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LINKING SWAT AND SOBEK USING OPEN MODELING INTERFACE (OPENMI) FOR SEDIMENT TRANSPORT SIMULATION IN THE BLUE NILE RIVER BASIN

G. D. Betrie, A. van Griensven, Y. A. Mohamed, I. Popescu, A. E. Mynett, S. Hummel

ABSTRACT. *Computer models assist basin-scale decision making by taking into account upstream-downstream interdependencies. The SWAT (hydrological) model code was developed into an OpenMI-compliant version and linked with the SOBEK (hydrodynamic) model to extend SWAT's simulations of basin-scale streamflow and sediment transport. The development of an OpenMI-compliant version of SWAT involved reorganizing the SWAT model code and wrapping it with the OpenMI wrapper utility. The modified SWAT model was linked to the SOBEK model and applied to simulate sediment transport in the Blue Nile River basin. The SWAT model simulated the streamflow and soil erosion in the upstream catchment, while the SOBEK model routed the streamflow and sediment downstream to the basin outlet. Prior to the linking, both the SWAT and SOBEK models were individually calibrated. The results showed that the coupled models simulated the observed hydrodynamics and sediment deposition due to backwater effects, which would not be possible with the SWAT model alone. The developed OpenMI-compliant SWAT model can further be linked to groundwater, climate change, and socioeconomic models to address integrated water resources management needs.*

Keywords. *Blue Nile, Model integration, OpenMI, Sediment transport, SOBEK, Soil erosion, SWAT.*

Integrated river basin modeling helps decision makers to understand basin-scale environmental problems, such as soil erosion from upstream areas and sedimentation of reservoirs in downstream parts of a basin. This understanding assists basin-scale decision making by considering upstream-downstream interdependencies. There are many catchment erosion and river sediment transport models in the literature. These models differ from each other mainly in the level of complexity of physical process representation, input requirements, scale (i.e., temporal and spatial), and kinds of outputs (Merritt et al., 2003). Catchment erosion models, e.g., AnnAGNPS (Bingner et al., 2003), HSPF (Donigian et al., 1984), and SWAT (Arnold et al., 1998; Neitsch et al., 2005), simulate runoff and soil erosion from the catchment and route them through stream networks to the watershed outlet. River sediment transport models, e.g., MIKE 11 (Havnø et al., 1995), HEC-RAS (Brunner, 2002), and SOBEK (WL/Delft Hydraulics, 1995), simulate flow and sediment transport in a given river reach without considering catchment processes. These models solve the full dynamic wave equation and are capable of simulating unsteady, non-uniform flow conditions. Thus, they represent effects of different flow control structures, such as weirs, dams, and culverts.

The SWAT model is widely applied as a decision-making tool for water quantity and quality management issues at a catchment scale (Borah and Bera, 2004; Gassman et al., 2007; Schuol et al., 2008). SWAT simulates erosion and sedimentation processes for both catchments and river reaches, but its flow and sediment routing modules use relatively simplistic equations. For flow routing, the SWAT2005 model uses the variable storage coefficient method (Williams, 1969) or the Muskingum (Cunge, 1969) method. These methods are approximations of the kinematic wave model that does not consider propagation of a wave in the upstream direction and, subsequently, does not simulate backwater effects that reduce flow velocity near hydraulic structures such as dams. For sediment routing, the SWAT2005 model uses peak channel velocity to transport the maximum sediment. This method is a simplification of the river power concept of Bagnold (1977), modified by Williams (1980). The modified river power equation implemented in the model does not consider all sediment transport characteristics (e.g., bottom shear stress) that determine whether erosion or deposition will occur at a given flow velocity (Benaman et al., 2005). Moreover, the SWAT model does not simulate sediment deposition due to backwater effects. Therefore, there was a need to improve the SWAT routing modules either by introducing dynamic wave equations instead of the existing routing modules or by coupling SWAT with a more appropriate model that has better flow and sediment routing. In this article, the model coupling approach was chosen because it is often less laborious and less time consuming than the former option.

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The literature shows various coupling approaches for hydrologic and hydrodynamic models (Refsgaard et al., 1998; Di Luzio et al., 2004; Gregersen et al., 2007; Lian et al., 2007; Debele et al., 2008). These coupling approaches include loose coupling, tight coupling, fully integrated coupling, and Open Modeling Interface (OpenMI) coupling. In loose coupling, models are separate and interoperate through an intermediate program that exchanges data between them, often in ASCII or binary file formats. For example, Debele et al. (2008) used an intermediate program to extract hourly SWAT outputs at required locations and converted them into CE-QUAL-W2 model input format. The loose coupling approach has the advantage of not changing the existing model code and involves lower cost. Its limitation is that it requires developing data conversion programs between each set of coupled models (Brandmeyer and Karimi, 2000). In tight coupling, each model computes using its own engine, exchanges data through an application program interface (API), and shares one of the models' graphical user interfaces. An application of tight coupling is shown by Di Luzio et al. (2004), in which the SWAT model is coupled to ArcView. ArcView exports GIS data to the SWAT model, and SWAT's outputs are sent back to ArcView for spatial processing and graphical display. The tight coupling approach has a faster execution time but lacks flexibility. In fully integrated coupling, a model is embedded as a routine in the watershed model. An application of fully integrated model coupling is presented by Refsgaard et al. (1998), where the MIKE SHE hydrologic model is fully coupled to the MIKE 11 hydraulic model. The simulation between MIKE SHE (flow flux) and MIKE 11 (water level) takes place simultaneously, and data are exchanged through shared memory. Fully integrated coupling is time consuming and lacks flexibility. In OpenMI coupling, components (i.e., models or databases customized into the OpenMI standard) exchange data at run time. The OpenMI standard is a defined software component interface for the computation core (the engine) of hydrological and hydraulic models (Gregersen et al., 2007). It potentially allows the development of a completely integrated modeling system consisting of GUI, engines, and databases. In this article, the OpenMI coupling approach is used because it provides a generic mechanism for model integration.

