run one time-step at time. SWAT has all the mentioned structures but initialization was done in each modules. Therefore, the initialization procedure was structured into one function. The other challenging task was the modification of SWAT to run one time-step at time. The time-step in SWAT has a loop from beginning to the end of simulation year and for every year it loops for 1-365 or 366 days. For example if it is simulating from beginning of 1980 to end of 2003, it starts at 1980 and loops 1-366 days. Next goes to 1981 and loops from 1-365 days and so on till the end of the last year. Thus, it was modified in such a way that it run one time-step, for the aforementioned example it runs from 1 to 8401 days. The last modification made to SWAT code was to split the sediment into sediment fractions such as clay, silt and sand to consider their role in sediment transport formula. However, the last point has nothing to do to be OpenMI compliant rather helps to capture the transport processes.

The next step was to create a C# class that implements the ILinkableComponent interface to wrap the SWAT model engine. The process involves creating SwatDLL, SwatNativeDLL, SwatDllWrapper and SwatEngine classes, see Figure 5.13. The former was done in Visual Fortran and the latter four classes were done using .Net framework.

Figure 5.13 Wrapping SWAT model engine

The SwatDLL is the SWAT engine core which is compiled into a DLL. The engine core reorganized to perform the following functions:

- initialize
- get_subbasin_count
- get_time_horizon
- compute_timestep
- get_values
- finalize
The SwatNativeDLL class is responsible to translate the Win32API from SwatDLL to .Net. It makes translation for each function exported in FORTRAN into a method .Net (C#). Figure 5.14 shows the SwatNativeDLL class, where all the functions are imported from the SwatDLL.

```csharp
private class SwatDLLNative
{
    const string dllName = "SwatOpenML.dll";

    [DllImport(dllName)]
    public static extern int INITIALIZE();

    [DllImport(dllName)]
    public static extern int GET_SUBBASIN_COUNT();

    [DllImport(dllName)]
    public static extern int GET_TIME_REGION(ref int dayfirst, ref int daylast, ref int yearfirst, ref int yearlast, ref int yearday);

    [DllImport(dllName)]
    public static extern int COMPUTE_TIMESTEP(ref int timestep);

    [DllImport(dllName)]
    public static extern int GET_VALUES(ref int locationType, ref int locationIndex, ref int quantType, ref double va);

    [DllImport(dllName)]
    public static extern int FINALIZE();
}
```

**Figure 5.14** SwatDLLNative class code

The SwatDllWrapper class plays a role to convert FORTRAN convention such as Array index into C# and error message into .Net exception. In this class all the methods from SwatDLLNative class called by referencing the class, see the Figure 5.15.

```csharp
public void Initialize()
{
    ChangeDir();
    int retVal = SwatDLLNative.INITIALIZE();
    if (retVal != 0)
    {
        throw new Exception("SwatDLLNative.INITIALIZE failed, return value: " + retVal);
    }
    RestoreDir();
}

public int SubBasinCount
{
    get
    {
        int count = SwatDLLNative.GET_SUBBASIN_COUNT();
        return count;
    }
}
```

**Figure 5.15** SwatDllWrapper class code
The SwatEngine class implements IEngine interface and can be accessed the SwatLinkableComponent class. It implements the following methods:

- Execution control methods (Initialize (), PerformTimeStep () and Finish ())
- Time methods (GetCurrentTime (), GetInputTime () and GetEarliestNeededTime () )
- Data access methods (SetValue () and GetValue () )
- Component description methods ( GetMissingValueDefinition (), GetComponentID () and GetComponentDescription () )
- Model description methods ( GetModelID (), GetModelDescription () and GetTimeHorizon () )
- Exchange items ( GetInputExchangeItemCount and GetOutputExchangeItemCount )

The SwatLinkableComponent class is responsible for the creation of the SwatEngine class and for assigning a reference to this class to a protected field variable in the LinkableEngine class, thus enabling this class to access the SwatEngine class.

## 5.3.4 SWAT - SOBEK-RE OpenMI Model Linkage

SWAT was linked to one dimensional hydrodynamic model, SOBEK-RE; it was made OpenMI compliant by WL | Delft Hydraulics of Deltares. However, both OpenMI models were tested carefully whether they were providing same result with their respective non-OpenMI compliant models. The test basically compared the number of files printed and their content. The next step was to link the two OpenMI compliant models using the OpenMI Configuration Editor (Figure 5.17). Figure 5.16 shows the linked models SWAT (left) and SOBEK-RE (Right) using OpenMI configuration (top centre).

![Figure 5.16 SWAT and SOBEK-RE Linked through OpenMI Configuration](image-url)
The following points were done to the link the model at run-time:
The calibrated SWAT (left in Figure 16) and SOBEK-RE (Right in Figure 16) models were populated with data using their interface and saved on the working disk together with their respective OMI files in separate folders. The OMI file contains the folder path and the filename of the OpenMI complaint LinkableComponent and the calibrated model folder name.

The two models were added to OpenMI editor using the Add Model method from Composition menu of the OpenMI editor (Figure 5.17). To load each models, the OMI files were browsed from file system using the Add Model method. Each time the OMI file is loaded the LinkableComponent reads its input file. In addition a Trigger model was also loaded and setup directional connection to the SOBEK-RE to trigger data request from SWAT.

Connection between the models were added by clicking the Add Connection method, drag the arrow from SWAT and drop on SobekRE model. The connection link contains the output exchange items, input exchange items, quantities and elements of the models as shown in Figure 5.18. Next exchange items, quantities and elements were defined using the connection properties dialog box.

![Figure 5.17 OpenMI configuration editor used to configure link between the models](image)

The output exchange items for SWAT defines quantities such as flow, sediment, clay, silt, sand, and etcetera as shown in Table 3, locations (subbasin outlet, and reach_in and reach_out) and quantity properties (unit), see Figure 5.18. The SOBEK-RE model accepts these items as an input exchange items either from node or reach at El Deim where its boundary condition defined. However, in this study the output at reach 14 was used as boundary conditions for SOBEK-RE model.
Table 3 SWAT exchange items

<table>
<thead>
<tr>
<th>iQuantity index</th>
<th>SWAT units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>deg C</td>
<td>temperature</td>
</tr>
<tr>
<td>2</td>
<td>m$^3$ H2O</td>
<td>water</td>
</tr>
<tr>
<td>3</td>
<td>metric tons</td>
<td>sediment or suspended solid</td>
</tr>
<tr>
<td>4</td>
<td>kg N</td>
<td>organic nitrogen</td>
</tr>
<tr>
<td>5</td>
<td>kg P</td>
<td>organic phosphorus</td>
</tr>
<tr>
<td>6</td>
<td>kg N</td>
<td>nitrate</td>
</tr>
<tr>
<td>7</td>
<td>kg P</td>
<td>mineral phosphorus</td>
</tr>
<tr>
<td>11</td>
<td>mg pst</td>
<td>pesticide in solution</td>
</tr>
<tr>
<td>12</td>
<td>mg pst</td>
<td>pesticide sorbed to sediment</td>
</tr>
<tr>
<td>13</td>
<td>kg</td>
<td>chlorophyll-a</td>
</tr>
<tr>
<td></td>
<td>carbonaceous</td>
<td>biological</td>
</tr>
<tr>
<td>16</td>
<td>kg</td>
<td>oxygen demand</td>
</tr>
<tr>
<td>17</td>
<td>kg</td>
<td>dissolved oxygen</td>
</tr>
<tr>
<td>18</td>
<td># cfu/100ml</td>
<td>persistent bacteria</td>
</tr>
<tr>
<td>19</td>
<td># cfu/100ml</td>
<td>less persistent bacteria</td>
</tr>
<tr>
<td>24</td>
<td>metric tons</td>
<td>clay load</td>
</tr>
<tr>
<td>25</td>
<td>metric tons</td>
<td>silt load</td>
</tr>
<tr>
<td>26</td>
<td>metric tons</td>
<td>sand load</td>
</tr>
</tbody>
</table>

The SWAT model runs from January 1990 to December 2003 while SOBEK-RE runs from January 2000 to December 2003. The time-step for SWAT was one day but for SOBEK-RE it was 3 hours. Computation starts with the Trigger performs Getvalues() call to SOBEK-RE linkable component at a specified timestamp. Thus SOBEK-RE starts to simulate but it requires data from SWAT hence it makes Getvalue() calls to SWAT linkable component. Then SWAT will compute till it reaches the required time-step (2000), interpolate to 3 hours and return the value to SOBEK-RE. In addition, the SWAT makes data unit conversion before providing to SOBEK-RE request.

