Supporting Information for "SWAT-Tb with improved LAI representation in the tropics highlights the role of forests in watershed regulation"

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Contents

Supplementary Material S1: SWAT-Tb implementation

Alemayehu, Griensven, Woldegiorgis, and Bauwens (2017) modified SWAT by adding two parameters (based on Strauch and Volk (2013)) that represent the end of the dry season (SOS1) and the beginning of the wet season (SOS2). In SWAT-Tb, we added three new parameters (SOS3, SOS4, and SOS5) to represent the seasonality of precipitation characterized by a bimodal regime with two wet and dry seasons. In this case, SOS1 and SOS2 represent the months of the end and beginning of the first dry-wet season transition, respectively. SOS3 represents the end of the first wet season and the beginning of the second dry season (i.e. a new growth cycle), whereas SOS4 and SOS5 indicate, respectively, the first and last month of the second dry-wet season transition. In SWAT-T, SOS1 and SOS2 parameters are estimated using the seasonal pattern of SMI based on precipitation and a reference evapotranspiration ratio (Figure 2; Alemayehu et al., 2017). The SOS(1,2,3,4,5) parameters are defined using mean monthly precipitation and LAI seasonality for each land cover category in the CR watershed.

Implementation of SWAT-Tb requires the user to add the lines shown below to the *allocate_parm.f, getallo.f, grow.f, modparm.f, readsub.f*, and *zero.f* subroutines from SWAT-T (Alemayehu et al., 2017). New lines are annotated as [svalencia]. The SWAT-Tb executable as well as the *.sub, *.mgt, and subroutines files, which must be adapted, are available online at `https://bit.ly/2XT8uxs`. This link is intended only to allow detailed revision of the manuscript. After publication, we may change the link to keep the files permanently available.

allocate_parm.f

```
  ! allocate tropical plant growth variables [talemayehu]
allocate (iseason(mhru))
allocate (sos1(msub))
allocate (sos2(msub))
```

```
allocate (sos3(msub)) !! Added by [svalencia]
allocate (sos4(msub)) !! Added by [svalencia]
allocate (sos5(msub)) !! Added by [svalencia]
```

getallo.f

```
  read (27,6100) subfile
call caps(subfile)
open (25,file=subfile)
do j = 1, 57 !! changed (54) [svalencia]
read (25,6000) titldum
end do
```

