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An efficient semi-distributed hillslope erosion model for the sub humid Ethiopian Highlands

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Abstract

During the last two decades, saturated excess runoff has become accepted as the main source for overland flow in humid regions. Erosion modeling has generally not kept up with this new reality and predictions are often not based on landscape topographic position, which is a main variable in saturation excess runoff. In addition, predicting sediment loss in Africa has been hampered by using models that have been developed in western countries and do not perform as well in the monsoon climate prevailing in most of the continent. The objective of this paper is to develop a simple erosion model that can be used in the Ethiopian highlands in Africa. We base our sediment prediction on a simple distributed saturated excess hydrology model that predicts surface runoff from severely degraded lands and from bottom lands that become saturated during the rainy season and estimates interflow and base flow from the remaining portions of the landscape. By developing an equation that relates surface runoff to sediment concentration generated from runoff source areas, assuming that base flow and interflow are sediment free, we were able to predict daily sediment concentrations from the Anjeni Watershed and Blue Nile Basin with a Nash Sutcliffe efficiency ranging from 0.64 to 0.77 using only two calibrated sediment parameters. Anjeni is a 113 ha watershed in the 17.4 million ha Blue Nile Basin in the Ethiopian Highlands. The daily flows were predicted with Nash Sutcliffe efficiency values ranging from 0.80 to 0.93 if degraded areas were assumed the major sediment source areas and covered 14 % of the Anjeni watershed and 20 % of the Blue Nile basin. The analysis suggests that identifying the runoff source areas and predicting the surface runoff correctly is an important step in predicting the sediment concentration.

1 Introduction

In the African highlands, erosion has occurred for a long time (Lal, 1985; Nyssen et al., 2004). In colonial times, the devastating effects of soil loss from newly developed agricultural lands was noted and the need to combat it was expressed (Champion, 1933).

However, despite large investments in soil and water conservation practices, sediment yields have been increasing in Africa (Lal, 1985; Fleitmann et al., 2007). The reasons mentioned for increased soil loss were greater population pressure and consequently more intensive cultivation (Fleitmann et al., 2007). In addition, most of the soil and water conservation practices were imported from the US without considerations of their appropriateness for the monsoon climate (Hudson, 1987). These imported practices were usually placed on steep slopes to reduce soil loss based on research recommendations at the plot scale (Wischmeier and Smith, 1978; El-Swaify et al., 1982; Hudson, 1957, 1983) rather than the watershed scale. In Ethiopia, Mituku et al. (2006) reported that 40 % of all erosion is caused by the wrong installation of soil and water conservation (SWC) practices.

For the Blue Nile basin, a part of the Ethiopian highlands, reported soil losses varying from 1 to over 400 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ (Hurni, 1988; Mitiku et al., 2006; Tebebu et al., 2010) with an average of 7 $\mathrm{t\,ha^{-1}}$, or equivalent to a depth 0.5 mm (Garzanti et al., 2006). At the same time several large dams are planned in the Blue Nile Basin; therefore, these future developments urgently need better ways to reduce soil loss in order to sustain the efficient operation of the dams well into the future.

In the coming decades, models will play an important role in erosion control of this basin, especially by prioritizing the location for erosion control. However, this is problematic because most erosion modeling (just as with evaluation of soil and water conservation practices) is based on plot scale research (Wischmeier and Smith, 1978; Vanmaercke et al., 2011). Scaling up plot scale soil estimates to watershed or basin scale invariably leads to overestimation or underestimation at the outlet (Vanmaercke et al., 2011). Discussions of scaling up from plot scale is not only limited to erosion. For example, for discharge predictions Savenije (2010) writes "physically based small scale basic principles (such as the Darcy, Richards, and Navier-Stokes equations) with detailed distributed modeling, leads to equifinality and high predictive uncertainty, mostly because these methods ill account for heterogeneity, preferential pathways and structural patterns on and under the surface". Other researchers are not as pessimistic and argue that Darcy's and Richards' law apply and can predict with a reasonable degree of accuracy the moisture contents and leaching patterns after some calibration of the parameters (Kung et al., 2000; Kim et al., 2005; Zehe et al., 2010; Klaus and Zehe, 2011). Although due to lack of fine and detailed information, the best way of finding the regularity in the "calibration" parameters is being intensively researched, there is agreement that there exists some measure of organized complexity at intermediate and larger scales (Dooge, 1986, 2005; Savenije, 2010; He et al., 2011).

Dooge (1986, 2005) and Savenije (2010), argue for the use of relatively simple watershed models because these models utilize the realm of the organized complexity implicit in naturally formed catchments and river basins. Our experience confirms that in (semi) humid Ethiopian highlands and in the Catskill mountain (New York State) watersheds with saturated excess runoff, simple catchment-scale models can make use successfully of emerging patterns of self-organization because these watersheds always wet up similarly (Bayabil et al., 2011). In the model that we developed for these landscapes, the watershed is divided into three distinct areas consisting of the periodically saturated bottom lands, severely degraded areas with very shallow soils over an impermeable layer, and hillsides (Steenhuis et al., 2009; Tesemma et al., 2010). The saturated and degraded areas produce surface runoff and sediment, but the hillsides release sediment-free interflow and base flow to the river. This model that was tested for discharge of Ethiopian Blue Nile basin at the border with Sudan is similar in structure to that of Savenije (2010) but simpler.

The objective of this study is therefore to improve erosion prediction by using a reasonably accurate hydrology model of Steenhuis et al. (2009) to improve sediment concentration predictions in the Ethiopian highlands at two scales. The sediment model closely follows the model of Hairsine and Rose (1992a, b) as developed by Rose (1993) and that of Ciesiolka et al. (1995) and Yu et al. (1997) assuming that a linear relationship between sediment concentration and velocity from runoff producing areas. It also assumes dilution with interflow similar to the Steenhuis et al. (2009) regression relationship.

Sediment concentration data are available for a few watersheds in Ethiopia. These watersheds were established by the Soil Conservation Research Program (SCRP) initiated in 1981 in order to support and monitor SWC efforts in the highlands of Ethiopia by the Governments of Ethiopia and Switzerland. In this paper, we used the data of one of these experimental watersheds located in the Ethiopian Highlands, Anjeni, and the Ethiopian Blue Nile basin at the Ethiopian-Sudan border.

2 Model descriptions

2.1 Overview of models

Erosion models applied in the Ethiopian Highlands range from empirical plot scale relationships (Universal Soil Loss Equation – USLE, Wischmeier and Smith, 1976) to physically-based models. Hurni (1985) adapted the empirical plot scale USLE for Ethiopian conditions. Eweg et al. (1998) and Zegeye et al. (2011) showed that the modified USLE can be used to estimate average annual soil losses but reliable predictions of the spatial and temporal distributions were questionable.