Once the models run completed the results were seen using the respective model graphical interface, see Figure 5.16.
Figure 5.18 OpenMI configuration editor link property from SWAT to SOBEK-RE model
6 Result and Discussion

6.1 SWAT

6.1.1 Sensitivity Analysis

Sensitivity analysis is useful to identify inputs parameters which significantly affect the model outputs. Automatic sensitivity analysis was conducted using input daily flow and sediment concentration data at El Deim gauging station (place at Ethiopia-Sudan boarder). After simulating serious of simulations, SWAT provides sensitivity of parameters in ranked order. The sensitivity result is summarized and shown in Table 4. It shows the most three sensitive parameters for flow and erosion are CN2 (Moisture condition II curve number), ALPHA_BF (Baseflow recession constant), and rchrg_dp (Recharge to deep aquifer fractions) and SPCON (Linear re-entrainment parameter for channel sediment routing), CN2 and SLOPE (Average slope steepness), respectively.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Rank</th>
<th>Flow (m³/s)</th>
<th>Sediment (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALPHA_BF</td>
<td>Baseflow recession constant</td>
<td>1</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>GWQMN</td>
<td>Threshold depth of water in the shallow aquifer required for return flow to occur</td>
<td>2</td>
<td>8</td>
<td>20</td>
</tr>
<tr>
<td>GW_REVAP</td>
<td>Groundwater revap coefficient</td>
<td>3</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>REVAPMN</td>
<td>Aquifer for revap to occur</td>
<td>4</td>
<td>18</td>
<td>24</td>
</tr>
<tr>
<td>ESCO</td>
<td>Soil evaporation compensation factor</td>
<td>5</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>SLOPE</td>
<td>Average slope steepness</td>
<td>6</td>
<td>13</td>
<td>3</td>
</tr>
<tr>
<td>SLSUBBSN</td>
<td>Average slope length</td>
<td>7</td>
<td>20</td>
<td>7</td>
</tr>
<tr>
<td>CH_K2</td>
<td>Effective hydraulic conductivity in main channel alluvium</td>
<td>8</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>CN2</td>
<td>Moisture condition II curve number</td>
<td>9</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>SOL_AWC</td>
<td>Available water capacity of the soil layer</td>
<td>10</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>surlag</td>
<td>Surface runoff lag time</td>
<td>11</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>GW_DELAY</td>
<td>Groundwater delay</td>
<td>12</td>
<td>11</td>
<td>21</td>
</tr>
<tr>
<td>rchrg_dp</td>
<td>Recharge to deep aquifer fractions</td>
<td>13</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>canmx</td>
<td>Maximum canopy index</td>
<td>14</td>
<td>12</td>
<td>18</td>
</tr>
<tr>
<td>sol_k</td>
<td>Saturated hydraulic conductivity</td>
<td>15</td>
<td>14</td>
<td>17</td>
</tr>
<tr>
<td>sol_z</td>
<td>Depth from soil surface to bottom of layer</td>
<td>16</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>BIOMIX</td>
<td>Biological mixing efficiency</td>
<td>17</td>
<td>15</td>
<td>19</td>
</tr>
<tr>
<td>USLE_C</td>
<td>Minimum USLE cover factor</td>
<td>18</td>
<td>21</td>
<td>16</td>
</tr>
<tr>
<td>SPCON</td>
<td>Linear re-entrainment parameter for channel sediment routing</td>
<td>19</td>
<td>34</td>
<td>1</td>
</tr>
<tr>
<td>SPEXP</td>
<td>Exponential re-entrainment parameter for channel sediment routing</td>
<td>20</td>
<td>34</td>
<td>9</td>
</tr>
<tr>
<td>USLE_P</td>
<td>USLE support practice factor</td>
<td>21</td>
<td>22</td>
<td>6</td>
</tr>
</tbody>
</table>
6.1.2 Flow calibration

Once the sensitive parameters for the model are identified, the next step is to calibrate and then validate the model. In the calibration we attempted to minimize model errors of the river flows. Thus model calibration involves modifications of model parameters values and comparison of predicted output to the measured data until a defined objective function achieved. In this case, the objective function is to minimise the volume error the Blue Nile at El Deim station (Sudan/Ethiopia border).

The calibration period is from 1981 to 1986. The year 1980 has been used to warm up the model, so not included in the results. The calibration results are given in Figure 6.1. It shows that the model has simulated the flow very well. Except for years 1982, and 1985, the model could reproduce peak flows quite well. Similarly, the model could capture dry period characteristics well. The over all performance of the model during calibration has been measured using Nash-Sutcliff (NS) and an efficiency of NS equal to 0.91 obtained. However, NS rise to 0.96 when results are aggregated to monthly time steps. For the daily as well as monthly time step used, this is very high model efficiency compared to earlier modelling results of the Blue Nile, see e.g., (Conway, 1997, Mishra and Hata, 2006, Rahel, 2007). Figure 6.2 shows comparison of observed and simulated monthly flow for the calibration period.

![Image](image-url)

Figure 6.1 Observed and Simulated Blue Nile daily flow for calibration period between 1981 and 1986 at El Deim
6.1.3 Flow validation

Validation of the model results is necessary to increase user confidence in model predictive capabilities. Thus, the model was validated with observed flow data at the same gauging station, but for the period from 1990 to 1996. Figure 6.3 presents the calibration results. It shows that the model could simulate the base flow for the most years while for peak flows the model could simulate it correctly for three years out of seven years. The model underestimates the peak flow for 1992, 1993 and 1994. It is not yet clear, why relatively large mismatch for 1994; this could be related to quality of input data (rainfall, evapotranspiration, flow measurements). There is time shift of the flow for years 1995 and 1996. The operation of the Chara Chara Weir located at the outlet of Lake Tana has started in 1996 (Kebede, et al., 2006). This may influence the Lake outflow, but likely not as significant, because of relatively small contribution of the Lake Tana to the Blue Nile flows (8%). The model performance was assessed using the Nash-Sutcliffe (NS) coefficient, and found to be equal to 0.81, which is quite good considering scarce hydrometeorological data over the Upper Blue Nile; NS for monthly aggregated results found to be 0.82. Figure 6.4 shows that monthly discharge of Blue Nile for the validation period. A probable reason for the difference of the flood peak in 1994 could be related to observational error of input data, since model showed good simulations of other validation years.
Figure 6.3 Observed and Simulated Blue Nile daily flow for validation period of 1990-1996 at El Deim.

Figure 6.4 Observed and Simulated Blue Nile monthly flow for validation period of 1990-1996 at El Deim.
6.1.4 Flow model result

Analysis of average annual flow (see Table 5) depicts that the model overestimated by 2% and underestimated by 6% on average for the whole calibration and validation period, respectively. During the calibration period highest overestimation by 24% was observed in the year 1984. This year was characterised by the driest period in the decade where the lowest rainfall recorded (Conway, 2000). Likely, the model could not capture this extreme dry condition. During the validation period, the highest underestimation (31%) and overestimation (34%) were observed in the years 1994 and 1995, respectively. These years were characterized by the higher flood level above average in the main Nile as result of the higher runoff from Blue Nile (Conway, 2000). Therefore, probably the model underestimated the runoff in the year 1994 due to the quality of rainfall data.

