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RESEARCH ARTICLE

Modeling discharge and sediment concentrations after landscape interventions in a humid monsoon climate: The Anjeni watershed in the highlands of Ethiopia

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Abstract

Increasing population and intensification of agriculture increase erosion rates and often result in severe land degradation and sedimentation of reservoirs. Finding effective management practices to counteract the increasing sediment load is becoming increasingly urgent especially in the Ethiopian highlands where the construction of the hydroelectric Grand Renaissance Dam on the Blue Nile is underway. In this paper, we examine the results of 9 years of a watershed experiment in which discharge and sediment losses were observed in the 113 ha Anjeni watershed of the Blue Nile Basin. The study period encompasses conditions before, during, and after the installation of graded *Fanya-Juu* ("throw uphill" bunds) soil and water conservation practices (SWCP), which had the ultimate goal of creating terraces. We use a saturation-excess runoff model named the parameter-efficient distributed model as a mathematical construct to relate rainfall with discharge and sediment losses at the outlet. The parameter-efficient distributed model is based on landscape units in which the excess rainfall becomes direct runoff or infiltrates based on topographic position or hardpan characteristics. Deviations in this rainfall–discharge–sediment loss relationship are ascribed to the changes in infiltration characteristics caused by SWCPs on the hillslopes. With this technique, we found that in the Anjeni basin, the Fanya-Juu SWCPs are only effective in increasing the infiltration and thereby reducing the direct runoff and sediment concentrations in the first 5 years. At the end of the 9-year observation period, the direct runoff and sediment concentrations were barely reduced compared to the levels before SWCP were installed. In addition, we found that the model structure based on landscape units was able to represent the varying runoff and erosion processes during the 9 years well by varying mainly the portion of degraded land (and thereby representing the effectiveness of the Fanya-Juu to reduce runoff by increasing infiltration).

KEYWORDS

East Africa, erosion, parameter-efficient distributed model, soil and water conservation, watershed

1 | INTRODUCTION

Erosion and sedimentation are challenging problems that are increasingly difficult to solve with the intensification of land use (Cerdà, Imeson, & Poesen, 2007; Erkossa, Wudneh, Desalegn, & Taye, 2015). In the Ethiopian highlands with rapid population growth, sediment concentrations have been increasing (Gebremicael, Mohamed, Betrie, van der Zaag, & Teferi, 2013; Mekonnen, Keesstra, Baartman, Ritsema, & Melesse, 2015; Steenhuis et al., 2013; Tesemma, Mohamed, & Steenhuis, 2010) without a significant precipitation increase in the past 40 years (Conway, 2000; El Kenawy et al., 2016; Kim & Kaluarachchi, 2008; Nyssen et al., 2008; Seleshi & Demaree, 1995; Tekleab, Mohamed, & Uhlenbrook, 2013; Tesemma et al., 2010). Measures are being taken to reduce erosion but only in a few cases have they been checked for their effectiveness (Dagnew et al., 2015; Mekonnen et al., 2015; Walling, 2006; Walter, Steenhuis, & Haith, 1979).

Evaluating the effectiveness of landscape modifications is especially timely in the Ethiopian highlands where, in an attempt to increase prosperity and assure food security for the rapidly increasing population in the context of recurring drought (El Kenawy et al., 2016; Hurni, 1988a, 1999; Nyssen et al., 2009b), the Ethiopian government is implementing management practices for increased rainwater productivity and increased life spans for hydroelectric power plants such as the Grand Ethiopian Renaissance Dam on the Blue Nile near Sudan (Chen & Swain, 2014; Dagnew et al., 2015; Humphreys et al., 2008; Mekonnen et al., 2015; MOA, 2013; MOFED, 2010). Defining the relationship between modifications in the landscape and resulting changes in hydrology (including runoff, sediment concentrations, and sediment load) has become possible in recent decades due to the efforts of various research programs in Ethiopia. In the semiarid Tigray region, short to medium term studies (1–4 years) have investigated the relationship between soil and water conservation (SWC) measures and catchment outlet runoff coefficients or sediment export variability (Nyssen et al., 2009a; Nyssen et al., 2010; Vanmaercke et al., 2010; Zenebe et al., 2013). This has also been studied experimentally on plots and at the watershed outlet of seven soil conservation research program (SCRP) sites started by the Ethiopian Ministry of Agriculture in cooperation with Berne University, Switzerland, in the 1980s in the highlands of Ethiopia and Eritrea (Haile, Harweg, & Stillhardt, 2006; Herweg & Ludi, 1999; Hurni, 1988a). Because the hydrological data are scarce in Ethiopia, much of the information on the long-term effects of SWC practices (SWCP) on runoff and sediment yields in Ethiopia has originated from these small headwater watersheds of the SCRP (all under 4 km^2). Published data from the subhumid areas of these watersheds (Herweg & Ludi, 1999) show that while the discharge for a given amount of rainfall increases with the progression of the rainy monsoon phase (Liu et al., 2008), the sediment concentration decreases for a given amount of runoff during the rainy phase (Guzman, Tilahun, Zegeye, & Steenhuis, 2013). Semiarid catchments also demonstrate similar trends (Vanmaercke et al., 2010). These studies further found that SWCP resulted in significant reduction in runoff and soil loss for at least a few years after installation. Other shorter duration watershed studies in subhumid areas, such as in the Debre Mawi watershed, showed that the runoff and sediment load contributions from the valley floors increased during the rainy phase after they became saturated and gully erosion became more severe (Tebebu et al., 2010; Tilahun et al., 2014). Actively eroding gullies in this watershed contributed up to 20 times greater sediment production than the uplands (Tebebu et al., 2010). The relationship between SWC and sediment transport is complex (de Vente et al., 2013), and finding consistent patterns requires systematic analysis of the data of the few existing long-term studies. Surprisingly, few have been carried out so far.

This study will focus on the soil and water conservation impacts of employed mechanical structures such as soil bunds and terraces (Herweg & Ludi, 1999) that use a combination of dug trenches and earthen embankments to interrupt overland flow and impede sediment entrainment. Thus, the overall objective of this study is to understand, in a data scarce context, the long-term effects of SWC measures on water and sediment transport of a watershed. Specifically, we will investigate in one of the SCRP experimental watersheds the change in the relationship of the input (rainfall) with its output (discharge and sediment concentration) using the parameter-efficient distributed (PED) model (Guzman et al., 2017; Tilahun, Guzman, et al., 2013a, Tilahun, Mukundan, et al., 2013b) as the mathematical construct to evaluate the effect of soil and water practices. At the same time, we will evaluate the performance of the PED model through split-sample and differential split-sample tests (Klemeš, 1986a; Refsgaard & Knudsen, 1996; Seibert, 2003) and assess its ability to simulate the effect of installation of soil and conservation practices (Montanari et al., 2013; Seibert & McDonnell, 2010; Thirel, Andréassian, & Perrin, 2015).

2 | STUDY AREA

In this study, we use the PED model to analyze the effect of improving degraded lands by implementing SWCP in the Anjeni SCRP catchment (a small 1.13 km^2 subhumid watershed in the Ethiopian highlands; Figure 1).

The Anjeni watershed is oriented north–south and flanked on three sides by plateau ridges. The topography is typical of Tertiary volcanic landscapes, incised by streams, resulting in a diversity of landforms (Bayabil, Tebebu, Stoof, & Steenhuis, 2016; SCRP, 2000). The elevation of Anjeni ranges between 2,407 and 2,507 m a.s.l. (Herweg & Ludi, 1999) and geologically belongs to the basaltic Trapp series of Tertiary volcanic eruptions, similar to most parts of central Ethiopia (SCRP, 2000) with a Precambrian basement complex covered by Mesozoic sediments (Kejela, 1995). The main geomorphic units are areas with steep denudation slopes, sedimentary basins and colluvial slopes, and small stable plateau areas with gullies in recent times (Kejela, 1995). It is located at 37°31′E and 10°40′N and lies 370 km NW of Addis Ababa, to the south of the Choke Mountains. The mean annual rainfall is 1,690 mm (wet weyna dega agroecological classification) arriving from around late April or early May to October in a unimodal pattern (meaning one large rainy season) with a low variability of 10% (SCRP, 2000). The months from November to March experience arid conditions with mean daily temperature ranging from 9 °C to 23 °C (SCRP, 2000). Agriculture is the dominant land use within the watershed, and at the end of 1985 into 1986 graded bunds, Fanya-Juu were installed to terrace the hillslopes. The Fanya-Juu bunds were installed from 1985 to 1987 under the auspices of the soil conservation research project led by Dr. Hans Hurni (1988b; Herweg & Ludi, 1999). Fanya-Juu (“throw uphill” in Swahili) bunds are constructed by digging a trench and throwing the removed soil uphill to form a bund. Eventually, the space just above the bund fills up with soil, having settled from ponded water or moved there by tillage, forming a terrace. Detailed precipitation, discharge, and storm event sediment concentrations are available from June 1, 1984, to December 31, 1993 (SCRP, 2000). Rainfall was measured with an automatic pluviograph, and daily evaporation was measured using screened Piche evaporimeters (Liu et al., 2008). Discharge was determined from automatic float gauges combined with manual stage readings, and storm event sediment concentration was estimated by taking 1-L samples at 10-min intervals during storm flow (Guzman et al., 2013; Liu et al., 2008). The river reach is characterized by appreciable meandering with a 2% gradient, and the natural cross section is U-shaped with high, steep banks (Bosshart, 1997). A concrete step-like cross section at which measurements are taken is located on a straight section approximately 30 m in length, with neither scouring nor later erosion being

