water

Supplementary Materials

S.1. CLM4 Model Description

In CLM4 [1,2], soil water up to 3.8 m from the surface is estimated using a 10-layer model governed by the one-dimensional Richards equation as:

$$\frac{\partial\theta}{\partial t} = -\frac{\partial q}{\partial z} - s \quad \text{(S1)}$$

where θ (mm^3/mm^3) is the volumetric soil moisture content; z is the height above some datum in the soil column; t is time; and s is a soil moisture sink term (e.g., root extraction or subsurface drainage distributed across the soil moisture profile). Hydraulic parameters, Clapp and Hornberger exponent (b), saturated soil matrix potential (Ψ_s) in units of mm, hydraulic conductivity (K_s) in units of $mm \cdot s^{-1}$, and porosity (θ_s) are used to estimate the soil water flux q ($kg \cdot m^{-2} \cdot s^{-1}$) in Equation (S1). The upper boundary condition of this equation—infiltration—is estimated as the difference between liquid precipitation reaching the ground plus any meltwater from snow, subtracted by evaporation from the top soil layer and the surface runoff:

$$q_{infl} = q_{liq,grnd} - q_{over} - q_{evp} \quad \text{(S2)}$$

where q_{evp} ($kg \cdot m^{-2} \cdot s^{-1}$) is the evaporation of liquid water from the top soil layer and $q_{liq,grnd}$ ($kg \cdot m^{-2} \cdot s^{-1}$) is the liquid precipitation reaching the ground plus any melt water from snow. q_{over} ($kg \cdot m^{-2} \cdot s^{-1}$), the surface runoff, is parameterized following [3,4] as:

$$q_{over} = f_{sat} q_{liq,grnd} + (1 - f_{sat}) max\left[0, \left(q_{liq,0} - q_{infl,max}\right)\right] \quad \text{(S3)}$$

where $q_{\text{infl,max}}$ ($kg\ m^{-2}\ s^{-1}$) is the maximum soil infiltration capacity; $f_{sat} = f_{max}\exp(-C_s f_{over} z_\nabla)$ is the saturated fraction of the grid cell, z_∇ is the water table depth; the maximum factional saturated area (f_{max}), shape parameter of topographic index distribution (C_s), decay factor that represents the distribution of surface runoff with depth (f_{over}) in units of m^{-1} are the selected input parameters.

The lower boundary condition of Equation (S1) is represented as a flux from the bottom of the soil column to the underlying unconfined aquifer is as:

$$q_{recharge} = \frac{\Delta\theta_{liq,N_{levsoi+1}} \Delta z_{N_{levsoi+1}}}{\Delta t} \quad \text{(S4)}$$

where $\Delta\theta_{liq,N_{levsoi+1}}$ and $\Delta z_{N_{levsoi+1}}$ are the change in liquid water content solved numerically based on Equation (S1) and the thickness of the bottom soil layer, respectively; Subsurface runoff (q_{drai} ($kg \cdot m^{-2} \cdot s^{-1}$)) is assumed to be generated from soil layers and distributed as sink terms in Equation (S1)) as:

$$q_{drai} = Q_{dm}\exp(-f_{drai} z_\nabla) \quad \text{(S5)}$$

where the decay factor that represents the distribution of subsurface runoff with depth (f_{drai}) in units of m^{-1}, and maximum subsurface drainage (Q_{dm}) in units of $kg \cdot m^{-2} \cdot s^{-1}$ are model parameters. Beneath the soil column, an aquifer with a 5 m depth was added as the low boundary condition, which could exchange water with the soil column. Specific yield, S_y, has been assigned to the aquifer as an important parameter that controls the water exchanges between the aquifer and the soil column. Total runoff is defined as the sum of surface and subsurface runoff.

S.2. The Uncertainty Ranges and Prior Information about Each Input Parameter

Table S1. The uncertainty ranges and prior information about each input parameter [6].

