

Watershed modeling for reducing future non-point source sediment and phosphorus load in the Lake Tana Basin, Ethiopia

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Abstract

Purpose Agricultural intensification to meet the food needs of the rapidly growing population in developing countries affects water quality. In regions such as the Lake Tana basin, knowledge is lacking on measures to reduce non-point source pollutants in humid tropical monsoon climates. The aim of this paper was, therefore, to develop a non-point model that can predict the placement of practices to reduce the transport of sediment and phosphorus (P) in a (sub) humid watershed.

Materials and methods In order to achieve the objective, hydrometeorological, sediment, and P data were collected in the watershed since 2014. The parameter efficient semi-distributed watershed model (PED-WM) was calibrated and validated in the Ethiopian highlands to simulate runoff and associated sediments generated through saturation excess. The P module added to PED-WM was used to predict dissolved (DP) and particulate P (PP) loads aside from discharge and sediment loads of the 700 ha of the Awramba watershed of Lake Tana basin. The PED-WM modules were evaluated using the statistical model performance measuring techniques. The model parameter based prediction of source areas for the non-point source sediment and P was also evaluated spatially

and compared with the Topographic Wetness Index (TWI) of the watershed.

Results and discussion The water balance component of the non-point source model performed well in predicting discharge, sediment, DP, and PP with NSE of 0.7, 0.65, 0.65, and 0.63, respectively. In addition, the predicted discharge followed the hydrograph with insignificant deviation from its pattern due to seasonality. The model predicted a sediment yield of 28.2 t ha⁻¹ year⁻¹ and P yield of 9.2 kg ha⁻¹ year⁻¹ from Awramba. Furthermore, non-point source areas contributed to 2.7 kg ha⁻¹ year⁻¹ (29%) of DP at the outlet. The main runoff and sediment source areas identified using PED-WM were the periodically saturated runoff areas. These saturated areas were also the main source for DP and PP transport in the catchment.

Conclusions Using the PED-WM with the P module enables the identification of the source areas as well as the prediction of P and sediment loading which yields valuable information for watershed management and placement of best management practices.

Keywords Lake Tana basin · Non-point source · PED-WM · Saturation excess

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1 Introduction

Increases in the flux of non-point sediment and phosphorus (P) into rivers, streams, lakes, and reservoirs result in turbid water and eutrophication given that P is often the limiting nutrient (Johnes 1996; Ginting et al. 1998; Klatt et al. 2003; Haygarth et al. 2005). Understanding the non-point sources of sediment and phosphorus fluxes in the landscape, its effect on water bodies and identifying suitable control mechanisms requires an evaluation of non-point source pollutants sources,

transport pathways (i.e., mobilization), delivery mechanisms, and prediction (Haygarth et al. 2005). Evaluation of non-point source P intrinsically covers dissolved and available P as well as its spatio-temporal scale. Throughout the year, the magnitude of natural (e.g. atmospheric deposition, soil-P) and anthropogenic (e.g., inorganic and organic fertilizer) P sources changes, results in different loads of dissolved P (DP), and particulate P (PP) forms (Nziguheba et al. 2016). These forms are transported (e.g., erosion, runoff, leaching), from fields, along hill slopes, within the watershed, further increasing the complexity of understanding the effect of dissolved and particulate P fluxes in a mosaic landscape (Chapman et al. 1997; Carpenter et al. 1998; Borah and Bera 2003; Girmay et al. 2009; Verheyen et al. 2015).

In developing and emerging countries, agricultural intensification has increased both sediment-associated as well as DP fluxes mainly in surface water and to a lesser extent in groundwater (Sharply 1995; Chapman et al. 1997; Sims et al. 1998; Maguire et al. 2005). For instance, in Ethiopia, decreasing water quality is caused by the rapid population increase and associated land-use change mainly from forest to agriculture resulting in soil degradation and increased direct runoff and soil erosion (Nyssen et al. 2005; Tebebu et al. 2010). This has become the path for non-point source sediment and P transport from the agricultural lands causing onsite effects, e.g., reduction of soil fertility (Morgan 2009; Hailesslassie et al. 2005) and offsite effects, e.g., siltation and eutrophication of surface waters (Awulachew and Tenaw 2008; Girmay et al. 2009).

Despite the country's erosion reduction strategy, the ongoing degradation of agricultural land and increased fertilizer usages continues, resulting in reservoir siltation and water quality issues in lakes like Lake Tana (Awulachew and Tenaw 2008). Best management practices to mediate the effects of increased non-point source P and sediment concentrations has resulted in reduction of pollutants and inflow of the surface by targeting hydrological sensitive areas (HSA's) (Bishop et al. 2005). This could be illustrated by an instance in the USA in one of the water supply watersheds of New York City where saturation excess runoff dominates (alike in the Ethiopian highlands). Water quality of the city was improved by installing management practices which targeted the HSA (bottom slope part of the watershed which is regularly saturated) for reducing the nutrient input such as P loads (Rao et al. 2009). Similarly, Moges et al. (2016a) has indicated that the P concentration was significantly higher in the saturated bottom part of the watershed and was understood as the hydrological sensitive area for dissolved phosphorus (HSA for DP). Hydrologically sensitive areas in the sub-humid watersheds are the degraded hill slopes and the saturated valley bottoms. Best management practices of placing furrows with 50-cm-deep increase infiltration thereby reduce

runoff and sediment from degraded areas (Dagneu et al. 2015). Effective best management practice in the valley bottoms are however not studied well for sub-humid, and the creation of buffer zones by planting grass could be one solution.

In areas where there is insufficient data of non-point source pollutants, the pollution and/or eutrophication levels in surface waters cannot be easily understood. Furthermore, the cost of monitoring sediment and the associated nutrient inflow to water bodies which causes water quality impairment is high. Hence, quantification of sediment and nutrient loads from the watersheds becomes difficult. To alleviate this problem and support monitoring systems, watershed models which are capable to predict sediment and nutrient outflow (e.g., P) is vital (Chu et al. 2004). In this case, locally adapted nonpoint source pollution models can help to estimate the pollution levels based on the amount of inflow to predict non-point source sediment and P loads into the water bodies and source areas in the watersheds. However, the sediment and nutrient models to simulate DP and PP are limited in most parts of the world by lack of datasets for calibrating and validating these models. Similarly, in Ethiopia, there is a lack of sufficient data to model DP and PP, to evaluate the extent of nonpoint source areas contributing to P loads and assess the on-site and off-site effects at watershed scale. Furthermore, there is a lack of hydrological models allowing for DP and PP simulations in areas where runoff generation is dominated by saturation excess. The use of suitable hydrological models with associated nutrient modules can help in elucidating the spatio-temporal character of these P fluxes and identifying suitable remediation mechanisms.