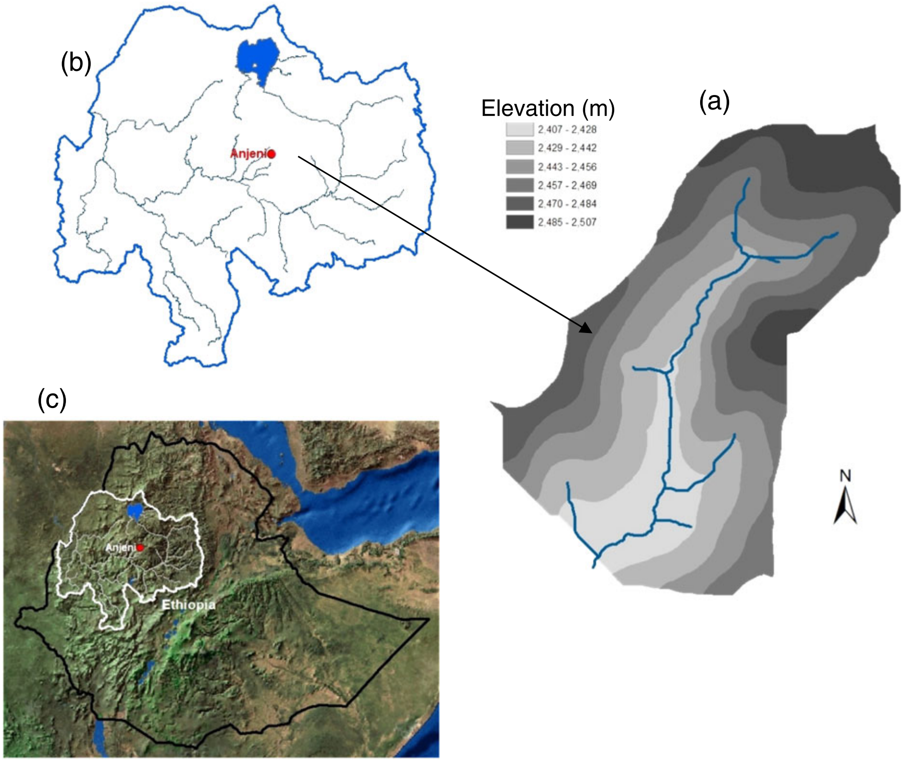

FIGURE 1 (a) Watershed boundary and digital elevation model (DEM) of Anjeni with (b) its location in the Blue Nile Basin and (c) the map of Ethiopia (Tilahun, Mukundan, et al., 2013b)

prevalent (Bosshart, 1997). Further information about data collection and processing is available in Hurni (1984), Bosshart (1997), and SCRP (2000). The periods observed for SWC impact can be summarized as before installation (Period I: 1984–1985), during installation (Period II: 1986–1987), after the establishment of bunds (Period III: 1988–1989), and beyond establishment (Period IV: 1990–1993). The period before change (Period I) was selected for calibration, and subsequent 2-year periods were selected for split-sample and differential split-sample tests (Klemeš, 1986a; Refsgaard & Knudsen, 1996; Seibert, 2003; Seibert & McDonnell, 2010). These data were made available by the Amhara Regional Agricultural Research Institute

The soils of Anjeni are generally acidic and low in organic carbon. They tend to have low to medium nitrogen and available phosphorus concentrations and are mainly characterized as deep Alisols in the foothills with moderately deep Nitosols in the transitional sloping areas of the catchment. In the highest elevation, shallow Regosols and Leptosols are found covering convex shapes (SCRP, 2000). Maps of soil erosion damage, degradation, soil types, and soil depths have been previously prepared by several reports and theses from the SCRP project (Kejela, 1995; SCRP, 2000; Zeleke, 2000).

3 | METHODS

3.1 | Modeling approaches: available models

Process-based mathematical relationships (i.e., models) between rainfall, runoff, and sediment concentrations can be employed to investigate how the parameter values in this relationship change during the period surrounding the installation of SWCP. A change in parameter values could then be attributed to the SWCP when other landscape factors are kept constant. This is a change-detection modeling approach described by Seibert and McDonnell (2010) and Seibert and van Meerveld (2016), which analyzes changes in system behavior as quantified by hydrological model parameters calibrated for different periods. Various models could be considered for this approach.

Examples of watershed models applied in Ethiopia include the agricultural non-point source pollution model (Haregeweyn & Yohannes, 2003; Mohammed, Yohannes, & Zeleke, 2004), the soil and water assessment tool (SWAT; Betrie, Mohamed, van Griensven, & Srinivasan, 2011; Setegn, 2008; Setegn, Dargahi, Srinivasan, & Melesse, 2010; Setegn, Rayner, Melesse, Dargahi, & Srinivasan, 2011; Van Griensven, Ndomba, Yalew, & Kilonzo, 2012; Yesuf, Assen, Alamirew, & Melesse, 2015), the water erosion prediction project (Zeleke, 2000), "Hydrologiska Byråns Vattenbalansavdelning" model (Abdo, Fisha, Rientjes, & Gieske, 2009; Rientjes, Perera, Haile, Reggiani, & Muthuwatta, 2011b; Wale, Rientjes, Gieske, & Getachew, 2009), and many others. White et al. (2010) and Easton et al. (2010) used a modified SWAT model that simulates saturation-excess runoff as commonly observed in Ethiopia (Bayabil, Tilahun, Collick, Yitaferu, & Steenhuis, 2010; Bewket & Sterk, 2003; Rientjes et al., 2011a; Tilahun et al., 2015; Zeleke, 2001). Other models that are partly deterministic (Saliha, Awulachew, Cullmann, & Horlacher, 2011) have used a Kohonen neural network and WaSiM-ETH to estimate flow in ungauged basins. According to these models, future discharge in Ethiopia will either increase (Legesse, Vallet-Coulomb, & Gasse, 2003), remain the same (Wagesho, Jain, & Goel, 2012), or cannot be determined (Setegn et al., 2011). These models also found that installing SWCP and better management will greatly decrease erosion, which in the case of SWAT can be directly related to the conservation practice factor in the Universal Soil Loss Equation (Betrie et al., 2011; Tesfahunegn, Vlek, & Tamene, 2012). These predictions are in most cases not checked with field observations and might not represent actual field conditions (Betrie et al., 2011; Van Griensven et al., 2012). In other words, these models developed for temperate climates may not be generalizable for the monsoonal climate of Ethiopia due to heavy reliance on the problematic curve number (Burt & McDonnell, 2015) and the Universal Soil Loss Equation approaches (Nearing et al., 1994).

Hydrological models specifically developed for Ethiopian conditions are mostly water balance–type models (Conway, 2000; Kebede, Travi, Alemayehu, & Marc, 2006; Mishra, Hata, & Abdelhadi, 2004; Rientjes, Haile et al., 2011b) and, in general predict, the monthly discharge with similar accuracy as the more complicated SWAT model (Setegn et al., 2010; Yesuf et al., 2015). Such models rely on simple approximations to simulate mass exchange processes of the hydrological cycle, requiring as inputs precipitation, temperature, and potential evapotranspiration to estimate local runoff or lake levels (Kebede et al., 2006; Rientjes, Haile et al., 2011b). However, these types of models are not without problems either. Water balance–type models do not always perform well at a daily timescale, and different parameter sets are required for different basin sizes (Kim & Kaluarachchi, 2008). Models used by Caballero, Easton, Richards, and Steenhuis (2013), Collick et al. (2009), Steenhuis et al. (2009), and Tesemma et al. (2010) are also water balance models but overcome shortcomings of earlier models by dividing up the landscape into landscape units that generate either direct runoff by saturation-excess overland flow or delayed subsurface flow by first-order (baseflow) or zero-order (interflow) reservoirs. Excess rainfall becomes direct runoff or infiltrates in these balance models based on topographic position or hardpan characteristics, which each have a different threshold moisture content above which the watershed zone begins contributing water to the total runoff. On the basis of these runoff concepts and differentiated landscape units, Tilahun, Guzman et al. (2013a) and Tilahun, Mukundan et al. (2013b) developed the PED model that added sediment concentration prediction (described in the next section) to the model of Steenhuis et al. (2009).

The PED approach was selected because (a) relatively few adjustable parameters are needed (nine for the hydrology and four for the erosion model; Table 1), (b) its representation of process-based mechanisms for (sub) humid, semi-monsoonal hydrology, and (c) daily discharge and sediment concentrations are predicted with similar or better Nash Sutcliffe efficiencies (NSE; Nash & Sutcliffe, 1970) as other more complicated models (Easton et al., 2010; Guzman et al., 2017; Moges et al., 2016; Tesemma et al., 2010; Tilahun, Guzman, et al., 2013a; Zimale et al., 2016, forthcoming). Although a high NSE does not necessarily mean a valid model (de Vente et al., 2013; Schaefli & Gupta, 2007), the model predicts consistently close to observational data.

Moreover, the advantages of this model lie primarily in its generalizable structure (water-balance type), its landscape-specific considerations (saturation-excess), its simple-routing method with minimal parameters (Jakeman & Hornberger, 1993; Montanari, Sivapalan, & Montanari, 2006; Perrin, Michel, & Andréassian, 2001), its model efficiency on the daily time step (Tilahun, Guzman, et al., 2013a; Tilahun, Mukundan, et al., 2013b), and its basis in processes observed in Ethiopia versus empiricism from the United States or Europe (Burt & McDonnell, 2015). It therefore provides an effective governing equation approach on a catchment scale based on a reduced form, direct field measurements spanning a range of scales, and theoretical studies (Burt & McDonnell, 2015; Kirchner, 2006). Finally, PED with its few parameters has the advantage over parameter-rich watershed models of structural identifiability (Seibert & McDonnell, 2010; Shin, Guillaume, Croke, & Jakeman, 2015) especially because four of the nine parameters in the PED hydrology model are insensitive (Tilahun, Guzman, et al., 2013a, Tilahun, Mukundan, et al., 2013b) and can be fixed without loss of accuracy. This leaves only five parameters to calibrate in the hydrology model and four in the sediment model that all are directly related to observable processes in the field. This makes it possible to identify processes in the field (Tilahun et al., 2015) that cause a change in fitted parameters (Shin et al., 2015) without the typical equifinality problems (Beven, 1993, 2006). Simply stated, given the aforementioned characteristics of the model, a change in the sensitive parameters reflects real changes in the catchment behavior, deviating from the specific conditions in the calibration period (Gelfan, Motovilov, Krylenko, Moreido, & Zakharova, 2015; Magand, Ducharne, Le Moine, & Brigode, 2015; Osuch, Romanowicz, & Booij, 2015; Semenova et al., 2015; Thirel et al., 2015) and is assumed not to be due to model structure insensitivity to hydrological processes in the watershed (Shin et al., 2015).