Agricultural Non-Point Source Pollution (AGNPS) model (Haregeweyn and Yohannes, 2003; Mohammed et al., 2004), and the Soil and Water Assessment Tool (SWAT) (Setegn et al., 2008) were applied in the Ethiopian highlands. These models that use both the curve number (infiltration excess runoff) for the hydrology and the USLE for erosion predictions do not perform satisfactorily even on a monthly basis. The modified SWAT-WB Water Balance model (Easton et al., 2010; White et al., 2010) with saturation excess gave better results in Ethiopia, while the Water Erosion Prediction Project (WEPP) (Zeleke, 2000), which has a more advanced erosion prediction tool but still used infiltration excess for runoff, performed below average.

Other erosion models available but not applied in Ethiopia are Areal Nonpoint Source Watershed Response Simulation (ANSWERS) (Beasley et al., 1980), European Soil Erosion Model (EUROSEM) (Morgen et al., 1998), Physical Water Erosion

Model (Hairsine and Rose, 1992a, b) and Griffith University Erosion System Template (GUEST) (Yu et al., 1997). Besides shear stress (Yalin, 1963), these models use a stream power function for predicting sediment carrying capacity (Rose, 2001) where the sediment concentration at the transport limit is related to runoff depth as a power function (Ciesiolka et al., 1995; Yu et al., 1997). Limited testing of these models has been done for monsoonal climates. The Hairsine and Rose model (1992a, b) that resulted in a linear relationship between sediment concentration and velocity of runoff predicted sediment concentrations successfully in the monsoon climate of the Philippines, Thailand and Malaysia using observed stream flows (Rose, 2001). In the foot hills of Nepal, WEPP predicted soil erosion the best from USLE type plots followed by the GUEST Technology and EUSROSEM (Kandel et al., 2001).

Our conceptual model will use the patterns of self-organization introduced by Savenije (2010) to model the discharge and the sediment concentration of two watersheds in the Ethiopian highlands varying greatly in size. We will combine (and test further at smaller scales) the hydrology model of Steenhuis et al. (2009) and Tesemma et al. (2010) with the simplified erosion models from the Rose and Hairsine group in Australia and test both the hydrology and erosion m0dels at small and large scales.

2.2 Model development

2.2.1 Conceptual model

The model predicts daily sediment concentrations. A daily time step was chosen for predicting discharge because the data for rainfall distribution within a day was generally not available. The prediction of daily sediment concentration is based on the concept that erosion is produced in areas with surface runoff. Thus, in our hydrology model that simulates surface runoff from saturated and degraded hillside areas, erosion is simulated only from these runoff producing source areas. Degraded lands are defined here as those lands that are shallow and store only small amounts of rainwater, and therefore, produce runoff and support very little vegetation. Erosion is negligible from the non-degraded hillsides because almost all water infiltrates. Erosion rates are greater from the more heavily degraded areas without plant cover than from the saturated source areas with natural vegetation. The only exception could be in the beginning of the rainy season in cases where these soils were used for growing a crop during the dry season. This is not simulated since we do not have this information.

The other concept is that baseflow and interflow play an important role in the conversion of event-based sediment concentration to daily sediment concentration. This directly affects how the sediment concentrations are simulated. To demonstrate this, two storms are depicted one in the beginning of the short rainy season (24 April 1992, Fig. 1a) and one later in the main rainy season (19 July 1992, Fig. 1b) when more than 500 mm of cumulative effective rainfall had fallen since the beginning of the main rainy season for the Anjeni watershed which will be discussed later in more detail. At this time, the watershed had wetted up and interflow occurred (Liu et al., 2008). The surface runoff for both events is similar with peak runoff at 400–500 $\mathrm{l\,s^{-1}}$ above the flow recorded prior to the beginning of the storm. The duration of the runoff event was approximately 2 h. The peak sediment concentrations were nearly the same around 30–35 $\mathrm{g\,l^{-1}}$. Base flow discharge is low during the beginning of the rainy season (around 10 $\mathrm{l\,s^{-1}}$ for April or equivalent to 0.8 $\mathrm{mm\,day^{-1}}$ over the whole watershed). Baseflow increases during the rainy season. It is approximately 50 $\mathrm{l\,s^{-1}}$ (equivalent to 4 $\mathrm{mm\,day^{-1}}$) in July. Despite the similar surface runoff characteristics, the April discharge was $2.4 \times 10^3\ \mathrm{m^3\,day^{-1}}$ and for July was $6.5 \times 10^3\ \mathrm{m^3\,day^{-1}}$. The average daily sediment concentrations can be obtained by dividing the load by the total flow resulting in concentrations of 11.3 $\mathrm{g\,l^{-1}}$ for the April storm and 4.4 $\mathrm{g\,l^{-1}}$ for the July storm. What is important to note is that in calculating the average daily stream flow data, the peak flows occur less than 10 % of the time, thus the baseflow contributions when averaged over a day is a significant portion of the daily flow for the July storm when the watershed is in equilibrium. In essence, the baseflow dilutes the peak storm concentration when simulated on a daily basis later in the rainy season. It is therefore important to incorporate the contribution of baseflow in the prediction of sediment concentration.

2.2.2 Hydrology model

The watershed is divided into three regions: two surface runoff source areas consisting of areas near the river that become saturated during the wet monsoon period and the degraded hillsides with little or no soil cover. Practically, saturated areas are identified in the watershed during most times of the year as green areas with flat or gentle slopes while degraded areas can be recognized easily in the landscape during the growing season as the areas with little or no vegetation. The remaining hillside areas have infiltration rates in excess of the rainfall intensity (Bayabil et al., 2010; Engda et al., 2011). Consequently, rainwater infiltrates and becomes either interflow or baseflow depending on its path to the stream. A daily water balance is kept for each of the regions using the Thornthwaite-Mather procedure (Thornthwaite and Mather, 1955; Steenhuis and van der Molen, 1986) for calculating the actual evaporation. Overland flow is simulated when the soil is at saturation for the potentially saturated areas and the degraded hillsides. Since the soil in the degraded areas is shallow, only minor amounts of rainfall are required before the soil saturates and runoff is produced. When the soil on the hillsides reaches field capacity, additional rainfall is released to the first order base flow reservoir and a linear interflow reservoir. More detail on the daily water balance and subsurface flow equations are given in Steenhuis et al. (2009) and Tesemma et al. (2010) where the model was applied to the whole Blue Nile Basin using a Microsoft Excel spreadsheet.