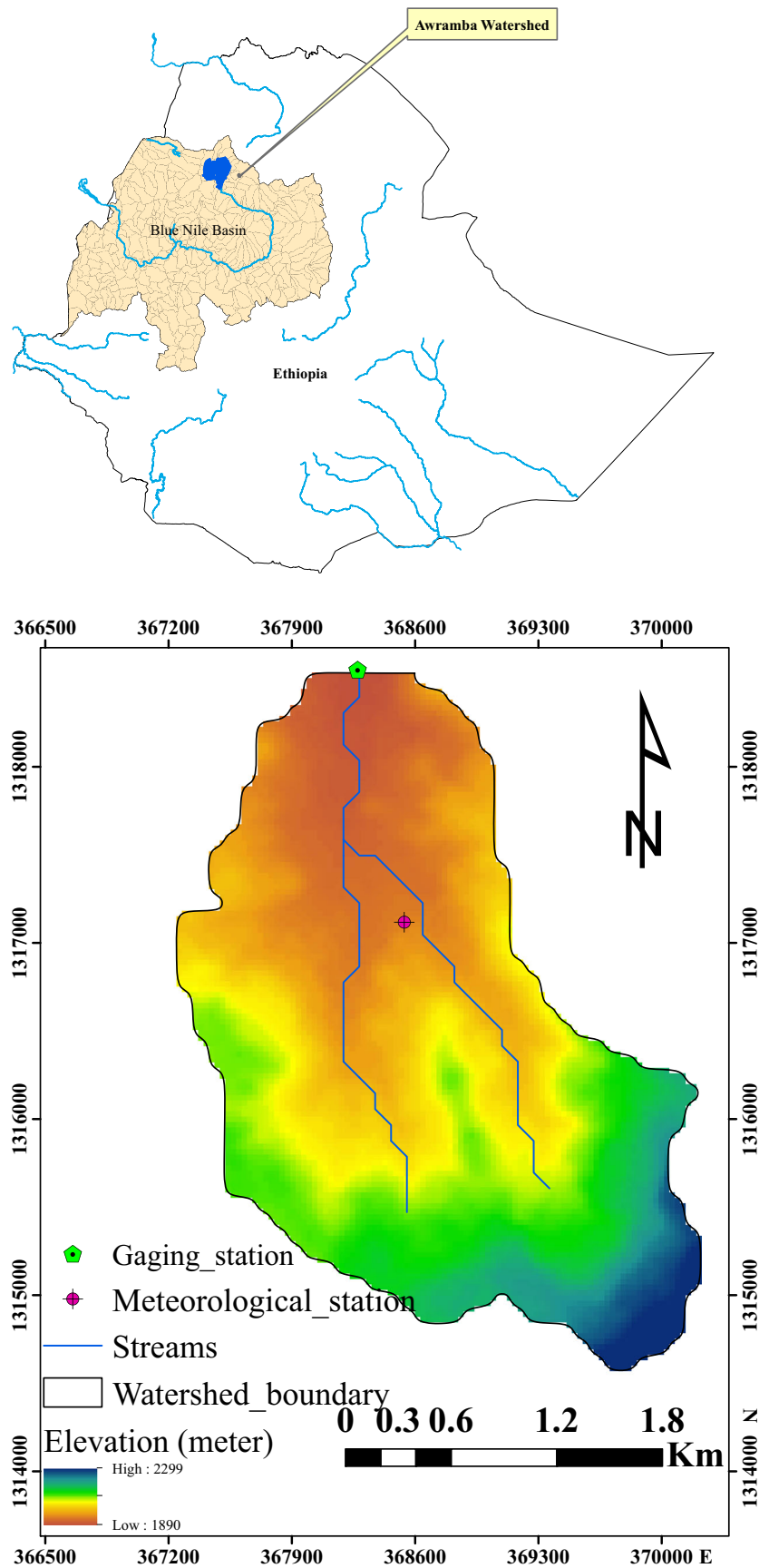
Therefore, the main objective of this study was to improve the capacity to evaluate non-point P transport in the landscape by (i) incorporating the P module into the parameter efficient semi-distributed watershed model (PED-WM) (Steenhuis et al. 2009; Tessema et al. 2010; Tilahun et al. 2013a, b, 2014) using field observations, (ii) evaluating non-point PP and DP sources as well as quantifying P loads from the 7-km² Awramba watersheds, and (iii) developing recommendations to reduce the non-point sediment and DP sources using the simulation results in combination with the relevant literature.

2 Materials and methods

2.1 Description of the study area

This study was carried out at the Awramba watershed (Fig. 1) (11.886–11.9253 N and 37.781–37.806 E and 1887 to 2291 m a.m.s.l.) located south east of Lake Tana, 75 km to the northwest of Bahir Dar city. The watershed is ideal as the

Fig. 1 Map of the Awramba watershed in the Lake Tana basin, Ethiopia



topography represents the complexity of the Ethiopian highlands that is characterized by elevated uplands, depressions, and flat surfaces. The climate in the watershed is sub-humid monsoonal. The average temperature is 22 °C in January and 19 °C in July. The annual average rainfall during the main rainy season (June to September) is 1098 mm. The soils are volcanic in origin and range from mainly clay texture throughout in the mid- and downslope positions and clay to sandy clay soils on the top slopes. Over 90% of the watershed based on classification from Food and Agriculture Organization (FAO 2003) consists of Haplic Luvisols. The bottom part of the watershed is mainly covered by grassland, with few agricultural patches and evergreen trees on the river banks whereas the mid- and upper slope areas have intensive agriculture.

2.2 Data collection and availability

2.2.1 Hydro-meteorological data

The daily precipitation and temperature for the Awramba watershed was collected from 2013 to 2015 using the meteorological station established at the center of the watershed. Potential evaporation (PET) was estimated using the temperature method developed by Enku and Melese (2014). Effective precipitation was calculated by subtracting the potential evapotranspiration from precipitation. Cumulative effective precipitation was calculated during the rainy phase of the monsoon from June till September. It was estimated by summing the daily effective rainfall, which is equal to the daily precipitation minus the daily potential evapotranspiration (Moges et al. 2016b).

The water levels were recorded at the outlet of the Awramba watershed in the rainy seasons of 2013–2015. Levels were converted to discharge data by using a location specific stage-discharge curve. The stage-discharge relationship was established by measuring the cross-section area at the outlet of the watershed, flow velocity using a current meter, and corresponding water level readings.