For these reasons, the PED model is suitable for analyzing the change in relationship between rainfall, discharge, and sediment

TABLE 1 Input parameters for the parameter-efficient distributed model, all but two of which (A_2 and A_3) are fixed over the various periods for surface flow, baseflow, and interflow components for the Anjeni watershed

Model component	Parameters	Description	Anjeni	Units
Hydrology	A_1	Fractional area, saturated bottom lands	0.02	—
	A_2	Fractional area, degraded hillsides	—	—
	A_3	Fractional area, permeable hillsides	—	—
	$S_{\max,1}$	Maximum water content in saturated lands	200	mm
	$S_{\max,2}$	Maximum water content in degraded hillsides	10	mm
	$S_{\max,3}$	Maximum water content in permeable hillsides	65	mm
	τ^*	Duration of interflow after rain event	10	days
	$t_{½}$	Half-life base flow aquifer	70	days
	$BS_{\max}$	Maximum water content aquifer	100	mm
Erosion	$a_{t,1}/a_{s,1}$	Transport or source limit erosion in saturated land	6/5.5	$(g/L)(mm/d)^{-0.4}$
	$a_{t,2}/a_{s,2}$	Transport or source limit erosion in degraded area	5/4.5	$(g/L)(mm/d)^{-0.4}$

concentrations due to the installation of management practices in the Anjeni watershed.

3.2 | Model description: PED model

The PED model is based on previous research that has shown, despite the complexity of the landscape, a regularity in the wetting up pattern of humid catchments as the rainy season progresses (Bayabil et al., 2010; Sayama, McDonnell, Dhakal, & Sullivan, 2011; Tilahun et al., 2014). This is mainly due to the predominant topographical and gravitational influences on natural slopes (Hewlett, 1961) and hence a consequent regularity in the resulting erosion patterns. This wetting up pattern, though not often included in models, is based on local data and field observations (Bayabil et al., 2010; Liu et al., 2008) that is an alternative to the prevalent curve-number approach (Burt & McDonnell, 2015) and focuses on modeling the excess of saturation (Dunne & Black, 1970; Hewlett, 1961; Hewlett & Hibbert, 1967; Kirkby & Chorley, 1967) induced over the course of a season generating runoff through different representative reservoirs (explained in detail below). Similar to the work of Dooge (1986, 2005), He, Bárdossy, and Zehe (2011), and Savenije (2010), the PED model employs an "organized complexity" framework to reduce the number of parameters needed to model the spatial processes in the landscape. "Organized complexity" in this case refers to the representation of the hydrological catchment as a system in the intermediate stages of complexity and randomness (or heterogeneity; Dooge, 2005); whereby, the organizing principles underlie heterogeneity and complexity (McDonnell et al., 2007), and runoff is produced due to the excess of saturation in conceptual groups of soil moisture storage units with similar landscape characteristics. Hence, the approach is process based, rather than Darcy scale physically based (Beven & Young, 2013; Montanari & Koutsoyiannis, 2012; Savenije, 2010). The disadvantage of the method is that it is difficult to set the input parameter values a priori because the exact boundaries between the groups are not known, but once fitted, it is possible to check if the values are in accordance with the landscape that is simulated.

3.2.1 | Hydrology model

In the PED model, various stores or reservoirs representing specific regions of the watershed become active contributors of overland and subsurface flow when threshold moisture content is exceeded. That is, a high level of antecedent soil moisture promotes runoff generation (Legates et al., 2011), and after these storage elements are filled, water will be released from the watershed (Sayama et al., 2011). The three regions distinguished in the model are (a) bottom lands that potentially can become saturated during the rainy phase of the monsoon, (b) degraded hillslopes that throughout the rainy season, saturate after a relatively small amount of rainfall during storm events and produce surface runoff and (c) permeable hillslopes (Figure 2). In the model, the permeable hillslopes contribute rapid subsurface flow (interflow) and baseflow. Each of the regions is the lumped average of all such areas in the watershed. Degraded hillslopes differ from permeable hillslopes mostly due to the decreased water storage capacity of the soil so that saturation and overland flow are more readily produced in patches of thin permeable soil either over rock (Kirkby & Chorley, 1967) or a slowly permeable layer formed due to land degradation (Tebebu et al., 2015; Tebebu et al., 2016) than in the deeper soils with high infiltration capacities. Some field observation (exposed bedrock, profiles showing hardpans, and compacted soils) or field measurements (e.g., soil-depth mapping in Kejela, 1995 and Zeleke, 1998, 2000 and soil penetrometer tests in Tebebu et al., 2016) can be used initially to roughly identify the difference between such areas. However, soils exist on a continuum from a zero infiltration capacity to a very high infiltration capacity (Kirkby & Chorley, 1967) and also have variable soil depths meaning that this distinction cannot always be practically measured in the field for larger catchments; similar to distributed physically-based models implicitly lumping processes for effective parameters at larger scales (Beven, 1989). Nevertheless, a Thornthwaite–Mather-type water balance (effectively averaging these differences) is calculated for soil moisture, S_{tj} for each of the three regions (saturated $j = 1$, degraded $j = 2$, and permeable $j = 3$; Steenhuis & van der Molen, 1986; Steenhuis et al., 2009; Thornthwaite & Mather, 1955; Figure 2).

$$S_{tj} = S_{(t-\Delta t)j} + \left(P - E - q_{rj}\right)\Delta t \tag{1}$$

where q_{rj} is either the runoff or percolation, P is the precipitation, and E is the actual evaporation. When $P < E_p$ and $S_{tj} < S_{\max j}$:

$$S_{tj} = S_{(t-\Delta t)j}\left[\exp\left(\left(P - E_p\right)\frac{\Delta t}{S_{\max j}}\right)\right] \tag{2}$$

where E_p is the potential evaporation and $S_{\max}$ is the threshold storage. When $P > E_p$ and $S_{tj} < S_{\max j}$:

$$S_{tj} = S_{(t-t)j} + \left(P - E_p\right)\Delta t \tag{3}$$

And finally when $P > E_p$ and $S_{tj} > S_{\max j}$, then runoff from each generating area ($q_{r1,2}$) and percolation (q_{r3}) are calculated by the difference between Equation 3 and $S_{\max\ j}$:

$$q_{r_j} = S_{t_j} - S_{\max_j} \quad j = 1, 2, 3 \tag{4}$$

Percolation flows through the subsoil becoming recharge and is routed to two reservoirs. The first reservoir produces baseflow, and the second produces interflow (after having exceeded the baseflow reservoir first). When the baseflow storage (BS_t) is less than the maximum storage capacity for the linear aquifer ($BS_{\max}$), then its outflow (q_b) is calculated by

$$BS_t = BS_{(t-\Delta t)} + \left(q_{r_3} - q_{b\ (t-\Delta t)}\right)\Delta t \tag{5}$$

$$q_{b,t} = BS_t\left[\frac{1 - \exp(-\alpha\Delta t)}{\Delta t}\right] \tag{6}$$

where $t_{1/2}$ (= 0.69/α) is the time it takes in days to reduce the volume of the baseflow reservoir by a factor of two under no recharge conditions and α is expressed as a recession coefficient. When the maximum storage is reached, then BS_t is replaced with $BS_{\max}$ in Equations 5 and 6, and the interflow (q_i), obtained as the superimposition of fluxes from individual events, can be found by

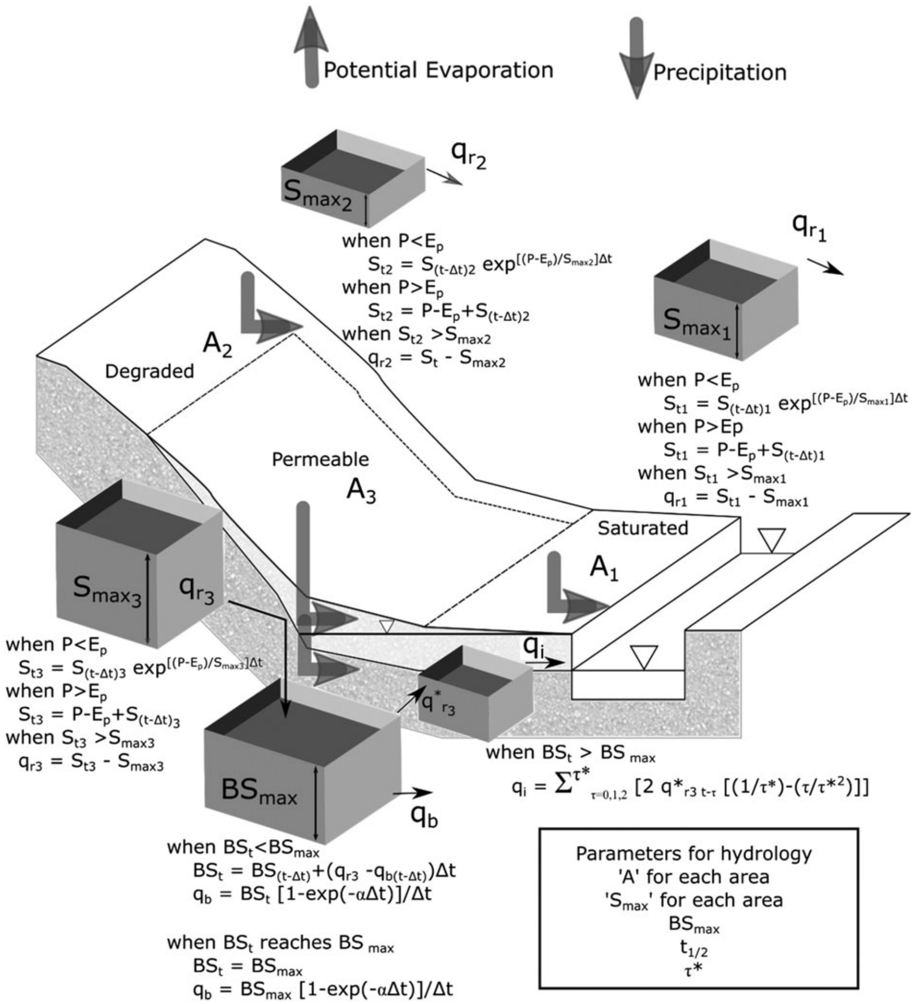

FIGURE 2 Diagram of the model structure for the hydrology submodel of the parameter-efficient distributed model. *A* denotes the area fraction for the different areas in the watershed: (1) saturated, (2) degraded, and (3) permeable hillsides. S_{max} is the maximum water storage capacity of these areas; BS_{max} is the maximum baseflow storage for the linear reservoir; $t_{½}$ (= 0.69/α) is the time in days required to reduce the baseflow volume by a factor of 2 under no recharge; and τ* is the duration of the time for interflow to cease after a single storm event (based on Tilahun, Mukundan, et al., 2013b). $q_{r3}{}^*{}_{t-\tau}$ is the percolation produced on *t*−τ days as derived by Steenhuis et al. (2009)

