Supplement of

Identifying Dominant Parameters Across Space and Time at Multiple Scales in a Distributed Model Using a Two-Step Deep Learning-Assisted Time-Varying Spatial Sensitivity Analysis

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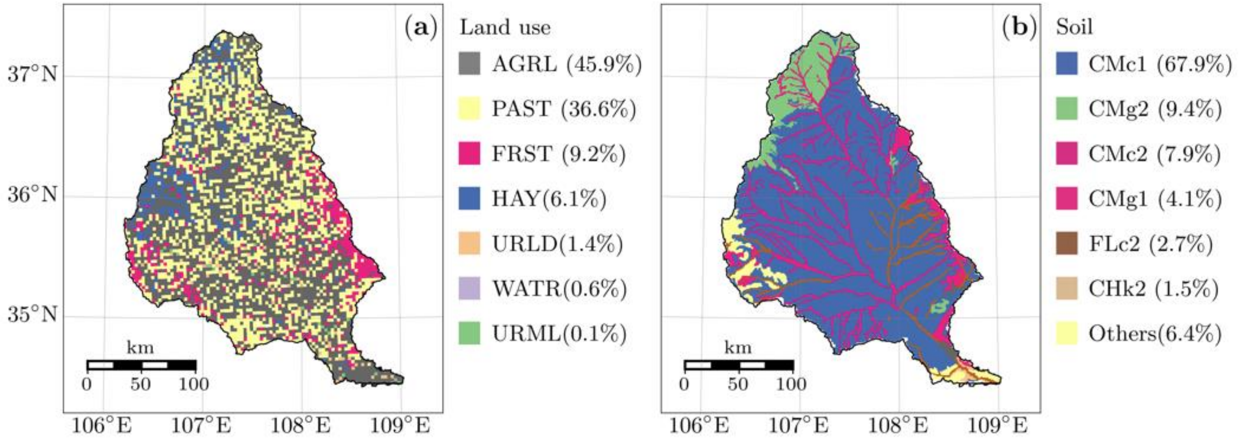

Figure S1: Classifications of (a) the resample land use (3,000 m resolution) from the 30-m Resolution Global Land Cover 2017 dataset (https://data-starcloud.pcl.ac.cn/iearthdata, accessed August 20, 2025). Categories include agricultural (AGRL), pasture (PAST), forest (FRST), hay (HAY), low-density residential (URLD), water (WATR), and medium/low-density residential (URML). (b) the soil data derived from the Harmonized World Soil Database (HWSD, 1 km resolution), provided by the National Cryosphere Desert Data Center (https://www.ncdc.ac.cn/portal/, accessed August 20, 2025). Categories include calcaric cambisols (CMc1, CMc2), calcaric regosols (CMg1, CMg2), fluvisols (FLc2), and chernozems (CHk2).