Index	Symbol	Definition	Relevant Process	Prior Information
1	f_{max}	Max fractional saturated area, from DEM	Surface runoff	Mean value taken from the default CLM4 input data set; STD = 0.160; upper and lower bounds (0.01–0.907) determined from the default global data set for CLM4
2	C_s	Shape parameter of topographic index distribution	Surface runoff	Mean = 0.5 for flux towers, no STD information, upper and lower bound 0.01 and 0.9
3	f_{over}	Decay factor (m^{-1}) that represents the distribution of surface runoff with depth	Surface runoff	Hard coded to be 0.5 in CLM4 Mean = 0.5 Upper and lower bounds: 0.1–5
4	f_{drai}	Decay factor (m^{-1}) that represents the distribution of subsurface runoff with depth	Subsurface runoff	Mean = 2.5; upper and lower bounds: 0.1–5
5	$q_{drai,max}$ (Q_{dm})	Max subsurface drainage ($kg \cdot m^{-2} \cdot s^{-1}$)	Subsurface runoff	Hard coded to be $5.5 \times 10^{-3} kg \cdot m^{-2} \cdot s^{-1}$ but typically should vary between 1×10^{-6} and 1×10^{-2} in hydrologic applications. Tuning range is 1×10^{-6} to 1×10^{-1} as suggested by NCAR
6	S_y	Average specific yield	Groundwater dynamics	Hard coded to be 0.2 Based on the dominant soil type of the site, converted to coarser soil texture classes using the USGS soil texture triangle. Mean = 0.02 for clay, 0.07 for sandy clay, 0.18 for silt, 0.27 for coarse sand; bounds are ±50% of the mean for the given soil texture.
7	b	Clapp and Hornberger exponent	Soil water	Based on the dominant soil type of the site.
8	Ψ_s	Saturated soil matrix potential (mm)	Soil water	Used equation from [5].
9	K_s	Hydraulic conductivity ($mm \cdot s^{-1}$)	Soil water	Mean values and STDs are from [5] Table 5,
10	θ_s	Porosity	Soil water	except for STD of Ψ_s, which is from [5] Table 4

S.3. Boxplots for Response Variables and Metrics as a Function of Input Parameters