$$q_{i,t} = \sum_{\tau=0,1,2}^{\tau^*} 2\left(q_{r_3}{}^*{}_{\ t-\tau}\right)\left(\frac{1}{\tau^*}-\frac{\tau}{\tau^{*2}}\right), \tau\le\tau^* \tag{7}$$

where τ* is the duration of the period after a single rainstorm when interflow ceases and $q_{r3}{}^*{}_{t-\tau}$ is the percolation produced on *t*−τ days as derived by Steenhuis et al. (2009). Extensive work and explanations for the equations are given in Steenhuis et al. (2009) and Figure S1 from Tilahun, Guzman, et al. (2013a), reproduced in the supplementary material with equations.

3.2.2 | Sediment model

Erosion processes are estimated as follows: sediment concentrations are obtained, according to theoretical and experimental work, as a function of the runoff per unit area and a coefficient that decreases steadily from the transport limit at the start of the rainy monsoon phase to the source limit after about 500 mm rainfall. Tilahun, Guzman, et al. (2013a) and Tilahun, Mukundan, et al. (2013b), based on the work of Hairsine and Rose (1992) and Ciesiolka et al. (1995), expressed the sediment concentration, C_T (g L^{-1}), in runoff from runoff source areas as

$$C_T = [a_S + \mathrm{H}\ (a_t - a_s)]\ q_r{}^n \tag{8}$$

where a_t is a variable derived from stream power and relates to the sediment concentration in the water when there is equilibrium between the deposition and entrainment of sediment, a_s relates to the sediment concentration in the stream when entrainment of the soil from the source area is limiting, and *H* is defined as the fraction of the runoff producing an area with active rill formation. For most catchments, including large ones, this fraction begins at unity during the beginning of the season and declines to zero after around 500 mm of cumulative effective precipitation (Figure 3) similar to the work by Zegeye et al. (2010) and Guzman et al. (2013) showing stabilized and lower sediment concentrations measured in Ethiopian highland watersheds after around the midpoint of the rainy season. Experimental findings from the diminished erodibility of wet soil (Defersha, Quraishi, & Melesse, 2011) and the achievement of steady state spatial rill network (Hofer, Lehmann, Stähli, Seifert, & Krafczyk, 2012) further support these observations. The interflow and baseflow are assumed to be sediment free. Runoff from each generating area is denoted as q_{r1} or q_{r2}.

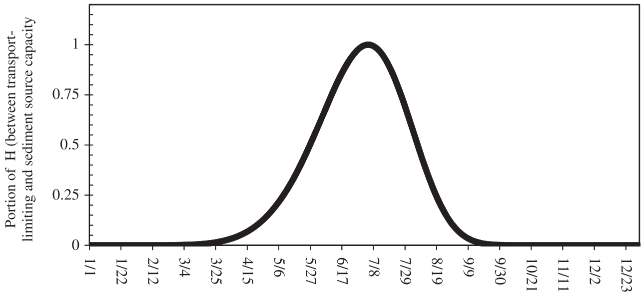

FIGURE 3 Fraction of H (between transport-limiting and sediment source capacity) indicating the variable conditions available for moving sediment. During plowing starting around June 1, it was assumed that the value of H is around 0.6 then is bounded at the upper limit by the transport capacity (H = 1); by the end of June and towards the end of August, it was bounded at the lower end by the sediment source conditions (H = 0). H indicates the fraction of the runoff producing an area with active rill formation

The exponent value (n = 0.4) used was derived for sediment concentration at the transport limit, C_T, from the following set of equations that assume Manning's formula is applicable and take into account the slope, S, mean overland flow velocity, V, and the effective sediment depositability, φ_e (Ciesiolka et al., 1995; Hairsine & Rose, 1992; Yu, Rose, Ciesiolka, Coughlan, & Fentie, 1997):

$$C_T = \frac{F\sigma SV}{(\sigma/\rho{-}1)\phi_e} \tag{9a}$$

$$V = \left(\sqrt{S}/n\right)^{3/5} L^{2/5} Q^{2/5} \tag{9b}$$

$$C_T = kQ^{0.4} \tag{9c}$$

$$k = \frac{F\sigma SL^{2/5}}{(\sigma/\rho{-}1)\phi_e}\left(\frac{\sqrt{S}}{n}\right)^{3/5} \tag{9d}$$

where F is the fraction of the stream power available to perform erosive work, Q is the runoff area per unit area, S is slope, and σ and ρ are sediment and water density, respectively. From Manning's formula, L is the slope length and n is Manning's roughness coefficient. The PED model uses the parallels derived from these equations to situate values of k in Equation 9c initiating at the transport capacity or limit (a_t) and then moving to the source limit (a_s) as shown in Equation 8 through the reduction of H. This coefficient then theoretically should contain within it factors that describe the net transport of sediment during different periods in a rainy season.

The sediment load per unit watershed area, Y ($\text{g} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$), from both the saturated and degraded runoff source areas, can be obtained as the relative area and the flux per unit area multiplied by the sediment concentration, C_T, in Equation 8, in each area ($Y = A_j q_{rj} {}^* C_T$):

$$Y = \sum_{j=1}^{2} A_j q_{rj}\left\{\left[a_{Sj} + \text{H}\left(a_{tj} - a_{sj}\right)\right] q_{rj}{}^{n}\right\} \tag{10}$$

where q_{r1} and q_{r2} would be the runoff rates expressed in depth units for contributing area A_1 (fractional saturated area) and A_2 (fractional degraded area), respectively. The sediment concentration in the stream can be obtained by dividing the sediment load Y (Equation 10) by the total watershed discharge from the three areas:

$$C = \frac{Y}{A_1 q_{r_1} + A_2 q_{r_2} + A_3(q_b + q_i)} \tag{11}$$

where q_b (mm day^{-1}) is the base flow per unit of permeable hillslope and q_i (mm day^{-1}) is the interflow per unit area of the non-degraded hillside, A_3, where the water is being recharged to the subsurface.

3.3 | Model calibration and validation

As mentioned in Section 2, the periods observed for change detection (Seibert & McDonnell, 2010; Seibert & van Meerveld, 2016) caused by SWC impact can be summarized as before installation (Period I: 1984–1985), during installation (Period II: 1986–1987), after the establishment of bunds (Period III: 1988–1989), and beyond establishment (Period IV: 1990–1993). Three phases of model calibration and validation take place. The first phase in the application of the PED model was to fit the landscape parameters and establish the values for those that were kept constant (Table 1) for the initial phase and remaining phases—all but two (A_2 and A_3) of the parameters. This establishes the main characteristics of the watershed (seven of the nine hydrology parameters and the four sediment parameters), yielding a set of parameters representative of watershed behavior (Andréassian, Parent, & Michel, 2003), and allows for intercomparison of degraded land (A_2) and permeable land (A_3) changes over the course of SWC implementation. This phase entailed the period before change (Period I) being selected for calibration, and subsequent 2-year periods were selected for differential split-sample (Period III) and simple split-sample (Period IV) tests (Fowler, Peel, Western, Zhang, & Peterson, 2016; Klemeš, 1986a; Refsgaard & Knudsen, 1996; Seibert, 2003; Seibert & McDonnell, 2010) to investigate the changing nature of the catchment (Seibert & van Meerveld, 2016; Thirel et al., 2015). Simple split-sample tests calibrate and test on two time series that represent similar conditions and exhibit similar behavior (Kirchner, 2006). Differential split-sample tests are rare in hydrology (Fowler et al., 2016; Kirchner, 2006; Seibert, 2003; Refsgaard & Knudsen, 1996), and very few have been published for sediment transport studies, however, results (even failures) could be informative for understanding model simulations in conditions that differ from the calibration period.

For quantitative assessment on the evolution of the relationship between rainfall, discharge, and sediment concentration, the hydrology submodel of the PED model was next used to assess the changes in the landscape (i.e., changing from degraded to permeable land) by performing two more phases of calibration and validation (recalibration on one selected period and revalidation on the remaining two periods) to demonstrate performance in each case when each period has a turn at being the calibration and evaluation period (Fowler et al., 2016). Fractions of degraded and permeable hillsides (hillslope parameters A_2 and A_3, respectively) were fit with the PED model (while fixing the remaining parameters) for Period III (conservation case) and Period IV (beyond conservation), omitting the period when Fanya-Juu bunds were being constructed and established in 1986 and 1987 (Table 2). In the second phase (recalibration on Period III), validation on the

TABLE 2 Areal portions of degraded (A_2) and permeable hillslopes (A_3) and average observed and predicted daily discharge in the Anjeni watershed for three periods: 1984 and 1985 before installation of the Fanya-Juu bunds; 1988 and 1989 immediate after the installation when the terrace was being formed; and 1990–1993 post installation

	1984–1985	1988–1989	1990–1993
Area of degraded hillsides, fraction, A_2	0.13	0.0	0.10
Area of permeable hillsides, fraction, A_3	0.40	0.50	0.47
Observed average discharge (mm/day)	1.70	1.85	1.97
Predicted average discharge (mm/day)	1.55	1.90	1.94

remaining two periods (Periods I and IV) will be both differential split-sample tests because conditions of sediment transport and discharge are higher comparatively (Hurni, 1999; Klemeš, 1986a; Refsgaard & Knudsen, 1996; Seibert, 2003; Soil Conservation Research Programme (SCRP), 2000). For the last phase (recalibration on Period IV), validation on the remaining two periods will be differential split-sample (Period III) and simple split-sample (Period I), due to different and similar conditions.