Inputs to the model are daily rainfall and potential evaporation. Parameters of the model are the extent of the three areas in the watershed, the amount of storage in the soil between witling point and saturation for the runoff producing areas, and wilting point and field capacity for the hillside. In addition, there are three more subsurface parameters: a maximum storage and half-life for the first order groundwater reservoir, and the time it takes for a hill slope to drain after a rain storm for the linear interflow reservoir.

2.2.3 Sediment model

In the sediment model, we assume for simplicity that the erosion process is transport limiting. Then for the two source areas, the mean suspended sediment concentration C ($\mathrm{kg\,m^{-3}}$) is a function of flow rate and a coefficient dependent on landscape and sediment characteristics (Hairshine and Rose, 1992a, b; Rose et al., 1993; Siepel et al., 2002; Ciesiolka et al., 1995; Yu et al., 1997).

$$C = aQ^n \tag{1}$$

where Q is the runoff rate per unit area from each source areas ($\mathrm{m\,day^{-1}}$), a is a constant which is a function of the slope, Manning's roughness coefficient, slope length, and the effective depositability (Yu et al., 1997) and n is the exponent that takes a value of 0.4 assuming a linear relationship between sediment concentration and velocity and wide channel on the runoff producing areas (Ciesiolka et al., 1995; Yu et al., 1997). As water depth increases a, essentially becomes independent of the runoff rate and can be taken as a constant such as in this application where we are interested in sediment concentration at the outlet of watersheds of over 100 ha (Lisle et al., 1996).

Sediment yield ($\mathrm{t\,day^{-1}\,ha^{-1}}$) Y_i, for each of the two runoff source areas, i, then becomes

$$Y_i = Q_i \times Q_i^{0.4} \times a \tag{2}$$

To calculate the suspended sediment concentration at the watershed outlet, we note that the discharge Q_T can be written in terms of the contributions of the three areas delineated in the watershed.

$$Q_{T_t} = A_1 Q_{1t} + A_2 Q_{2t} + A_3\left(Q_{\mathrm{BF}_t} + Q_{\mathrm{IF}_t}\right) \tag{3}$$

where Q_{1t} and Q_{2t} are the runoff rates expressed in depths units for contributing area A_1 is the fractional saturated area and A_2 is the fractional degraded area. A_3 is the fractional contributing area for baseflow Q_{BF_t} and interflow $\mathrm{Q}_{\mathrm{IF}_t}$.

Sediment yield in the stream depends on the amount of suspended sediment delivered by each component of the stream flow. The daily sediment yield equation in its most general form is:

$$Y_t = A_1 Q_{1t} C_{1t} + A_2 Q_{2t} C_{2t} + A_3 (Q_{\mathrm{BF}_t} C_{\mathrm{BF}_t} + Q_{\mathrm{IF}_t} C_{\mathrm{IF}_t}) \tag{4}$$

where C_1 and C_2 and C_3 are the sediment concentration in runoff from the saturated area, and degraded area, respectively C_{BF_t} is the sediment concentration in the baseflow and C_{IF_t} the concentration in interflow. Recalling that sediments concentration, C, is related to the discharge as shown in Eq. (1), Eq. (4) can be rewritten as:

$$Y_t = a_1 A_1 Q_{1t}^{n+1} + a_2 A_2 Q_{2t}^{n+1} + A_3 \left(a_{\mathrm{BF}} Q_{\mathrm{BF}_t}^{n+1} + a_{\mathrm{IF}} Q_{\mathrm{IF}_t}^{n+1} \right) \tag{5}$$

Which simplifies to a relationship between sediment yield and discharge for $n = 0.4$

$$Y_t = a_1 A_1 Q_{1t}^{1.4} + a_2 A_2 Q_{2t}^{1.4} + A_3 \left(a_{\mathrm{BF}} Q_{\mathrm{BF}_t}^{1.4} + a_{\mathrm{IF}} Q_{\mathrm{IF}_t}^{1.4} \right) \tag{6}$$

The superscript of Q in Eq. (6) is within the range from 0.5 to 2 in the most common sediment transport capacity models (Prosser and Rustomji, 2000). By dividing Eq. (6) by the total discharge (Eq. 4) and taking the sediment concentration in the base and interflow as zero (i.e. $a_{\mathrm{BF}} = 0$ and $a_{\mathrm{IF}} = 0$), the sediment concentration can be found as:

$$C_t = \frac{a_1 A_1 Q_{1t}^{1.4} + a_2 A_2 Q_{2t}^{1.4}}{A_1 Q_{1t} + A_2 Q_{2t} + A_3 (Q_{\mathrm{BF}_t} + Q_{\mathrm{IF}_t})} \tag{7}$$

All parameters in Eq. (7) can be obtained from the hydrologic simulation with the exception of a_1 and a_2 that need to be calibrated with existing field data.

3 Material and methods

3.1 Description of Anjeni watershed and Blue Nile Basin

Anjeni is one of the seven experimental watersheds that were in operation in June 1984 as part of the Soil Conservation Research Program (SCRP), a collaborative project of the University of Berne, Switzerland, and the Ministry of Agriculture, Ethiopia. This watershed is in the Ethiopian Highlands and drains into the Blue Nile Basin.

The Anjeni watershed (Fig. 2 and Table 1) covers an area of 113.4 ha with elevations ranging between 2405 and 2507 m. It is located approximately at the center of the Blue Nile Basin that covers 17 400 000 ha. Anjeni is sub-humid in climate while the Blue Nile flows from humid to semi-arid climates on the way to the Ethiopian Sudan border. The annual rainfall of the basin ranges from approximately 2000 mm in the southeast to nearly 1000 in the northeast and 1690 mm at Anjeni. The rainfall at Anjeni is unimodal which lasts from the middle of May to the middle of October. Mean daily temperature ranges from approximately 6 to 25 °C in the basin as well as in the Anjeni Watershed.

The basin has a rugged topography and considerable variation in altitude ranging from 480 m to 4260 m highly incised by Blue Nile River and its tributaries in the northwest direction. The highlands of the basin are mainly basaltic rock and the lower part is predominantly basement complex rocks. The Anjeni watershed at the highland of the basin is oriented north-south and flanked on three sides by plateau ridges. Most of the watershed is on slopes ranging from 8 to 30 %. The geological formation of this watershed area belongs to the basaltic Trap series of the Tertiary volcanic eruptions, and the topography of the area is typical of Tertiary volcanic landscapes deeply incised by streams (Zeleke, 2000). There is high gully formation at the upper part of the watershed where a perennial spring is located at the head of the gully and becomes a source for a river called Minchet.