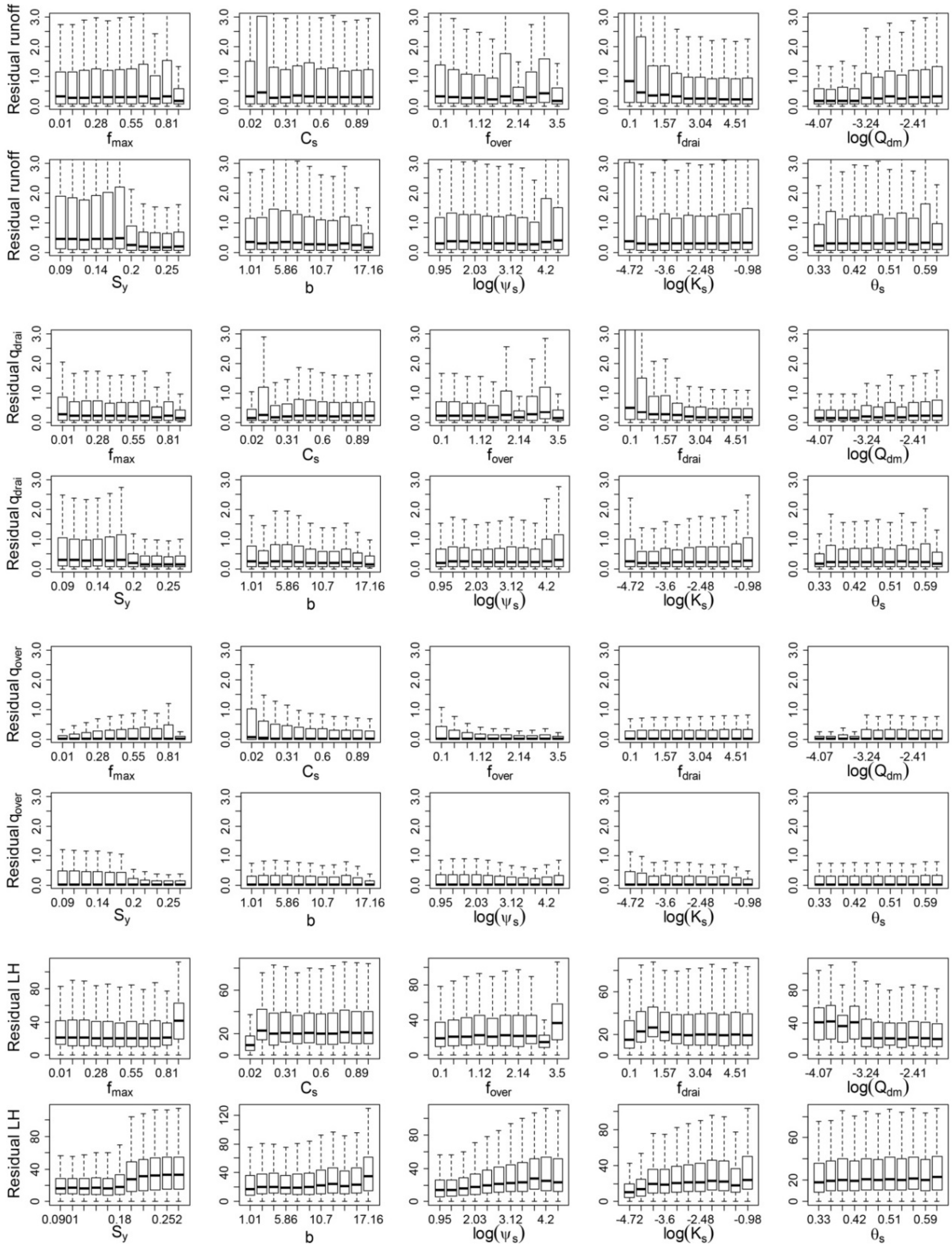

Figure S1. Residuals of response variables as a function of input parameters. First and second rows: residual of total runoff; third and fourth rows: residual of subsurface runoff; the fifth and sixth rows: residual of surface runoff; and the seventh and eighth rows: residual of latent heat flux.