Effects on sediment concentrations caused by these changes in the landscape (nonconservation to conservation to beyond conservation) were independently validated by comparing the PED-predicted sediment concentrations with the observed sediment concentrations without changing the erosion parameters in Equations 8 to 11.

The basic procedure therefore was to fit the PED model (calibrate and validate) for this small watershed on different complementary sub-periods of the discharge time series, by optimizing NSE values and minimizing root mean square error (RMSE) for runoff and sediment concentrations by only changing the fractional areas of the degraded and permeable hillsides for consistency. All other variables were fitted only once, during the first time period (Period I). This procedure (having two sensitive model parameter) assured that changes between the time periods could be related to changes in infiltration in the degraded areas. The initially calibrated parameter values were assessed either from field data or indirectly through experience from values in similar studies in other catchments (Refsgaard, 1997). In previous research, piezometer readings by Legesse (2009) showed a deep water table throughout except very near the stream in this steep watershed indicating a small fractional area of saturated land. The fractional area of the degraded land was initially set as the value observed from previous studies on shallow soils in the study site approximately 10–12% (Legesse, 2009; Zeleke, 2000), while the initial permeable hillsides area fraction is informed by direct observation of the soils and other studies on the deep and well-drained nature of the hillside soils (Kejela, 1995; Legesse, 2009; Tilahun, Guzman, et al., 2013a). The remaining landscape and erosion parameters were kept constant as indicated above (Table 1). The hydrology-related parameters kept constant for the other periods include the fractional area (A_1) and the maximum water storage in the root zone of the periodically saturated area ($S_{\max1}$), the maximum water storage in the root zone of the degraded and permeable hillslope areas ($S_{\max2}$ and $S_{\max3}$), and the three subsoil parameters for interflow and baseflow ($t_{1/2}$, τ^*, and $BS_{\max}$). Sediment parameters that were kept constant for the watershed include the transport and the source-limiting parameters (a_t and a_s) for the overland runoff generating areas delineated in the watersheds and the H function indicating the fraction of fields in the watershed with a readily available supply of sediment (fields that were plowed and with active rill formation) for which the erosion rate was at the transport capacity (Figure 3).

The time series was apportioned slightly differently than previous studies in this watershed (Tilahun, Guzman, et al., 2013a; Tilahun, Mukundan, et al., 2013b) due to the data that were available and focus on changes made in the watershed. These time periods, however, described four unique periods that are reiterated here: (1) prior to bunds installation in 1984–1985; (2) during installation in 1986–1987; (3) immediately after Fanya-Juu installation was established in 1988 and 1989, and terraces were likely being formed; and (4) post installation from 1990 through the end of 1993.

3.4 | Simulation approach for hydrological and sediment transport process changes

This study's approach, instead of being overly based on vegetative characteristics and small-scaled physics that are inefficiently scaled up in heterogeneous systems (Beven, 1989; Beven, 2002; Beven & Young, 2013; Kirchner, 2006), employs the PED model that uses temporally consistent landscape parameters for conceptual “process-based” (Montanari & Koutsoyiannis, 2012) land units. The relationship between discharge and sediment concentrations is inherently part of the landscape units (equations discussed in Section 3.2). The effect of SWCP will be described by the flow processes that result then in changes in sediment load and concentrations. Essentially, when overland flow infiltrates in part of the landscape, then entrained sediment concentration is not affected but sediment load at the outlet is decreased (as shown experimentally by Dagnew et al., 2015, 2016). Experimental plots have shown this change in flow processes on cultivated areas to be a reduction in surface runoff of around 40% compared to nonconserved cultivated land and effectively an enhancement in groundwater contributions, while catchment runoff does not decrease substantially (Hurni, Tato, & Zeleke, 2005; SCRP, 2000a;). This is a departure from studies that relate sediment yield directly to land use and vary both sediment parameters and hydrology parameters to simulate SWCP impacts.

4 | RESULTS

4.1 | Discharge and sediment concentrations after Fanya-Juu installation

Figure 4 shows the average daily discharge (grey line, Figure 4a) and sediment concentrations (red open spheres, red line, Figure 4b,c)

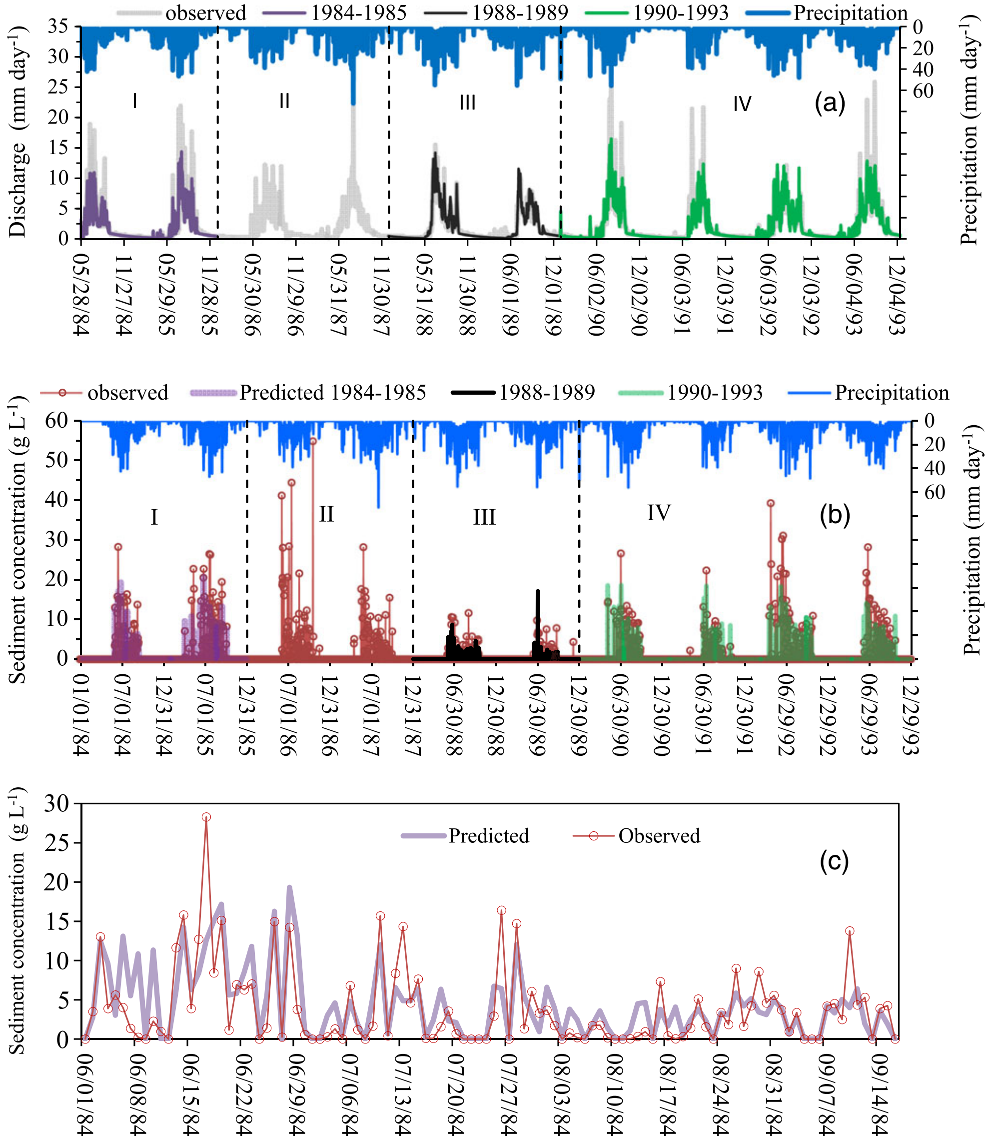

FIGURE 4 (a) Observed daily discharge (grey line) and predicted discharge and (b) observed daily sediment concentrations (red spheres) and predicted sediment concentrations for the Anjeni watershed. The predicted discharge and sediment concentration use different values for portions of permeable and degraded hillsides (as specified in Table 2) for three periods: 1984–1985 (purple line); 1988–1989 (black line); and 1990–1993 (green line). A closer look at sediment concentration in 1984 (c) shows the flashy nature of the small watershed's sediment transport patterns

before, during, and after Fanya-Juu installation. Though rainfall is at or above pre-intervention levels (Figure 5b), sediment concentrations were greatly reduced in 1987, 1988, and 1989 (Figure 6). Comparison of measured versus predicted values for each calibration period is available in the supplementary materials. The transitional period when Fanya-Juu bunds were being constructed and established in 1986 and 1987 (Period II) showed lower discharge peaks, but high sediment concentration peaks due to the emerging effects of the ditches and disrupted soil on the embankments. This period was omitted from the analysis due to the uncertain effects.

The aforementioned four period divisions were used to assess the effect of the installation of the Fanya-Juu bunds (shown to be initially improving the degraded soils): (1) prior to bunds installation in 1984–1985; (2) during installation in 1986–1987; (3) immediately after Fanya-Juu installation was completed in 1988 and 1989; and (4) post installation from 1990 through the end of 1993. Cumulative discharge (depicted as the gray line in Figure 5a) and annual sediment losses (red dashed line in Figure 6a) for each of the periods clearly show that sediment losses were small during and shortly after the graded Fanya-Juu bunds were constructed from July 1986 through the end of 1989, after which time sediment losses increased. Sediment concentrations (red open spheres in Figure 4b) decreased gradually from 1986 to 1989 and then in 1990 rose again and remained at a higher level (Hurni, 1999; SCRP, 2000). We can also see in Figure 4a that for the 1986 period, when the rainfall was relatively small, the discharge was also reduced.