Alisols and Leptosols (21 %), Nitosols (16 %) and Vertisols (15 %) are the dominant soil types in the basin with shallow and permeable soil underlain by bedrock on the highlands and deeper soil at the lower reaches of the basin and its tributaries (Betrie et al., 2011). The soils of Anjeni have developed on the basalt and volcanic ash of the plateau. The southern part of the watershed with valley floors and the depressions of the foothill land consist of deep and highly conductive Humic Alisols and Haplic Nitosols, while moderately deep Cambisols cover the middle area and the very shallow Haplic Alisols and Humic Nitosols cover the hillsides indicating land degradation processes (Zeleke, 2000).

Before 1986, no management activities existed in the Anjeni watershed and were monitored without any SWC (SCRP, 2000). Fanya juu (SWC structure comprised of a bund above and a drainage ditch below the bund, Thomas and Biamah, 1991) were then constructed in early 1986 throughout the watershed and by 1992 had generally developed into terraces (Fig. 3, Hanggi, 1997).

3.2 Data

Since the establishment of the micro-watersheds by the Soil Conservation Research Project (SCRP) in 1984, fine resolution data on climate, hydrology, and suspended sediment from both river and test plots have been collected. In addition, an expansive data base has been established that serves as a data source to carry out hydrological, soil erosion, and conservation research activities at regional, national, and international levels. This watershed provided the most comprehensive data of daily rainfall, potential evaporation, stream flow, and sediment concentrations (Mitiku et al., 2006).

Stream flow and sediment concentration were measured at a station located at the outlet of each watershed by SCRP. The depth of water was taken with float-actuated recorders. The water level in the stream was measured daily at 08:00 a.m. local time. In case of peak stream flow events, water level measurements and sediment samples were usually taken at ten-minute intervals during the event and every 30 min when water level decreased. Discharge was evaluated using the relation between the water level and stream discharge (Bossahart, 1997). The river stage-discharge relationship was determined using salt-dilution and current-meter methods.

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One liter samples were taken from the river at the gauging station during the storm to determine the sediment concentration. Sampling started once the water in the gauging station looked turbid (brown), and the sampling continued at ten-minute intervals. When the runoff became clearer, the sampling interval was extended to thirty minutes and sampling continued until the runoff was visibly sediment free. The collected water samples were filtered using filter paper, sundried, and finally oven dried and weighed and net dry soil loss was calculated. Event-based sediment yields were summed over a daily period to determine daily sediment load. Daily sediment concentration was determined by dividing the daily sediment load by the total discharge during that day. These were then compared to the daily predicted sediment concentrations.

3.3 Model calibration and validation

3.3.1 Data

We calibrate first daily discharge values with the water balance model and subsequently the sediment concentrations with the sediment model of Eq. (7). The data used in the model is summarized in Table 1. In Anjeni, the period from 1988 to 1997 was used as data source for daily rainfall, potential evaporation and stream flow in this study. For calibration of the water balance model in Anjeni (Table 2), the data of year 1988 and 1990 were used and 1989, 1991–1994 and 1997 were used for validation. The climate data for the years 1995 and 1996 were incomplete and excluded from model development processes.

The sediment concentration data for the same years, except 1988, was excluded because of very low sediment concentration measurements. The low concentration might have been caused by bunds installed (Fanya juu) in the watershed in 1986 that captured all sediment effectively. Equilibrium was likely established in 1990, when the terraces were formed behind the bunds in the runoff source area. In the non-source area terrace were established in 1992 (Hanggi, 1997). Consequently, the year 1990 was used for calibration and the period 1991–1993 was used for validation in the sediment modeling.

The years with sediment concentrations data for the Blue Nile at the Sudan border was limited to three years 1993, 2003 and 2004. The period of 1993 was used to calibrate both hydrology and sediment models in the Blue Nile basin while the other two years 2003 and 2004 were used for validation.

3.3.2 Methods of calibration and validation

All the nine input parameters were calibrated for the hydrology model (Table 2). Initial values for calibrating parameters were based on Steenhuis et al. (2009) and Collick et al. (2009). These initial values were changed manually through randomly varying input parameters in order that the best "closeness" or "goodness-of-fit" was achieved between simulated and observed subsurface and overland flow in the watershed. For partitioning the rainfall into surface runoff and recharge for sub-surface reservoirs, they consisted of the size (A) and the maximum storage capacity (S_{max}) for the three areas, and for the subsurface they involved the half-life ($t_{1/2}$) and maximum storage capacity (BS_{max}) of a linear aquifer and the drainage time of the zero order reservoir (τ^*).

In the sediment model, daily sediment load was first computed and then divided by the total daily stream flow using Eq. (7) to compute the daily sediment concentration. In the equation, there are two calibration parameters consisting of the constants for each of the two runoff source areas a_1 and a_2. These constants are changed manually in order to get a best fit between measured and simulated daily sediment concentration.

During model calibration and validation period, the Nash-Sutcliffe coefficient (NSE), coefficient of determination (R^2) and the Root Mean Squared Error (RMSE) were used to evaluate the performance.

4 Results and discussion

The calibrated input parameters are shown in Table 2 and the goodness of fit Nash-Sutcliffe coefficient (NSE), coefficient of determination R^2 and root mean squared error

(RMSE) for the hydrology and sediment model are presented in Table 3. A comparison of predicted and observed daily stream flow for the Anjeni watershed is shown in Fig. 4 and in the Supplement Fig. S1 and for sediment concentrations in Fig. 5 and in the Supplement Fig. S2. For the Blue Nile Basin, Fig. 6 shows both predicted and observed 10-day stream flow and 10-days average sediment concentration were shown in Fig. 7.

4.1 Hydrology model

The hydrology model performed quite well (Table 3) for both the Anjeni watershed (Fig. 4) and the Blue Nile Basin (Fig. 6). The model calibration suggests (Table 2) that 14 % of the Anjeni watershed and 20 % of the Blue Nile Basin areas consists of degraded area with shallow soil or exposed hardpan, which requires only a little rain to generate direct runoff (i.e. $S_{\text{max}} = 10\,\text{mm}$) and approximately 2 % of Anjeni and 20 % of Blue Nile Basin are of saturated bottom lands that needed 70 and 200 mm, respectively, of effective precipitation to generate runoff (i.e. $S_{\text{max}} = 70$ and 200 mm). The hillside or the infiltration (recharge) areas in Anjeni and Blue Nile Basin represent 50 and 60 %, respectively, of the total area and require 100 and 300 mm of effective precipitation to reach field capacity. Thirty four percent of the discharge in the Anjeni watershed is not accounted for and leaves the watershed as deep regional flow while this cannot be (and is not) the case for the Blue Nile Basin.