<table>
<thead>
<tr>
<th>Year</th>
<th>Observed flow (m$^3$·year$^{-1}$)</th>
<th>Simulated (m$^3$·year$^{-1}$)</th>
<th>Delta</th>
<th>Delta %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1981</td>
<td>1356</td>
<td>1348</td>
<td>-8</td>
<td>-1</td>
</tr>
<tr>
<td>1982</td>
<td>1089</td>
<td>980</td>
<td>-109</td>
<td>-10</td>
</tr>
<tr>
<td>1983</td>
<td>1254</td>
<td>1211</td>
<td>-43</td>
<td>-3</td>
</tr>
<tr>
<td>1984</td>
<td>940</td>
<td>1169</td>
<td>229</td>
<td>24</td>
</tr>
<tr>
<td>1985</td>
<td>1430</td>
<td>1477</td>
<td>47</td>
<td>3</td>
</tr>
<tr>
<td>1986</td>
<td>1097</td>
<td>1124</td>
<td>27</td>
<td>2</td>
</tr>
<tr>
<td>Average</td>
<td>1194</td>
<td>1218</td>
<td>24</td>
<td>2</td>
</tr>
<tr>
<td>1990</td>
<td>1205</td>
<td>1309</td>
<td>104</td>
<td>9</td>
</tr>
<tr>
<td>1991</td>
<td>1439</td>
<td>1139</td>
<td>-300</td>
<td>-21</td>
</tr>
<tr>
<td>1992</td>
<td>1398</td>
<td>1062</td>
<td>-336</td>
<td>-24</td>
</tr>
<tr>
<td>1993</td>
<td>1946</td>
<td>1484</td>
<td>-462</td>
<td>-24</td>
</tr>
<tr>
<td>1994</td>
<td>1665</td>
<td>1147</td>
<td>-518</td>
<td>-31</td>
</tr>
<tr>
<td>1995</td>
<td>1177</td>
<td>1582</td>
<td>405</td>
<td>34</td>
</tr>
<tr>
<td>1996</td>
<td>1773</td>
<td>2213</td>
<td>440</td>
<td>25</td>
</tr>
<tr>
<td>Average</td>
<td>1515</td>
<td>1419</td>
<td>-95</td>
<td>-6</td>
</tr>
</tbody>
</table>

Table 6 shows average annual basin values for water balance component. The result shows that average annual rainfall received at upper Blue Nile is 1500 mm. About 45% of the water lost as evapotranspiration, 5% of the rainfall converted to surface runoff, 10% of the rainfall converted to lateral flow, 40% of the rainfall recharge the shallow aquifer. The contribution of return flow and deep aquifer recharge are seen negligible. The lateral flow was found to be double to the surface runoff due to higher area coverage of the Vertisols soil type. The water yield that is contributed at the outlet of El Deim was found to be 15% of the total rainfall. In general, the model result is acceptable compared to the explanation given about Blue Nile by Sutcliffe and Parks, (1999).
Table 6: Average annual basin values

<table>
<thead>
<tr>
<th>Annual water balance components</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRECIP (mm)</td>
<td>1501</td>
</tr>
<tr>
<td>SURFACE RUNOFF Q (mm)</td>
<td>79</td>
</tr>
<tr>
<td>LATERAL SOIL Q (mm)</td>
<td>151</td>
</tr>
<tr>
<td>GROUNDWATER (SHAL AQ) Q (mm)</td>
<td>3</td>
</tr>
<tr>
<td>REVAP (SHAL AQ =&gt; SOIL/PLANTS) (mm)</td>
<td>310</td>
</tr>
<tr>
<td>DEEP AQ RECHARGE (mm)</td>
<td>0.6</td>
</tr>
<tr>
<td>TOTAL AQ RECHARGE (mm)</td>
<td>594</td>
</tr>
<tr>
<td>TOTAL WATER YLD (mm)</td>
<td>218</td>
</tr>
<tr>
<td>PERCOLATION OUT OF SOIL (mm)</td>
<td>593</td>
</tr>
<tr>
<td>ET (mm)</td>
<td>683</td>
</tr>
<tr>
<td>PET (mm)</td>
<td>1852</td>
</tr>
<tr>
<td>TRANSMISSION LOSSES (mm)</td>
<td>14</td>
</tr>
</tbody>
</table>

Average annual water balance

Figure 6.5: Annual average subbasins precipitation of Upper Blue Nile
The annual average subbasins precipitation of the Upper Blue Nile deceases Northward from subbasin 13 (1766 mm) to subbasin 2 (1124 mm), see Figure 6.5. The highest precipitation received by subbasin 13 (1766 mm), followed subbasins 8 and 9 (1694 mm). The lowest precipitation received by subbasins 2 and 10 (1124 mm).

In general, the evapotranspiration increases westward from 451 to 897 mm. The annual average evapotranspiration in the Upper Blue Nile subbasins is shown in Figure 6.6. It shows the highest evapotranspiration occurred at subbasin 8 (897 mm) in the west followed by subbasin 9 (837 mm) and next subbasin 14 (755 mm). The lowest evapotranspiration occurred at subbasin 2 (451 mm) followed by subbasin 10 (542 mm).

![Figure 6.6 Annual average subbasins evapotranspiration of the Upper Blue Nile](image)

Figure 6.6 Annual average subbasins evapotranspiration of the Upper Blue Nile
The highest surface runoff occurred at subbasin 10 (151 mm) followed subbasin 1 (128 mm) and subbasin 11 (128 mm). The lower runoff occurred at subbasins 12 (26 mm) and 2 (36 mm), see Figure 6.7.

Figure 6.7 Annual average subbasins surface runoff of the Upper Blue Nile

Subbasin 2 contributes the maximum return flow, 628 mm and followed by subbasin 12 that is 182 mm. The lowest return flow contributed by subbasin 7 (21 mm) and followed by subbasin 8 (22 mm).
6.1.5 Sediment calibration

The sediment parameters were calibrated using sediment concentrations that were generated using sediment rating curve (flow sediment relations derived from historical data). The calibration period was 1981 to 1986 while 1980 was used for warming the model. During the calibration period the model showed good agreement with sediment concentration of rating curve, see Figure 6.9. Similar result was obtained by Arnold et al., (1999) in Texas Gulf, USA. In fact the model simulated the low flow erosion and sediment transport although in the observed data set, it was assumed zero relative to the peak period erosion. The Nash-Sutcliffe efficiency of 0.72 was found during the calibration period which is quite satisfactory for soil erosion modelling.

6.1.6 Sediment validation

The sediment modelling validated since 1990 to 1996 period, see Figure 6.10. The model was able to simulate the peak sediment for most of the years. Similar to calibration period the model simulate sediment transport during dry period and beginning of wet period.
flow which is assumed zero in the observation data. The model performance $N_s$ equal to 0.66 was obtained that is reasonable.