2.2.2 Sediment and phosphorus data

Baseflow and rainfall event-based samples were collected at the outlet of the catchment and analyzed for sediment concentration in the rainy seasons of 2014 and 2015. The measured concentrations from 2014 were used to calibrate and refine the sediment module in PED-WM whereas 2015 was used for validation. The P module was only calibrated using the data collected in 2015.

In addition, groundwater samples were collected from installed piezometers in the watershed for various topographic land uses (Moges et al. 2016a). The filtered surface and

groundwater samples were analyzed for DP using a molecular absorption dye indicator method that was quantified by a UV-VIS spectrophotometer (Wagtech model 7100) at a wavelength of 550 nm with the detection limit of 0.01 mg l⁻¹.

Soil-bound P (or PP) was measured in soil samples taken from the top 15 cm at different locations within the watershed covering various land use types and topographic positions. More information on the methodology and location of the sampling can be found in Moges et al. (2016a). The data were used to develop and calibrate (for 2015) the P module within the PED-WM.

2.3 Parameter efficient (semi)-distributed watershed model

From the various available watershed models, the PED-WM model was selected. The selection was based on the earlier study by Moges et al. (2016c) which showed the suitability of PED-WM given that saturation excess flow was the principal runoff generating mechanism. The discharge prediction by the water balance module in PED-WM was validated for other micro-watersheds in Lake Tana basin (e.g., DebreMawi, 0.91 km² by Tilahun et al. 2013a) and larger watersheds (e.g., the Blue Nile basin, 180,000 km² by Steenhuis et al. 2009). In addition, the PED-WM, besides the water balance module, incorporates an erosion/sediment module, developed by Tilahun et al. (2013b). The sediment module, developed and tested for Debre Mawi watershed (0.91 km²), uses discharge simulated by the PED-WM water balance module. The module was modified based on the sediment concentration rating curve developed by Moges et al. (2016b). Subsequently, the P module was developed and integrated into PED-WM which uses both the discharge obtained from the water balance and the sediment load predicted by the sediment/erosion module.

2.3.1 PED-WM water balance module

The water balance module in PED-WM is a semi-distributed module, capable of predicting discharge at a daily time step by considering saturation excess runoff (Steenhuis et al. 2009; Tessema et al. 2010). Within the module the watershed is divided into three zones: two surface runoff zones: the valley bottoms which become saturated during the main rainy season and the degraded hillsides with a slowly permeable sub-horizon within 10–20 cm from the soil surface. The remaining part of the watershed is the hillsides where the rainwater infiltrates and either contributes to interflow (zero order reservoirs) or base flow (first order reservoir). The model computes the water balance (Eq. 1) using Thornthwaite Mather (Steenhuis and Van Der Molen 1986) for defining the

actual evapotranspiration. The water balance for each of the three zones can be written as

$$S_t = S_{t-\Delta t} + [P - AET - Q_{sf} - Perc] \Delta t \tag{1}$$

where S_t is the moisture storage (mm/day), $S_{t-\Delta t}$ is previous time step storage (mm/day), P is precipitation (mm/day), AET is actual evapotranspiration (mm/day), Q_{sf} is runoff from excess of saturation in zones 1 (periodically saturated bottom lands) and 2 (degraded hill sides), and Δt is the time step which is 1 day in our application. Finally, $Perc$ is percolation to the sub soil (mm/day) in permeable hillside (zone 3) and equals the sum of the interflow Q_{if} and the base flow Q_{bf} . The model has nine main parameters including the area fraction (A) and the maximum storage capacity (S_{max}) for the three zones and three subsurface parameters: the half-life ($t_{1/2}$) to describe the exponential decay in time and maximum storage capacity (B_{Smax}) of the first-order reservoir and the drainage time of the zero-order reservoirs (τ^*) describing a linear decrease in time for the interflow. Detailed description about

the model can be found from Steenhuis et al. (2009) and Tilahun et al. (2013a).

2.3.2 PED-WM sediment module

The sediment module was developed by Tilahun et al. (2013b) and assumes that there are predominantly two runoff producing areas: (i) the saturated bottom slope and (ii) the degraded areas of watershed. The sediment concentrations from these two areas are transport limited during the beginning of the rainy period and source limited towards the end of the rainy period (Tilahun et al. 2013b). The module considers that sediment concentrations are decreasing for the same discharge throughout the rainy season (Guzman et al. 2013; Tilahun et al. 2013b). The sediment concentration in the runoff water C_s is found by using the calculated flow components from the water balance module (Eq. 1) and assuming that only the surface runoff from degraded areas and the valley bottoms contain sediment. Sediment concentrations are transport limited after the fields are plowed and source limited at the end of the rain phase. The module can be written as (Tilahun et al. 2013b)

$$C_s = \frac{\left[\left(A_1 Q_1^{1.4} (a_{s1} + (a_{t1} - a_{s1}) H) \right) + A_2 Q_2^{1.4} (a_{s2} + (a_{t2} - a_{s2}) H) \right] + A_3 (Q_{bf} + Q_{if}) a_{t3}}{A_1 Q_1 + A_2 Q_2 + A_3 (Q_{bf} + Q_{if})} \tag{2}$$

where A is the dimensionless fraction of watershed area; Q is the amount of runoff for each of the three zones as indicated by the subscripts where subscript 1 relates to the periodically saturated valley bottom lands, subscript 2 for the degraded soils, and subscript 3 for the remaining permeable hillsides in mm d^{-1} ; a_t in $\text{g L}^{-1} (\text{mm day}^{-1})^{-0.4}$ is the calibrated transport limiting sediment factor for the three areas 1, 2, and 3 as indicated by the subscripts; and a_s is the source limiting sediment factor. H is the ratio of the area in which rills are being formed to the total area in each zone. It varies therefore between 1 in the beginning of the rain phase to 0 near the end of the rains.

For this study, the sediment module as expressed in Eq. 2 was modified by replacing the H , by M_s which is the soil

moisture condition during the rainy monsoon phase. The modified parameter, M_s was defined as the ratio of the cumulative effective precipitation, P_e (mm d^{-1}) to the maximum threshold effective precipitation, P_T (mm d^{-1}) (Moges et al. 2016a, b, c):

$$M_s = \frac{P_e}{P_T} \text{ for } P_e < P_T \tag{3a}$$

$$M_s = 1 \text{ for } P_e \geq P_T \tag{3b}$$

M_s varies with P_e while P_T remains constant and is calibrated. As a result, the modified sediment module of PED-W model could be written as

$$C_s = \frac{\left[\left(A_1 Q_1^{1.4} (a_{s1} + (a_{t1} - a_{s1}) M_s) \right) + A_2 Q_2^{1.4} (a_{s2} + (a_{t2} - a_{s2}) M_s) \right] + A_3 (Q_{bf} + Q_{if}) a_{t3}}{A_1 Q_1 + A_2 Q_2 + A_3 (Q_{bf} + Q_{if})} \tag{4}$$

where M_s is the soil moisture condition during the rainy monsoon phase; the remaining variables are similar to Eq. 2.