The objective of this study is to develop the SWAT model code into an OpenMI version and explore the OpenMI integration approach for linking SWAT with the SOBEK model, which has sophisticated river hydraulic modules, to improve SWAT's simplistic river routing modules. This article is organized as follows. Brief descriptions of the SWAT and SOBEK models and the OpenMI interface are presented. The migration of SWAT2005 into the OpenMI-compliant version, model integration, and application of the integrated model to simulate sediment transport in the Blue Nile basin are then provided. Finally, the results of the integrated modeling are presented.

MATERIALS AND METHODS

THE HYDROLOGIC MODEL: SWAT

The Soil and Water Assessment Tool (SWAT) is a physical process-based model for simulating continuous-time landscape processes at catchment scale (Arnold et al., 1998; Neitsch et al., 2005). The catchment is divided into hydrological response units (HRUs) based on soil type, land use, and slope classes that allow a high level of spatial detail simulation. The major model components include hydrology, weather, soil erosion, nutrients, soil temperature, crop growth, pesticides, agricultural management, and stream routing.

The model predicts the hydrology at each HRU using the water balance equation, which includes daily precipitation, runoff, evapotranspiration, percolation, and return flow components. Surface runoff is estimated in the model using two options: (1) the USDA-NRCS curve number (CN) method (USDA-SCS, 1972), and (2) the Green and Ampt method (Green and Ampt, 1911). Percolation through each soil layer is predicted using storage routing techniques combined with a crack-flow model (Arnold et al., 1998). Evapotranspiration is estimated using three options: (1) Priestley-Taylor (Priestley and Taylor, 1972), (2) Penman-Monteith (Monteith, 1965), and (3) Hargreaves (Hargreaves and Riley, 1985).

The SWAT model uses the Modified Universal Soil Loss Equations (MUSLE) to compute HRU-level soil erosion. It uses runoff energy to detach and transport sediment (Williams and Berndt, 1977). Sediment routing in the channel (Arnold et al., 1995) consists of channel degradation using stream power (Williams, 1980) and deposition in the channel using fall velocity. Channel degradation is adjusted using USLE soil erodibility and channel cover factors.

THE HYDRODYNAMIC MODEL: SOBEK

The SOBEK model is a one-dimensional hydrodynamic numerical modeling system capable of solving the equations that describe unsteady water flow, sediment transport and morphology, and water quality. The flow module is described by the continuity and momentum equations, and the morphological module is described by the sediment continuity equation (WL/Delft Hydraulics, 1995). Simulations in the SOBEK model are carried out following a decoupled approach. In this approach, the flow, sediment, and morphology simulation are decoupled in such a way that they are sequentially called at every time step. The model uses a Lax-Wendroff type of scheme for morphology computation, and the Preissmann scheme is used for solving the flow equations.

THE OPENMI STANDARD

The OpenMI standard is a software component interface for the computational core (the engine) of hydrological and hydraulic models (Gregersen et al., 2007). If the model engine implements this interface, it becomes an OpenMI linkable component. The OpenMI approach provides a way to exchange data at run time between linkable components and avoids the use of files for data exchange. It relies on a "pull-based" principle in which the communicating components (source and target components) exchange data in a predefined way and in a predefined format. The OpenMI standard was developed by the EU co-financed HarmonIT project to address easy model linking of existing and new models. OpenMI provides the advantages of speed and ease of customization for other models. However, the advantages of OpenMI depend on the availability of compliant models. The OpenMI standard includes the following interfaces:

Data definition: Defines what data are exchanged and the quantity (e.g., sediment tons per day), including where (e.g., catchment outlets), when (i.e., a single point in time or simulation period), and how (e.g., hourly, daily, monthly) values are applied.

Metadata to express what can be exchanged: Defines data that can be potentially exchanged between linkable components as inputs and outputs.

Link definition: Defines quantities, where and how linkable components provide and accept data as outputs and inputs, respectively.

Linkable component: Defines generic access to components to become OpenMI compliant. This interface has functionalities to initialize, inspect, configure, establish, and validate links, run time sections (i.e., preparation, computation, and finish), and dispose.

Discrete times and manage state: These interfaces are optional and are defined to extend the OpenMI functionality with discrete time information and state management.

Event definition: Defines messages (e.g., stack tracing and progress monitoring) that are passed by linkable components when an irresolvable internal error happens.