![Figure 6.9 Observed and simulated sediment concentration comparison during calibration period at El Deem station](image1)

![Figure 6.10 Observed and Simulated sediment concentration comparison during calibration period at El Deem station](image2)
6.1.7 Sediment model result

The total amount of soil erosion simulated by the model, 5 ton per ha per year from upper Blue Nile is comparable to 7.5 ton per ha per year which is deposited in Roseries dam, Sudan according to literatures, (BCEOM, 1999) and (NBCBN-RE, 2005). The highest soil erosion occurs at subbasin 10. Medium soil erosion occurs in subbasins 11 and 1 and low erosion occurs in the remains subbasins, see Figure 6.11. Similar result was reported by BCEOM after analysing long years observed data. They explained that the north-east and east of the basin is an area generally acknowledged as severely eroded. The low-slope areas of the main highland area Gojam, Agew Awe, and North and West Shewa appear to have high current erosion rates. The south-west of the highlands has many low slopes and current erosion is low but the move to continuous cultivation will result in serious erosion in the future. The lowland parts of the basin are currently relatively uneroded, simply by virtue of the absence of vegetation clearance and their use for cultivation.

Figure 6.11 Simulated soil erosion in upper Blue Nile subbasins
The model estimated the amount of soil erosion to be 86 Million ton per year. Most literatures have mentioned that the amount of soil erosion is 122 Million ton per year but from the comparison of Figure 6.12 the result of this model (86 Million ton per year) was found to be rational. After erosion processes there is deposition of sediment in river channel which account 24 Million ton per year as shown in figure 6.12. The amount of sediment yield delivered out of the upper Blue Nile estimated to be 62 Million ton per year at Ethiopia-Sudanese boarder.

![Figure 6.12 Erosion, transport and deposition process in upper Blue Nile](image)

6.2  SOBEK-RE

6.2.1 Calibration
The SOBEK-RE model was setup between year 2000 and 2005. A time controller was calibrated with observed water level at Roseries dam for the year 2000 (Figure 6.13) to get good fit between observed and simulated discharge. Figure 6.14 shows the comparison of observed and simulated discharge for the year 2000. In general the model accurately simulated the behaviour of the flow during calibration period. In addition, the model simulated very well the rising and falling limb of the flow. However, the model did not catch the peak flow and last week of September. The former was attributed to inflow runoff to the reservoir which is generated from the surrounding catchment. The latter was attributed to the fact that sudden opening of gate flush sediment from reservoir.
The calibration of discharge at Sennar dam is shown in Figure 6.15. It shows that very good fit of model simulation to observed flow. The peak flow simulated accurately unlike the Roseries reservoir since there is negligible incoming flow to the Sennar dam from the surrounding catchment. Moreover, the amount of rainfall received on the surface area of Sennar (160 km$^2$) is less than Roseries (290 km$^2$) which extending over the length of 75 km. However, the model could not simulate sudden lowering of gate to flush sediment at the last week of September. In addition, the model overestimated the falling limb.
Figure 6.15 Observed and Simulated Blue Nile discharge calibration year 2000 at Sennar reservoir.

6.2.2 Validation

The model validation was done for year 2003 at Roseries and Sennar dams. Figure 6.16 and Figure 6.17 depict good fit between simulated and observed discharge at Roseries and Sennar reservoirs, respectively.

The rising limb and the peak flow were well captured by the model. The model did not catch the peak in the beginning of September in which the reservoir starts to be filled if the discharge is at El Deim drops to 350 M m$^3$/day. This is attributed to the fact that during the calibration period the flow at El Deim satisfied the reservoir filling condition so the model was not trained to lower the weir in a case the flow does not drop to 350 M m$^3$/day; in fact the flow at El Deim for the validation period was 432 M m$^3$/day. Similar to the calibration period the model could not simulate the sudden opening of the weir to flush the sediment at both Roseries and Sennar.
Figure 6.16  Observed and Simulated discharge validation year 2003 at Roseries

Figure 6.17  Observed and Simulated Blue Nile discharge validation year 2003 at Sennar
6.2.3 Model result

The deposition of the suspended sediment transported from the upper Blue Nile has occurred at 35 km before Roseries dam because of the backwater effect, see Figure 6.18. At the beginning of the reach there is erosion because the amount of bed load transported from Upper Blue Nile was neglected. However, after the Roseries dam there is severe erosion since sediment transport capacity has increased due to deposition of the upstream of the dam. Although in reality there is erosion after the dam, it should not erode the bed that much because there is wash load which is not deposited upstream of the dam. The excessive erosion happened due to the fact the model does not have routine that consider the wash load otherwise the effect might have been different.

Most of the sediment eroded downstream of Roseries deposited upstream of the Sennar dam. However, there is no excessive erosion downstream of Sennar dam unlike the Roseries since the sediment transport capacity is lowered due to enough eroded sediment. After Sennar to Khartoum there is local erosion and deposition as shown in Figure 6.18.

Figure 6.19 shows the area change occurred as a result of deposition and erosion processes. It depicts the increased flow area due to erosion at 0-20 km reach, followed by huge deposition at 20-90 km reach which decreased the flow area significantly and finally increase of the area due to erosion before the dam. The volume of sediment deposition at Roseries was estimated by integrating the area differences (Figure 6.19) along the distance between El Diem, the mouth of the Reservoir and Roseries dam. Annual average sediment deposition of 19 M m$^3$ was obtained for the simulation period. The obtained sediment deposition result was quiet comparable to 20 M m$^3$/yr reported by NBCBN-RM, 2005.

![Figure 6.18 Erosion and deposition of Blue Nile river bed](image-url)
6.3 SWAT-SOBEK-RE OpenMI result

Before applying the coupled models to the Blue Nile case it was tested with hypothetical flow, for instance providing constant flow boundary condition to the calibrated SOBEK-RE and observes the result; in most cases it was crushed. Next provide the input files from the crushed models to OpenMI-SOBEK-RE, link it with SWAT-OpenMI, run the linked models. If the run finished successfully then we are assured that the SWAT output was exchanged as boundary conditions for SOBEK-RE at run time. Figure 6.20 shows the run time information when data exchange undergoes.

The integrated model was verified with the observed flow at Roseries and Sennar dams for the year 2003. During verification processes the model that was validated in section 6.2.2 was used without further calibration with SWAT input. Figure 6.21 shows flow verification at Rosaries for the year 2003. It shows the flow comparison between observed, the integrated (SWAT-SOBEK-RE) OpenMI models and manual linked model, i.e., SOBEK-RE model that used the output flow from SWAT OpenMI model as boundary condition done manually. The integrated (SWAT-SOBEK OpenMI) and manual linked simulations were quiet similar except truncation error introduced in the latter case since the output is written in ASCII file while the former passed from the memory directly, see Figure 6.21. Comparison of Figure 6.21 and Figure 6.16 show that the integrated model captured the behaviour of the observed flow similar to the model that used observed data as boundary conditions except minor time shift. The reason we did not calibrate the SOBEK-RE model with SWAT-OpenMI output flow as boundary condition was to avoid double calibration since SWAT was calibrated and validated with observed data that was used as boundary condition during SOBEK-RE calibration.

![Area change (2000-2005) due deposition and erosion in Roseries reservoir](image)

**Figure 6.19** Area change (2000-2005) due deposition and erosion in Roseries reservoir
Figure 6.20 Data exchange between linked models

Figure 6.21 Flow verification at Roseries dam for year 2003
Flow verification of the integrated model simulation with observed data at Sinnar dam depicted alike result to Roseries verification, see Figure 6.22. Comparison of Figure 6.22 and Figure 6.17 reveal that the integrated model well capture the trend of the observed flow except slight peak shift. Moreover, analysis of SWAT-SOBEK OpenMI and Manual linked simulation result were found to be almost similar except the truncation error difference.