As such, the modified equation (Eq. 5) has five parameters that require calibration. This includes transport limiting and

source limiting factors for both the saturated and degraded areas and the maximum or threshold cumulative effective precipitation (P_T). The sediment concentrations in both the baseflow and the interflow can be assumed zero in small watersheds like the Awramba watershed.

2.3.3 PED-WM phosphorus module

The P module of PED-WM model was developed to predict sediment-bound P (i.e., PP) and DP loads and to identify non-point P source areas within the watershed. The total P load (L_{TP}) per ha was predicted as the sum of PP (L_{SP}) and the DP (L_{DP}) at the outlet of the watersheds as each of the components estimated using Eqs. 5–7

$$L_{TP} = L_{PP} + L_{DP} \quad (5)$$

$$L_{PP} = Q C_S C_{SP} \quad (6)$$

$$L_{DP} = Q C_{DP} \quad (7)$$

where Q (mm/day) is the discharge at the outlet, C_S (mg l^{-1}) is the sediment concentration in the runoff water (Eq. 4), C_{SP} (mg kg^{-1}) is the PP, and C_{DP} (mg l^{-1}) is the DP concentration which originates partly from DP concentration in the subsurface flow (both interflow and base flow), C_{DPsf} , and in the overland flow, C_{DPof} .

Development of the P module was based on the findings by Moges et al. (2016a) who investigated P concentrations in Awramba watershed in 2013 and by Flores et al. (2010, 2011) observing the relationship of P concentration in groundwater near the stream for the Catskill mountain watershed in New York state, USA. Flores et al. (2010, 2011) found that base and interflow emerging from the soil is in equilibrium with DP concentration, C_{DPsf} , in the surface soil near the stream, is independent of the discharge rate and varies with temperature. Since in Ethiopia the temperatures vary less than in New York, we expect that the DP concentration, C_{DPsf} , in the subsurface flow (both interflow and base flow) remains constant independent of temperature and flow rate.

Dissolved P concentration in surface runoff ($C_{DP, of}$) is greater than in the subsurface (Flores et al. 2010, 2011) and increases with flow rate. Hence, the concentration in the surface runoff can be simulated as a function of the discharge. Since the C_{DP} concentration depends on how well water mixes with the soil, we decided to use the same Q dependence as for the sediment loss in Eq. 2 (i.e., $Q^{0.4}$):

$$C_{DP, of} = b_{DP} Q^{0.4} \quad (8)$$

where C_{DPof} is the DP concentration in the overland flow (mg l^{-1}), Q_{of} is discharge in mm day^{-1} , and b_{DP} ($\text{L mg}^{-1} \text{mm}^{-0.4} \text{day}^{-0.4}$) is a constant that can be fitted.

Finally, for small surface runoff rates in the valley bottoms (e.g., Awramba watershed), the water is assumed to be in

continuous contact with the soil. Thus, before a critical discharge Q_{of}^* is reached, the concentration in the surface runoff was assumed the same as in the subsurface flow (Moges et al. 2016a). Based on these assumptions and observations, the form of the DP concentration can be written as

$$C_{DP} = C_{DP, sf} + b_{DP2} Q_{of2}^{0.4} \quad \text{for } Q_{of1} < 1.1 \text{ mm/day} \quad (9)$$

$$C_{DP} = C_{DP, sf} + b_{DP1} Q_{of1}^{0.4} + b_{DP2} Q_{of2}^{0.4} \quad \text{for } Q_{of1} > 1.1 \text{ mm/day} \quad (10)$$

where C_{DP} is the total DP at the outlet of the watershed; $C_{DP, sf}$ is the DP concentration in the subsurface flow (g l^{-1}); and Q_{sf1} and Q_{sf2} in mm/day are the overland flow from the periodically saturated valley bottom (zone 1) and overland flow from the degraded area (zone 2), respectively. The concentration in the groundwater which was nearly equivalent to the concentrations in the subsurface flow was measured in well samples (Moges et al. 2016a), and the average from the wells was used as DP concentrations of subsurface flow. The constants b_{DP1} and b_{DP2} are found by calibration. Finally, Moges et al. (2016a) also showed that the minimum dissolved concentration during a storm in August was greater than in July and related to both the fertilizer application and the wetness of the soil. To simulate this, we assumed that zone 2 contributed a minimum of 0.4 mm/day in overland flow in August on days that it rained.

The PP depends on similar conditions with very low concentration during base flow and greater concentration when the P-rich sediment from the agricultural areas is mixed with a relatively greater portion of organic matter than that in the original soil. This is known as the enrichment ratio (Sharpley 1980). Therefore, the form is like DP concentration

$$C_{SP} = C_{SP, sf} + b_{SP2} Q_{of2}^{0.4} \quad Q_{of1} > 1.1 \text{ mm/day} \quad (11)$$

$$C_{SP} = C_{SP, sf} + b_{SP1} Q_{of1}^{0.4} + b_{SP2} Q_{of2}^{0.4} \quad Q_{of1} < 1.1 \text{ mm/day} \quad (12)$$

where C_{SP} is the PP concentration in the stream flow (mg kg^{-1}), $C_{sp, sf}$ is the concentration of PP from the runoff-transported sediment, Q_{of1} is the total surface (overland) flow from zone 1, and b_{SP1} and b_{SP2} are dimensionless constants to be fitted by regression that are intended to simulate the enrichment.

2.3.4 Model calibration, validation, and performance

Discharge data from 2013 to 2014 was used for calibration whereas stream flow data of 2015 was used for validation of the water balance module. For the sediment and P module, calibration was carried out using sediment concentrations obtained during 2014 and 2015. However, validation was not carried out due to limited data availability.

During calibration of the PED-WM modules, initial/default parameter values were used from past water balance module calibrations by Steenhuis et al. (2009), Tessema et al. (2010), and Collick et al. (2009) and sediment module calibration by Tilahun et al. (2013a). For the P module, the initial model parameters were used from field observations as reported by Moges et al. (2016a) for Awramba watershed. The three PED-WM modules were calibrated systematically by changing sensitive parameters stepwise to maximize the “goodness of fit” measured by Nash-Sutcliffe efficiency, NSE (Nash and Sutcliffe 1970). The rate of goodness of fit was evaluated utilizing similar methods as Moriasi et al. (2007).