grow.f

```
  !!    INCOMING VARIABLES
!! sos1(:) |month |starting month of transition to first wet season added by [talemayehu]
!! sos2(:) |month |ending month of transition to first wet season added by [talemayehu]
!! added by [svalencia]
!! sos3(:) |month |ending of the first wet season and the starting of the second dry season
!! sos4(:) |month |starting month of transition to second wet season
!! sos5(:) |month |ending month of transition to second wet season


  if (smi_tr <=0.0) smi_tr = 0.5
idp = idplt(j)
```

```
if (Abs(sub_lat(hru_sub(j))) < 20. .AND.
iseason(j) == 0 .AND.
& i_mo >= sos1(hru_sub(j)) .AND.
& i_mo <= sos2(hru_sub(j))) then
smi=0.

  if (count_D(j)>0) then
do kk = 1, w_size-1
pet_subA(w_size-kk+1,(j)) = pet_subA(w_size-kk,(j))
end do
pet_subA(1,(j)) = pet_sub((j))
else
pet_subA(1,(j)) = pet_sub((j))
end if
if (count_D(j) > 0) then
do kk = 1, w_size-1
sub_pcpA(w_size-kk+1,(j)) =
& sub_pcpA(w_size-kk,(j))

  end do
sub_pcpA(1,(j)) = sub_pcp(hru_sub(j))
else
sub_pcpA(1,hru_sub(j)) = sub_pcp(hru_sub(j))
```

```
end if
count_D(j) = count_D(j) +1
if(count_D(j) > w_size) count_D(j) = w_size
if(count_D(j) == w_size) then
smi = sum(sub_pcpA(:,(j)))/sum(pet_subA(:,(j)))
if (smi >= smi_tr) then
call changeseason
count_D(j) = 0
end if

  end if
if(count_D(j) < w_size) then
smi = 0.0
end if
else if (Abs(sub_lat(hru_sub(j))) < 20. .AND.
& iseason(j) == 0 .AND. i_mo > sos2(hru_sub(j))
.AND. i_mo <= sos3(hru_sub(j))) then !! Added by [svalencia]
call changeseason
count_D(j) = 0

  !! Added by [svalencia]
else if (Abs(sub_lat(hru_sub(j))) < 20.
.AND. iseason(j) == 1 .AND.
```

```
& i_mo >= sos4(hru_sub(j)) .AND.
& i_mo <= sos5(hru_sub(j))) then
smi=0.

  if (count_D(j)>0) then
do kk = 1, w_size-1
pet_subA(w_size-kk+1,(j)) = pet_subA(w_size-kk,(j))
end do
pet_subA(1,(j)) = pet_sub((j))
else
pet_subA(1,(j)) = pet_sub((j))
end if
if (count_D(j) > 0) then
do kk = 1, w_size-1
sub_pcpA(w_size-kk+1,(j)) =
& sub_pcpA(w_size-kk,(j))

  end do
sub_pcpA(1,(j)) = sub_pcp(hru_sub(j))
else
sub_pcpA(1,hru_sub(j)) = sub_pcp(hru_sub(j))
end if
count_D(j) = count_D(j) + 1
```

```
if(count_D(j) > w_size) count_D(j) = w_size
if(count_D(j) == w_size) then

  smi = sum(sub_pcpA(:,(j)))/sum(pet_subA(:,(j)))
if (smi >= smi_tr) then
call changeseason
count_D(j) = 0
end if
end if
if(count_D(j) < w_size) then
smi = 0.0
end if

  else if (Abs(sub_lat(hru_sub(j))) < 20. .AND.
& iseason(j) == 0 .AND. i_mo > sos5(hru_sub(j))) then
call changeseason
count_D(j) = 0
end if
```

modparm.f

```
  !! added for plant growth modification for tropics added by [talemayehu]
integer, dimension (:), allocatable :: iseason, sos1, sos2, sos3, sos4, sos5 !! last three added by [svalencia]
```

readsub.f

```
  read (101,*) sos1(i) !! added by [talemayehu]
read (101,*) sos2(i) !! added by [talemayehu]
read (101,*) sos3(i) !! added by [svalencia]
read (101,*) sos4(i) !! added by [svalencia]
read (101,*) sos5(i) !! added by [svalencia]
```

zero0.f

```
  !!initialize tropical plant growth variables added by [talemayehu]
iseason = 0
sos1 = 0
sos2 = 0
sos3 = 0 !! added by [svalencia]
sos4 = 0 !! added by [svalencia]
sos5 = 0 !! added by [svalencia]
smi_tr = 0.
```

Supplementary material S2: Leaf Area Index (LAI) data and calibration

LAI data were obtained from the MCD15A2H-MODIS product (Myneni et al., 2015) for the GR watershed with a spatial and temporal resolution of 0.5 km and 8-days (composites), respectively. Only pixels with a corresponding "best quality" flag (LAI_QC=0) were kept for the analysis. We processed LAI data following methods used in Alemayehu et al. (2017) and Hoyos et al. (2019). For most land cover types, LAI values were extracted as follows: (i) polygons with an area at of least 5 km^2 within the CR watershed are selected for each land cover, (ii) LAI values are associated to each land cover type only in pixels where such land cover type covers at least 60% of the area. For shrubs (RYEB) and planted forest (PINE), which cover less than 12% of the CR watershed, polygons are smaller than 5 km^2. Therefore, the corresponding LAI values were extracted from polygons in the vicinity of the CR watershed, within the GR watershed. Median LAI values for each land cover type and period (8-day composites) were calculated from the aforementioned polygons as suggested by Strauch and Volk (2013) and Alemayehu et al. (2017).