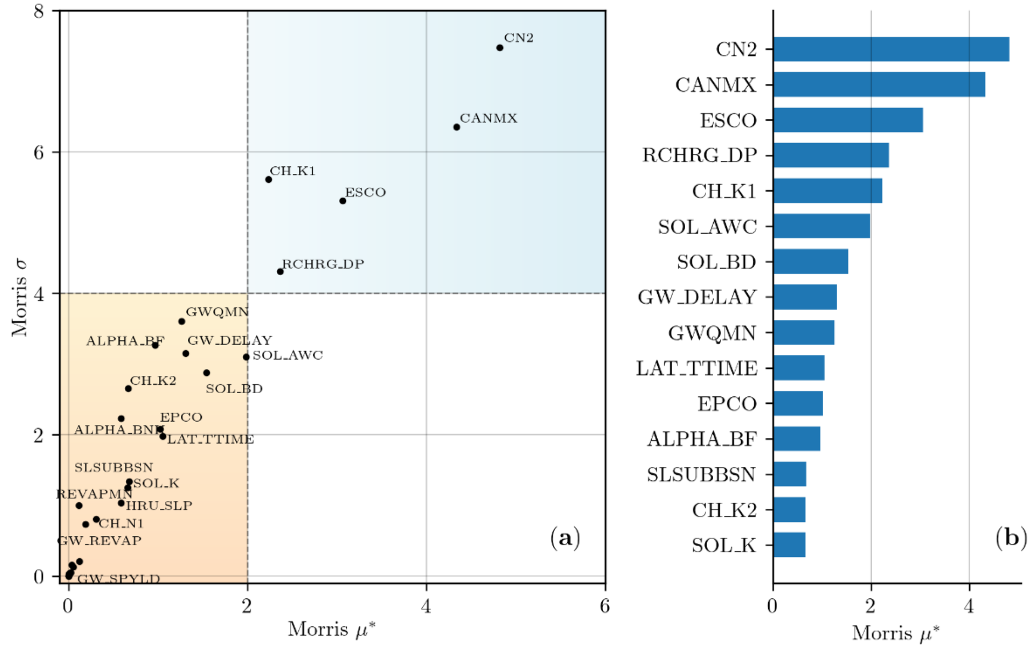

Figure S2: Sensitivity analysis results by Morris screening method for NSE-based runoff simulations: (a) scatter plot of the mean absolute elementary effect (μ*) versus its standard deviation (σ) for 33 selected parameters. (b) bar chart ranking the top 15 parameters by μ*. Parameters with larger μ* values exert stronger overall influence on model performance, while higher σ values indicate nonlinear or interaction effects. The shaded gradient zones in panel (a) highlight regions of dominant influence: the upper-right blue zone denotes parameters with both high overall impact and strong interactions, whereas the lower-left orange zone indicates parameters with limited influence. The parameter GW_SPYLD is not active in the SWAT model, therefore, both its μ* and σ values are zero, confirming the effectiveness of the Morris method in identifying non-influential parameters.