After the model components have implemented the OpenMI standard, an OMI file is required to locate the software units. The OMI file is an XML file of a predefined XSD format that contains information about the class to instantiate, information about the assembly hosting the class, and the arguments needed for initialization.

MIGRATING SWAT2005 INTO OPENMI

For SWAT2005 model migration, the OpenMI standard interface and utilities of version 1.4 were used, as provided on the SourceForge website (SourceForge, 2005). The migration of SWAT2005 into OpenMI was done in two steps using the Visual FORTRAN and C# languages. In first step, the engine of SWAT2005 was reorganized into initialize, perform a time step, and finalize functions to allow the model to run one time step at a time. These are key requirements to migrate models into OpenMI. In the "initialize" function, models open files and read input files. The "perform a time step" function triggers a model engine to make a single time step. The "finalize" function closes files and de-allocate memories. The SWAT model includes these three functions; however, SWAT'S initialization is done through several modules, and the engine of SWAT runs daily loops within yearly loops (i.e., it does not perform a single time step). The initialization functions were modified into a single function, and the SWAT engine was modified to make a single time step instead of running in loops. Furthermore, the SWAT2005 model code was modified to split sediment into three sediment fractions (clay, silt, and sand) using empirical relationships. This modification is not related to OpenMI, but it helps to capture the right sediment transport processes. The reorganized SWAT code was compiled into DLL (i.e., SWATDLL) to make it accessible from outside, as shown in figure 1.

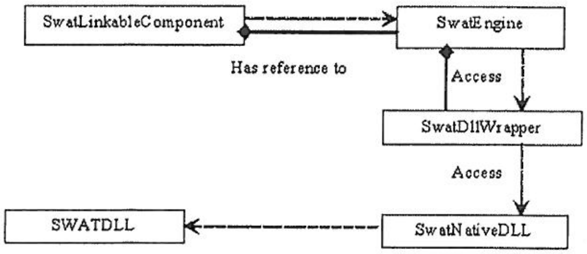

Figure 1. SWAT model engine wrapping design.

Table 1. SWAT exchange items.

iQuantity Index	SWAT Units	Description
1	$m^3\ d^{-1}$	Discharge
2	metric tons d^{-1}	Sediment
3	kg N d^{-1}	Organic nitrogen
4	kg P d^{-1}	Organic phosphorus
5	kg N d^{-1}	Nitrate
6	kg P d^{-1}	Mineral phosphorus
7	mg pst d^{-1}	Pesticide in solution
8	mg pst d^{-1}	Pesticide sorbed to sediment
9	mg d^{-1}	Chlorophyll *a*
10	mg d^{-1}	Carbonaceous biological oxygen demand
11	mg d^{-1}	Dissolved oxygen
12	metric tons d^{-1}	Clay load
12	metric tons d^{-1}	Silt load
14	metric tons d^{-1}	Sand load

In the second step, the SWAT engine (SWATDLL) was wrapped using the OpenMI wrapper utility. The OpenMI wrapper provides the engine interface that defines metadata, run time section, and data exchange. The SWAT model engine wrapping design is shown in figure 1. The SwatEngine class implemented the linkable component interface and accesses the SwatDllWrapper class. The SwatDllWrapper class implemented the engine interface and accesses the SWAT engine through the SwatNativeDLL class. SwatNativeDLL is an extension of Win32API.

The developed OpenMI-compliant version of SWAT, named SWAT-IHE, is freely available and can be obtained from UNESCO-IHE. Its input and output exchange items are shown in table 1. These exchange items are accepted and provided at each subbasin outlet, reach inlet, and reach outlet. Detailed descriptions of the SWAT OpenMI-compliant components are provided on the OpenMI website (OpenMI, 2008).

THE BLUE NILE RIVER BASIN

The Blue Nile River starts from the Ethiopian highlands around Lake Tana (at 1780 m a.s.l), and enters Sudan at an elevation of 500 m, after a distance of 940 km (fig. 2). The Ethiopian Plateau is hilly terrain with grassy downs, swamp valleys, and scattered trees. Precipitation progressively decreases northward in the Upper Blue Nile, from more than 2000 mm per year near the Baro basin to approximately 1500 mm per year (Sutcliffe and Parks, 1999). In the Lower Blue Nile, rainfall decreases significantly, from about 1000 m at the Ethiopia-Sudan border to 200 mm per year at the outlet near Khartoum. Since the rainfall is highly seasonal, the Blue Nile displays a highly seasonal flood regime, with over 80% of annual discharge occurring between July and October, while 4% of the flow occurs during the driest period from January to April. Annual potential evaporation decreases with increasing elevation in the basin, from 1800 mm to 1200 mm over the upper parts, and increases significantly northward to 2400 mm near Khartoum. The Blue Nile crosses humid to semiarid climate conditions in Sudan and receives a negligible runoff except for two tributaries, the Dinder and the Rahad, which originate from the Ethiopian Plateau as well. The Blue Nile below Roseires is a mild stream with a slope of about 0.12×10^{-3}, which is about one-tenth of the torrential stream that prevails all the way from the exit of Lake Tana to Roseires (Shahin, 1985). Two dams were built

