Supplement of Hydrol. Earth Syst. Sci., 24, 1031–1054, 2020
https://doi.org/10.5194/hess-24-1031-2020-supplement

Hydrology and Earth System Sciences
Open Access

Supplement of

Calibration of hydrological models for ecologically relevant streamflow predictions: a trade-off between fitting well to data and estimating consistent parameter sets?

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Documentation

Rainfall-Runoff Model SMART (Soil Moisture Accounting and Routing for Transport)

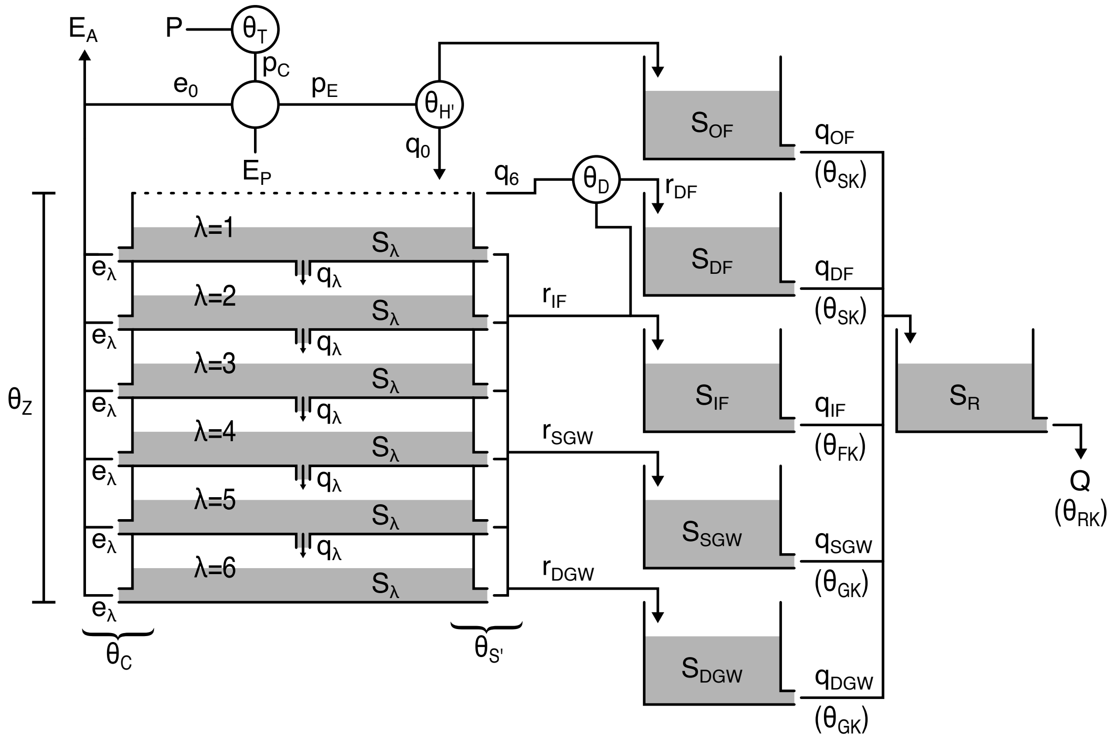

Figure S1 Conceptual representation of the bucket-type rainfall-runoff model SMART (after Mockler et al. 2016).

Model inputs and outputs

Table S1 List and Description of the inputs of the SMART model.

Input	Description	Unit
P	Precipitation	mm per time step
E_P	Potential evapotranspiration	mm per time step

Table S2 List and Description of the outputs of the SMART model.

Output	Description	Unit
Q	Discharge	mm per time step
E_A	Actual evapotranspiration	mm per time step

Model parameters

Table S3 List and Description of the ten parameters of the SMART model.

Parameter	Description	Unit
θ_T	Rainfall aerial correction factor	–
θ_C	Evaporation decay coefficient	–
θ_H	Quick runoff ratio	–
θ_D	Drain flow ratio	–
θ_S	Soil outflow coefficient	–
θ_Z	Effective soil depth	mm
θ_{SK}	Surface reservoir residence time	time step
θ_{FK}	Interflow reservoir residence time	time step
θ_{GK}	Groundwater reservoir residence time	time step
θ_{RK}	Channel reservoir residence time	time step

Conceptual model equations

The SMART model forcings are precipitation P [mm/time step] and potential evapotranspiration E_P [mm/time step]. The precipitation input is first transformed into the corrected precipitation p_C [mm/time step] using the aerial correction parameter θ_T [–] (Eq. S1).