![Figure 6.22 Flow verification at Sennar dam for year 2003](image)

Unfortunately, the morphology module of the SOBEK-RE was not made OpenMI compliant and hence we could not able to conduct the verification test for sediment transport. Nevertheless, from the two verifications result we could conclude that the hydrodynamic result of the integrated model was replicated section 6.2.2 except the peak phase shift occurred. The reason for the slight shift could be attributed to introduction of reservoirs after SWAT was validated at the Upper Blue Nile. Subsequently, we can conclude that the sediment transport should replicate similar result to section 6.2.3.
7 Conclusions and Recommendations

7.1 Conclusions

The Blue Nile River basin is characterized by limited data, especially for the Upper Blue Nile, and hence physical modelling was limited. Sediment transport modelling involves modelling of the hydrology as well as sediment. This poses more challenge to the regional water resources management. To the author’s knowledge daily simulation of the basin was not mentioned in the literatures both for hydrology and sediment transport modelling.

In this study SWAT hydrological model was integrated to SOBEK-RE 1D hydrodynamic model using OpenMI interface. The SWAT was used to model the hydrology and erosion from Upper Blue Nile (Ethiopia). The SOBEK-RE was used to model the Lower Blue Nile (Sudan) where there are two reservoirs. Both models were calibrated and validated independently.

The SWAT model was setup from January 1980 to December 2003; 1980 was used as warm up period for the model. The model was calibrated from 1981 to 1986 and validated from 1990 to 1996. Sensitivity analysis was conducted to identify key parameters that affect runoff and soil erosion from the catchment. Those key parameters were used to calibrate the model using autocalibration module. The model showed very good fit with observed data both for flow and sediment at the outlet of Upper Blue Nile, El Deim gauging station. The Nash-Sutcliffe coefficient for the calibration period for flow and sediment were found to be 0.91 and 0.72, respectively. The Nash-Sutcliffe coefficient for the validation period for flow and sediment were found to be 0.81 and 0.66, respectively. The model overestimated the annual flow by 2 percent for calibration period and underestimated by 6 percent for the validation period. The annual water balance result showed that average annual rainfall received at upper Blue Nile is 1500 mm. About 45 % of the water lost as evapotranspiration, 5 % of the rainfall converted to surface runoff, 10 % of the rainfall converted to lateral flow, 40 % of the rainfall recharge the shallow aquifer. The contribution of return flow and deep aquifer recharge were seen negligible. The water yield that is contributed at the outlet of Upper Blue Nile, El Deim was found to be 15 % of the total rainfall. The total amount of soil erosion that is eroded from Upper Blue Nile basin is found to be 86 Million ton per year, 28 % of it deposited in the channel and 72 % transported to lower Blue Nile. It was observed that subbasins 1, 10 and 11 characterized by higher surface runoff and hence sensitive to erosion.

The SWAT model has simulated the flow and sediment over Upper Blue Nile that is characterized by data scarcity very well. Availability of free global data in the basin proved to be extremely useful for such data scarce area. Moreover, the use DEM with 90 m resolution provided reasonable soil erosion result than 1 km DEM that was used at the beginning of the study. Thus selection of appropriate spatial resolution DEM plays
crucial role to get acceptable result. In addition, to have good soil erosion result care should be taken when threshold area is defined during catchment delineation processes. Although there may be some uncertainty in this study, the model could be used to analyse the effect of different management practices on the amount of flow and sediment transported from Upper to Lower Blue Nile basin.

The SOBEK-RE model was setup 2000 to 2005. It was calibrated in 2000 at Roseries and Sennar Dams. During the calibration period good fit was found between observed and simulated discharge. At Rosaries the peak flow was not captured by the model might be flow contribution from surrounding catchment and rainfall at reservoirs. At Sennar the model overestimated the reservoir release flow to certain extent. The sudden opening of the gate to flush sediment was not captured by the model in both of the reservoirs due to the fact the model does not have routine to simulate such scenario. The model was validated in 2003 with observed discharge at the Rosaries and Sennar. It depicted good fit between the observed and simulated flow. Nevertheless, when the model applied to new rule which was not calibrated for, it does not capture well the observed data. Therefore, it is important to calibrate the model with different rules if data is available. In addition, for such kind of study appropriate selection of controller type and usage is very crucial. About 19 Million m³ per year of the suspended sediment transported from Upper Blue Nile deposited 35 km before Roseries dam. Also it was seen that there exist river bed erosion at the beginning of the reach. After Roseries dam there exist sever bed erosion since the sediment transport capacity of the river increased. However, it seems that the extent of the erosion is a bit overestimated since the sediment transport formula (Van Rijn) of SOBEK-RE does not consider the existence of fine sediment. There was slight deposition before Sennar dam, there after it was observed that local erosion and deposition happening. This model could be used to identify optimal water level operations at the dam that could help more deposition of sediment in the upper reach. Moreover, it gives insight how the delta development in the Roseries reservoir progress through time.

The model integration mainly involved software development of SWAT into OpenMI compliant. The SWAT model modified to provide sediment output in to sediment fractions such as clay, silt and sand. To develop SWAT into OpenMI compliant the initialization procedures were restructured into one function since it was initialized in each module. Next the compute time-step was modified to compute one time-step at a time which demanded more time. Once the restructuring finished, the next task was to create five classes i.e., one SwatDLL class using FORTRAN compiler and SwatNativeDLL, SwatDllWrapper, SWATEngine, SwatLinkableComponent classes using C# which is fully object oriented programming (OOP) under .Net environment. Thus SWAT engine was wrapped by SwatEngine class that implemented the OpenMI interfaces. This task was quiet challenging without prior adequate knowledge of OOP since the OpenMI concept and terminologies based on C# and debugging of the code. Various comparisons were done on the number of files and content between the OpenMI and the original model. The result was found satisfactory except negligible difference that rose due to numerical truncation. Finally linking the two OpenMI compliant models SWAT and SOBEK-RE was done using OpenMI Configuration Editor which was
relatively easier task. This result showed the successful migration SWAT in to OpenMI compliant.

The integrated model was verified by comparison of SOBEK-RE hydrodynamic validation result at Rosaries and Sennar dams in the year 2003. The result showed that the integrated model capture the behaviours of the flow at both testing locations except slight shift of the peak which could be attributed construction of reservoirs at Upper Blue Nile. It was observed that the integrated model result is highly determined by the model that has courser time step, SWAT than finer time step, SOBEK-RE. Unfortunately, the sediment transport was not tested because the Morphology module of SOBEK-RE was not made OpenMI compliant. However, it is expected that the morphology of the integrated model should be alike the original SOBEK-RE since sediment transport is dependent on the hydrodynamic result. The integrated model could be used to identify dam operation rule that could reduce the rate of sedimentation of the Roseries reservoir for various scenarios such as landuse change and management practices at Upper Blue Nile.

As a conclusion, the integrated sediment transport modelling showed that 86 ton per year soil is eroded from Upper Blue Nile, 24 million ton per year deposited in the channel and 62 million ton per year transported to Lower Blue Nile. About 19 million ton per year deposited at Roseries reservoir and the remaining transported downstream. The sensitive area to erosion and deposition were found to be the North and North East of Upper Blue Nile subbasins and Rosaries dam, respectively. Moreover, the developed SWAT OpenMI compliant model could be linked to other hydroinformatics tools to address integrated water resource management problems such as water quality and quantity.

7.2 Recommendations

This study provided detail insight to hydrological and sediment transport at Upper Blue Nile basin level. Nevertheless, further research should be done on both hydrological and sediment transport at subbasins level to improve local decision making.

SWAT OpenMI compliant model should be integrated to other OpenMI compliant river model that has transport formula to consider fine sediment as exchange item to improve the study.

In this study SWAT OpenMI compliant was used as provider of output items since there was no tributary river cross-section data. However, SWAT could also accept flow and sediment from river model at main channel from its tributary once the crosssection problem solved. Thus, further research could be continued by extracting tributary river cross-section from remotely sensed data.
More attention was given to use of OpenMI to flow related module. The OpenMI community further expand the concept to module that addresses water quality problem.

