

Response to Comments of Reviewer 1

In the section below we address the specific comments directly. One will note that we have implemented most of the major changes suggested by the reviewer. In the few cases that we did not agree we explain the reason. In this section, we will repeat the major comments of the reviewer in shortened form since the full comments already have been published. We will answer the comments on a page per page basis of the discussion paper.

Pages 2123 and 2124. The comments regarding pages 2123 and 2124 have been addressed in the general comments with the exception of the following three comments that we discuss below:

- a) We did not address in the general comments, the comment of the reviewer that the modeling approach of Klaus and Zehe can overcome the shortcomings of the deficiencies noted by van Savenije. We agree that it is possible to make a model that can start with Darcy's, law conservation of mass etc. and simulate the watershed but the question remains whether the soil properties can be measured in sufficient detail. This detailed soil survey is certainly not available in the Ethiopian highlands. In this paper we start with using the organized complexity. We are aware that we could have used a more fundamental approach, but the input data are simply not available at this time in Ethiopia.
- b) Our sediment model in this paper “closely” follows the Hairsine and Rose (1992a) model. As detailed below, it was showed that, for sheet flow, the sediment concentration (kg/m^3) at the transport limit, c_t , can be expressed in

$$C_t = \frac{F\sigma SV}{\left(\frac{\sigma}{\rho}-1\right)\varphi_e} \quad 1$$

F is the fraction of the stream power effective in erosive processes, S (m/m) is the slope of the land surface, V (m/s) is mean overland flow velocity φ_e (m/s) is the effective sediment depositability and ρ (kg/m^3) and σ (kg/m^3) are soil particle and water density, respectively.

The following derivation was derived first by Yu et al (1997). It is closely followed here with some minor modifications. In this derivation a sloping field of unit width and a

length L and a rainfall rate R (m/s) is considered. The runoff at the end of the field is q (m^2/s).

$$q = hV = RL \quad 2$$

Where h is the depth of the water at L . Assuming kinematic flow approximation and flow to be turbulent we can write Manning equation for a the cross section at L where the width is many time greater than the depth

$$V = \frac{1}{n} h^{\frac{2}{3}} S^{\frac{1}{2}} \quad 3$$

Combining Eqs. 2 (i.e., $q = hV$) and 3 gives

$$q = kh^{5/3} \quad 4$$

$$\text{Where, } k = 1/n * S^{1/2} \quad 5$$

Using the relationship in Eq. 2 (i.e., $h = \frac{RL}{V}$) and substituting this in Eqs 4 and 5 and rearranging we find that

$$V = \left(\frac{\sqrt{S}}{n}\right)^{\frac{3}{5}} L^{\frac{2}{5}} R^{\frac{2}{5}} \quad 6$$

By substitution of Eq. 6 into Eq. 1 we find that

$$C_t = aQ^{0.4}$$

Where

$$a = \frac{F\sigma SL^{2/5}}{\left(\frac{\sigma}{\rho} - 1\right) \varphi_e} \left(\frac{\sqrt{S}}{n}\right)^{3/5}$$

Therefore “ a ” is a function of both watershed and sediment characteristics.

For sediment load per unit area Y_t :

$$Y_t = C_t * Q = a * A * Q^{1.4}$$

- c) Finally we kept the section on the detail needed for simulating discharge from watershed approximately the same. There is a debate in the literature what is the best approach. We present both sides and chose for the simpler of the two because the input data is not available for the more complicated rural Ethiopia.

Page 2125-2127: We appreciate the organizational suggestions of the reviewer and as suggested shortened section 2.1 on model development (see below), moved the paragraphs of the various models to the introduction, moved the “objective” to the introduction, renamed the section to “model development “and introduced the sites before the model development in the material and methods (part is on page 2127). The latter allowed us to first introduce the effect of base and interflow on sediment concentration.

The shortened introduction of the model development section now reads:

“3. Model development

The model predicts daily sediment concentrations. Sediment concentration are predicted by assuming that all erosion is produced in areas with surface runoff consisting of degraded hillsides with shallow soils and saturated areas formed during the rainy phase. Erosion rates are greater from the more heavily degraded areas without plant cover than from the saturated source areas with natural vegetation. Erosion is negligible from the non-degraded hillsides because almost all water infiltrates (Bayabil et al., 2010; Engda et al., 2011)”.