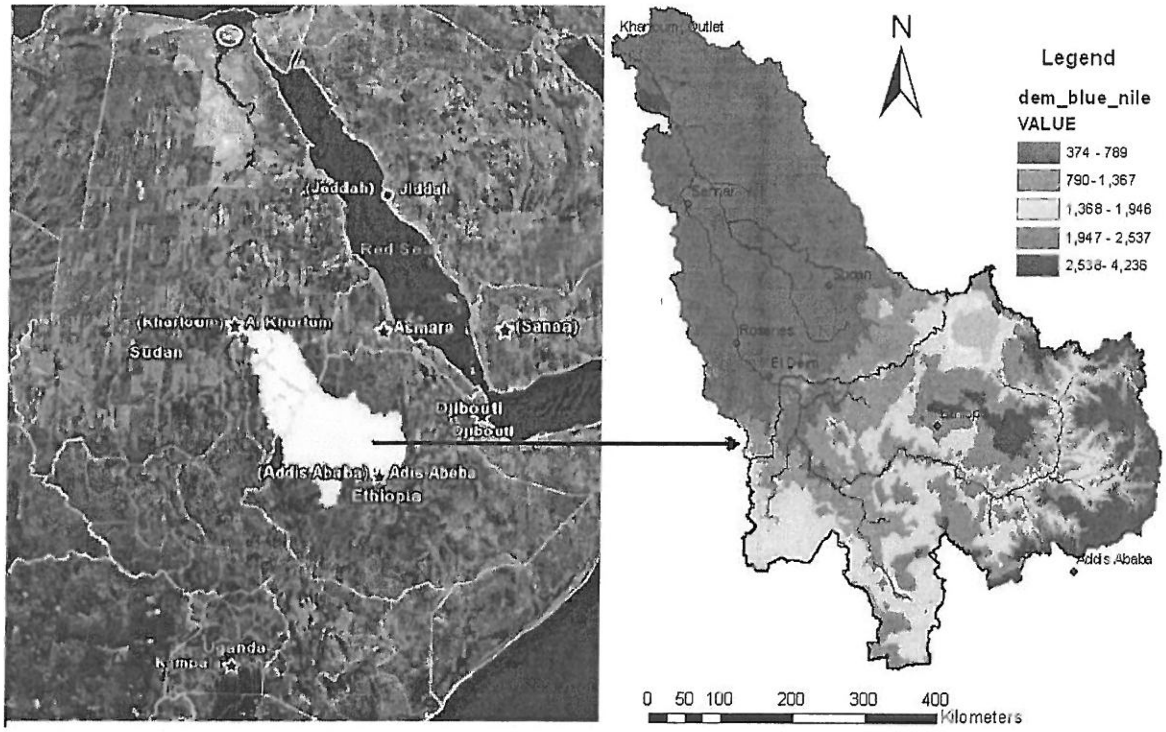

Figure 2. Location map of the study area of the Blue Nile.

across the Blue Nile: the Sennar dam in 1925, and the Roseires dam in 1966. The Roseires reservoir originally had a volume of 3,000 Mm^3 at a level of 480 m, with a surface area of 290 km^2 extending over a length of 75 km. The Sennar reservoir originally had a volume of 930 Mm^3 at a level of 425 m, with a surface area of 160 km^2 (WL/Delft Hydraulics, 1992). The Upper Blue Nile is characterized by a rapid land use change from forest to agricultural due to rapid population growth (Conway, 1997). Therefore, the predominant processes occurring in the Blue Nile basin are inordinate soil erosion in the highlands of the Ethiopian Plateau, and sedimentation of reservoirs and irrigation canals in the Lower Blue Nile. For instance, the Roseires and Sennar reservoirs have lost their original storage capacity due to siltation by two-thirds and a half, respectively (WL/Delft Hydraulics, 1992).

SWAT Model Setup

The Upper Blue Nile watershed was delineated using the digital elevation model (DEM) approximately 90 m grid of SRTM (Jarvis et al., 2006), a mask, and a digitized stream network input under the AVSWAT interface. The mask was used to extract the study area, since the DEM covers a wider area than the study area. The digitized stream network was used to improve the delineation of some hydrologic features of the watershed that may be obscured or oversimplified because of problems of map scale and lack of adequate DEM vertical resolution in areas of low relief (Di Luzio et al., 2004). A threshold value for the drainage area of 10,000 km^2 was used to discretize the watershed into 14 subbasins. The geomorphological parameters of the basin and subbasins were calculated from the DEM. The USGS land use map of 1 km resolution (USGS, 1997) and the FAO soil map of 10 km resolution (FAO, 1995) were overlaid to obtain 110 unique combinations of land use and soil hydrologic response units (HRU). Such a definition of HRUs helps to reflect the differences in hydrological processes (e.g., evapotranspiration) within the subbasins. Weather variables used to force the hydrological balance include measured daily rainfall and minimum and maximum temperature. These daily data were obtained from the Ethiopian Ministry of Water Resources. The remaining weather variables, such as wind speed, solar radiation, and relative humidity, were generated using the weather generator implemented in SWAT2005.