4.2 | Fixed landscape parameters in the PED model for the initial watershed conditions

In the first step of the application of the PED model, the landscape parameters were fit in order to establish those that were kept constant

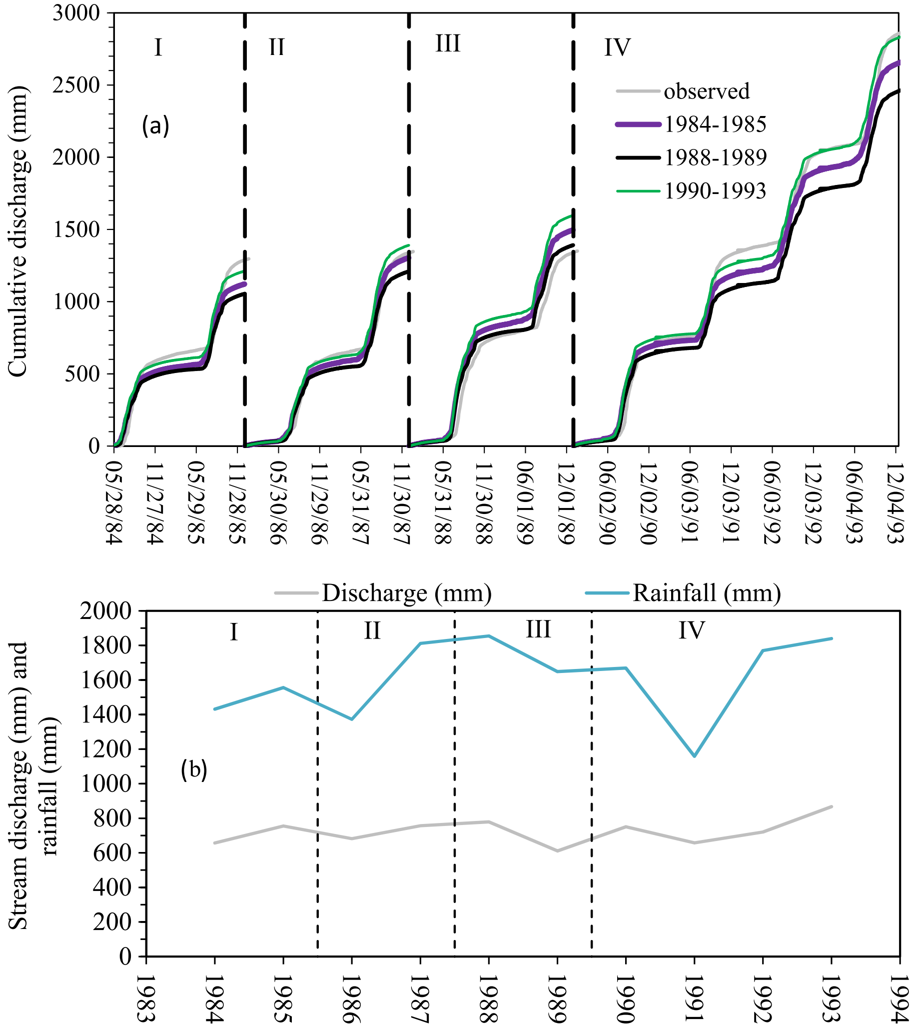

FIGURE 5 (a) Cumulative discharge and (b) observed annual stream discharge and rainfall for the same periods as indicated in Table 2. The gray lines are the observed data. The other lines represent the simulated discharge with parameter set calibrated for the various periods. The purple line is calibrated for 1984–1985. The black line for 1988–1989 and the green line for 1990–1993; parameter values are given in Tables 1 and 2 and statistical fit in Table 3

throughout the analysis (Table 1). We selected the period from 1984 through 1985 before installation of SWC for calibration and found, as expected, similar parameter values as Tilahun et al. (2013a,b) who studied the same catchment. This period was selected to progressively track the landscape changes and its effects starting from the initial watershed conditions. For Tilahun and coauthors, data before 1986 were not available, and the years 1986–1989, corresponding to the period when the Fanya-Juu were installed and immediately thereafter, were not included. Their study performed the simple split-sample test with similar behavior for calibration or validation, and hence, they calibrated for the year 1990. Fitted parameter values in Tables 1 and 2 were in agreement with the landscape characteristics: saturated area was small and amounted to 2% in accordance with the deep and uniformly sloping soil without any major bottomlands. Soil surveys and piezometric data further confirm this (Kejela, 1995; Legesse, 2009; Zeleke, 2000) showing deep and well-drained soils and only saturated areas near the stream. The half life of the first-order ground water reservoir ($t_{1/2}$ = 70 days, in Table 1) is long for upper basin watersheds and can be explained by the deep soil. The 10-day interflow period is common for upper basins (Steenhuis et al., 2009). The choice of maximum root zone moisture contents has little effect on the discharge pattern (Tilahun et al., 2013a), and the storage capacities were kept mostly the same (Table 2). Sediment transport coefficients in Table 1 were slightly different from the earlier study (Tilahun et al., 2013a) mainly because we had more years of sediment data (Tilahun et al., 2013a used 1990 for calibration and 1991–1993 for validation). These additional years altered how the transport limit (upper bound) and source limit (lower bound) were calibrated because the range of the sediment concentrations (with different standard deviations, median, and mean values) occurred in different conditions (Hairsine & Rose, 1992).

4.3 | Fractional area parameters: changing degraded areas and permeable hillsides

Fractions of degraded and permeable hillsides (hillslope parameters A_2 and A_3, respectively) were fit with the PED model for three of the four periods (Periods I, III, and IV), omitting the period when Fanya-Juu bunds were being constructed and established in 1986 and 1987 (Table 2). Depending on the calibration–recalibration period, we used

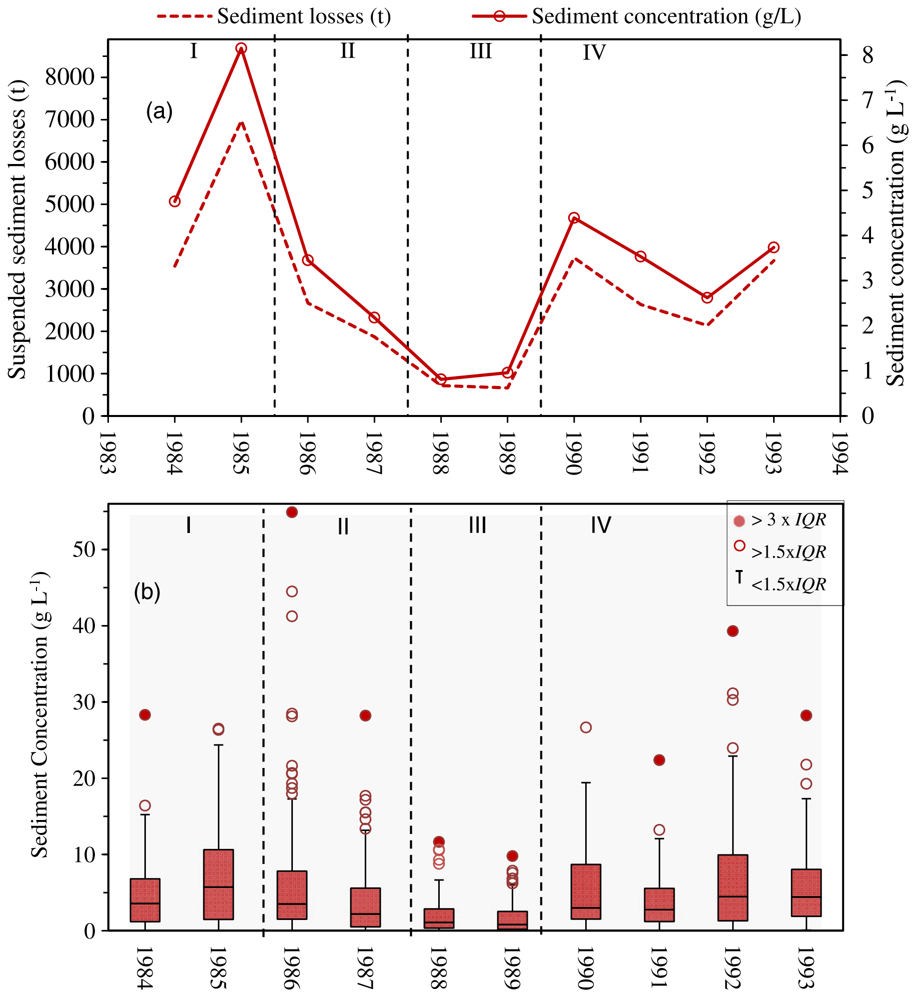

FIGURE 6 (a) Annual suspended sediment losses and mean annual sediment concentration and (b) sediment concentration boxplots for the periods studied: (I) prior to bund installation in 1984–1985, (II) during installation 1986–1987, (III) immediately after Fany-Juu installation was completed in 1988 and 1989, and (IV) post installation from 1990 through the end of 1993 based on Hurni (1999) and SCRP (2000). Solid red circle in (b) depict concentration values that are three times the interquartile range (IQR) larger than the third quartile. Open circles are values 1.5 times the IQR larger. Whisker above third quartile is taken to 1.5 × IQR from the quartile

various line colors for the predicted discharge (daily, Figure 4a, and cumulative, Figure 5a) and sediment concentration (Figure 4b). The purple line indicates that the two hillslope parameters (A_2 and A_3) were fitted for Period I in 1984 and 1985 (prior to Fanya-Juu installation) with the values for the two hillslope parameters given in Table 3. The black line indicates that the model was calibrated during Period III in

TABLE 3 Nash Sutcliffe efficiencies and root mean square error for the Anjeni watershed for discharge. The first set of columns represents the possible hillslope parameters we select based on the expected effect of the soil and water conservation practices. The farthest set of columns represents performance metrics for the fourth period (Period IV). The columns to the left of that represent those values for the first and third periods (Periods I and III). The bolded values represent the best performance during each period for the different possible parameter sets. For each row, the validation periods are distinguished by superscripts that indicate conditions that present differential split-sample test (a) or split-sample test (b) for validation

Period	Hillslope parameters		Calibration						Validation					
			I		III		IV		I		III		IV	
	(A_2)	(A_3)	NSE	RMSE	NSE	RMSE	NSE	RMSE	NSE	RMSE	NSE	RMSE	NSE	RMSE
I	0.13	0.40	**0.69**	**1.50**	—	—	—	—	—	—	0.84[a]	1.00[a]	0.82[b]	1.27[b]
III	0.00	0.55	—	—	**0.91**	**0.75**	—	—	0.66[a]	1.55[a]	—	—	0.74[a]	1.52[a]
IV	0.10	0.47	—	—	—	—	**0.82**	**1.25**	0.67[b]	1.53[b]	0.80[a]	1.13[a]	—	—

Note. NSE = Nash Sutcliffe error; RMSE = root mean square error.