Page 2128: We followed the suggestion of the reviewer and removed redundancies, provided a brief description on the modeling approaches (see below). By developing schematic representation of the model as shown in Figure 2 and giving more detail in the text (see the comments to reviewer 2 and the citation below), we improved the description of the hydrology model. The reasons that we cannot predict the patterns and structures of the landscape a priori, but can show afterwards that the predicted patters fit what is seen in the landscape is given in the “general response” above.

The introduction to the hydrology model in the revised manuscript is as follows:

“The watershed is divided into three regions (Fig. 2): 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. The remaining hillsides are the third zone where rainwater on the hillside 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 (Fig.2). 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 (Fig. 2). There are two types subsurface flows simulated: Interflow and baseflow. Interflow is relatively fast and is simulated as a zero order reservoir (i.e. the flow decrease as linear function of time and last for a fixed time t^* , after a rainstorm. This time is landscape dependent but invariant of storm size. Baseflow is simulated as a linear reservoir with and exponentially decreasing flow with a watershed specific half-life. In order to separate interflow from baseflow, we assume that the first order baseflow reservoir fills up first and then the remaining recharge is contributed to the zero order base flow 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.”

Page 2129: The reviewer would like more details on the sediment model and its simplifying assumptions. Before answering those, we would like to repeat that our modeling results are as good as or better than another model that has been applied (although that is being questioned as well by the reviewer). Both the linear relation due to power “ n ” between sediment concentration and velocity, channel wide and how it depends on landscape characteristics is explained in the response to the comments on page 2113 ad 2114. As noted by the reviewer, we have provided the missing units of a in the discussion paper in HESSD that was mentioned only in Table 2 page 2147. It is $(\text{g l}^{-1})(\text{mm day}^{-1})^{-0.4}$. We revisited the assumption of transport limited in the response to reviewer 2. We explained already in our general response that we need better models to simulate management practices and this model is part of the learning process. We agree with the comment of the reviewer that we were unclear about the purpose of the paper. Finally with respect to the last comment, “ a ” is dependent on the velocity for shallow flows but for sufficient deep flows it becomes independent. It is the same assumption as made by Ciesiolka et al (1995).