For the LAI calibration, the initial values of parameters such as the initial (LAI_INIT), minimum (ALAI_MIN) and maximum (BLAI) LAI values for each land cover type were set based on the long-term MODIS-LAI time series (Figure 3 and Supplementary Figure S1). Initial values of Plant Heat Units (PHU) were calculated using the long-term daily mean temperature, as suggested by Strauch and Volk (2013). Other initial parameters were defined based on literature (e.g., T_BASE, T_OPT, CHTMX, and CANMX; see Table S2) and default values (e.g., FRGW1, FRGW2, LAIMX1, LAIMX2, and DLAI). These parameters were calibrated by a trial-and-error process to ensure that the LAI values simulated by SWAT-T and SWAT-Tb mimicked the smoothed MODIS-LAI. The Pearson correlation coefficient (r), the percent of bias (PBIAS), and the Kling–Gupta efficiency (KGE) (Gupta et al., 2009) were used to evaluate the agreement between simulated and observation-based estimates (MODIS) of LAI.

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Table S1. Reclassification of land cover types in the CR watershed according to SWAT categories.

Land cover type	**SWAT category**	**Description**	**Area (%)**
Pasture	RYEL	Pasture dominated by *Pennisetum clandestinum Hochst, ex Chiow (Poaceae)*, used for cattle dairy	51.24
Native Andean forest	FRST	Forest dominated by mature Andean Oak (*Quercus humboldtii* Bonpl. Fagaceae)	29.30
Shrubs	RYEB	Secondary succession with little to no human intervention	11.42
Paramo vegetation	BROM	High altitude native grasslands with sparse vegetation cover and ocasional presence of shrubs	4.89
Pasture with secondary growth	RYEE	Unmanaged grasslands with occurrence of sparse secondary vegetation	2.93
Planted forest	PINE	Forest dominated by *Pinus patula* Schltdl. Cham	0.09

Table S2. LAI-ralated parameters for each land cover type and their initial and calibrated values in the SWAT-Tb model.

Parameter	Description	Calibrated values (initial values)					
		FRST	RYEL	RYEB	RYEE	BROM	PINE
LAI_INIT[1]	Initial leaf area index (m^2/m^2)	4.20* (4.17)	1.80* (1.90)	3.50* (3.74)	2.30 (-)	3.10* (3.16)	3.60* (3.80)
BIO_INIT	Initial dry weight biomass (kg/ha)	50000[2] (-)	20000[3] (-)	20000 (-)	20000 (-)	20000[4] (-)	50000 (-)
PHU_PLT[5]	Total number of heat units or growing degree days needed to bring plant to maturity	3000* (1700)	3000* (1700)	1700 (-)	1800* (1700)	2000 (-)	5000 (-)
BLAI[1]	Maximum potential leaf area index (m^2/m^2)	4.40* (3.79)	1.95* (1.68)	4.50* (3.22)	2.80* (2.0)	3.20* (2.62)	3.90* (3.50)
ALAI_MIN[1]	Minimum leaf area index (m^2/m^2)	2.60* (3.38)	1.25* (1.35)	1.85* (1.44)	1.45* (1.41)	2.0* (1.19)	2.0* (2.70)
FRGRW1	Fraction of PHU corresponding to the 1st point on the leaf area development curve	0.15* (0.05)	0.10* (0.20)	0.07* (0.20)	0.07* (0.20)	0.07* (0.45)	0.10* (0.15)
FRGRW2	Fraction of PHU corresponding to the 2nd point on the leaf area development curve	0.38* (0.40)	0.40* (0.45)	0.20* (0.45)	0.40* (0.45)	0.20* (0.80)	0.38* (0.25)
LAIMX1	Fraction of BLAI corresponding to the 1st point on the optimal leaf area development curve	0.70* (0.05)	0.10* (0.32)	0.15* (0.32)	0.10* (0.32)	0.15* (0.02)	0.40* (0.70)
LAIMX2	Fraction of BLAI corresponding to the 2nd point on the optimal leaf area development curve	0.90* (0.95)	0.99* (0.95)	0.99* (0.95)	0.99* (0.95)	0.99* (0.95)	0.90* (0.99)
DLAI	Fraction of PHU when LAI beings to decline	0.20* (0.99)	0.99* (0.50)	0.5** (-)	0.99* (0.50)	0.85** (-)	0.99* (-)
T_BASE	Minimum temperature for plant growth (∘C)	9.30[6] (-)	0* (7.0[7])	9.30[7] (-)	9.30[7] (-)	7.0* (4.0[8])	0* (10.0[7])
T_OPT	Optimal temperature for plant growth (∘C)	18.60[6] (-)	18.0[7] (-)	18.6[6] (-)	18.60[6] (-)	18.0* (10.0[8])	14.0[7] (-)
BIO_E	Radiation use efficiency ((kg/ha)/(MJ/m^2))	18.0* (15.0)	10.0* (30.0)	10.0* (30.0)	10.0* (30.0)	15.0* (35.0)	10.0* (15.0)
CHTMX	Maximum canopy height (m)	25.0[9] (-)	0.30[3,10] (-)	1.20[10] (-)	1.20[10] (-)	0.50[8] (-)	25.0[9] (-)
CANMX	Maximum canopy storage (mm H_2O)	0.30[11,12](-)	0.05[10](-)	0.20[10,12](-)	0.05[10,12](-)	0.15[13](-)	0.10(-)
BMDIEOFF	Biomass die-off fraction	0.1 ** (-)	0.05** (0.1)	0.1** (-)	0.1**(-)	0.1*(-)	0.1*(-)
SOS1[14]	First month of the 1st dry-wet season transition	3 (-)					
SOS2[14]	Last month of the 1st dry-wet season transition	4 (-)					
SOS3[14]	End of first wet season and the beginning of second dry season	6 (7)					
SOS4[14]	First month of the 2nd dry-wet season transition	10 (9)					
SOS5[14]	Last month of the 2nd dry-wet season transition	11 (10)					