In this study uncertainty that is introduced from each model is unaccounted. However, it is necessary to consider the uncertainty introduced in model integration that a raise from each models.

There is severe data scarcity in the Blue Nile basin which hampers model application. The gap should be bridged in short term by developing hydroinformatics tool that generates data and in long term increasing the number and quality of climatological and hydrometric networks evenly over the basin.
References


Alemneh AT (2005) Impacts of Large Reservoirs on Downstream River Morphology. Master of Science, UNESCO-IHE Institute for Water Education


Christensen FD (2004) Coupling between the river basin management model (MIKE BASIN) and the 3D hydrological model (MIKE SHE) with the use of the OpenMI system. In: Liong PaB (ed) 6th International Conference on Hydroinformatics World Scientific Publishing Company, Singapore.


Monteith JL (1965) Evaporation and environmentThe state and movement of water in living organisms Cambridge University Press, Swansea, United Kingdom.


Seyoum SD (2005) A Generic Software Tool for OpenMI-compliant Ensemble Kalman Filtering. MSc., UNESCO-IHE Institute for Water Education


Sloff K (2006) SOBEK one-dimensional morphological modelling, Delft, the Netherlands.


USDA SCS (1972) National Engineering Handbook Hydrology Section 4 Chapter 4-10


Appendix

I. SWATDLL Class

function initialize() result(retVal)

!DEC$ ATTRIBUTES DLLEXPORT :: initialize

! return value: 0 == succes
! arguments TODO
! body

use parm
implicit none

integer :: retVal, nopt

prog = "SWAT Sept '05 VERSION2005"

write (*,1000)
1000 format(1x,"                      SWAT2005 OpenMI        ",/,
&          "      Soil & Water Assessment Tool      ",/,
&          "     UNIX Version            ",/,
&          "               PC Version             ",/,
&          " Program reading from file.cio . . . executing",/)
if (iclb == 4) then
open (18010, file='changepar.dat')
call telpar(nopt)
rewind(18010)
call bestrun(nopt)
end if

! End calibration mode

call readatmodep

call readinpt
call std1
call std2
call openwth
call headout

!! set ending day of simulation for year
idlst = 0
if (nbyr == 1.and. idal > 0) then
  idlst = idal
else
  idlst = 366 - leapyr
end if

! initialize annual variables

call sim_inityr

!! write header for watershed annual table in .std file

call std3

iscen = 1
retVal = 0

end function initialize

!======================================================================
===================
function get_subbasin_count()
result(subbasin_count)

use parm

!DEC$ ATTRIBUTES DLLEXPORT :: get_subbasin_count

! return value: #subbasins in model
integer :: subbasin_count

! body
subbasin_count = msub

end function get_subbasin_count

!======================================================================
============
function get_time_horizon(idfst, idls, iyfst, iylst, day_total)

   result(retVal)

use parm
!DEC$ ATTRIBUTES DLLEXPORT :: get_time_horizon

! return value: 0 == succes
! arguments
! idfst = first day (1-366)
! idls = last day (1-366)
! iyfst = first year
! iylst = last year
! day_total = total simulation days

integer :: day_total, retVal
integer :: idls, idfst, iyfst, iylst

! body
!! set beginning day of simulation for year
idi = 0
if (idal > 0) then
   idi = idal
else
   idi = 1
end if
idfst=idi

!! determine total number of dates of simulation
day_total = 0
iyfst= iyr
iylst= iyr+ nbyr - 1
iday=idf
iyear=iyr
do curyr = 1, nbyr
   if (Mod(iyear,4) == 0) then
      leapyr = 0 ! leap year
   else
      leapyr = 1 ! regular year
   end if
   !! set ending day of simulation for year
   idls = 0
   if (curyr == nbyr .and. idal > 0) then
      idls = idal
   else
      idls = 366 - leapyr
   end if
   iyear=iyear+1
day_total = day_total+ idls - iday + 1
iday=1
end do

! set internal SWAT time settings
curyr = 1
if (Mod(iylst,4) == 0) then
  leapyr = 0  !!leap year
else
  leapyr = 1  !!regular year
end if
id1=id1-1  !! set ending day of simulation for year
idls = 0
if (idal > 0) then
  idls = idal
else
  idls = 366 - leapyr
end if
retVal = 0
end function get_time_horizon

!======================================================================
function compute_timestep(day_counter)
  result(retVal)
  use parm
  !DEC$ ATTRIBUTES DLLEXPORT :: compute_timestep
  ! return value: 0 == succes
  ! arguments
  integer ::  day_counter, retVal
  ! body
  id1 = id1 + 1
  if (id1 == 1) then
    !! initialize annual variables
    call sim_inityr
    !! write header for watershed annual table in .std file
    call std3
  end if

  !! simulate day
  call simulateOpenMI
  if (id1 == idlst) then
    !! perform end-of-year processes
    do j = 1, nhru
      !! compute biological mixing at the end of every year
      if (biomix(j) > .001) call tillmix (j,biomix(j))
      !! store end-of-year data
      iix = 0
      iiz = 0
      iix = nro(j)
      iiz = icr(j)
      !! update sequence number for year in rotation to that of
!! the next year and reset sequence numbers for operations
if (idx(idplt(nro(j),icr(j)),j)) == 7) then
  curyr_mat(j) = curyr_mat(j) + 1
  curyr_mat(j) = Min(curyr_mat(j), mat_yrs(idplt(nro(j),icr(j)),j))
end if

nro(j) = nro(j) + 1
if (nro(j) > nrot(j)) then
  nro(j) = 1
end if
icr(j) = 1
ncut(j) = 1
ntil(j) = 1

!! if crop is growing, reset values for accumulated heat units,
!! etc. to zero in northern hemisphere
if (igro(j) == 1) then
  if (sub_lat(hru_sub(j)) > 0.) then
    phuacc(j) = 0.
    laimxfr(j) = 0.
    hvstia(j) = 0.
  endif
  phu_plt(nro(j),icr(j),j) = phu_plt(iix,iiz,j)
  idplt(nro(j),icr(j),j) = idplt(iix,iiz,j)
  hi_targ(nro(j),icr(j),j) = hi_targ(iix,iiz,j)
  ncrops(iix,iiz,j) = ncrops(iix,iiz,j) + 1
end if

!! update target nitrogen content of yield with data from
!! year just simulated
do ic = 1, mcr
  xx = 0.
  xx = Real(curyr)
  tnylda(nro(j),ic,j) = (tnylda(nro(j),ic,j) * xx + tnyld(nro(j),ic,j)) / (xx + 1.)
end do

end do

write (*,1234) iyr
1234 format (1x,' Executed year ', i4)

  curyr = curyr + 1
  iyr = iyr + 1
if (Mod(iyr,4) == 0) then
  leapyr = 0 !!leap year
else
  leapyr = 1 !!regular year
end if
!! set ending day of simulation for year
idlst = 0
if (curyr == nbyr .and. idal > 0) then
  idlst = idal
else
  idlst = 366 - leapyr
end if
!! set starting day of simulation for year
id1 = 0
!! initialize annual variables

call sim_inityr
!! write header for watershed annual table in .std file
   call std3

end if

c   end do

retVal = 0

end function compute_timestep

!======================================================================
===
function get_values(i_loctype, i_locindex, i_qindex, value)
   result(retVal)
   use parm
!DEC$ ATTRIBUTES DLLEXPORT :: get_values
!
! return value: 0 == succes
! arguments
   integer, intent(in) :: i_loctype ! type identifier 1=sub
     2=reach
   integer, intent(in) :: i_locindex ! location identifier, node #
   integer, intent(in) :: i_qindex ! quantity identifier

   double precision, intent(out):: value ! returned value
!
     ! locals (todo: put in param module?)
     double precision, parameter :: swat_missing_value = -99.D+0
     integer :: retVal
!
   ! body

   retVal = -1
value  = -99
if (i_loctype == 1) then

value = varoute(i_qindex, ihoutsb(i_locindex))
retVal = 0

end if
if (i_loctype == 2) then

value = varoute(i_qindex, ihoutrt(i_locindex))
retVal = 0

end if
end function get_values

!======================================================================
function set_values(i_loctype, i_locindex, i_qindex, value)
! result(retVal)
!DEC$ ATTRIBUTES DLLEXPORT :: get_values