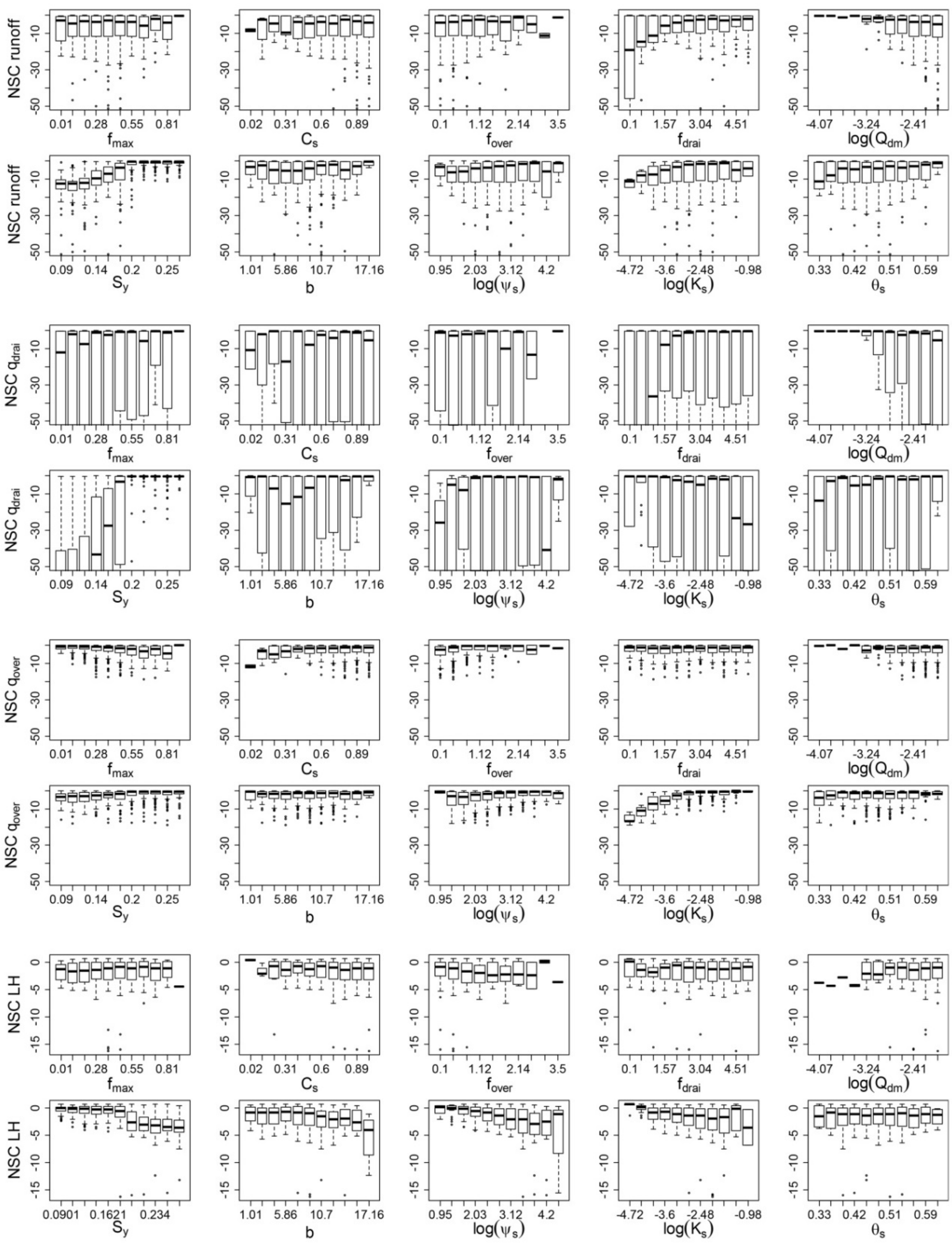

Figure S2. Nash-Sutcliffe coefficient of response variables as a function of input parameters. First and second rows: Nash–Sutcliffe coefficient (NSC) of total runoff; third and fourth rows: NSC of subsurface runoff; fifth and sixth rows: NSC of surface runoff; and seventh and eighth rows: NSC of latent heat flux.