Sensitivity analysis was carried out to identify input parameters that significantly affect the model outputs. SWAT2005 uses LH-OAT (Latin Hypercube, One factor At a Time), which is the automatic global sensitivity analysis developed by van Griensven et al. (2006). The sensitivity analysis was conducted using daily streamflow and sediment concentration data at the El Deim gauging station (Ethiopia-Sudan border).

The SWAT model can be calibrated either using manual or automatic calibration. In this study, the Parameter-Solutions (ParaSol) method, which is the automatic calibration algorithm implemented in SWAT2005 (van Griensven and Meixner, 2007), was used to calibrate the SWAT model. The SWAT model was calibrated from 1980 to 1986 and validated from 1987 to 1997 using daily observed flow and sediment concentration data at the Upper Blue Nile outlet (El Deim). The model performance for both variables was measured using Nash-Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970). The model calibration results are presented in the Results and Discussion section.

SOBEK Model Setup

The SOBEK model was set up for the lower Blue Nile River using river cross-sections, hydraulic and morphologic inputs. The river cross-section data were obtained from the Sudanese Ministry of Irrigation. The data include 40 cross-sections with an average distance of 20 km for the Khartoum-Sennar reach and 36 cross-sections with an average distance of 10 km for the Sennar-Roseires reach. Only five cross-sections were available at an average distance of 20 km between the Roseires dam and El Deim. The two dams (Roseires and Sennar) were represented in the Blue Nile model using a compound structure, which is a combination of a general structure and a broad weir, from the options provided in the SOBEK model. The general structure simulates the five deep sluices that flush sediment, while the broad weir mimics the six spillways of the dams. SOBEK's model time controller was applied to represent the reservoir water level and simulate the operating rules of the reservoir. A Chezy coefficient of 50 for both positive and negative flows was applied to represent the channel roughness. The observed discharge hydrograph was used for the upstream boundary condition at El Deim, and the water level in Khartoum was used for the downstream boundary condition. The upstream boundary condition, located at 100 km upstream of Roseires dam, was not affected by the dam's backwater since the backwater influence only extends 53 km upstream from the dam. For sediment transport simulation, observed sediment concentration data were used as the upstream boundary condition at El Deim, and the river bed level of 368 m in Khartoum was used for the downstream boundary condition. A time step of 3 h and a distance step of 1000 m were applied for the numerical input.

The SOBEK model for the lower Blue Nile was manually calibrated at the Roseires and Sennar dams. The manual calibration involved adjusting the time controller parameter of the dams by trial and error to obtain a good fit between the observed and simulated streamflows. The periods of calibration and validation of the SOBEK model were 2000 and 2003, respectively. The calibration and validation results are given in the Results and Discussion section.

OpenMI Linked Model Setup

The integrated modeling of the Blue Nile comprised the OpenMI-compliant versions of SWAT and SOBEK. The OpenMI-compliant version of SOBEK was developed by WL/Delft Hydraulics. The SWAT model simulated the streamflow and sediment hydrographs from the Upper Blue Nile catchment and provided those outputs to SOBEK at El Deim (fig. 2). Then SOBEK routed streamflow and sediment downstream to the outlet in Khartoum. Prior to linking, however, both OpenMI-compliant models were meticulously tested to ensure that they provide the same results as their respective non-OpenMI-compliant versions. The test basically compared the number of files printed and their content. The OpenMI Configuration Editor, displayed in figure 3, was used to link the OpenMI-compliant SWAT and SOBEK models using the following steps:

Step 1. The calibrated SWAT and SOBEK models were populated with data using their interfaces 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 and folder name of the OpenMI-compliant model (i.e., linkable component).

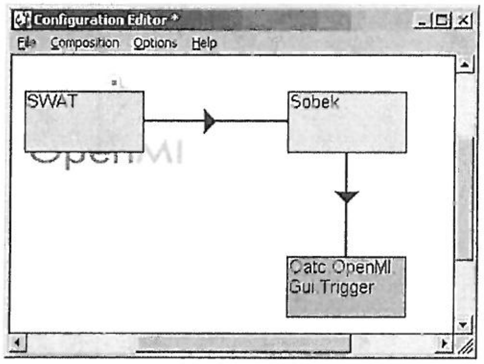

Figure 3. OpenMI configuration editor used to configure link between the models.

Step 2. The models were added to the OpenMI editor using the Add Model button from the Composition menu of the OpenMI editor. To load the models, the OMI files were opened from the file system using the Add Model button. Each time the OMI file is loaded, the model reads its input file. A trigger component was also created by default. The trigger component was linked to the SOBEK model; its purpose was to trigger SOBEK to request data from SWAT.

Step 3. The connection link between the models was added, using the Add Connection button, by dragging the arrow from the SWAT model and dropping it on SOBEK model. This connection link contains the models' potential output exchange items (shown in table 1), potential input exchange items, data operation properties, and locations where data exchange items occur. Next, the actual exchange items, data operations, and locations were defined using the connection properties dialog box. The actual output exchange items of the SWAT component are discharge and sediment fractions (i.e., clay, silt and sand). These items are accepted by the SOBEK component at El Deim as its boundary condition. It is important to note that the SWAT component interpolates its daily outputs to hourly before providing them to the SOBEK component, which runs at an hourly time step.