FRST: native Andean forest, RYEL: pasture, RYEB: shrubs, RYEE: pasture with secondary growth, BROM: paramo vegetation, PINE: planted forest.[1]BFAST-MODIS LAI time series; *Manual adjustment during calibration process; **Default values in SWAT; [2]Spracklen and Righelato (2016); [3]Peters, Franco, Schmidt, and Hincapié Carvajal (2011); [4]Hofstede, Castillo, and Osorio (1995); [5]Initial values estimated from local temperature records following Strauch and Volk (2013) and other studies (Hoyos et al., 2019); [6]González-Orozco[1], Jarvis, and Palacio (2011); [7]Cook et al. (2005); [8]Cárdenas Agudelo et al. (2016); [9]Orwa et al. (2009); [10]García-Leoz et al. (2017); [11]Veneklaas and Van Ek (1990);[12]Jaramillo-Robledo (2003);[13]Leguizamon and Marín (2017);[14] Parameters determined using LAI filtered data, precipitation seasonality, and manual LAI calibration.

Table S3. Global sensitivity analysis in the SWAT-Tb model. Sensitivity is indicated by a high t-statistic value (in absolute terms) and a low p-value. Parameters are listed from high to low sensitivity.

Parameter[1]	Description	Scaling type[2]	Range Min	Range Max	t-statistic	p-value
CN2.mgt_RYEL	Runoff curve number for moisture condition II	r	-0.25	0.25	-16.989	0.000
ESCO.hru_RYEL	Soil evaporation compensation factor	v	0.01	1	-9.989	0.000
ESCO.hru_FRST	Soil evaporation compensation factor	v	0.01	1	-8.197	0.000
ALPHA_BF.gw	Baseflow alpha factor (1/days)	v	0.01	1	-7.299	0.000
CN2.mgt_FRST	Runoff curve number for moisture condition II	r	-0.25	0.25	-6.280	0.000
SOL_K(1).sol_RYEL	Saturated hydraulic conductivity (mm/hr)	r	-0.50	0.50	-4.802	0.000
GWQMN.gw_FRST	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O)	v	0	5000	4.669	0.000
CH_K2.rte	Effective hydraulic conductivity in main channel alluvium (mm/hr)	v	0	150	4.428	0.000
GWQMN.gw_RYEL	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O)	v	0	5000	3.996	0.000
ESCO.hru_BPRR	Soil evaporation compensation factor	v	0.01	1	-3.314	0.001
SOL_K(1).sol_FRST	Saturated hydraulic conductivity (mm/hr)	r	-0.50	0.50	-3.158	0.002
SOL_BD(1).sol_BPRR	Moist bulk density (g/cm^3)	r	-0.20	0.20	-2.902	0.004
CN2.mgt_BPRR	Runoff curve number for moisture condition II	r	-0.25	0.25	-2.774	0.006
SOL_AWC(1).sol_FRST	Available water capacity of the soil layer (mm H_2O/mm soil)	r	-0.50	0.50	-2.599	0.009
SOL_BD(1).sol_RYEL	Moist bulk density (g/cm^3)	r	-0.20	0.20	-2.468	0.014
GWQMN.gw_BPRR	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O)	v	0	5000	-2.399	0.017