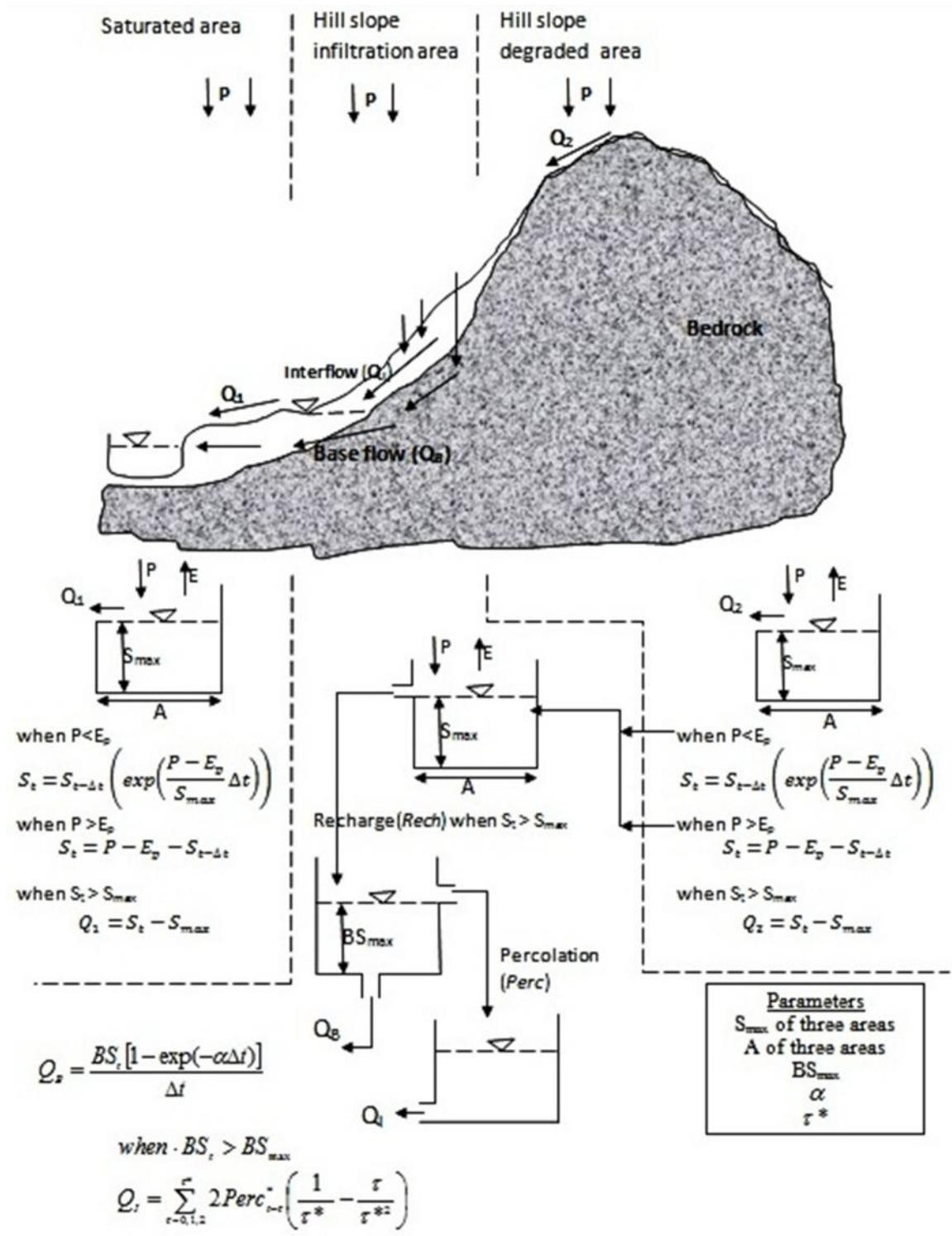


Figure 2: Schematic of the hydrology model

Page 2130: The factor “n+1” for discharge, q , in Eq. 5 is explained in the derivation (see our response to the comments related 2123 and 2124 and is for sediment load that is obtained by multiplying the concentration by the discharge q

Page 2134: Thank you for the suggested changes in the text. The changes have been made according to the comments. The equifinality question has been addressed in the general response above. In the text we have added the following

“In the supplementary material we showed that the sediment model was sensitive to the a_2 coefficient and one can assume that the fitted values in Table 2 are reasonably close to the optimum values.”

Page 2135: In Figure 3 the Anjeni watershed is shown. Thanks for noting the inconsistency in BS_{\max} and corrected the value to 100 mm in the Table 2.

Page 2136. In our general response we show that calibrated values for the fractional areas are in agreement with that observed in Anjeni. Equifinality is addressed as well. Whether the SWAT-WB and WEPP models are validated and calibrated for the same time period in our opinion is not so as relevant as they are for the same watershed using the same observed data

Page 2138: The reviewer suggest that for the evaluation soil and water conservation practices WEPP might be more appropriate since it has many more parameters than our simple model. We agree that WEPP has adjustable parameters that lend it for looking at conservation practices. However the question remains how well WEPP represent the watershed hydrology and therefore

the expected changes in soil loss when soil and water practices are introduced. The reviewer is correct that one need more than two parameters to model the effect of soil and water conservation practices. We expect that our model structure can be adapted to predict the effect of soil and water conservation practices. In previous papers (Dahlke et al., 2012; deAlvis et al. 2007; Harpold et al., 2010), we have shown for the Catskill Mountains, where New York City receives its water from that we can use the topindex to distribute the saturated source areas in the landscape. Theoretically, we can also use the topindex to find the degraded areas, but the information about the soil thickness is limiting and therefore we have to use a soil map to find the degraded area. Our future work will focus on how to explicitly locate those locations on the map in Ethiopia. The current paper was not intended to address the soil and water conservation practices. This was a misunderstanding. We did not express this well in the discussion paper.

In addition on this page we removed the word “likely” and corrected the paragraph as follows:

“This is due to, first, the under and over-estimations in the hydrology model being propagated to the simulation of sediment concentration. Secondly, it is reported in Bosshart (1997), that poor maintenance of SWC in the watershed during these years resulted in higher sediment concentrations.”

Finally as a closing remark on the thoughtful comments of reviewer 1, it would be reasonable to ask the question that despite all the efforts invested in modeling, if there is any model in the Ethiopian highlands that has been validated for its prediction on management practices. Simulation models are in almost all cases validated on the monthly basis with discharge and sometimes sediment load at the watershed outlet. The predictions on management practices are not verified in many cases. It is, therefore, a big burden to require from us in this new approach to model the effect of soil and water conservation practices. In our humble opinion that is beyond the current scope of the manuscript. We intend to do this in the future when we have data for validation.