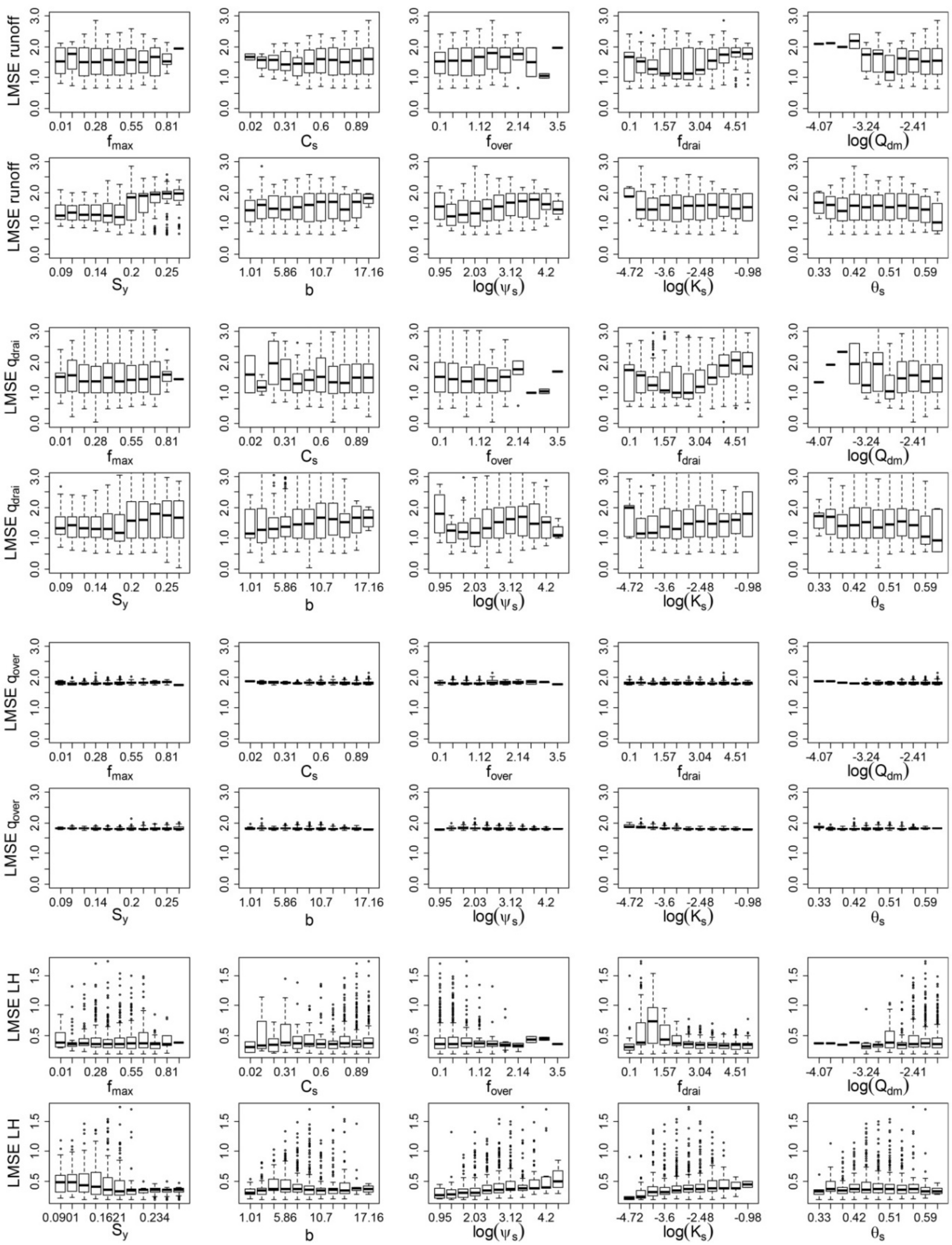

Figure S3. Log mean square error of response variables as a function of input parameters. First and second rows: log mean square error (LMSE) of total runoff; third and fourth: LMSE of subsurface runoff; fifth and sixth rows: LMSE of surface runoff; and seventh and eighth rows: LMSE of latent heat flux.

S.4. Proportion of Sensitivity for Residuals of Runoff, q_{drai}, q_{over}, and LH in 108 Months