In the Anjeni watershed, the small proportion of saturated area is consistent with the piezometer readings of Leggesse (2009) that showed a deep water table throughout the uniformly steep watershed except in very close proximity to the stream (Fig. 3). This is unlike the Maybar (Bayabil et al., 2010) and Andit Tid (Engda et al., 2011) watersheds where large flat areas near the river usually saturate during the rainy season with annual precipitation over 500 mm (Liu et al., 2008). In the Anjeni watershed where the soils are deep at the middle and lower part and there are no flat areas, all the water that otherwise would have saturated the soil drains directly into the stream. The maximum baseflow storage (BS_{max}) was calibrated to be 100 mm and τ^* was 10 days for the watershed. The half-life for the baseflow storage was set to be 70 days.

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The good fit in Figs. 4 and 6 and in the Supplement Figs. S1 and S2 was confirmed by the performance statistics. The R^2, NSE and RMSE values for Anjeni (Table 3) were 0.88, 0.84 and 1.29 mm, respectively for calibration and 0.82, 0.80 and 1.19 mm for validation indicating that the model has reasonably captured the watershed response to rainfall. For the case of the Blue Nile, the R^2, NSE and RMSE values were 0.97, 0.93 and 2.59 mm for calibration and 0.93, 0.92 and 2.73 mm for validation, respectively.

Despite the good statistics, the model over-predicted low flows and under-predicted flows of greater than 20 mm day^{-1} during the calibration period for Anjeni (Figs. 4a and 5a). The same is true for the Blue Nile Basin where the peak flows during August were underestimated during the calibration period, 1993 (Fig. 6a). During validation (Figs. 4b, 5b and 6b), there is a reasonable agreement between observed and predicted low flows especially for the Blue Nile Basin in year 2003, even though there is under prediction for flows greater than 20 mm day^{-1} for Anjeni. The under prediction of peak flows is likely caused by an expansion of runoff producing areas during heavy storms of longer duration. This expansion is not captured because our model fixes the fraction of the runoff-generating areas. The overestimation of low flows early in the period of 1988–1990 for Anjeni is likely due to the impact of the implementation of Fanya juu (SWC with bunds and drainage ditches) in the watershed in 1986. Initially water could be stored behind the bunds (decreasing discharge), but by 1990 the storages behind the bunds were filled up with sediment (Bosshart, 1997) and runoff increased thereafter.

In the Supplement we show that the hydrology model was only sensitive to fractional areas and one can assume that the fitted values in Table 2 are reasonably close to the optimum values. For the other model parameters a wide range of values exists that give the same *N*-*S* efficiencies.

In summary, the simple model was able to simulate the discharge patterns quite well in the small 113 ha watershed and large 17.4 million ha Blue Nile basin watershed with area fractions that were approximately similar. The R^2 and NSE values obtained were equal or better than the simulation of Easton (2010) for the SWAT-WB model, indicating that the concept of patterns of self-organization on a watershed scale is realistic. This pattern suggest that the initial rains following the dry season first need to replace the water that has been lost due to evaporation during the dry season before the watershed discharge can begin to respond to precipitation (Liu et al., 2008) from less than 1/3 of the watershed. The remaining watershed is the source of the base and interflow.

4.2 Sediment model

According to the hydrology model, there are two surface runoff source areas in the watershed. We assume that these runoff source areas are sources of sediment in our modeling. The simulation results fit quite well (Figs. 5 and 7, Table 3). The calibration results in Table 2 show that the degraded runoff source areas (represented by a constant a_2 in Table 2) generate most of the erosion. Because of the low proportion of level lands in the Anjeni watershed and the low coefficient value of a_1, sediment transported by runoff from saturated source areas was relatively low. The assumption that no sediment concentration is generated from interflow and base flow seems to be reasonable as the agreement between observed and predicted sediment concentration deteriorates rapidly in the trial of increasing the coefficients a_{IF} and a_{BF} from zero. The finding that a small portion of the watershed (14 % for Anjeni and 20 % for Blue Nile Basin) delivers most of the sediment is also shown by the study of Easton et al. (2010) for multi-watersheds in the Blue Nile Basin. The coefficient a_2 for degraded areas in Anjeni is three times higher than Blue Nile Basin (Table 2). This was expected because the Anjeni watershed has a much greater slope than the Blue Nile Basin. In Anjeni, these areas are located on the fields in which the farmers have traditional small drainage (or cultural) ditches on shallow and slowly permeable soils (Leggesse, 2009) while in the Blue Nile Basin, the degraded areas are located at Mount Choke in East and West Gojam where Anjeni is located, Lake Tana sub basin, Jema sub basin in Wolo and Abay Gorge in East Wollega (Hydrosult Inc. et al., 2006).

The coefficient of determination, R^2, values of 0.9 and 0.7 were found between measured and modeled daily suspended sediment concentration during calibration and validation periods, respectively (Table 3). The Nash-Sutcliffe efficiencies were also relatively better; 0.77 for calibration and 0.64 for validation. These results are comparable with the work of Easton et al. (2010) in which the modified SWAT-WB for monsoonal climates was used and that of Zeleke (2000) which used WEPP. Our model uses only two parameters whereas SWAT and WEPP models incorporate more calibration parameters, such as plant cover, slope, soil and water management or soil type. Since such factors interact to affect soil erosion at a spot, sediment data homogenization is a very challenging task. This makes sediment modeling very difficult. Therefore, getting these relatively high coefficients of determination and NSE for daily data using only two calibration parameters is highly valuable.

Despite the good fit, the model under-predicted sediment concentrations during high measurements and overestimates during low measurements in Anjeni (Figs. 5 and 7). This occurred during the validation period specifically in 1992 and 1993. This is likely due, first, to the under and over-estimations in the hydrology model being propagated to the simulation of sediment concentration.

The incorporation of base flow and interflow in the model helps to capture the lower sediment concentration after July for Anjeni Watershed Fig. 5. The drop and subsequent low sediment concentration at the end of the rainy season is also reported in Tigray, in the northern part of Ethiopia by Vanmaercke et al. (2010). They argued that lower concentrations of sediment are due to sediment depletion. Others (Descheemaeker et al., 2006; Bewket and Sterk, 2003) suggested that the lower sediment concentrations are a result of the increased plant cover. Although this effect could exist, Tebebu et al. (2010) showed that such a relationship does not exist for the Debre Mawi watershed. In the Blue Nile Basin, it seems that base flow and interflow play an important role in diluting the sediment after July and decreasing the sediment concentration.