Results and Discussion

SWAT Model Results

The SWAT model flow predictions were calibrated against the observed daily flow at El Deim from 1980 to 1986 and validated with observed daily flow data from 1987 to 1996. The year 1980 was used to warm up the model. The simulated daily flow matched the observed values with NSE values of 0.91 for calibration and 0.82 for the validation. A comparison of the observed and simulated daily streamflow for the calibration and validation periods is shown in figure 4. The model accurately simulated the rising and recession limbs of the hydrographs for the calibration and validation periods, as shown in figures 4a and 4b. Furthermore, the model accurately captured the peak flow in the calibration period, except in 1982, which is important for sediment simulation. However, the model was not able to capture the observed peak flow in the validation period. This could be attributed to the precipitation data, since many of the days had missing precipitation values. The literature has also reported that precipitation data quality is the main constraint for accurate

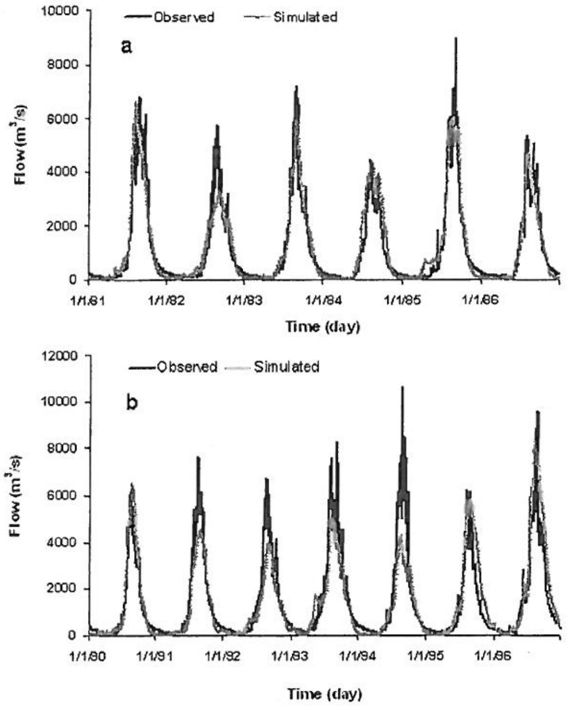

Figure 4. Observed and SWAT-simulated streamflow results for (a) calibration and (b) validation at El Deim gauging station.

modeling of discharge in the Blue Nile (Steenhuis et al., 2009).

The SWAT model sediment predictions were calibrated against observed daily sediment concentrations at the El Deim gauging station from 1980 to 1986 and validated with observed daily sediment concentrations data from 1990 to 1996. The year 1980 was used to warm up the model. The simulated daily sediment concentrations matched the observed values with NSE values of 0.72 for calibration and 0.66 for validation. These results are satisfactory for soil erosion modeling according to Moriasi et al. (2007), who stated that sediment simulation is judged as satisfactory if NSE > 0.5. A comparison between observed and simulated daily sediment concentrations for the calibration and validation periods is shown in figure 5. The model simulated the rising and recession limbs of the sediment concentrations for the calibration and validation periods. The model peak sediment predictions were able to capture the observed peak sediment concentrations in most of the calibration years. However, the model was not able to capture the observed peak sediment in most of the validation years. The model simulations overestimated the observed sediment concentrations during the dry period for both the calibration and validation periods.

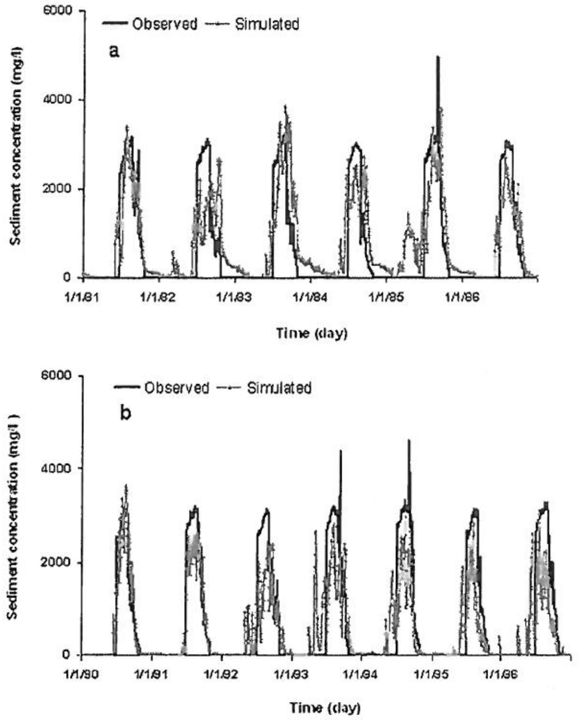

Figure 5. Observed and SWAT-simulated sediment results for (a) calibration and (b) validation at El Deim gauging station.

