SUPPLEMENTAL MATERIAL SECTION S1

Phosphorus export from two contrasting rural watersheds in the (sub) humid Ethiopian Highlands

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Overview of the Parameter Efficient Distributed model

The PED (Parameter Efficient Distributed) model is a semi-distributed hydrological model developed for the sub-humid Ethiopian highlands. The model has been widely applied in the highlands of northern Ethiopian (Collick et al., 2009; Steenhuis et al., 2009; Tessema et al., 2010; Zimale et al. 2017; Moges et al., 2017; Guzman et al., 2017a,b; Tilahun et al., 2013a,b, 2015, 2020; Ochoa-Tocachi et al. 2018). The landscape is divided into four units, three of which contribute flow to the outlet and are simulated by the PED model. Two units contribute direct runoff to the outlet consisting of the valley bottoms that become saturated during the monsoon rain phase and the degraded hillsides with a slowly permeable sub-horizon at a shallow depth. The rest of the watershed consists of the remaining hillsides and comprises the third and the fourth zone. In the third zone, the rainwater infiltrates and recharges a zero-order reservoir that contributes to interflow and a first-order reservoir that provides base flow (Steenhuis et al., 2009; Tilahun et al., 2015; Guzman et al., 2017a,b). In the fourth zone, the rainwater leaves the watershed through fissures and faults. The PED model does not perform any calculations for the fourth zone

The PED is run at a daily time step. It updates the water balances for the three zones, calculates groundwater tables for the three zones and predicts discharge at the outlet consisting of interflow, baseflow and direct runoff at a daily time (Tilahun et al., 2013a, 2015;)

Predicting flows with the PED model

The **interflow** is simulated in the PED model using a zero-order reservoir. In zero-order reservoirs, the flow velocity is driven by the topographic gradient and is thus independent of the groundwater level. Since it is assumed that the slope is uniform, the velocity of the flow in the zero-order aquifer is constant. It means that a travel time can be established for the water to travel from the watershed divide to the outlet (indicated by τ^*). The outflow from the reservoir is equal to the product of the depth of water above the impermeable layer, the drainable porosity and the flow velocity. The water table height is a function of the recharge on the hillslope and the outflow.

Simulation of the zero-order reservoir has been modified slightly over time in the PED model. The original model had a zero-order reservoir in which the water table depth was the same along the hillside at any time. In Alemie et al. (2019), the method of characteristics was used to simulate the water table along the hillside. With this method, the flux at the outlet becomes equal to the average of all recharge over the previous τ^* days (the time it takes a water particle to travel from the groundwater divide to the outlet).

Baseflow in the PED model is simulated as a first-order reservoir in which the outflow is proportional to the water table height. A halflife characterizes the reservoir. It is defined as the time it takes for the outflow (or water table height) the decrease by a factor of two. The water table can be calculated from the recharge to the aquifer, the outflow and the drainable porosity.

Direct runoff from the degraded areas is simulated as the excess rainfall above what can be stored in the soil before it is saturated. Originally the runoff from the periodically saturated areas was simulated similar to the degraded areas, but recently as a recognition that saturated areas do not drain in one day and direct runoff consists mainly of subsurface runoff, the flow is simulated as a short hillslope with a travel time of 2 or 3 days

Actual evaporation is simulated with the Thornthwaite Mather model (Steenhuis and Van der Molen, 1986), assuming that the evapotranspiration is a linear function of the moisture content between the wilting point and field capacity.

Simulation setup for the Robit Bata and Dangishta watersheds

For the **Robit Bata** watershed, the same model set up by Tilahun et al. (2020) was used. The watershed was divided into the degraded upland with shallow soils and the hillslopes in the middle and lower regions. The degraded upland (A_{upland}) with basalt at shallow depth generated saturation excess overland flow. The hillslopes with deep (up to 20 m) soils was divided once more into three parts: The relatively flat area close to the stream with limited contribution from the upland (with a relative area A_1 generating a mixture of surface and subsurface flow for a short period after it became saturated); the hillslope aquifer (with a relative area, A_2) that produced the interflow and the part that did not contribute water to the outlet. Baseflow was not simulated.

The **Dangishta** watershed subsoil consisted of various weathered and fractured layers above the basalt at 20-40 m in the valley (Yenehun et al., 2019). The subsoil had a good permeability based on the many dug wells in the area. The simulated watershed was relatively flat, and the aquifer was therefore simulated as a first-order aquifer. Very few near-surface layers were present that restrict flow (Yenehun et al., 2019). The grassed areas around the river were periodically saturated, generating subsurface flow. In Dangishta, subsurface flow appeared as springs downstream in the watershed where the flow is blocked by volcanic dikes, creating a water table close to the surface during the rain phase.