The low sediment concentration measurements in 1989 due to SWC were difficult to capture using the model and hence excluded from the data set. This justifies that incorporating more calibration parameters, such as SWC management for the different runoff areas, might improve the sediment concentration prediction.

5 Conclusions

Using the principle of organized complexity, a simplified watershed sediment model coupled with a hydrology model was developed and used to simulate sediment concentrations and runoff at two widely varying scales. Such simplified models that require very few calibration parameters to simulate runoff and sediment transport are important in the data limiting environment. Using these models, it was possible to identify the proportion of runoff source areas which are also sources of sediment. The analysis showed that the model could capture the variability in discharge and sediment concentrations quite well with parameters that were not greatly different between the scales. The model basically assumes in its simplest form that a watershed in a monsoon climate wets up after the dry season and produces increasing amounts of inter- and base flow as the rainy season progresses. At the same time this dilutes the sediment in the rivers that originates mainly from relatively small portions of degraded hillsides. More research is needed into how the model parameters vary between scales and watershed characteristics.

Supplementary material related to this article is available online at: http://www.hydrol-earth-syst-sci-discuss.net/9/2121/2012/ hessd-9-2121-2012-supplement.pdf.

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Table 1. Location, description, and data used in the model for the Anjeni sites (SCRP, 2000).

Area description	
Size of the area (ha)	113.4
Location	37°31′ E and 10°40′ N
Elevation (m a.s.l)	2405–2507
Mean Annual Rainfall (mm)	1690
Length of data	
Precipitation (mm day^{-1})	1988–1997
Potential evaporation (mm day^{-1})	1988–1997 (1995–1996 incomplete)
Stream flow (mm day^{-1})	1988–1997
Sediment concentration (g l^{-1})	1988–1997 (1988, 1994 and 1997 incomplete)
Periods regarding conservation practices	
No conservation	1984–1985
Fanya Juu conservation implementation	1986
Full terraces developed	1992

Table 2. Input parameters for daily and 10-days stream flow and sediment concentration modeling in the Anjeni watershed and Blue Nile Basin.

Components	Description	Parameters	Unit	Calibrated values	
				Anjeni	Blue Nile
Hydrology	Saturated area	Area A_1	%	2	20
		$S_{\max}$ in A_1	mm	200	200
	Degraded area	Area A_2	%	14	20
		$S_{\max}$ in A_2	mm	10	10
	Hill side	Area A_3	%	50	60
		$S_{\max}$ in A_3	mm	100	300
	Subsurface flow parameters	$\mathrm{BS}_{\max}$	mm	20	20
		$t_{1/2}$	days	70	35
		τ	days	10	140
Sediment	Subsurface flow	a_{BF}	$(\mathrm{g\,l^{-1}})(\mathrm{mm\,day^{-1}})^{-0.4}$	0	0
		a_{IF}	$(\mathrm{g\,l^{-1}})(\mathrm{mm\,day^{-1}})^{-0.4}$	0	0
	Saturated area	a_1	$(\mathrm{g\,l^{-1}})(\mathrm{mm\,day^{-1}})^{-0.4}$	0.2	0.2
	Degraded area	a_2	$(\mathrm{g\,l^{-1}})(\mathrm{mm\,day^{-1}})^{-0.4}$	3.40	1.2

A_i is area fraction for components of 1-saturated area, 2-degarded area and 3-infiltration zone;
$S_{\max}$ is maximum water storage capacity;
$t_{1/2}$ is the time it takes in days to reduce the volume of the base flow reservoir by a factor of two under no recharge condition;
$\mathrm{BS}_{\max}$ is maximum base flow storage of linear reservoir;
τ^* is the duration of the period after a single rainstorm until interflow ceases;
a_i is calibrated parameter in sediment concentration model for components of base flow (BF), interflow (IF), saturated area (1) and degraded area (2).

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Table 3. Runoff and sediment concentration simulation efficiency as evaluated by statistical measures for daily time step in Anjeni watershed and Blue Nile Basin.

Site	Year		Stream flow (mm)		Sediment concentration ($g\,l^{-1}$)	
			Calibration 1988 and 1990	Validation 1989 and 1991–1997	Calibration 1990	Validation 1991–1993
Anjeni	Mean	Observed	2.1	1.9	0.72	0.67
		Predicted	2.3	1.9	0.65	0.65
	Standard deviation	Observed	3.2	2.7	2.24	2.19
		Predicted	3.6	2.8	1.94	1.78
	Statistical parameters	NSE	0.86	0.80	0.78	0.64
		R^2	0.88	0.82	0.80	0.67
		RMSE	1.6	1.5	1.66	1.32
Blue Nile Basin	Year		1993	2003–2004	1993	2003–2004
	Mean	Observed	9.7	9.4	0.85	1.28
		Predicted	9.5	9.2	1.26	0.92
	Standard deviation	Observed	9.9	9.9	1.51	2.32
		Predicted	11.8	9.2	1.98	1.87
	Statistical parameters	NSE	0.93	0.92	0.76	0.76
		R^2	0.97	0.93	0.88	0.80
		RMSE	2.6	2.7	0.73	1.89

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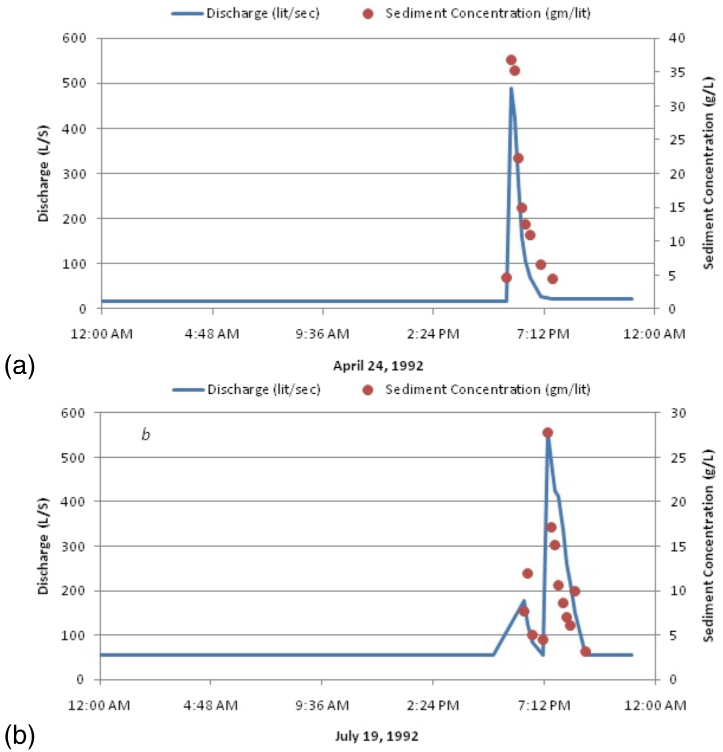

Fig. 1. Measured discharge and sediment concentration during **(a)** 24 April 1992 and **(b)** 19 July 1992 for Anjeni watershed.