[a] Differential split-sample test.

[b] Split-sample test.

1988 and 1989, and the green line designates the Period IV calibration period from 1990 to 1993.

Period I (1984–1985) prior to Fanya-Juu installation: Using the hillslope parameters in Table 2, where 13% of the area is degraded and 40% of the area contributed to the interflow and baseflow (second column, Table 2), the observed cumulative discharge (Figure 5) in Period I in 1984 and 1985 are simulated well, indicating an NSE of 0.69 for daily discharges in the 1984–1985 period (Table 3, Figure 4a). Sediment concentrations were at NSE = 0.60 (Table 4) due to the flashy nature of the small watershed (Figure 4c). Consequently, the total area that contributed water to the gage is 55% (consisting of 53% hillside, Table 2, and 2% saturated area, Table 1). Rain falling on the remaining 45% of the area is leaving the watershed by both evaporation and deep percolation. The latter appears as springs at lower elevations below the gage. Applying the hillslope fractions of 13% and 40% from Period I to the remaining periods, the PED model overpredicts the soil loss (t/ha) for Period III in 1988–1989 after the graded Fanya-Juu were installed, and terraces were being formed (57.2 t/ha vs. 6.3 t/ha, not shown). Daily discharge cumulative yield was marginally overpredicted in Period III but slightly underpredicted in Period IV (purple line, Figure 5), with NSE values of 0.84 and 0.82 and RMSE values 1.00 and 1.27, respectively (Table 3). These differential split-sample and simple split-sample tests show that the hydrology submodel performs well, however the sediment submodel tests show these parameters may not optimally account for the changing sediment transport conditions (Table 4; simple split-sample test: NSE = 0.67 vs. differential split-sample test: NSE = −2.06).

Period III (1988 and 1989) immediately after Fanya-Juu installation: Bund construction (Figure 7a) began at the end of the rainy season in 1985 and took some time before completion, as evidenced by high sediment concentrations early in 1986 (Figure 4b). In 1988, these bunds were effective. Accordingly, to fit the daily discharge (black line in Figure 4a), cumulative discharge (black line in Figure 5a), and sediment concentration data (black line in Figure 4b) for 1988–1989, we assumed that the Fanya-Juu became quite effective in infiltrating rain water and reducing runoff in the degraded areas (essentially reducing the representation of A_2 in the model). The degraded area made up only a relatively small portion of the watershed, and hence, the cumulative discharge (Figure 5a) was not greatly reduced from the other years. Because most rainfall would have infiltrated and sediment deposition also would have occurred before it could reach the stream, the effect of the degraded land becomes minimal. The fraction of degraded areas was calibrated as 0% (Table 2) with increased permeable hillsides of 50% (Table 2), assuming that some of the water from the previously degraded areas would become deep percolation as well. Decreasing the degraded area to zero resulted in a good fit for discharge (Figures 4a and 5a), with a Nash Sutcliffe value of 0.91 for the period 1988–1989 (Table 3). Sediment concentration simulation results in NSE = 0.53 for daily concentrations (Table 4). This parameter set fits the observed cumulative load (not shown) and reproduced and reduced the sediment concentrations trend (black line in Figure 4b) without changing any sediment transport properties in Table 1. This hillslope parameter set for any other period reduced the NSE values and increased the RMSEs (Tables 3 and 4) showing satisfactory hydrological performance of the differential split-sample test but not for the sediment transport dynamics clearly demonstrating the different conditions. By comparing the black line (indicating what the discharge would have been in the case that Fanya-Juu practices are implemented and effective) and gray lines in Figure 5a (for Periods I, II, and III), we find that the Fanya-Juus, and the terraces that formed behind them, reduced the discharge in the watershed considerably in the 3-year period after construction (1987, 1988, and 1989). Sediment concentration and loss decreases are evident in Figures 4b and 6. We should note that we attributed the differences in runoff and sediment concentration between years to the landscape change (i.e., Fanya-Juu construction) and not rainfall difference in years because the rainfall variability was taken into account by the PED model, which uses the Thornthwaite–Mather procedure for the water balance of water fluxes (Steenhuis & van der Molen, 1986), and rainfall is actually higher during this period (Figure 5b).

Period IV (1990 to 1993) post Fanya-Juu installation: In 1990, the discharge increased slightly compared to the period before (Figure 5a), and sediment concentrations became much greater (compare the black and green lines in Figure 4b and boxplots in Figure 6b). Runoff increase could be simulated as a greater portion (10%, Table 2)

TABLE 4 Nash Sutcliffe efficiencies and root mean square error for the Anjeni watershed for sediment concentrations. The first set of columns represents the possible hillslope parameters we select based on the expected effect of the soil and water conservation practices. The farthest set of columns represents performance metrics for the fourth period (Period IV). The columns to the left of that represent those values for the first and third periods (Periods I and III). The bolded values represent the best performance during each period for the different possible parameter sets. For each row, the validation periods are distinguished by superscripts that indicate conditions that present differential split-sample test (a) or split-sample test (b) for validation

Period	Hillslope parameters		Calibration						Validation					
			I		III		IV		I		III		IV	
	(A_2)	(A_3)	NSE	RMSE	NSE	RMSE	NSE	RMSE	NSE	RMSE	NSE	RMSE	NSE	RMSE
I	0.13	0.40	**0.60**	**2.45**	—	—	—	—	—	—	−2.06[a]	2.30[a]	0.67[b]	1.99[b]
III	0.00	0.55	—	—	**0.53**	**0.90**	—	—	0.13[a]	3.59[a]	—	—	0.28[a]	2.92[a]
IV	0.10	0.47	—	—	—	—	**0.67**	**1.97**	0.57[b]	2.52[b]	−0.96[a]	1.88[a]	—	—

Note. NSE = Nash Sutcliffe error; RMSE = root mean square error.

[a] Differential split-sample test.

[b] Split-sample test.

FIGURE 7 Photographs of the Anjeni watershed for (a) just installed Fanya-Juu around 1986 during 3″ storm (Hurni, 1988b); (b) terraces in 2013; (c) 20–30 m deep gully in 2013

of the watershed that started to contribute to surface runoff. This increase in degraded area, A_2, could also simulate the increase in erosion (Figure 4b, green line). NSE = 0.67 for this period for sediment concentration predictions (Table 4). The performance of the hydrology submodel for split-sample and differential split-sample tests is good, however much like the first phase of calibration, the sediment model is only performing well when conditions are similar (simple split-sample test Periods III and I).

The amount of sediment deposited can be estimated by summing, for Periods II and III, the difference in soil loss between the observed soil loss in those years and the potential soil loss when no intervention had taken place (111 t during Period I). For instance, the difference in soil loss between Periods I and II was 89.66 t/ha, and between Periods I and III was 104.8 t/ha. This amounts to 194 t/ha or 1.9 cm of soil over the whole watershed in 4 years (1986–1989), assuming 10 t/ha corresponds to approximately 1 mm (Hurni, 1988a). This would be sufficient to fill up some of the area behind the bunds. Figure 7b shows the terraces as they are today in the watershed. Herweg and Ludi (1999) indicate that the Fanya-Juu structures have an average spacing of 10 m between each installation, though exact density measurements are complicated by the fact that some are not maintained and others are intentionally destroyed (Assefa, 2007).

Recent research by Bayabil, Stoof, Lehmann, Yitaferu, and Steenhuis (2015) and Bayabil et al. (2016) in this watershed and earlier studies (Herweg & Ludi, 1999) observed that the drainage ditch outlets constructed as parts of terraces to drain water along the contour frequently become saturated and generate runoff. It is likely that this process started in the 1990s at which point Hurni (1999) explains that there were local reactions to the implementation program and neglect of conservation structures, possibly explaining why the watershed started producing more surface runoff again. In addition, the extra water that infiltrated during Period III could have been one of the causes that increased the water table and saturated the soil in the bottom part of the watershed and as shown by Tebebu et al. (2010) can result in gully formation and soil loss. This is corroborated by local residents who indicated that the gully started to incise or develop when the terraces were initiated. In 2013, this gully has greatly expanded (Figure 7c, note the size of the people in the picture).

5 | DISCUSSION

Nine years of discharge and sediment concentration data at the outlet of this 113 ha watershed were analyzed during a period when Fanya-Juu soil and water conservation practices were installed. This study is unique because it is based on a longer record than most previous studies (Herweg & Ludi, 1999; Dagnew et al., 2015), and the PED computer model is used to indicate differences in the actual observed record given actual landscape changes (Seibert & McDonnell, 2010; Seibert & van Meerveld, 2016) and not to forecast the (unverified) hypothetical future sediment load reduction by changing model parameters. For example, consider the study by Betrie et al. (2011) who predicted a reduction in sediment load of approximately 40–45% for a proposed installation of grass strips along the banks of the streams. This scenario consideration (predicted by altering parameters) by Betrie et al. (2011) is an example of change prediction (Seibert & van Meerveld, 2016) not verified in actual recorded data.