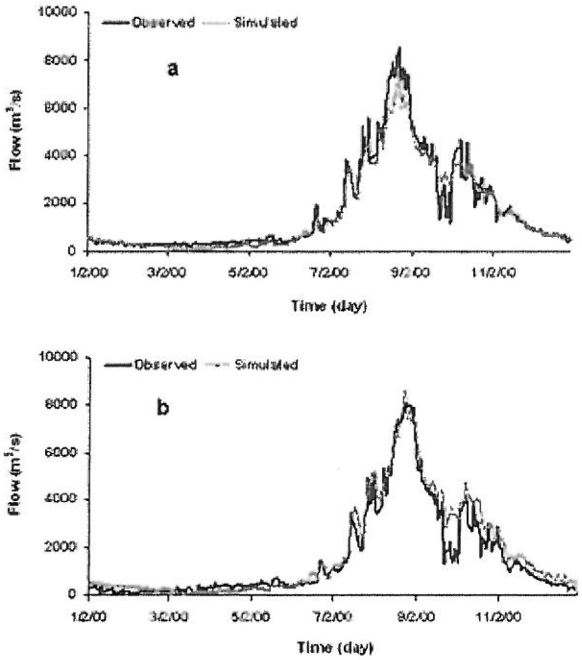

Figure 6. Observed and SOBEK-simulated streamflow calibration at the (a) Roseires and (b) Sennar gauging stations.

SOBEK Model Results

Figure 6 shows a comparison between the observed and simulated daily streamflows for the SOBEK model calibration in the year 2000 at the Roseires and Sennar gauging stations. The results for Roseires (fig. 6a) show that the model accurately simulated the flow regime. In particular, it simulated the propagation and magnitude of the rising and falling limbs of the hydrographs. Nevertheless, the peak streamflow was slightly underestimated. This could be attributed to ungauged inflow into the reservoir from the catchment between El Deim and Roseires, although it is difficult to rule out other factors. The predicted daily streamflow result at Sennar captured the observed peak streamflow, which is shown in figure 6b. However, the model could not simulate the sudden lowering of the gate, which is meant to flush sediment, during the last week of September 2000. In addition, the model slightly overestimated the falling limb, which is due to streamflow abstraction to the Gezira irrigation scheme.

Figure 7 shows a good fit between the observed and simulated daily streamflows for the SOBEK model validation at the Roseires and Sennar gauging stations. The model captured the rising limb and the peak streamflow. However, the model did not simulate the peak in the beginning of September, when the reservoir would have been starting to fill if the streamflow had dropped to 350 Mm^3 d^{-1} at El Deim. This is attributed to the fact that, during the calibration, the flow at El Deim satisfied the reservoir filling condition, so the model was not trained to lower the weir in case the flow did not drop to 350 Mm^3 d^{-1}. In fact, the flow at El Deim for the validation period was 432 Mm^3 d^{-1}. Similar to the calibration period, the model did not simulate the sudden opening of the weir to flush the sediment at both Roseires and Sennar.

The sediment transport module was not calibrated due to lack of data on sediment grain size. Nevertheless, the model could be assumed to predict the sediment transport with reasonable accuracy, since the hydrodynamic and sediment transport simulations are closely interconnected. The calibration and verification of the hydrodynamic and sediment transport modules are closely interlinked because the morphological changes are fed to hydrodynamics, and flow resistance and sediment transport have a close relationship (Hassan and Dibike, 2000). Note that satisfactory calibration results were obtained for the hydrodynamic simulation. Figure 8 shows a comparison between the observed and simulated daily sediment transport results at the Wad Elias station, which is located downstream of the Roseires station. These sediment transport results corroborate the interlinked nature of the hydrodynamic and sediment transport simulations. Therefore, after satisfactory sediment transport verification, the SOBEK model was run to simulate erosion and deposition along the river bed.

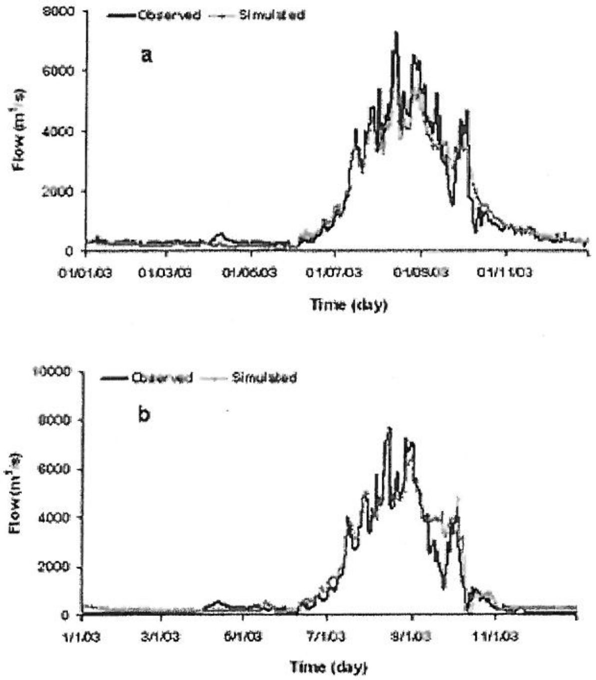

Figure 7. Observed and SOBEK-simulated streamflow validation at the (a) Roseires and (b) Sennar gauging stations.