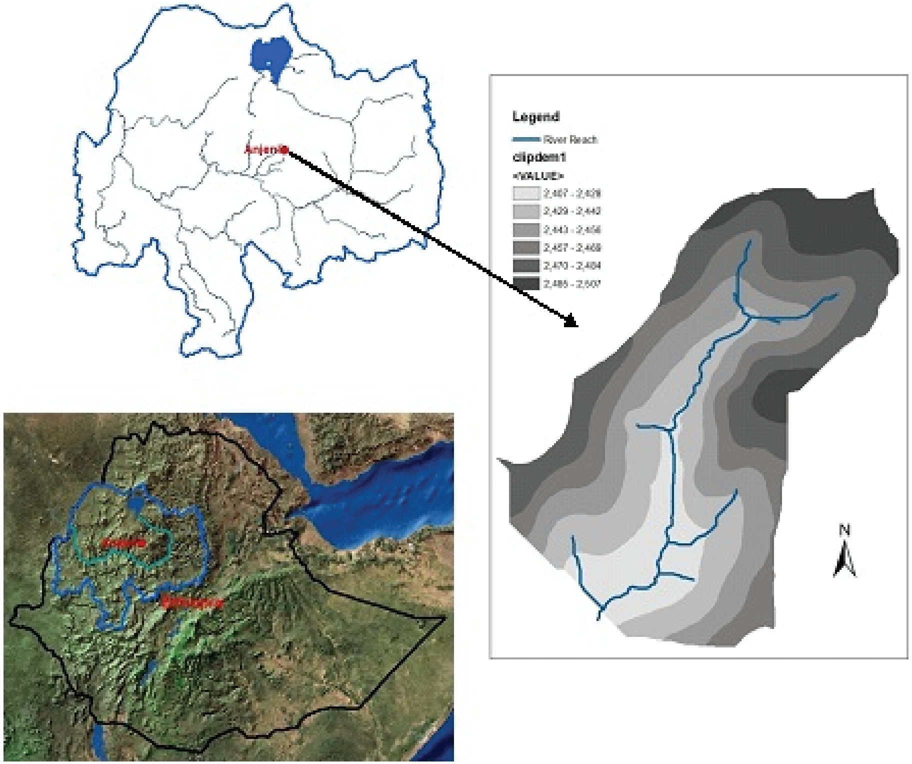

Fig. 2. Location, watershed boundary and drainage map of Anjeni Watershed and Blue Nile Basin.

Fig. 3. Flank portion of the Anjeni watershed which was developed to full terraces from Fanya juu conservation practices.

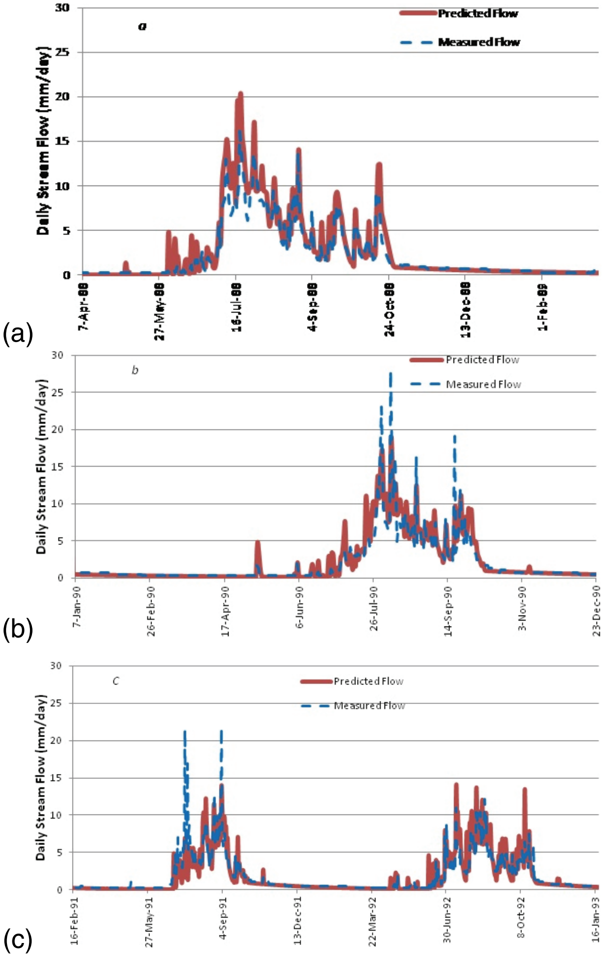

Fig. 4. Predicted and observed daily stream flow for Anjeni watershed **(a)** and **(b)** calibrated discharge using 1988 and 1990 daily data **(c)** validated discharge (shown only 1991 and 1992).