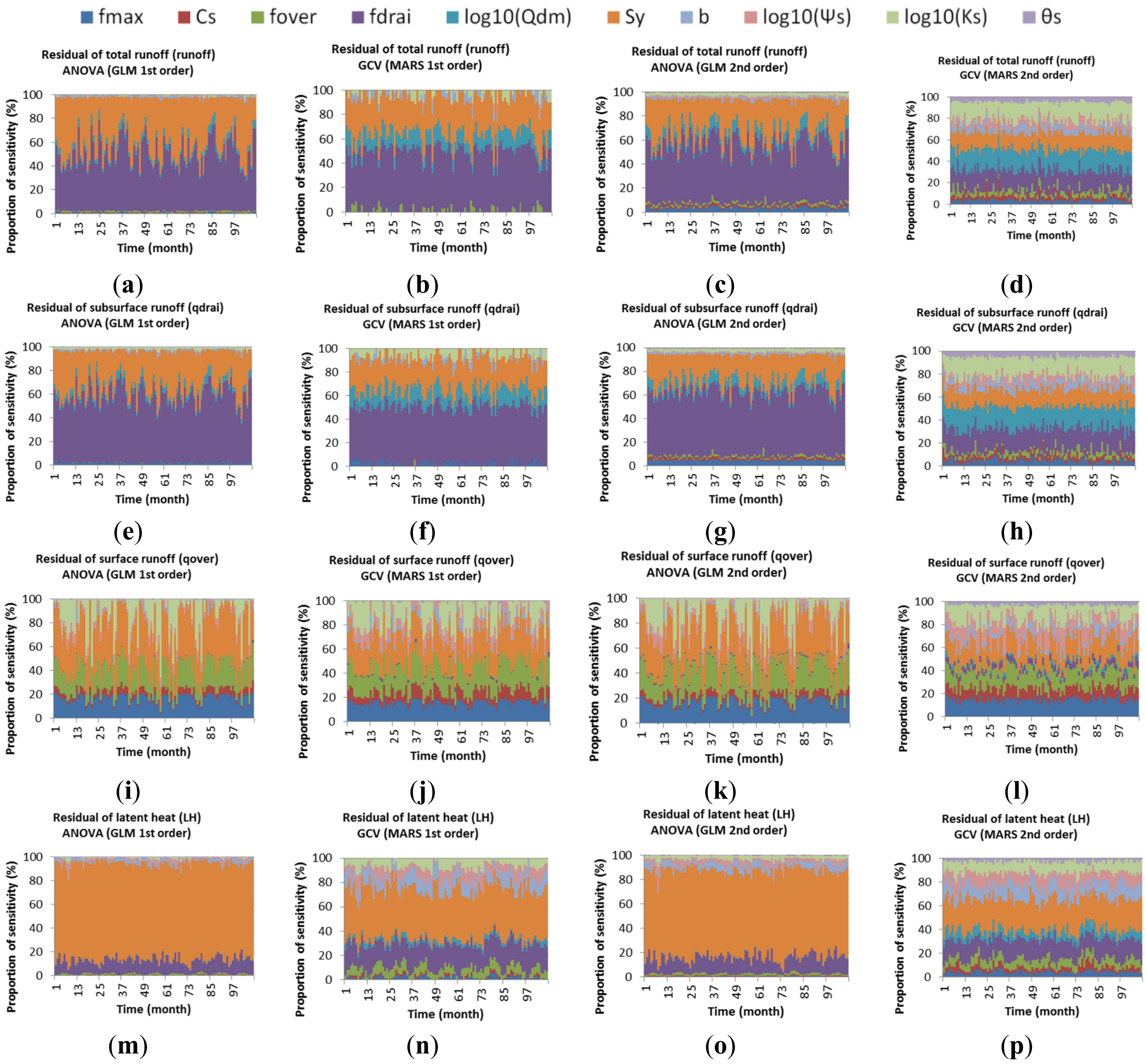

Figure S4. Proportion of sensitivity for residual. The first and second columns contain the sensitivity scores based on first-order regression models, and the third and fourth columns contain the scores based on second-order regression models. The first and third columns contain the scores based on ANOVA, and the second and fourth columns contain the scores based on GCV. The first row shows the residual of total runoff (runoff), the second row shows the residual of subsurface runoff (q_{drai}), the third row shows the residual of surface runoff (q_{over}), and the fourth row shows the residual of latent heat flux.

S.5. Sensitivity Score Convergence for Different Response Variables and SA Approaches