2.4 Identification of non-point sediment and DP sources

To locate and evaluate the spatial distribution of the non-point sediment and DP sources, a combination of field observations, model results, and GIS was used. The knowledge regarding the spatial distribution was important to recommend best management practices. As such, from field observation, the bottom valleys of the watershed which are regularly saturated were demarcated using a GPS tracking in Awramba watershed in 2014 (Moges et al. 2016a). The topographic Wetness Index (TWI) which is the ratio of upslope contributing area to slope of the watershed (Beven and Kirkby 1979) was used. This will help for mapping the source area (bottom slope) and partially upper slope part of the watershed.

The principal source areas of non-point sediment and P sources were identified using field observation, the produced maps using the TWI index, and the sensitivity of model parameters. Non-point sediment source areas were based on the transport-limiting (a_t) and source-limiting (a_s) model parameter sensitivity. Relatively sensitivity parameters (specifically source limiting in both saturated bottom land portion and degraded areas) resulted in the assumption of high sediment contributing areas. In addition, potential gully formation areas were considered as the main source of non-point sediment source in the watersheds aside from areas with high parameter sensitivity.

The P source areas were determined through comparison of the measured DP concentration and PP from field observations (Moges et al. 2016a) together with the calibrated PED model parameters and derived TWI maps. Subsequently, the PED-WM model results were combined with the identification of the various runoff contributing areas using the topographic wetness index to identify the non-point P sources in Awramba watershed.

3 Results and discussion

Presentation of the results and discussion is categorized in three main sections: (i) evaluation of three modules of PED-

WM was presented separately for Awramba watersheds, (ii) the non-point sediment and DP sources, based on the model results and field observations, were identified and quantified in Awramba watershed; and (iii) recommendations to reduce non-point sediment and DP sources using techniques from available studies. The model performance for the three modules in the PED-WM model showed satisfactory results for predicting discharge (Fig. 3), sediment (Fig. 4), and P (both dissolved (Fig. 5a) and soil-bound (Fig. 5b)) in the watershed as summarized in Table 4.

3.1 PED-WM model results

3.1.1 The water balance module

The calibrated parameters for Awramba (Table 1) indicated that the dominating runoff source area contained nearly 16% of the watershed from which 7% was situated in the saturated valley bottom and 10% was degraded area. More than 72% of the watershed area was identified as mid-slope with minor runoff contribution compared to the other two areas. A fraction of the mid-slope area constituted a source of subsurface flow resulting into base flow at the watershed outlet. The total stream flow response in Awramba watershed was contributed by 88.9% watershed area. The remaining portion of the watershed considered as confined depression or the water percolates deep without flowing at the outlet.

Model performance for stream flow at the outlet of Awramba has indicated an $R^2 = 0.68$ and $NSE = 0.65$ during calibration (2013–2014) and an $R^2 = 0.65$ and $NSE = 0.65$ during the validation (2015) periods (Fig. 2). The model was good at capturing the rising and recession limb of the hydrograph, while slightly under-predicting the peak flows in the watershed (Fig. 2). The under-prediction of peak flows might be due to that a majority but not the entire watershed was contributing to the stream flow at the outlet of the watershed.

3.1.2 PED-WM sediment module

Sediment concentration prediction called for the calibration of the soil moisture condition (M_s) which is a function of the cumulative effective precipitation (P_e) and the maximum threshold precipitation (P_T) with the latter being watershed specific. The initial value of 600 mm was taken as P_T based on Moges et al. (2016b) for both watersheds and was calibrated as it is unique to watersheds. The remaining PED-WM sediment module parameters were derived from Tilahun et al. (2013a). Degraded and saturated areas were the main contributing runoff areas and hence were found to be contributing non-point sources for sediment concentration and respective loads. The calibrated transport-limiting and source-limiting factors for Awramba were 13 and $8.5 \text{ g l}^{-1} (\text{mm d}^{-1})^{-0.4}$ for the saturated 16 and $12 \text{ g l}^{-1} (\text{mm d}^{-1})^{-0.4}$ for

Table 1. Calibrated parameters of water balance module of the PED-W model for predicting discharge at the Awramba watershed

Parameter notation	Description of the parameter	Unit	Calibrated parameter value Awramba
A_s	Portion of saturated area	%	6.9
A_h	Portion of hillside area	%	72
A_d	Portion of degraded area	%	10.0
$S_{max,s}$	Maximum soil water storage in A_s	mm	70
$S_{max,h}$	Maximum soil water storage in A_h	mm	150
$S_{max,d}$	Maximum soil water storage in A_d	mm	15
BS_{max}	Maximum storage for base flow linear reservoir	mm	100
$t_{1/2}$	Base flow half-life time	days	12
τ^*	Interflow	days	8

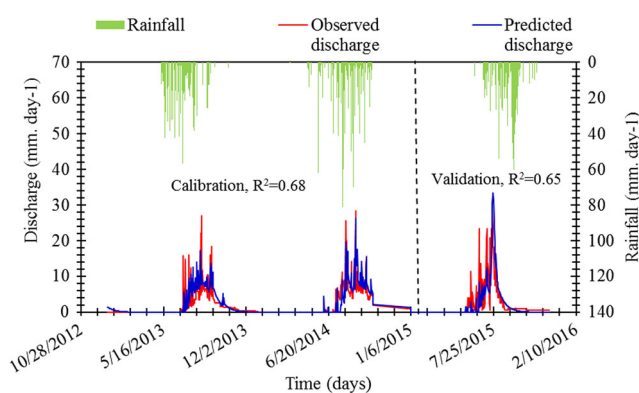
degraded areas, respectively (Table 2). The cumulative maximum threshold, P_T , was 595 mm which was similar to the other watersheds (with an area ranging from 0.9 to 1656 km²) as estimated in Moges et al. (2016b). The calibrated PED sediment module with $R^2 = 0.7$ and NSE = 0.63 (Fig. 4) resulted in an annual sediment load estimation of 28.6 t ha⁻¹ year⁻¹ from Awramba watershed. Model results showed that the degraded areas were a larger sediment source compared to the saturated area.