SOL_K(1).sol_BPRR	Saturated hydraulic conductivity (mm/hr)	r	-0.50	0.50	-2.238	0.026
SOL_AWC(1).sol_RYEL	Available water capacity of the soil layer (mm H_2O/mm soil)	r	-0.50	0.50	-1.950	0.050
SOL_K(2).sol_RYEL	Saturated hydraulic conductivity (mm/hr)	r	-0.50	0.50	-1.867	0.062
SOL_BD(2).sol_BPRR	Moist bulk density (g/cm^3)	r	-0.20	0.20	-1.770	0.077
SOL_BD(1).sol_FRST	Moist bulk density (g/cm^3)	r	-0.20	0.20	-1.607	0.109
SOL_K(2).sol_BPRR	Saturated hydraulic conductivity (mm/hr)	r	-0.50	0.50	-1.541	0.124
RCHRG_DP.gw	Deep aquifer percolation fraction	v	0	1	-1.527	0.128
SOL_AWC(2).sol_FRST	Available water capacity of the soil layer (mm H_2O/mm soil)	r	-0.50	0.50	-1.186	0.236
SOL_AWC(2).sol_RYEL	Available water capacity of the soil layer (mm H_2O/mm soil)	r	-0.50	0.50	-1.175	0.241
SOL_K(2).sol_FRST	Saturated hydraulic conductivity (mm/hr)	r	-0.50	0.50	-1.010	0.313
GW_DELAY.gw_RYEL	Groundwater delay times (days)	v	0.01	500	0.406	0.685
GW_DELAY.gw_FRST	Groundwater delay times (days)	v	0.01	500	-0.379	0.705
SOL_AWC(1).sol_BPRR	Available water capacity of the soil layer (mm H_2O/mm soil)	r	-0.50	0.50	0.354	0.723
GW_DELAY.gw_BPRR	Groundwater delay times (days)	v	0.01	500	0.309	0.758
SOL_AWC(2).sol_BPRR	Available water capacity of the soil layer (mm H_2O/mm soil)	r	-0.50	0.50	-0.170	0.865
SOL_BD(2).sol_FRST	Moist bulk density (g/cm^3)	r	-0.20	0.20	0.115	0.908
SOL_BD(2).sol_RYEL	Moist bulk density (g/cm^3)	r	-0.20	0.20	0.027	0.978

[1]Numbers (1, 2) refer to the soil layer number. Land cover types are native Andean forest (FRST), pasture (RYEL) and BPRR (paramo vegetation, planted forest, shrubs, and pasture with secondary growth). [2]Scaling type: v (absolute) indicates that the parameter is replaced by the given value, r (relative) indicates that the parameter is multiplied by [1 + (given value)].

Table S4. Comparison of SWAT average water flux components before and after calibration with reference values.

Model	SWAT average water flux components [1] (mm/yr)								Ratios		
	PREC	**SURQ**	**LATQ**	**GWQ**	**PET**	**ET**	**REVAP**	**WYLD**	**Baseflow ratio (GWQ/ WYLD)**	**Runoff ratio (SURQ/ WYLD)**	**ET ratio [(ET+REVAP)/ PREC]**
SWAT-T	1841.43	114.36	60.67	590.47	862.68	358.19	17.25	1464.77	0.40	0.07	0.20
SWAT-Tb (LAI calibration)	1841.43	96.52	46.28	401.03	862.68	747.19	17.25	1074.82	0.37	0.09	0.42
SWAT-Tb (LAI + streamflow calibration)	1841.43	16.72	49.88	319.97	862.68	838.80	17.25	954.23	0.33	0.02	0.46
Reference value									0.4-0.5[2]	0.04-0.16[3]	0.5-0.6[4]