! return value: 0 == succes
! arguments return value: 0 == succes

integer, intent(in) :: i_loctype ! type identifier 1=sub 2=reach
! i_loctype = 2 : reachout
! i_loctype = 3 : reachin
integer, intent(in) :: i_locindex ! location identifier, node #
integer, intent(in) :: i_qindex ! quantity identifier

! i_qindex = 2 : flow (m3/day)
! i_qindex = 3 : sed (metric tons/day)
! i_qindex = 23: clay (metric tons/day)
! i_qindex = 24: silt (metric tons/day)
! i_qindex = 25: sand (metric tons/day)
double precision, intent(out):: value ! returned value

! locals (todo: put in param module?)
double precision, parameter :: swat_missing_value = -99.D+0
integer :: retVal

! body

retVal = -1

value  = -99
select case (i_loctype)
case (1)
varoute(i_qindex, ihoutsb(i_locindex))=value
ihoutget(ihoutsb(i_locindex))=1
retVal = 0
end if
if (i_loctype == 2) then

value = varoute(i_qindex, ihoutrt(i_locindex))
retVal = 0

end if
end function set_values
varoute(i_qindex,ihoutrt(i_locindex))=value
retVal = 0

case(3)
varoute(i_qindex,ihoutrtin(i_locindex))=value
retVal = 0
end select

end function set_values

function finalize() result(retVal)

!DEC$ ATTRIBUTES DLLEXPORT :: finalize
!
return value: 0 == succes

!! perform summary calculations
call finalbal
call writeaa
call pestw

write (*,1001)
1001 format (/," Execution successfully completed ")

retVal = 0

end function finalize
II. SwatDllWrapper

public class SwatDllWrapper
{
    private readonly string _modelWorkdirectory = null;
    private string _oldDirectory = null;

    public SwatDllWrapper(string modelWorkingDirectory)
    {
        _modelWorkdirectory = modelWorkingDirectory;
    }

    private void ChangeDir()
    {
        if (_modelWorkdirectory != null)
        {
            {
                Environment.CurrentDirectory = _modelWorkdirectory;
            }
        }
    }

    private void RestoreDir()
    {
        if (_oldDirectory != null)
        {
            _oldDirectory = null;
        }
    }

    public void Initialize()
    {
        ChangeDir();
        int retVal = SwatNativeDLL.INITIALIZE();
        if (retVal != 0)
        {
            throw new Exception(" SwatNativeDLL.INITIALIZE failed, return value: " + retVal);
        }
        RestoreDir();
    }

    public int SubBasinCount
    {
        get
        {
            ChangeDir();
            int count = SwatNativeDLL.GET_SUBBASIN_COUNT();
            RestoreDir();
            return count;
        }
    }
}
public ITimeSpan GET_TIME_HORIZON()
{
    int dayfirst = 0;
    int daylast = 0;
    int yearfirst = 0;
    int yearlast = 0;
    int daytotal = 0;

    ChangeDir();
    int retVal = SwatNativeDLL.GET_TIME_HORIZON(ref dayfirst,
                                                ref daylast, ref yearfirst, ref yearlast, ref
daytotal);//(ref year, ref month, ref day);
    RestoreDir();

    ITimeStamp start = determineDateTime(yearfirst, dayfirst);
    ITimeStamp end = determineDateTime(yearlast, daylast);

    if (retVal != 0)
    {
        throw new Exception("SwatNativeDLL.GET_TIME_HORIZON
failed, return value: " + retVal);
    }

    return new Oatc.OpenMI.Sdk.Backbone.TimeSpan(start, end);
}

public void COMPUTE_TIMESTEP(int currenttimestep)
{
    ChangeDir();
    int retVal = SwatNativeDLL.COMPUTE_TIMESTEP(ref
currenttimestep);
    RestoreDir();

    if (retVal != 0)
    {
        throw new Exception("SwatNativeDLL.COMPUTE_TIMESTEP
failed, return value: " + retVal);
    }
}

public double[] GetValues(int locType, int locIndex, int
qIndex)
{
    double value = 0;
    ChangeDir();
    int retVal = SwatNativeDLL.GET_VALUES(ref locType, ref
locIndex, ref qIndex, ref value);
    RestoreDir();
    if (retVal != 0)
    {

throw new Exception("SwatNativeDLL.GET_VALUES failed, return value: " + retVal);
}
return new double[] { value };

public double[] SetValues(int locType, int locIndex, int qIndex)
{
    double value = 0;
    ChangeDir();
    int retVal = 0;
    Console.WriteLine("Setting values for locType " + locType + ", locIndex" + locIndex + ", qIndex" + qIndex);
    RestoreDir();
    if (retVal != 0)
    {
        throw new Exception("SwatNativeDLL.SET_VALUES failed, return value: " + retVal);
    }
    return new double[] { value };
}

public void FINALIZE()
{
    ChangeDir();
    SwatNativeDLL.FINALIZE();
    RestoreDir();
}

DateTime dateTime = new DateTime(IFirstYear, IFirstMonth, IFirstDay);
double dateTimeAsMJD=
Oatc.OpenMI.Sdk.DevelopmentSupport.CalendarConverter.Gregorian2ModifiedJulian(dateTime);
return new TimeStamp(dateTimeAsMJD);
class SwatEngine : IEngine
{
    int _numberOfNodes;
    int _numberOfReaches;

    ITimeSpan _timeHorizon;
    readonly double _deltaTAsMJD = 1; // one day

    IElementSet[] _nodeElementSets;
    IElementSet[] _reachElementSets;

    readonly IList<InputExchangeItem> _inputExchangeItemList = new
    List<InputExchangeItem>();
    readonly IList<OutputExchangeItem> _outputExchangeItemList =
    new List<OutputExchangeItem>();

    int _currentTimeStepNumber = 0;

    SwatDllWrapper swatDllWrapper = null;

    #region IEngine Members
    public string GetModelID()
    {
        return "MytestengineModelID";
    }

    public string GetModelDescription()
    {
        return "MytestengineModelDescription";
    }

    public ITimeSpan GetTimeHorizon()
    {
        return _timeHorizon;
    }

    public int GetInputExchangeItemCount()
    {
        return _inputExchangeItemList.Count;
    }

    public int GetOutputExchangeItemCount()
    {
        return _outputExchangeItemList.Count;
    }

    public OutputExchangeItem GetOutputExchangeItem(int
    exchangeItemIndex)
    {
        OutputExchangeItem oei =
        _outputExchangeItemList[exchangeItemIndex];
        return oei;
    }
}
public InputExchangeItem GetInputExchangeItem(int exchangeItemIndex)
{
    InputExchangeItem iei = _inputExchangeItemList[exchangeItemIndex];
    return iei;
}

#region IRunEngine Members

public void Initialize(System.Collections.Hashtable properties)
{

    string modelWorkingDirectory = null;
    string modelWorkingDirectoryInOmiFile = properties["modelWorkingDirectory"] as string;
    if (modelWorkingDirectoryInOmiFile != null)
    {
        modelWorkingDirectory = Path.GetFullPath(Convert.ToString(modelWorkingDirectoryInOmiFile));
    }