3.1.3 PED-WM phosphorus module

The limited daily P data collected in 2015 at the outlet of the watershed was used for calibration. Since the data was limited, we could simply curve fit the observed DP concentration vs predicted value using Eqs. 8–10 by systematically varying the b_{SP1} and b_{SP2} parameters using linear regression to find the best fit. Based on measurements, we set $C_{DP,bf} = 0.5$. Hence, Eqs. 8 and 9 could be rewritten according to

$$C_{DP} = 0.5 + 0.7Q_{of2}^{0.4} \quad Q_{of1} < 1.1 \text{ mm day}^{-1} \quad (13)$$

$$C_{DP} = 0.5 + 0.5Q_{of1}^{0.4} + 0.7Q_{of2}^{0.4} \quad Q_{of1} \geq 1.1 \text{ mm day}^{-1} \quad (14)$$

**Fig. 2** Predicted and observed discharge hydrographs for the calibration (2013–2014) and validation (2015) for the Awramba watershed

where C_{DP} is dissolved P in mg L⁻¹, Q_{of1} surface flow from saturated area (zone 1) in mm day⁻¹, and Q_{of2} is the surface flow from degraded area (zone 2) in mm day⁻¹.

The calibrated parameters are summarized in Table 3. We found that if the sediment concentrations were more than 15 mg l⁻¹, the P concentration was at base levels, likely because sediment from the banks that have little P were mixed within the streams. Therefore, we set the minimum Q_{sf2} at 0 on early July and increased it linearly to 0.4 mm day⁻¹ to early August and kept it constant. When the observed value for runoff was in almost all cases greater than the minimum value, we used the predicted values by the PED-WM model.

Since the subsurface flow is sediment free, a linear relationship was obtained between C_{DP} and C_{SP} when using the DP concentration found in the baseflow ($C_{DP, sf}$) as intercept. The equation was obtained through omission of one outlier P concentration in August (that could only be explained by fertilizer addition on the day of rainfall). The following linear equation was obtained and calibrated to yield and R^2 of 0.65:

$$C_{DP} = C_{DP,bf} + 0.0894C_{SP} \quad (15)$$

and hence, we found the relationships for the PP as

$$C_{SP} = 7.8Q_{sf2}^{0.4} \quad Q_{sf} < 1.1 \text{ mm/day} \quad (16)$$

$$C_{SP} = 5.6Q_{sf1}^{0.4} + 7.8Q_{sf2}^{0.4} \quad Q_{sf} > 1.1 \text{ mm/day} \quad (17)$$

Table 2. PED-WM sediment module calibrated parameters used for predicting sediment concentration in the Awramba watershed

Contributing area landscape	A factors		Rainfall factor
	Transport limiting (a_s) [g l ⁻¹ (mm/day) ^{-0.4}]	Source limiting (a_d) [g l ⁻¹ (mm/day) ^{-0.4}]	Maximum effective cumulative rainfall P_T (mm)
Saturated area	13	8.5	595
Degraded area	16	12	595

Table 3. Calibrated parameters of phosphorus module in PED-WM for Awramba watershed

Parameter description	Parameter notations	Calibrated parameter values
Dissolved P coefficients	b_{DP1}	0.5
	b_{DP2}	0.7
Sediment bound P coefficients	b_{SP1}	5.6
	b_{SP2}	7.8

where the C_{SP} is expressed in $mg\ kg^{-1}$ of sediment. This equation is not valid when there is no surface runoff and only base flow is occurring. In that case, there is no sediment in the stream and therefore we could not determine the sediment P concentration.

The model performance for the three modules in the PED-WM model has indicated satisfactory results for predicting both discharge (Figs. 2 and 3), sediment (Fig. 4), and P (both dissolved (Fig. 5a) and soil bound (Fig. 5b)) in the watershed as summarized in Table 4. The water balance component predicted discharge, sediment, DP, and PP with NSE of 0.7, 0.65, 0.65, and 0.63, respectively. The model predicted a sediment yield of $28.2\ t\ ha^{-1}\ year^{-1}$ and associated P of $9.2\ kg\ ha^{-1}\ year^{-1}$ from Awramba. Furthermore, non-point source areas contributed to $2.7\ kg\ ha^{-1}\ year^{-1}$ (29%) of DP at the outlet. Main runoff and sediment source areas identified using PED-WM were the periodically saturated runoff areas.

3.2 Non-point sediment and phosphorus sources

3.2.1 Sediment source areas

As indicated in the PED-WM sediment module, the transport (a_t)- and source (a_s)-limiting parameters control the sediment yield from the watershed. As a result, both the valley bottom and degraded part of the watershed resulted in sediment

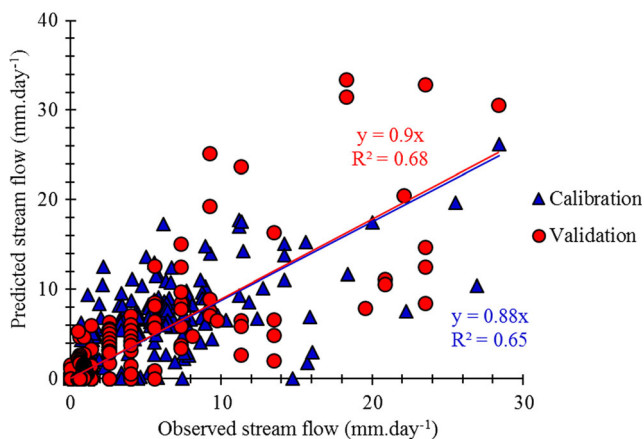


Fig. 3 Predicted and observed discharge scatter plots during calibration and validation periods for the Awramba watershed

source areas following their sensitivity as runoff contributing areas in the water balance module. Therefore, 16.4% of the Awramba watershed (degraded portion and saturated bottom part of the watershed) areas were identified as the dominant sediment source area. Out of the two high source areas, the degraded area contributed relatively more runoff (36%) and sediment compared to the saturated valley bottoms.

Gullies in most of the watersheds of the Ethiopian highlands were created at the bottom slope of the watershed and expanded through saturation excess. Gullies in the watershed were mainly located in the saturated valley bottoms. The high sediment contribution of gullies was attributed to the groundwater table rise in the bottom slope part of the watershed resulting in gully head migration and slumping of banks leading to the rapid gully expansion (Zegeye et al. 2016). Hence, Gully formation was the main contributing factor for the sediment loads simulated through the valley bottoms. Zegeye et al. (2016) showed that the gullies contributed up to 90% of the sediment load in Debra Mawi, a watershed located less than 90 km from Awramba watershed having similar watershed physiography.