Linked Model Results

The SWAT model performed simulations from 1980 to 2003, while the SOBEK model performed simulations from 2000 to 2003. The time steps for SWAT and SOBEK were one day and three hours, respectively. Computation started with the trigger performing a "Getvalue()" call to the SOBEK linkable component at a specified time stamp. Thus, the SOBEK made "Getvalue()" calls to the SWAT linkable component to request data. Accordingly, SWAT computed until the requested time step (i.e., year 2000), interpolated the data to three hours, and returned the values to SOBEK. It is important to note that the SWAT model accounted for data unit conversion before providing data to SOBEK. Once the coupled model simulation was completed, the results were visualized using SOBEK's graphical user interface.

A comparison between the observed and simulated daily streamflows at the Roseires gauging station is shown in figure 9. The coupled model accurately simulated the observed daily streamflow on the rising limb. The coupled model was able to simulate the falling limbs of the hydrograph, except for the sudden lowering of the gate to flush sediment. However, the linked model underestimated the observed peak streamflow.

Erosion and deposition of sediment along the Blue Nile river bed is shown in figure 10. The bed level in the year 2000 shows the initial river bed level. Since the year 2001, a significant bed level change was observed compared to the base year due to erosion and deposition processes. Figure 10

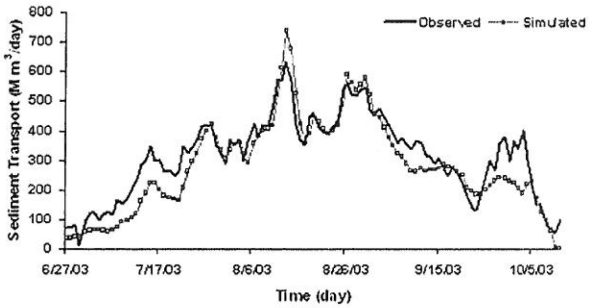

Figure 8. Observed and SOBEK-simulated daily sediment transport at Wad Elias gauging station (downstream of Roseires station).

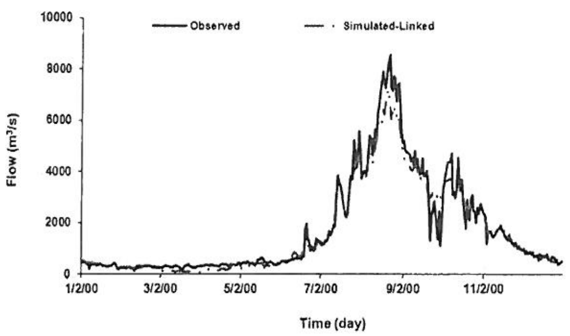

Figure 9. Observed and linked model (SWAT and SOBEK) simulated streamflows at Roseires gauging station.

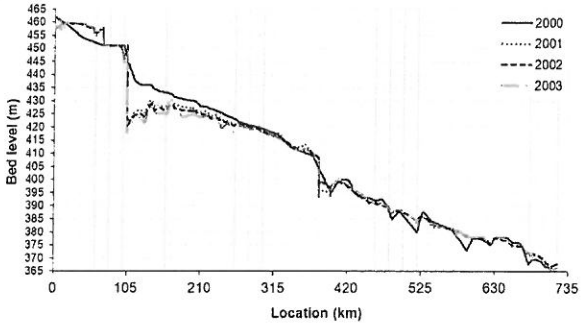

Figure 10. Erosion and deposition of sediment in the Lower Blue Nile river bed.

clearly shows that most of the suspended sediment transported from the Upper Blue Nile is deposited at 35 km before the Roseires dam. This is expected due to the effect of the backwater curve, which reduces the streamflow velocity and sediment transport capacity. The sediment deposition gradually led to the formation of the reservoir delta. This delta formation agrees with the principle of reservoir sedimentation of the Tarbela reservoir in Pakistan (Sloff, 1997). It is important to note that the effect of backwater on sediment deposition cannot be simulated with SWAT alone because SWAT uses a kinematic wave equation to route flows. Lian et al. (2006) reported that observed peak flows and magnitudes were not reproduced for the Illinois River using SWAT because SWAT was less capable of routing flows in that complex river, which has locks and dams, backwater lakes, and backwater effects from the Mississippi River. In this study, however, the linked model simulated the effect of backwater on sediment deposition where there are reservoirs. After Roseires, there are local erosion and deposition of sediment.

CONCLUSIONS

In this article, the SWAT2005 (hydrologic) model code was adapted into an OpenMI-compliant version and coupled to the SOBEK (hydrodynamic) model to improve SWAT's flow and sediment routing capability. SWAT simulated the streamflow and soil erosion in the upstream catchment, and SOBEK accepted the streamflow and sediment input from SWAT and routed them through the downstream reach. The linked model simulated the observed hydrodynamics and sediment deposition due to backwater effects, which is not possible with the original SWAT model. The linked model could be used to relate upstream management issues, such as the introduction of agricultural best management practices, to downstream issues, such as sedimentation of reservoirs. The development process for the OpenMI-compliant SWAT model was a very tedious way to link models for a single application. Nevertheless, it is promising for future integrated modeling since linking to OpenMI-compliant models has recently become much easier. The developed OpenMI-compliant SWAT model could be linked to other models, such as groundwater, climate change, and socioeconomic models, to address integrated water resources management problems, including water quality and quantity issues.

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