$$p_C = \theta_T P \tag{S1}$$

The ratio between corrected precipitation and potential evapotranspiration determines whether the modelling time step is under energy-limited conditions (condition γ is true) or water-limited conditions (γ is false) (Eq. S2).Then, the effective precipitation p_E [mm/time step] (Eq. S3) and the precipitation contribution to the actual evapotranspiration e_A [mm/time step] (Eq. S4) are determined accordingly.

$$\gamma : p_C \geq E_P \tag{S2}$$

$$p_E = \begin{cases} \theta_T P - E_P, & \text{if } \gamma \\ 0, & \text{otherwise} \end{cases} \tag{S3}$$

$$e_A = \begin{cases} E_P, & \text{if } \gamma \\ \theta_T P, & \text{otherwise} \end{cases} \tag{S4}$$

The two parameters for quick runoff ratio θ_H [–] and soil outflow coefficient θ_S [–] are adjusted according to the antecedent soil moisture conditions to become $\theta_{H'}$ [–] (Eq. S5) and $\theta_{S'}$ [–] (Eq. S6), respectively. The six soil moisture layers are of equal depths and sum up to a total field capacity defined by the parameter θ_Z [mm].

$$\theta_{H'} = \theta_H \frac{\sum_{\lambda=1}^{6} S_\lambda}{\theta_Z} \tag{S5}$$

$$\theta_{S'} = \theta_S \frac{\sum_{\lambda=1}^{6} S_\lambda}{\theta_Z} \tag{S6}$$

Under energy-limited conditions:

The infiltration flux q_0 [mm/time step] and the percolation fluxes through the soil layers q_λ [mm/time step] are then calculated as described in Equations S7 and S8, respectively.

$$q_0 = (1 - \theta_{H'}) p_E \tag{S7}$$

$$q_\lambda = \begin{cases} q_{\lambda-1} - \left(\frac{\theta_Z}{6} - S_\lambda\right), & \text{if } q_{\lambda-1} + S_\lambda > \frac{\theta_Z}{6} \\ 0, & \text{otherwise} \end{cases} \tag{S8}$$

If all soil layers reach saturation, the saturation excess flux q_6 [mm/time step] is divided into quick runoff as drainflow r_{DF} [mm/time step] (Eq. S9) and slow runoff as interflow. The outflow from the six soil layers contributes to the three runoff pathways: interflow r_{IF} [mm/time step], shallow groundwater flow r_{SGW} [mm/time step], and deep groundwater flow r_{DGW} [mm/time step]. First, the soil outflow contributes to the interflow runoff following a power law from the top layer to the bottom layer (Eq. S11). Then, the soil outflow contributes to the shallow groundwater runoff following an inverse law from the top layer to the bottom layer (Eq. S13). Finally, the soil outflow contributes to the deep groundwater runoff following a power law from the bottom layer to the top layer (Eq. S15). The parameter $\theta_{S'}$ is used in each of the three law distributions to determine the fraction of each soil layer that contributes to runoff during the modelling time step.

$$r_{DF} = \theta_D q_6 \tag{S9}$$

$$s_{IF\lambda} = \begin{cases} S_\lambda (\theta_{S'})^\lambda, & \text{if } \gamma \\ 0, & \text{otherwise} \end{cases} \tag{S10}$$

$$r_{IF} = \begin{cases} \sum_{\lambda=1}^{6} s_{IF\lambda}, & \text{if } \gamma \\ 0, & \text{otherwise} \end{cases} \tag{S11}$$

$$s_{SGW\lambda} = \begin{cases} S_\lambda \left(\frac{\theta_{S'}}{\lambda}\right), & \text{if } \gamma \\ 0, & \text{otherwise} \end{cases} \tag{S12}$$

$$r_{SGW} = \begin{cases} \sum_{\lambda=1}^{6} s_{SGW\lambda}, & \text{if } \gamma \\ 0, & \text{otherwise} \end{cases} \tag{S13}$$

$$s_{DGW\lambda} = \begin{cases} S_\lambda (\theta_{S'})^{7-\lambda}, & \text{if } \gamma \\ 0, & \text{otherwise} \end{cases} \tag{S14}$$

$$r_{DGW} = \begin{cases} \sum_{\lambda=1}^{6} s_{DGW\lambda}, & \text{if } \gamma \\ 0, & \text{otherwise} \end{cases} \tag{S15}$$

Under water-limited conditions:

The water deficit d_0 [mm/time step] (Eq. S16) to meet the potential evapotranspiration demand is totally or partially provided by the available soil moisture evapotranspiration fluxes e_λ [mm/time step] (Eq. S18). The variable b_λ [–] (Eq. S20) acts as a boolean to stop the soil moisture contribution to evapotranspiration as soon as the remaining water deficit d_λ [mm/time step] (Eq. S19) has been fully met by a given soil layer; it is initiated with a value of 1 if a deficit exists (Eq. S17). The first soil layer can fully meet the water deficit if it contains enough water, otherwise the second layer can contribute to meet the remaining water deficit with a depleted rate using the evaporation decay parameter θ_C [–] (see Eq. S19), and so forth for the next downward layer up to the bottom layer. Effectively, a lesser fraction of the available soil moisture in a layer can meet the remaining water deficit moving downwards following a power law (Eq. S19).

$$d_0 = \begin{cases} 0, & \text{if } \gamma \\ E_P - e_A, & \text{otherwise} \end{cases} \tag{S16}$$

$$b_0 = \begin{cases} 0, & \text{if } \gamma \\ 1, & \text{otherwise} \end{cases} \tag{S17}$$

$$e_\lambda = \begin{cases} b_{\lambda-1} d_{\lambda-1}, & \text{if } S_\lambda \geq d_{\lambda-1} \\ b_{\lambda-1} S_\lambda, & \text{otherwise} \end{cases} \tag{S18}$$

$$d_\lambda = \begin{cases} 0, & \text{if } S_\lambda \geq d_{\lambda-1} \\ \theta_C (d_{\lambda-1} - S_\lambda), & \text{otherwise} \end{cases} \tag{S19}$$

$$b_\lambda = \begin{cases} 0, & \text{if } S_\lambda \geq d_{\lambda-1} \\ b_{\lambda-1}, & \text{otherwise} \end{cases} \tag{S20}$$

Under water-limited and energy-limited conditions:

At each time step, whether under water-limited or energy-limited conditions, the soil layer states S_λ [mm] are updated given their inward and outward fluxes during the time step as described in Eq. S21.

$$\frac{dS_\lambda}{dt} = q_{\lambda-1} - s_{IF\lambda} - s_{SGW\lambda} - s_{DGW\lambda} - e_\lambda \tag{S21}$$

The routing for the five runoff pathways is conceptualised as five linear reservoirs which are characterised by three residence time parameters θ_{SK} [time step], θ_{FK} [time step], and θ_{GK} [time step] (see Equations S22–S26). The five runoff pathways contribute to a final linear reservoir for channel routing which is characterised by the residence time parameter θ_{RK} [time step] to compute the catchment total flow Q [mm/time step] (Eq. S27).

$$q_{OF} = \frac{S_{OF}}{\theta_{SK}} \tag{S22}$$

$$q_{DF} = \frac{S_{DF}}{\theta_{SK}} \tag{S23}$$

$$q_{IF} = \frac{S_{IF}}{\theta_{FK}} \tag{S24}$$

$$q_{SGW} = \frac{S_{SGW}}{\theta_{GK}} \tag{S25}$$

$$q_{DGW} = \frac{S_{DGW}}{\theta_{GK}} \tag{S26}$$

$$Q = \frac{S_R}{\theta_{RK}} \tag{S27}$$

Finally, the reservoir states [mm] are updated given their inward and outward fluxes during the time step as described in Equations S28–S33.

$$\frac{dS_{OF}}{dt} = (p_E - q_0) - q_{OF} \tag{S28}$$

$$\frac{dS_{DF}}{dt} = r_{DF} - q_{DF} \tag{S29}$$

$$\frac{dS_{IF}}{dt} = (q_6 - r_{DF}) + r_{IF} - q_{IF} \tag{S30}$$

$$\frac{dS_{SGW}}{dt} = r_{SGW} - q_{SGW} \tag{S31}$$

$$\frac{dS_{DGW}}{dt} = r_{DGW} - q_{DGW} \tag{S32}$$

$$\frac{dS_{RK}}{dt} = q_{OF} + q_{DF} + q_{IF} + q_{SGW} + q_{DGW} - Q \tag{S33}$$

Procedural model

The procedural implementation of the SMART conceptual model equations is open-source (Hallouin et al., 2019). It is available in a pure Python version, and a Python version boosted with a C++ extension. This procedural model works with any 2.7.x, 3.5.x, or 3.6.x version of Python. The procedural model numerically solves the model conceptual equations using the Explicit Euler approach, and the procedural model executes the conceptual model equations in the order shown in the above section, i.e., using an operator splitting technique.

References

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