3.2.2 Sources of dissolved phosphorus

The non-point P source in Awramba was based on the measured DP concentration from the piezometers and surface water samples as well as from the measured PP in the topsoil in the watershed. As reported by Moges et al. (2016a, b, c), the measurements of DP concentrations from the piezometer wells showed that the concentrations were greatest from piezometers located at the bottom part of the watershed than those obtained from the mid- and upper slopes. In general, the main source of sediment and DP were from regularly saturated areas. The measured soil available P was higher in the mid-slope topographic position (Table 2), where agricultural land is mainly located. Spatially over the watershed, the

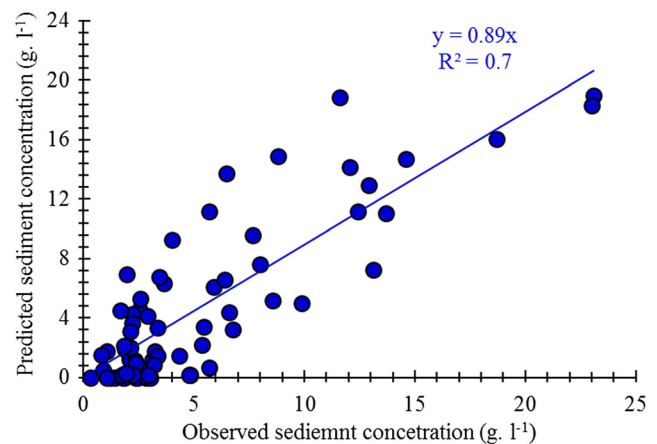


Fig. 4 Predicted versus observed sediment concentration for the Awramba watershed

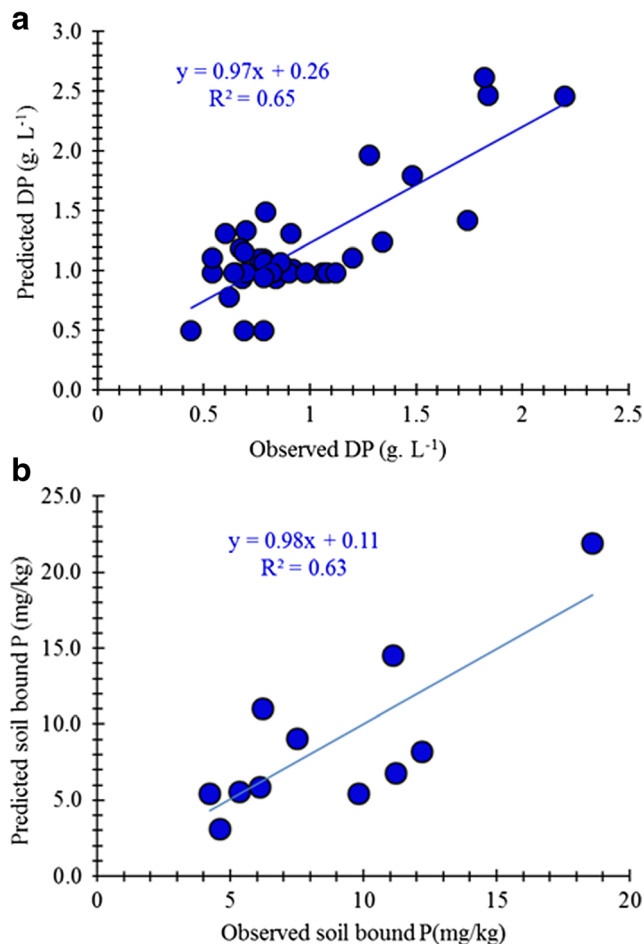


Fig. 5 Predicted versus observed phosphorus concentration (above, dissolved P) and (below sediment-bound P) for the Awramba watersheds

greater amount of PP at the mid-slope position can therefore be related to application of inorganic fertilizers to increase productivity. Hence, greater DP and PP concentrations were directly linked to topographic positions and their respective specific land uses, i.e., grassland in the wet bottom valleys, agricultural land in the moderately sloping mid-slope positions, and bush land on the steep upslope areas.

As indicated from the model results and the DP measurements, the saturated valley bottoms are the main source for DP transport whereas the degrading mid-slope areas produce the largest concentrations of PP (Fig. 6). Mapping the source

Table 4. Performance of PED-W model for predicting discharge, sediment, and phosphorus sediment for Awramba watershed

Time scale	PED-WM module	Performance criteria	
		R ²	NSE
Daily	Water balance	0.66	0.63
	Sediment	0.72	0.60
	Phosphorus	0.65	0.6

areas in the Awramba watershed indicated that sediment and dissolved P sources were found to be nearly 17.8% of the total watershed area, which is relatively similar to the PED-WM results of the runoff generating area estimates (6.9% of the watershed as saturated area and 7.2% of watershed as degraded portion with total dominate runoff generating area equal to 16.1% from total watershed area). Therefore, the runoff-generating areas calibrated from the PED-WM can predict the source of sediment and P sources in the watershed.

3.3 Reduction of non-point sediment and phosphorus

Reducing the non-point source sediment and P from the agricultural watershed likely would take years of watershed management, planning, and development. This is especially true for reducing the P load from P that attaches itself to erodible, fine particles in the soil matrix due to enrichment via inorganic fertilizers, as opposed to being P which is chemically available from the parent soil material (Alberts and Orlandini 1981). To minimize the extent of non-point sediment and P load from the watershed, the future watershed management planning and implementation should focus on two major tasks. Firstly, one needs to identify the source area (hot spots). Secondly, one needs to design efficient best management practices (BMPs) by targeting these source areas. Application of the BMPs in the source areas has been shown to reduce non-point sediment and nutrient load from agricultural watersheds (Wenger 1999).

This is mainly dependent on the landscape and other physical catchment characteristics (Borin et al. 2005). In this study, some successful intervention mechanisms from literature were assessed according to similarities in agro-ecology compared to the Awramba watershed. Overall, the amount of sediment-associated P, originating from the cultivated slope of the watershed, can be reduced using an optimum amount of fertilizer with the implementation of conservation agriculture and an understanding of the local soil chemistry (Tayyab and McLean 2015).