Additional references

Dahlke, H.E., Easton, Z.M., Walter M.T., and Steenhuis, T.S.: Field Test of the Variable Source Area Interpretation of the Curve Number Rainfall-Runoff Equation. *Journal of Irrigation and Drainage Engineering-ASCE* 138: 235-244, 2012.

deAlwis D.A, Easton, Z.M., Dahlke, H.E. Philpot W.D., and Steenhuis, T.S.: Unsupervised classification of saturated areas using a time series of remotely sensed images. *Hydrol. Earth Syst. Sci.* 11:1609-1620, 2007

Harpold, A.A., Lyon, S.W., Troch P.A. and Steenhuis T.S. The hydrological effects of lateral preferential flow paths in a glaciated watershed in the Northeastern United States *Vadose*

Addendum

Revised 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; EI-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 t ha⁻¹year⁻¹ (Hurni, 1988; Mitiku et al., 2006; Tebebu et al., 2010) with an average of 7 t ha⁻¹year⁻¹, or equivalent to a depth 0.5 mm year⁻¹ (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 optimizing erosion control of this basin. In the past several models have been used in the (semi) humid Ethiopian highlands to predict water and soil loss. Models that employ the SCS curve number method (infiltration excess runoff) for runoff and Universal soil loss equation (USLE) for sediment load are the 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). These models had limited success in predicting daily runoff and sediment load. As expected the modified SWAT-WB Water Balance model (Easton et al., 2010; White et al., 2010) with saturation excess gave better results than models used previously, because experimental evidence showed that saturation excess was the dominant runoff process in the Ethiopian highlands (Bayabil et al. 2010).

An additional limitation with these models is that they use the standard USLE (Wischmeier and Smith, 1978) or related versions (such as the one modified for Ethiopian conditions Hurni, 1985; Eweg et al. 1998; and Zegeye et al., 2011) where the parameters values are based on small plot

measurement. However, despite using rigorous theoretically justified erosion prediction routines, the Water Erosion Prediction Project (WEPP, Zeleke, 2000), did not perform well because runoff predictions were based on the curve number.

Thus, scaling up USLE (i.e., plot scale) soil loss estimates to watershed or basin scale invariably leads to overestimation or underestimation at the outlet (Vanmaercke et al., 2011). Discussions of scaling up 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 in naturally formed catchments at intermediate and larger scales (Dooge 1986, 2005; Savenije, 2010; He et al, 2011). Field research such as in the semi humid Ethiopian highlands (Bayabil et al., 2011); Catskill Mountains (in New York State, Lyon et al. 2006; de Alvis et al 2007; Harpold et al 2010; Dahlke et al. 2012) and Australia (Western et al. 2002) confirms that these emerging patterns of self-organization in watersheds exists, because the similarity in moisture contents from year to year.

Many different approaches are being developed to incorporate this organized complexity into discharge predictions (Borga et al., 2011; Rimmer and Hartmann 2012; and Sivapalan et al. 2010). These models are often much simpler when compared with models that use Darcy’s law and conservation of mass (Dooge, 1986, 2005; and Savenije, 2010)). Our nine parameters hydrology that uses three fractional areas that either produces overland flow or subsurface flow developed by us for the Ethiopian Highlands (Steenhuis et al. 2009 and Tesemma et al. 2010) is one example of such models.

The objective of this study is therefore to develop an erosion model that goes beyond scaling up plot erosion estimates to improve sediment concentration prediction for a monsoon climate prevailing in the Ethiopian highlands at several scales. Our erosion 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. To the best of our knowledge this is first attempt to include organized complexity in sediment concentrations predictions at the watershed scale.

In this new approach, we combined the hydrology model of Steenhuis et al. (2009) and Tesemma

et al. (2010) with the erosion models from the Rose and Hairsine group in Australia and test both the hydrology and erosion models at small and large scales. The hydrology model employs organized complexity to define the areas that recharge the subsurface storages and generate surface runoff. Magnitude of the fluxes is calculated with a water balance type approach. The erosion 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) sediment concentration prediction approach. The Hairsine and Rose model 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 Griffith University Erosion System Template (GUEST) Technology (based on Hairsine and Rose Model) and European Soil Erosion Model (EUSROSEM) (Kandel et al., 2001).

Sediment concentration data are available for a few watersheds in Ethiopia. These watersheds were established by the Soil Conservation Research Program (SCRCP) 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.”