    _nodeElementSets = new IElementSet[_numberOfNodes];
    _reachElementSets = new IElementSet[_numberOfReaches];

    for (int i = 0; i < _numberOfNodes; i++)
    {
        string nodeId = "node_" + (i + 1);
        Element element = new Element(nodeId);
        ElementSet elementSet = new ElementSet(nodeId, nodeId,
            ElementType.IDBased, new SpatialReference("not important"));
        elementSet.AddElement(element);

        _nodeElementSets[i] = elementSet;
    }

    for (int i = 0; i < _numberOfReaches; i++)
    {
        string reachId = "reach_" + (i + 1);
        Element element = new Element(reachId);
        ElementSet elementSet = new ElementSet(reachId, reachId,
            ElementType.IDBased, new SpatialReference("not important"));
        elementSet.AddElement(element);
    }

#endregion
_reachElementSets[i] = elementSet;
}

Quantity siltQuantity = new Quantity(siltUnit, "silt", "silt", global::OpenMI.Standard.ValueType.Scalar, siltDimension);

Unit sandUnit = new Unit("1000*kg/day", 1.0D / 86400, 0D);
Dimension sandDimension = new Dimension();
sandDimension.SetPower(DimensionBase.Mass, 1);
sandDimension.SetPower(DimensionBase.Time, -1);

Quantity sandQuantity = new Quantity(sandUnit, "sand", "sand", global::OpenMI.Standard.ValueType.Scalar, sandDimension);

for (int i = 0; i < _numberOfNodes; i++)
{
    // flow on nodes, input
    InputExchangeItem inputExchangeItem = new InputExchangeItem();
    inputExchangeItem.ElementSet = _nodeElementSets[i];
    inputExchangeItem.Quantity = flowQuantity;
    _inputExchangeItemList.Add(inputExchangeItem);

    // sediment on nodes, input
    InputExchangeItem inputExchangeItem = new InputExchangeItem();
    inputExchangeItem.ElementSet = _nodeElementSets[i];
    inputExchangeItem.Quantity = sedimentQuantity;
    _inputExchangeItemList.Add(inputExchangeItem);

    // clay on nodes, input
    InputExchangeItem inputExchangeItem = new InputExchangeItem();
    inputExchangeItem.ElementSet = _nodeElementSets[i];
    inputExchangeItem.Quantity = clayQuantity;
    _inputExchangeItemList.Add(inputExchangeItem);

    // silt on nodes, input
    InputExchangeItem inputExchangeItem = new InputExchangeItem();
    inputExchangeItem.ElementSet = _nodeElementSets[i];
    inputExchangeItem.Quantity = siltQuantity;
    _inputExchangeItemList.Add(inputExchangeItem);

    // sand on nodes, input
    InputExchangeItem inputExchangeItem = new InputExchangeItem();
    inputExchangeItem.ElementSet = _nodeElementSets[i];
    inputExchangeItem.Quantity = sandQuantity;
    _inputExchangeItemList.Add(inputExchangeItem);

    // flow on nodes, output
    OutputExchangeItem outputExchangeItem = new OutputExchangeItem();
    outputExchangeItem.ElementSet = _nodeElementSets[i];
    outputExchangeItem.Quantity = flowQuantity;
    _outputExchangeItemList.Add(outputExchangeItem);
    outputExchangeItem = new OutputExchangeItem();
for (int i = 0; i < _numberOfReaches; i++)
{
    //flow on reaches, input
    InputExchangeItem inputExchangeItem = new InputExchangeItem();
    inputExchangeItem.ElementSet = _reachElementSets[i];
    inputExchangeItem.Quantity = flowQuantity;
    _inputExchangeItemList.Add(inputExchangeItem);

    //sediment on reaches
    inputExchangeItem = new InputExchangeItem();
    inputExchangeItem.ElementSet = _reachElementSets[i];
    inputExchangeItem.Quantity = sedimentQuantity;
    _inputExchangeItemList.Add(inputExchangeItem);

    //clay on reaches, input
    inputExchangeItem = new InputExchangeItem();
    inputExchangeItem.ElementSet = _reachElementSets[i];
    inputExchangeItem.Quantity = clayQuantity;
    _inputExchangeItemList.Add(inputExchangeItem);

    //silt on reaches, input
    inputExchangeItem = new InputExchangeItem();
    inputExchangeItem.ElementSet = _reachElementSets[i];
    inputExchangeItem.Quantity = siltQuantity;
    _inputExchangeItemList.Add(inputExchangeItem);

    //sand on reaches, input
    inputExchangeItem = new InputExchangeItem();
    inputExchangeItem.ElementSet = _reachElementSets[i];
    inputExchangeItem.Quantity = sandQuantity;
    _inputExchangeItemList.Add(inputExchangeItem);

    OutputExchangeItem outputExchangeItem = new OutputExchangeItem();
    outputExchangeItem.ElementSet = _reachElementSets[i];
}
outputExchangeItem.Quantity = flowQuantity;
_outputExchangeItemList.Add(outputExchangeItem);

outputExchangeItem = new OutputExchangeItem();
outputExchangeItem.ElementSet = _reachElementSets[i];
outputExchangeItem.Quantity = sedimentQuantity;
_outputExchangeItemList.Add(outputExchangeItem);

outputExchangeItem = new OutputExchangeItem();
outputExchangeItem.ElementSet = _reachElementSets[i];
outputExchangeItem.Quantity = clayQuantity;
_outputExchangeItemList.Add(outputExchangeItem);

outputExchangeItem = new OutputExchangeItem();
outputExchangeItem.ElementSet = _reachElementSets[i];
outputExchangeItem.Quantity = siltQuantity;
_outputExchangeItemList.Add(outputExchangeItem);

outputExchangeItem = new OutputExchangeItem();
outputExchangeItem.ElementSet = _reachElementSets[i];
outputExchangeItem.Quantity = sandQuantity;
_outputExchangeItemList.Add(outputExchangeItem);

}

public void Finish()
{
    swatDllWrapper.FINALIZE();
}

public void Dispose()
{
}

public bool PerformTimeStep()
{
    _currentTimeStepNumber++;
    swatDllWrapper.COMPUTE_TIMESTEP(_currentTimeStepNumber);
    return true;
}

public ITime GetCurrentTime()
{
    double startTimeAsMJD =
    _timeHorizon.Start.ModifiedJulianDay;
    double currentTimeAsMJD = startTimeAsMJD + _deltaTAsMJD *
    _currentTimeStepNumber;
    return new TimeStamp(currentTimeAsMJD);
}

public ITime GetInputTime(string QuantityID, string
ElementSetID)
ITimeStamp currentTime = (ITimeStamp)GetCurrentTime();
return new TimeStamp(currentTime.ModifiedJulianDay +
_deltaTAsMJD);

public ITimeStamp GetEarliestNeededTime()
{
    return (ITimeStamp)GetCurrentTime();
}

public void SetValues(string quantityID, string elementSetID,
IValueSet values)
{
    int locIndex = -99;
    int locType = -99;
    int qIndex = -99;
    DetermineIndices(quantityID, elementSetID, ref locIndex, ref
locType, ref qIndex);

    swatDllWrapper.SetValues(locType, locIndex, qIndex);
}

public IValueSet GetValues(string quantityID, string
elementSetID)
{
    int locIndex = -99;
    int locType = -99;
    int qIndex = -99;
    DetermineIndices(quantityID, elementSetID, ref locIndex, ref
locType, ref qIndex);

    double[] values = swatDllWrapper.GetValues(locType, locIndex, qIndex);

    return new ScalarSet(values);
}

public double GetMissingValueDefinition()
{
    return -99;
}

public string GetComponentID()
{
    return "MytestengineComponentID";
}

public string GetComponentDescription()
{
    return "MytestengineComponentDescription";
}

#endregion