Grass buffer strips are one of the intervention mechanisms to reduce sediment and P loading within watersheds (Burt et al. 1996; Dorioze et al. 2006). Research based on experimental runoff plots with integrated grass/tree filter strips indicated a reduction of 40% runoff, 87% TSS, and 64% DP (Duchemen and Hogue 2009). Large grass strips can be installed at the saturated valley bottoms. Thus, enclosures that are being implemented in valley bottoms currently to prevent gully erosion will decrease the non-point source of P as well. This type of intervention has the capability of reducing runoff energy, therefore reducing the transportation capacity of sediment and nutrients (Rose et al. 2002). In addition, vegetative strips filter out the sediment and consequently the associated nutrients (i.e., P). However, given that grasslands are frequently communal grazing lands, changing these grazing lands into exclosures could be a viable way improving soil fertility

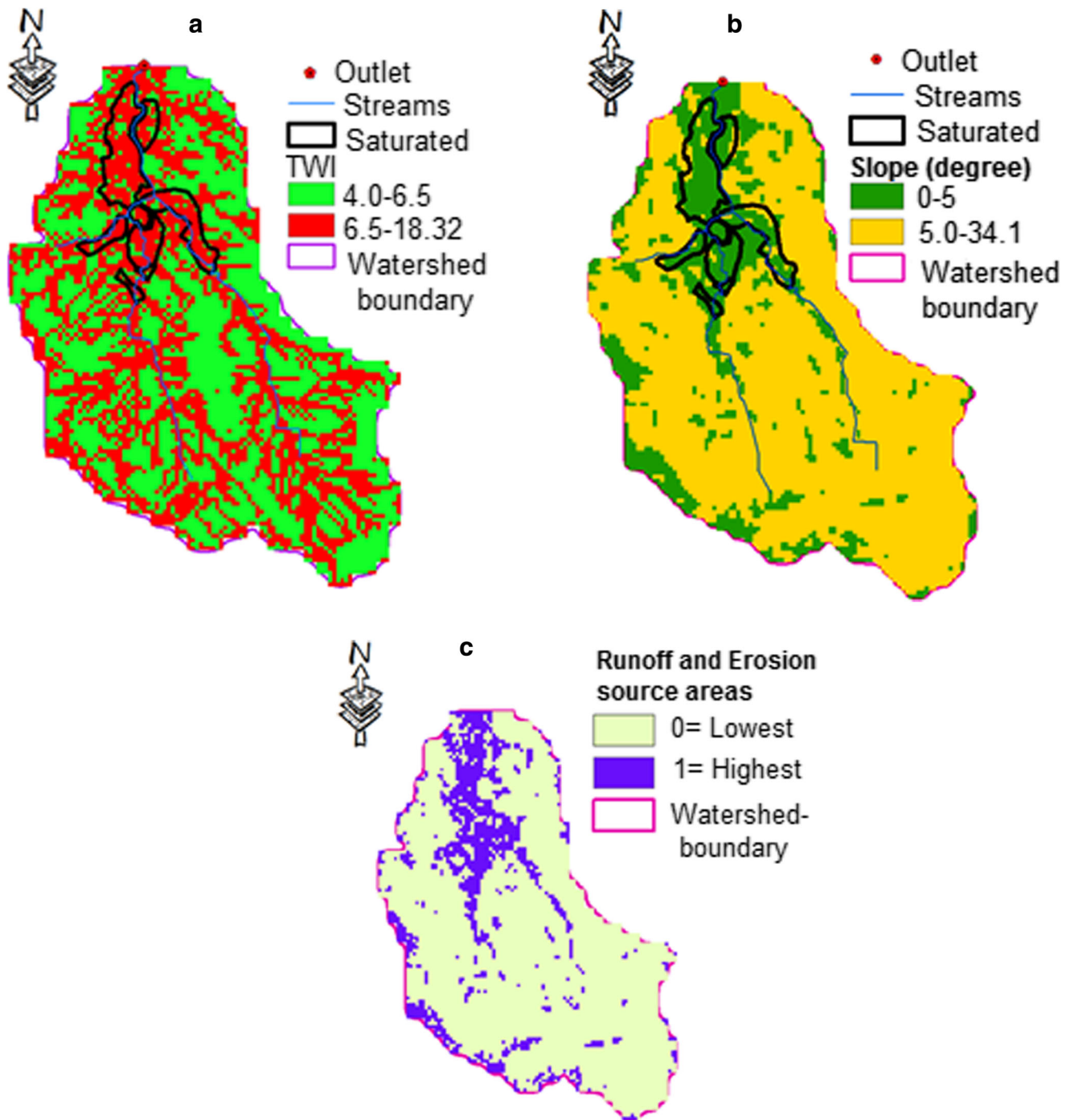


Fig. 6 Estimation of non-point source sediment and phosphorus source areas in the Awarmaba watershed (bottom) from upper right (slope) and upper left (TWI) calibrated by the saturated part of the watershed

(Mekuria and Aynekulu 2013) by reducing the nutrient outflow from the bottom part of the watersheds.

Another potential sediment and DP source are the sensitive gully-forming areas and expansion of existing gullies. A review of available studies shows that physical intervention mechanisms such as check dams do not stop already existing gullies from expanding or reduce gully formation in Lake Tana basin (Langendoen et al. 2014). In drier parts of northern

Ethiopia where physical infrastructure such as check dams are used, a resulting reduction of sediment loading has occurred (Zegeye et al. 2016). Another technique suggested by Zegeye et al. (2016) is to lower the level of the local water table by vegetating those areas with appropriate plants like vetiver grasses. In addition, vetiver grasses on the side of the gully could aid in physically stabilizing the soil matrix and decrease gully head cuts when the water table rises. The approach

suggested by Langendoen et al. (2014) on bank stabilization using location identification models and the rehabilitation of active gullies (Ayele et al. 2014) could be potential solutions for Awramba and other watershed, given their success rate in other Ethiopian highlands.

Implementing appropriate interventions to reduce runoff by targeting the high runoff source generating area, controlling the potential gully-forming areas, and rehabilitating existing gullies are likely to be crucial tools to reduce non-point source sediment and P in the Lake Tana basin. Ultimately, it will help to safeguard future possible eutrophication of Lake Tana. In addition, after implementing the interventions based on the source areas identified so far, there are mainly two tasks that need to be executed to achieve the desired reduction: (1) intervention mechanisms with regular monitoring and evaluation and (2) nutrient management strategies to assess the sustainability of this management practice must be in place very soon.

4 Conclusions

The three modules of the PED-W (water balance, sediment, and P) model simulated the stream flow, sediment, PP, and DP reasonable well resulting in an acceptable model performance. The sediment model which has been modified from the existing erosion model accounts for moisture condition of the soil rather than utilizing soil-related complex parameters. This would likely simplify the sediment model since the moisture of soil can be derived from rainfall and evapotranspiration data. The study has also indicated the possibility of prediction dissolved and particulate P loads separately for specific address of the sources of eutrophication. Unlike the traditional way of putting the watershed alterations in the uphill section of the watershed, this study has devised or provided methodology to look at other source areas based on observations and PED-WM. Therefore, incorporating BMPs for installing in these source areas would reduce the non-point source loads from the watershed and could minimize the future surface water pollution in the region.

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contributed in editing the manuscript and providing reagents for P tests. Tammo S. Steenhuis contributed in designing the methodology and the manuscript set up.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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