Calibration period from 2003 to 2016.[1] PREC = precipitation, SURQ = surface runoff contribution to streamflow, LATQ = lateral flow contribution to streamflow, GWQ = grundwater contribution to streamflow, PET = potential evapotranspiration, ET = actual evapotranspiration, REVAP = amount of water moving from shallow aquifer to plants/soil profile, and WYLD = water yield. Reference values from: [2] baseflow filter (`https://engineering.purdue.edu/mapserve/WHAT/`), [3] Jaramillo-Robledo (2003), and [4] García-Leoz et al. (2017).

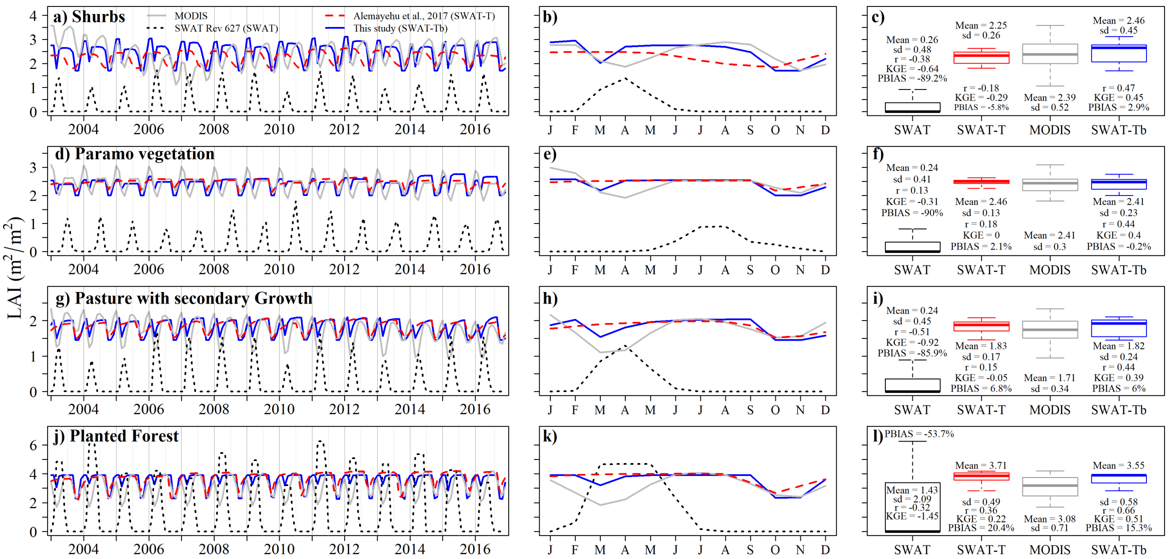

Figure S1. Observed (MODIS) and simulated (SWAT, SWAT-T, and SWAT-Tb) seasonality of LAI in the CR watershed for for (a-c) shrubs (RYEB), (d-f) paramo vegetation (BROM), (g-i) pasture with secondary growth (RYEE), and (j-k) planted forest (PINE). Time series (a,d,g,j), average annual cycle (b,e,h,k), and the (c,f,i,l) corresponding boxplots and performance statistics.