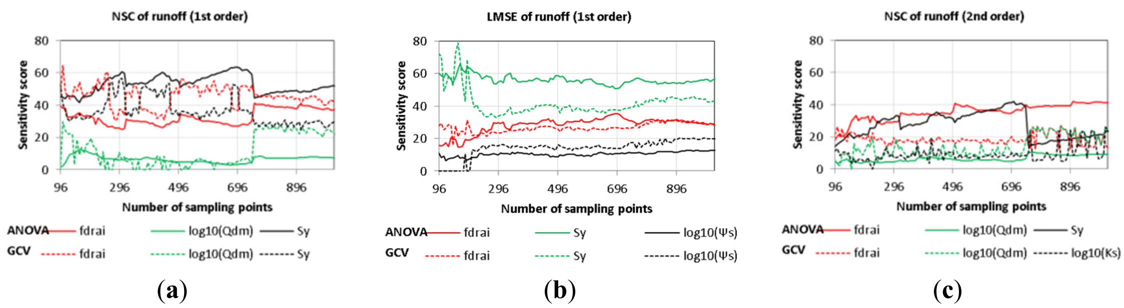

Figure S5. *Cont.*

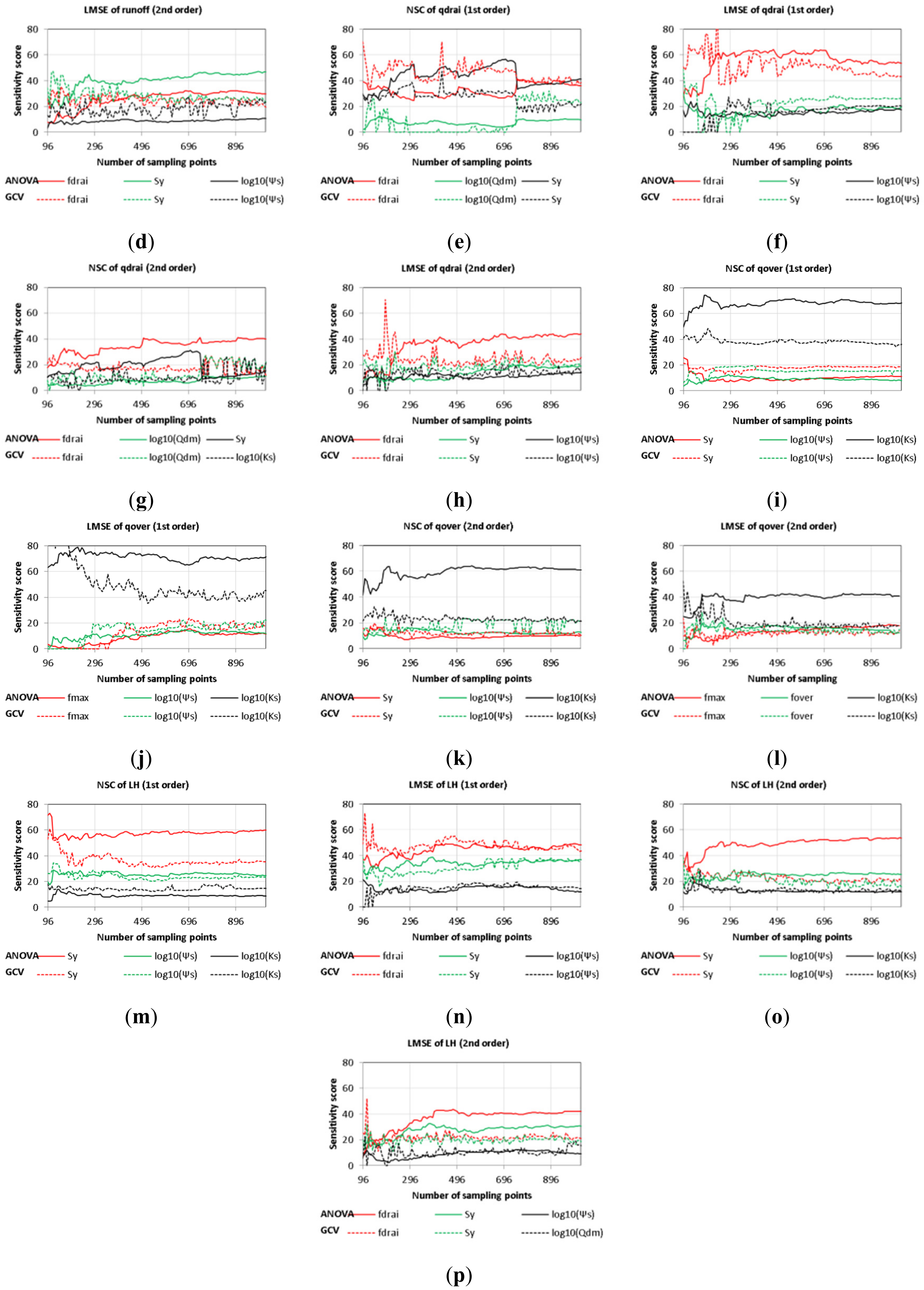

Figure S5. Comparison of sensitivity score convergence. The first and second columns contain the sensitivity scores based on first-order regression models, and the third and fourth columns contain the score based on second-order regression models. The first and third columns contain the scores for NSC, and the second and fourth columns contain the scores for LMSE. The first row shows for total runoff (runoff), the second row shows subsurface runoff (q_{drai}), the third row shows surface runoff (q_{over}), and the fourth row is for of latent heat flux. The solid lines are the scores of ANOVA, and the dashed lines sow the GCV scores.

References

1. Oleson, K.W.; Dai, Y.J.; Bonan, G.B.; Bosilovich, M.; Dickinson, R.; Dirmeyer, P.; Hoffman, F.M.; Houser, P.R.; Levis, S.; Niu, Y.; *et al. Technical Description f Version 4.0 of the Community Land Model (CLM)*; National Center for Atomospheric Research: Boulder, CO, USA, 2010.
2. Lawrence, D.M.; Oleson, K.W.; Flanner, M.G.; Thornton, P.E.; Swenson, S.C.; Lawrence, P.J.; Zeng, Z.; Yang, Z.L.; Levis, S.; Sakaguchi, K.; *et al.* Parameterization Improvements and Functional and Structural Advances in Version 4 of the Community Land Model. *J. Adv. Model. Earth Syst.* **2011**, *3*, 27.
3. Niu, G.-Y.; Yang, Z.-L.; Dickinson, R.; Dickinson, R.; Gulden, L.E.; Gulden, L.E. A simple TOPMODEL-based runoff parameterization (SIMTOP) for use in global climate models. *J. Geophys. Res.* **2005**, *110*, doi:10.1029/2005JD006111.
4. Niu, G.Y.; Yang, Z.-L.; Dickinson, R.E.; Gulden, L.E.; Su, H. Development of a simple groundwater model for use in climate models and evaluation with Gravity Recovery and Climate Experiment data. *J. Geophys. Res.* **2007**, *112*, doi:10.1029/2006JD007522.
5. Cosby, B.J.; Hornberger, G.M.; Clapp, R.B.; Ginn, T.R. A statistical exploration of the relationships of soil moisture characteristics to the physical properties of soils. *Water Resour. Res.* **1984**, *20*, 682–690.
6. Hou, Z.; Huang, M.; Leung, L.R.; Lin, G.; Ricciuto, D.M. Sensitivity of surface flux simulations to hydrologic parameters based on an uncertainty quantification framework applied to the Community Land Model. *J. Geophys. Res.* **2012**, *117*, doi:10.1029/2012JD017521.