The discussion has three parts. First, we will discuss the effect of installation of Fanya-Juu on discharge and sediment transport at the outlet. Next, we will go into more depth on the model assumptions, and finally, we will discuss how the PED model provides a credible change-detection modeling approach for the saturation-excess hydrology of subhumid and humid Ethiopian and other highlands.

5.1 | Effect of Fanya-Juu installation on sediment loss and discharge

Our results show that in the short term installing the Fanya-Juu soil and water conservation practices decreased annual discharge by less than 10% (Figures 4a and 5), and the annual sediment yield and median and geometric mean of daily sediment concentrations were reduced to their lowest (Figures 4b and 6) for the initial 3-year period following the installation in 1986 (1987, 1988, and 1989). Annual sediment yields reduce to 16.5, 6.3, and 5.9 t/ha in 1987, 1988, and 1989 respectively, or 1868, 716, and 663 t (Figure 6a). After this period, both sediment and discharge were approximately at the level as before the intervention. Our results are in accordance with the findings of Dagnew et al. (2015), Herweg and Ludi (1999), and Hurni (1999) who all reported a reduction in discharge and sediment losses by a factor of 5 in the first years after installation.

Note that in order to obtain these results, the only parameter values that were adjusted (after initial calibration on the data before the Fanya-Juu were installed) were the portions of degraded and permeable hillside areas, with the total area of the hillsides being similar. The sediment parameters themselves were not adjusted (unlike when plant cover would be the driving force), and thus, the change in sediment concentration with time was caused by a greater or smaller portion of surface runoff and soil loss originating from the degraded areas and to a lesser degree by a change in baseflow and interflow from the remaining hillsides "diluting" the sediment concentrations. The area is called "degraded" because it generates runoff. This is different from the many modeling studies that link the change in land cover with increased erosion (Gebremicael et al., 2013; Setegn et al., 2009).

These assumptions are justified for saturated excess conditions because as shown above (Section 3.2), when the proportion of degraded areas increases (or decreases) and its influence expands during the middle and end of the rainy monsoon phase, both surface runoff and erosion processes should increase (or decrease) proportionally (Bayabil et al., 2010), all else being equal. While it is well known that the relationship between rainfall, runoff, and sediment is highly nonlinear (de Vente & Poesen, 2005; de Vente et al., 2013; Nyssen et al., 2004; Parsons, Brazier, Wainwright, & Powell, 2006), it is expected that on this catchment scale (1 km^2), the net effect of increasing erosion processes, connectivity, and sediment storage will lead to increased sediment transport (de Vente & Poesen, 2005). The assumption that runoff and erosion can increase proportionally is supported by the experimental work of Hairsine and Rose (1992) and the regional assessment in Gebremicael et al. (2013) as well as rating curve studies (Guzman et al., 2013; Moges et al., 2016; Vanmaercke et al., 2010), though seasonality and scale play a role. Above 10 km^2, the effect of sediment sinks, and (re)deposition within the landscape often becomes more dominant than sediment sources resulting in gradually declining sediment yield for increasing area (de Vente & Poesen, 2005). However, complete certainty is not possible regarding the relationship between observed trends and actual landscape changes, but this is a more systematic issue that is not easily overcome even with the most well-gauged catchments as has been discussed by several ongoing debates in the field of hydrology (Beven, 1989, 1993, 2002; Kirchner, 2006; McDonnell et al., 2007).

5.2 | Vegetative cover, landscape elements, and small-scale physics

The assumptions for the PED model are different than those for the many watershed studies that considered land cover changes as the dominant explanation (Balthazar, Vanacker, Girma, Poesen, & Golla, 2013; de Vente et al., 2013; Guzman et al., 2013; Rientjes et al., 2011a) for changes in the hydrology in Ethiopia. These assumptions are justified below and summarized as direct runoff being generated as the precipitation in excess of a threshold value for moisture content over a specified portion of the watershed. The water that infiltrates in the remaining portions of the watershed is delayed and becomes baseflow (first-order reservoir) or interflow (zero-order reservoir). Vegetation indeed plays an important role in affecting vulnerability of soil and water resources to environmental processes (Balthazar et al., 2013; Bewket and Sterk, 2003; Haregeweyn et al., 2012; Rientjes et al., 2011a), but we posit that these changes are in concert with changes in hydrology and water availability (because broad classes of land cover can be identified with landscape position and water availability). We find in the humid Ethiopian highlands grazing land in the wet valley bottoms and dry steep uplands, cropland on the deeper intermediate sloping hillsides, and forest cover on the steep and droughty hillsides (Bayabil et al., 2010). In the semiarid monsoonal highlands, croplands are usually in the valley bottoms. Furthermore, based on research in this landscape where the infiltration capacity of the surface soil exceeds the median rainfall intensity most of the time, changes in land use often reflect a change in hydrologic regime rather than vice versa (Steenhuis et al., 2013). Though this assumption may be seen as a limitation of the model, it is based on our field observations, reviews on model complexity and sediment transport at catchment scales (de Vente & Poesen, 2005; de Vente et al., 2013), and an attempt to limit the model structure to the most dominant influences (Kirchner, 2006). Though land use may change independent of the hydrologic regime, de Vente et al. (2013) explain that catchment sediment transport is not necessarily as strongly affected by land use changes as the spatial patterns of sediment sources and sinks.

5.3 | Validity of the PED model structure based on saturation-excess runoff

Model structure recently is a hotly debated topic in hydrology and involves the discussion of the specific nature of models and the uncertainty present in the modeling process (Beven, 2006; Shin et al., 2015; Wagener & Gupta, 2005). On the basis of the equifinality thesis, Beven (2006) argues that there can be many acceptable representations of environmental processes that cannot be easily rejected and that this can be viewed as a problem of decidability between feasible descriptions of how the hydrological system is working. This problem of "structural identifiability" can be addressed by fixing the insensitive parameters, using simple models that are fit for purpose, improving models, or to use auxiliary soil or groundwater data (Shin et al., 2015). Tilahun et al. (2013a) showed in their sensitivity analysis of the PED model that the specified water storage capacity ($S_{\max}$) for each of the three fractional areas of a watershed (saturated, degraded, and permeable hillsides) in this model seemed to be much less sensitive than the fraction of each of these areas (A_1, A_2, and A_3). Hence, these less sensitive parameters were fixed after the initial calibration phase (on Period I). Using the soil and groundwater data of Kejela (1995), Legesse (2009), and Zeleke (2000), the fraction of saturated area was further constrained to follow observable physical representations within the watershed. This use of local data and spatial or physical consistency is what many advocate as a way of constraining parameters to have a more realistic model structure (Andréassian et al., 2012; Seibert & McDonnell, 2002, 2010), bringing together the knowledge of experimentalists and modelers (Dunne, 1983; Klemeš, 1986b). Finally, the limited complexity formulated here enabled a simple approach that could simulate the measured runoff and sediment transport. Beven (2006) writes that another sense of the term identifiability (usually meant for model structure, parameter values, and sets of parameter values) is whether the dominant modes of response of the system are identifiable. Using the saturation-excess mechanism (or variable source area concept) for watershed runoff, several studies have been able to better understand and simulate runoff at different scales (Easton et al., 2010; Montanari et al., 2006; Tilahun, Guzman, et al., 2013a; Shanley, Sebestyen, McDonnell, McGlynn, & Dunne, 2014; Tilahun et al., 2015). Using this mechanism as the basis for the analysis for the impact of SWC on degraded lands, and hence the water balance, yielded very interesting results that are in accordance with what is and has been observed spatially. Given there is a certain level of aggregation in time and space of physical processes, it is unrealistic to expect to escape parameter identification problems entirely (Andréassian et al., 2012), however by choosing this sound model structure, incorporating sediment data and trying to address the aforementioned issues, this investigation aimed to demonstrate the plausibility of the model detecting changes in watershed behavior (Seibert & McDonnell, 2010).

This change in the water balance dynamics due to portions of the watershed changing is in agreement with our conceptual framework, where portions with restrictive soil moisture storage and soil profile are the main important factors considering the infiltration capacity of the soil is many times greater than the rainfall rate (Bayabil et al., 2010; Engda et al., 2011; Tilahun et al., 2016). Though degraded areal fractions calibrated during Periods I or IV were capable of performing well for the hydrologic differential split-sample tests (on Period III), the sediment NSE evaluation showed that the best performance for Period III is obtained when the model is readjusted to take into account the catchment landscape changes. De Vente et al. (2013) in their discussion on the difficulty of choosing an appropriate model structure indicate that for European and Ethiopian catchments, spatially lumped models are generally more effective and efficient for sediment yield predictions than spatially distributed models. They also mention that water balance simulations should theoretically have the best potential for assessing effects of changes in climate, land use, and soil conservation measures. Moreover, studies cited in the introduction (Bewket & Sterk, 2005; Gebremicael et al., 2013) mention that surface runoff from degraded lands is one of the causes for increased runoff loss and implicitly soil loss indicating the model's approach to simulating the Anjeni watershed's changes can be supported in other locations.

6 | CONCLUSION

The semihumid Blue Nile Basin is an important catchment for the future economic progress of the Ethiopian people as well as several neighboring countries, which makes the fluctuations in water quality and quantity all the more important. As shown through the application of the PED model for the Anjeni watershed, located in a strategic agroclimatic zone, the changes (in hydrology and sediment transport) over a 9-year period prompted by the installation of SWCP had important implications for the assessment of long-term environmental rehabilitation projects. Important changes in soil loss were mostly related to the landscape changes in the amount of water that infiltrated. As this simple water balance saturation-excess approach was able to simulate, more water infiltrated (by decreasing the portion of degraded lands in the model) when SWC structures are installed. Later, however, this influence of the SWC structures diminishes, and the catchment response to rainfall returns to preinstallation sediment and hydrological patterns especially in the midst of difficulty maintaining the SWCP in 1990s. The limited time period of effectiveness of SWC measures can explain why sediment concentration in rivers in the Ethiopia highlands is not decreasing despite the large efforts in soil conservation.

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