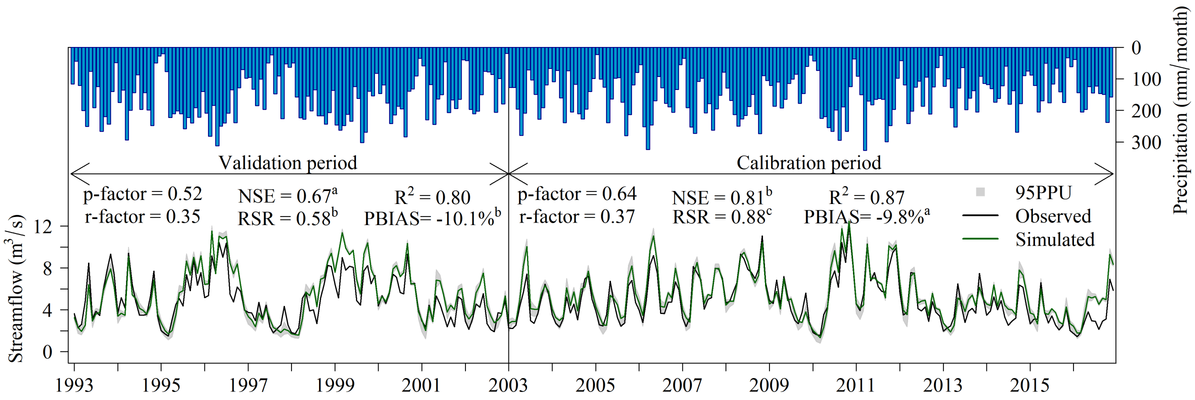

Figure S2. Calibration (2003–2016) and validation (1993–2002) of SWAT for monthly streamflow. Vertical bars show monthly rainfall from SWAT outputs, calculated from records in climate stations. Model performances based on the criteria of Moriasi et al. (2007): ^{a} Good (0.65<NSE≤0.75, 0.50<RSR≤0.60, ±10%<BIAS< ±15%) and ^{b} Very Good (0.75<NSE≤1.00, 0.00<RSR≤0.50, BIAS≤±10%).

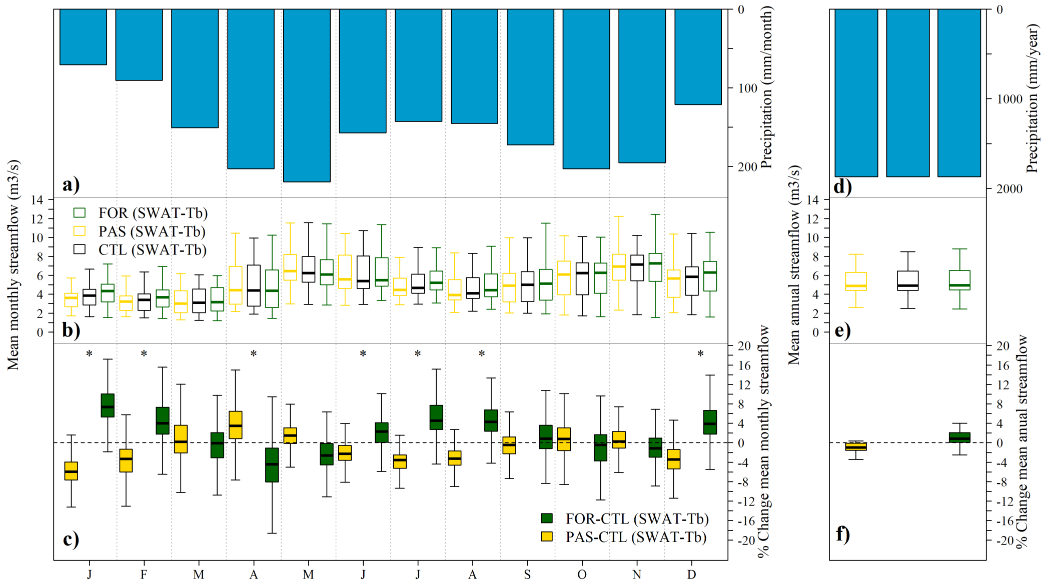

Figure S3. Comparison of monthly (left) and annual (right) streamflow between scenarios using 1000 simulations with parameters ranges as we did for the model calibration. Input precipitation (blue bars) is the same for all scenarios and models (a,d). Average seasonal cycle (b) and annual streamflow (e) in all scenarios for 1993–2016. Percent differences between monthly (c) and annual (f) streamflow in the control (CTL) and LULC (FOR and PAS) scenarios for 1993–2016 as simulated by SWAT-Tb and SWAT using best fit parameters. Positive (negative) values indicate that streamflow is increased (decreased) in the LULC change scenario. Asterisks identify months for which the difference between medians in the FOR and PAS scenarios is statistically significant (n=24000, $p < 0.05$) for SWAT-Tb output.