Flow Separation and Quantification with the modified PED model

There were eight parameters to fit for each watershed. Tilahun et al. (2015) showed that the maximum storage was not sensitive for predicting outflow except for the first few storms after the dry phase. The remaining five parameters consisted of the portion of the watershed with restrictive layers at shallow depth (A_{upland}), the portion with the short hillslope near the stream (A_1) with a travel time τ_1^* and the aquifer portion (A_2). For the aquifer in Dangishta, a halflife ($t_{½}$) was fitted. In Robit Bata, a travel time from the divide to the stream (τ_2^*) was determined for the hillslope aquifer. These five parameters were systematically varied until a good fit between observed and predicted flows was obtained and parameter values related to the watershed characteristics. The fitted parameters are shown in Table S1.1.

Table S1.1: Fitted parameters values of the PED model for simulated and observed discharge of the Dangishta and Robit Bata watersheds for the two years from 2017 to 2018.

Parameter description and location	Parameter units and symbol	Calibrated value	
		Dangishta	Robit Bata
Watershed with short hillslope near stream	Area fraction, A_1	0.12	0.10
	Max storage, AWC_1, mm	200	30
Watershed with aquifer and long hillslope	Area fraction, A_2	0.87	0.50
	Max storage, $AWC_{2,}$ mm	40	40
Degraded land with shallow soils over bedrock	Area fraction, A_{upland},	0.02	0.20
	Max storage, $AWC_{upl,}$ mm	250	30
Baseflow halflife	$t_{1/2}$, days	15	-
Travel time for short hillside A_1	τ_1^*, days	3	3
Travel time from long hillside A_2	τ_2^* days	-	80

The model fit is displayed in Figure 4A B. The fitted parameters are shown in Table S1.1. Figures S1.1 and S1.2 are scatter plots of predicted versus observed discharges at the outlet. For Robit Bata, the upper overland runoff source area was nearly 20% of the watershed area. Ten percent of the watershed near the river had a short travel time of 3 days. The hillslope aquifer underlaid 50% of the watershed. It took 85 days for the water to travel from the top of the hillside aquifer to the lowest point of the hillslope aquifer.

Adding up the area fractions in Table S1.1 indicates that rainfall on 20% of the watershed did not flow through the outlet.

In Dangishta, only 2% of the watershed contributed direct runoff that encompassed less than 5% of the total outflow. Eighty-seven percent of the watershed contributed baseflow with a halflife of 15 days. Twelve percent from the watershed could potentially saturate and was simulated as interflow with a three-day travel time.

Model performance for streamflow at the outlets of the Dangishta showed an R^2 value of 0.87 (Figure S1.2) and NSE of 0.82. For Robit Bata outlet R^2 of 0.82 (Figure S1.2) and NSE of 0.80 were found.

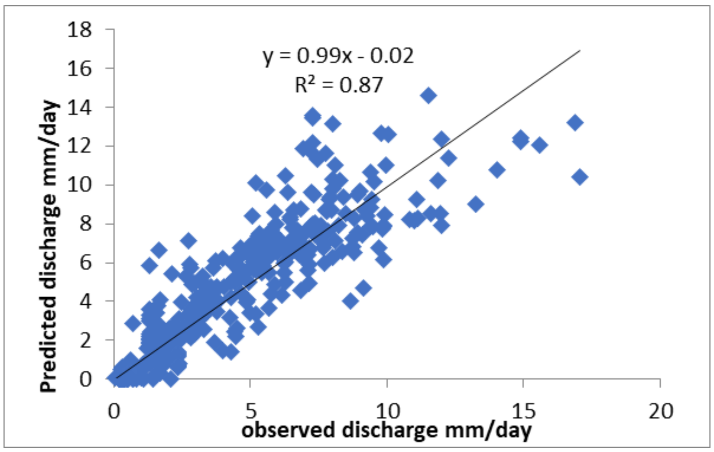

Figure S1.1: Scatter plot measured and predicted flow for Dangishta watershed

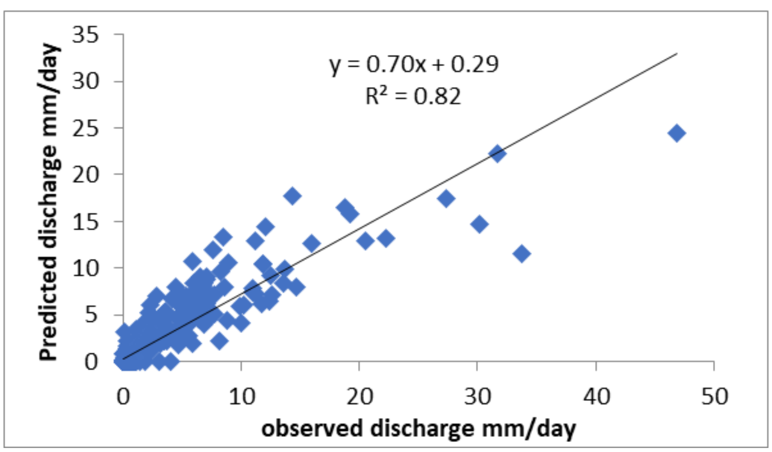

Figure S1.2: Scatter plot measured and predicted flow at Robit Bata

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