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Comparison of sediment transport computations using hydrodynamic versus hydrologic models in the Simiyu River in Tanzania

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ABSTRACT

This paper presents the results of a study that compares the sediment routing of the Simiyu River using the hydrologic model, Soil and Water Assessment Tool (SWAT) and the 1D hydrodynamic simulation software for Rivers and Estuaries (SOBEK-RE) model. Routing in SWAT is completed using the simplified Bagnold's equation and in the SOBEK-RE model is undertaken using the Saint Venant equation. The upstream boundary conditions for the routing modules were derived from the subcatchments sediment yields that were estimated by SWAT using the Modified Universal Soil Loss Equation (MUSLE). The sediment loads extrapolated or interpolated from the sediment rating curve for the catchment outlet were used for calibration and validation purposes. The SWAT model predicted an erosion rate of 2.09 Mt/yr. The total sediment load transported to the main outlet of the catchment simulated by the SWAT and SOBEK-RE models was equal to 2.94 and 2.72 Mt/yr, respectively. Thus the models computed a net erosion in the channels of 0.84 Mt/yr (SWAT) and 0.63 Mt/yr (SOBEK-RE). When comparing the results of the models for the different reaches of the main channel and main tributaries, the models showed different results both in magnitude and in sign (erosion/deposition). However, in a situation where data is scarce (such as grain size, channel geometry), the more complex hydrodynamic model does not necessarily lead to more reliable results.

1. Introduction

The application of numerical models has become an essential tool for the understanding of natural processes occurring at the watershed scale (Gichamo et al., 2012). Amongst these are sediment transport and sedimentation processes (Betrie et al., 2011; Mwanuzi, 2006). The main processes determining the transport behavior of fine sediments are the availability of sediments, water movements and sedimentary processes such as flocculation, consolidation and erosion (Van Leussen, 1991).

Sedimentation is one of the major problems affecting water quality in Lake Victoria and its ecosystem. There is an alarming deterioration of lake water quality and its ecosystem because of environmental degradation of the basin over the past two decades. This degradation has forced the governments of the riparian countries to embark on the conservation of the Lake Victoria basin environment through the Lake Victoria Environment Management Project (LVEMP, 2000). When sediments are in suspension, they alter the native aquatic habitat by blocking light penetration, affecting water chemistry, and changing the substrate where it is deposited. When plant material and other organic matter decompose, the process uses up dissolved oxygen required by native flora and fauna for their survival. Decomposition of organic matter, which is always accompanied by sedimentation, eventually goes to the bottom of the lake and over a long period of time fills in the lake basin. Lake Victoria, which is typically shallow and warm, is sensitive to sedimentation effects.

The Simiyu River sub-catchment, which is located in the Lake Victoria catchment in the northern part of Tanzania, is important for agriculture and other economic activities such as fishing and livestock production. The erosion and sedimentation processes of this catchment have been simulated previously using the SWAT model alone (Ndomba et al., 2005).

The SWAT model uses the Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt, 1978) to estimate sediment yields and the Bagnold's equation (Bagnold, 1977) to route the sediment loads. However, this sediment routing method uses a simplistic sediment concept that does not consider sediment transport

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characteristics such as bottom shear stresses (Benaman et al., 2005). Choosing a sediment transport formula which is suitable for the existing problem in the Simiyu River is based on verifying the river field data/information availability. The river is a sand river and the chosen hydrodynamic model should be able to compute both bed load and suspended load in order to compare these results with the results from the SWAT model (Betrie et al., 2011). It was assumed that the use of a hydrodynamic model such as SOBEK-RE for computing the sediment routing after the SWAT model computes the sediment quantity could improve the performance of the SWAT model sediment prediction at a catchment outlet.

Therefore, in this study, two independent simulations were performed (i) the SWAT model was used to simulate the erosion from the sub-catchment and route sediment in the channel and (ii) the sediment routing in the channel was simulated using a one dimensional hydrodynamic (SOBEK-RE) model. The SOBEK-RE model uses the Saint Venant's equation for the flow and the Engelund and Hansen equation (Riza, 2005a) for sediment transport.

This study compares the quantitative (i.e. volume of sediment) and qualitative (i.e. identification of main erosive river reaches) simulation results obtained from the two approaches. Sections 2 and 3 present descriptions of the two models and the case study, respectively. Results and discussion of this study are presented in Section 4, and the conclusions are presented in Section 5.