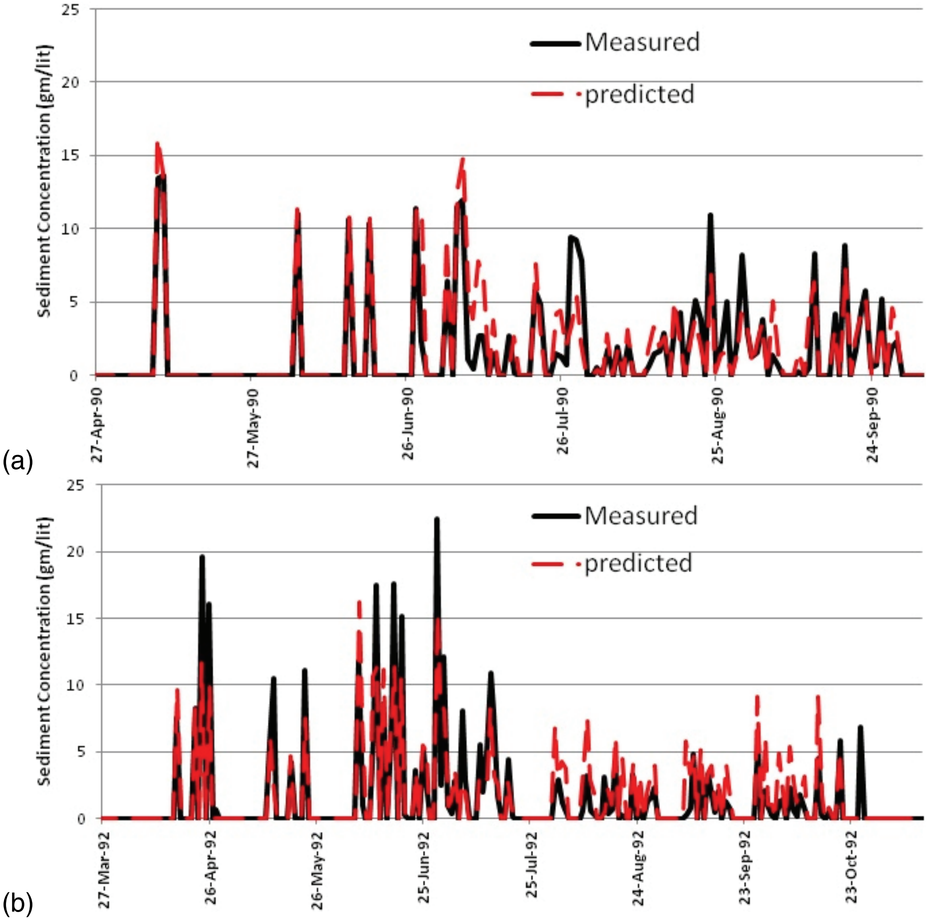

Fig. 5. Predicted and observed daily sediments concentration for the Anjeni watershed **(a)** calibrated 1990 and **(b)** validated period (shown only 1992).

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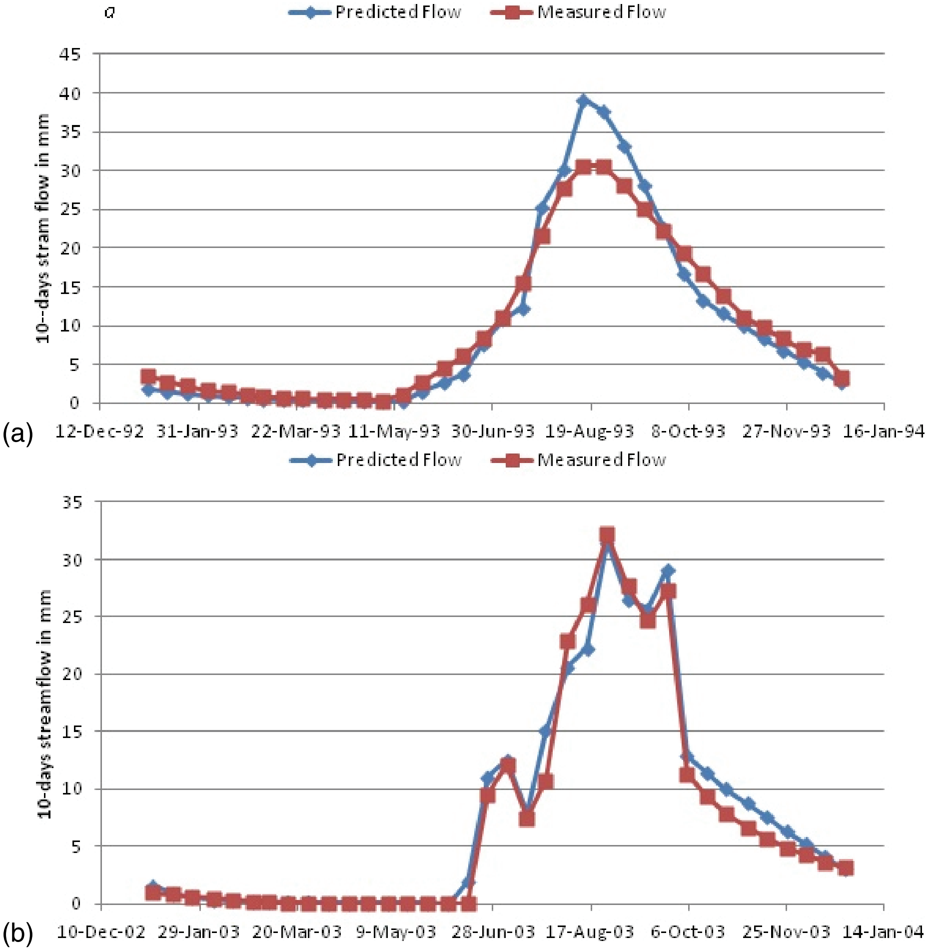

Fig. 6. Observed and predicted 10-day stream flow for the Blue Nile basin at the border with Sudan **(a)** calibration and **(b)** validation.

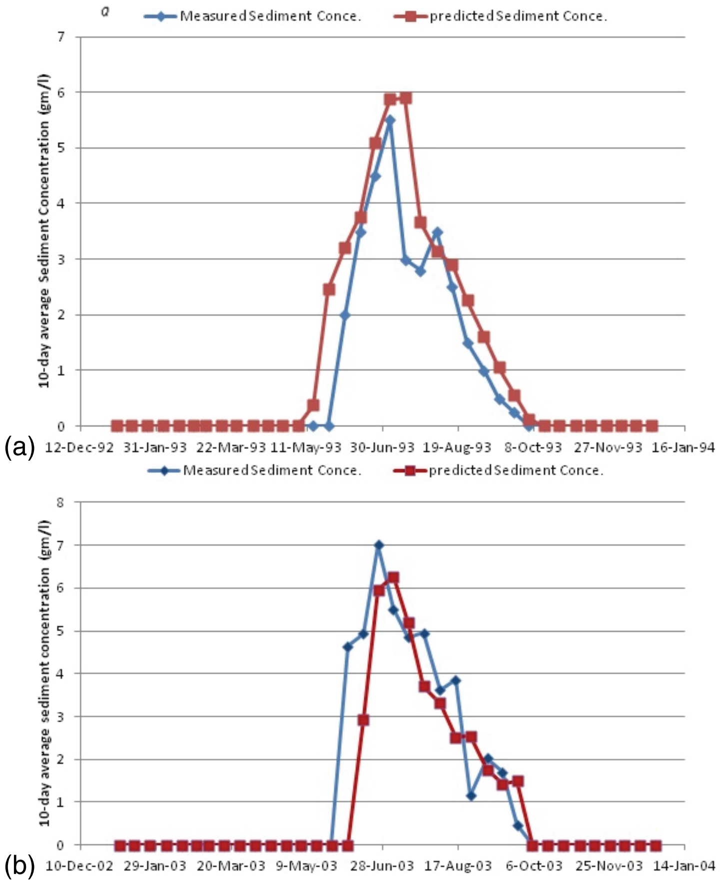

Fig. 7. Observed and predicted 10-day average sediment concentration for the Blue Nile Basin at the border with Sudan: **(a)** calibration and **(b)** validation.

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