2. Modeling tools

2.1. SWAT model descriptions

2.1.1. Overview

The SWAT model is a basin-scale, continuous time model that operates on a daily time step (Arnold et al., 1998). The model's major components include weather, hydrology, erosion, soil temperature, plant growth, nutrients, pesticides, land management, channel, and reservoir routing. It divides a catchment or basin into sub-basins (van Griensven et al., 2002). Each sub-basin is connected through a stream channel and further divided into Hydrologic Response Unit (HRU). HRU is a unique combination of a soil and vegetation type in a sub-catchment. SWAT simulates hydrology, vegetation growth and management practices at the HRU level. Water, nutrients, sediment, and other pollutants from each HRU are summarized in each sub-catchment and then routed through the stream network to the catchment outlet. The foundation behind the hydrologic simulation in SWAT is a soil water balance equation (Neitsch et al., 2005), as presented in Eq. (1) below.

SWAT provides two methods for estimating surface runoff: the SCS curve number method and the Green–Ampt infiltration method (Arnold et al., 1998). In this study, the SCS curve number method was used. Since the curve number method uses readily available daily rainfall amount data from the government ministries and/or offices, the authors employed it for this study to simulate surface runoff. The peak runoff is an indicator of the erosive power of a storm and is used to predict sediment loss. This is estimated by the modified rational method. Groundwater flow contribution to total stream flow is simulated by creating a shallow aquifer storage (Arnold and Allen, 1996). Percolation from the bottom of the root zone is considered as recharge to the shallow aquifer. In SWAT, there are three methods for estimating potential evapotranspiration: Priestley and Taylor (1972), Penman–Monteith (Monteith, 1965) and Hargreaves and Samani (1985)). The latter method requires less data than the former two methods. The Hargreaves method was used for this study.

The water flow is routed through channel networks using the variable storage routing or Muskingum River routing method. The sediment yield in SWAT is estimated with MUSLE, which is developed by Williams and Berndt (1978). This equation replaces the rainfall factor with a runoff factor (Wischmeier and Smith, 1978). The MUSLE is applied for each HRU and final sediment yields are routed down through the main channels by using a stream power equation, which is the modified Bagnold's equation (Bagnold, 1977) as reported in Neitsch et al. (2005). The most relevant components are described below.

2.1.2. Hydrological component of SWAT model

SWAT in the land phase simulates the hydrological cycle based on the water balance equation.

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw})_i \tag{1}$$

where SW_t is the final soil water content (mm), SW_0 is the initial soil water content (mm), t is time (days), R_{day} is the amount of precipitation on day i (mm), Q_{surf} is the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), W_{seep} is the amount of water entering the vadose level zone from the soil profile on day i (mm), and Q_{gw} is the amount of return flow on day i (mm) (Setegn et al., 2008).

2.1.3. Sediment component of SWAT model

Erosion and sediment yield in SWAT are estimated for each HRU with the Modified Universal Soil Loss Equation (MUSLE), (Eq. (2)). It uses the amount of runoff to simulate erosion and sediment yield. The hydrology module/component supplies estimates of runoff volume and peak runoff rate, which, with the subbasin area, are used to calculate the runoff erosive energy variable. The crop management factor is recalculated every day that runoff occurs. It is a function of aboveground biomass, residue on the soil surface, and the minimum crop factor for the plant (Betrie et al., 2011; Neitsch et al., 2005).

$$S = 11.8\ (Q * q_p)^{0.56} K * L * S * C * P \tag{2}$$

where S is the sediment yield in tons, Q is the volume of runoff in m^3, and q_p is the peak flow rate in $m^3\ s^{-1}$; and K, L, S, C, and P are the soil erodibility factor, slope length, slope steepness, crop management factor, and soil erosion control practice, respectively.

2.1.4. Routing phase of the hydrologic model

The sediment transport in the channel network consists of two components operating simultaneously, which are deposition and degradation (Setegn et al., 2008). To determine the deposition and degradation process the maximum concentration of sediment is calculated using following equation:

$$Conc_{sed,ch,mx} = C_{sp} * V_{ch,pk}^{sp\,\exp} \tag{3}$$

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

$$V_{ch,pk} = \frac{prf \cdot q_{ch}}{A_{ch}} \tag{3a}$$

where prf is the peak rate adjustment factor (a user specified parameter), q_{ch} is the average rate of flow ($m^3\ s^{-1}$), and A_{ch} is the cross sectional area of flow (m^2).

The maximum concentration of sediment ($Conc_{sed,ch,mx}$) that is calculated from the previous equation is compared to the concentration of sediment in the reach at the beginning of the time step