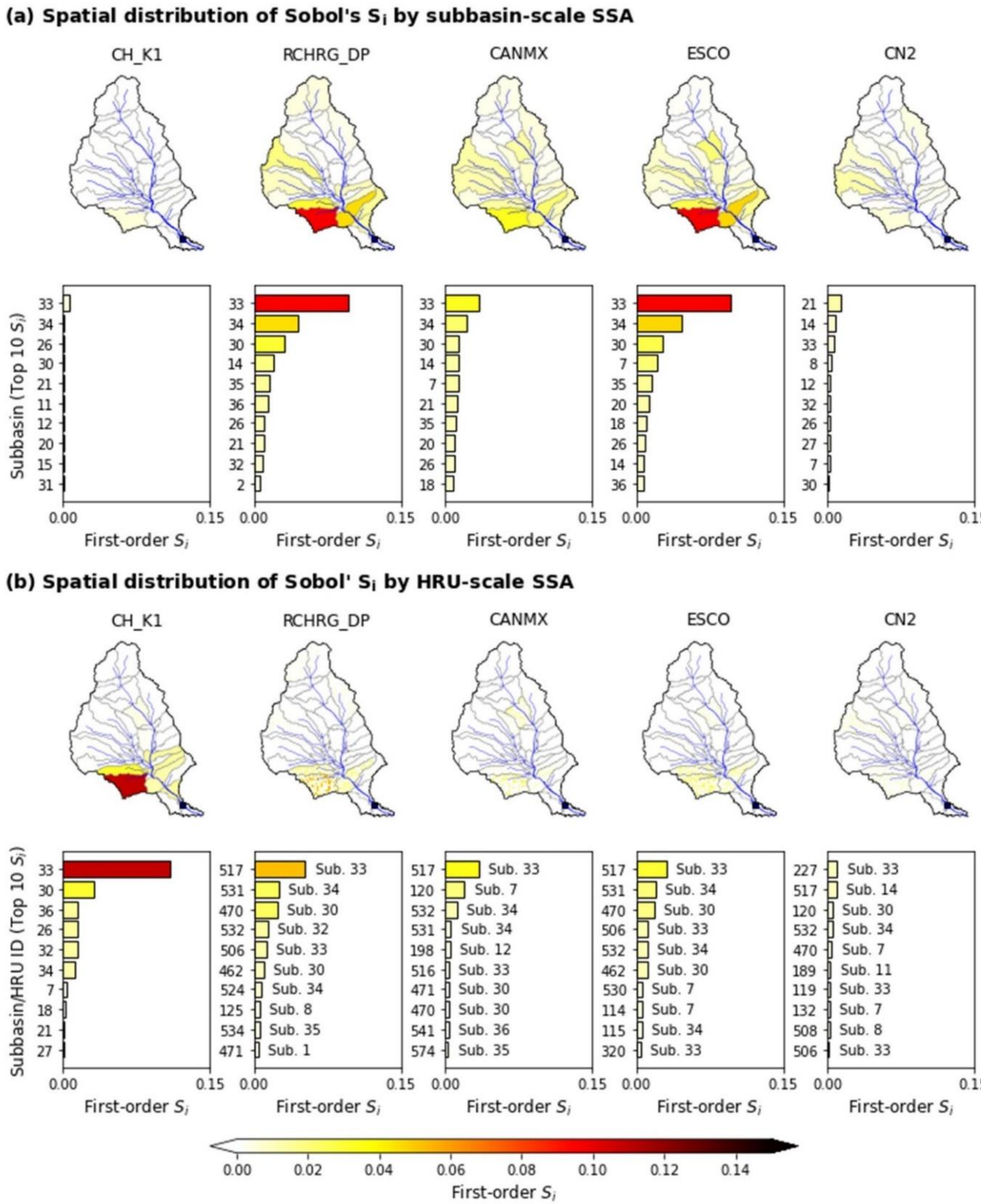

Figure S3: Spatial distribution of Sobol's first-order S_i sensitivity index based on the full-period NSE by (a) subbasin-scale SSA and (b) HRU-scale SSA. Bar plots below each map show the top ten subbasins/HRUs ranked by S_i. For the HRU-scale plots, the text to the right of each bar indicates the parent subbasin (e.g., HRU 517 belongs to subbasin 33, denoted as Sub. 33).

Table S1: Relationship between 39 subbasins and 630 HRUs used in the SWAT model. For each subbasin, the table lists its area and the contiguous HRU ID range, as derived from the ArcSWAT HRU Analysis Report.

Subbasin ID	Area (km^2)	HRU ID range	Subbasin ID	Area (km^2)	HRU ID range
1	2010.2	1 – 17	21	3139.8	324 – 346
2	2560.8	18 – 41	22	296.6	347 – 361
3	692.75	42 – 64	23	178.16	362 – 378
4	857.59	65 – 83	24	327.67	379 – 387
5	1765	84 – 101	25	15.57	388 – 393
6	922.77	102 – 113	26	1005.4	394 – 413
7	1714.2	114 – 123	27	1668.2	414 – 433
8	3022.1	124 – 135	28	388.87	434 – 442
9	371.99	136 – 144	29	248.92	443 – 460
10	826.02	145 – 165	30	1466.7	461 – 475
11	2412.6	166 – 194	31	95.963	476 – 487
12	928.62	195 – 203	32	927.52	488 – 504
13	280.24	204 – 213	33	2430.7	505 – 521
14	3370.4	214 – 231	34	1931.6	522 – 532
15	981.13	232 – 251	35	1256.5	533 – 555
16	801.04	252 – 270	36	929.68	556 – 577
17	151.16	271 – 284	37	63.36	578 – 598
18	1278.4	285 – 296	38	996.46	599 – 618
19	56.745	297 – 313	39	596.29	619 – 630
20	1340.5	314 – 323	-	-	-

Table S2: List of the 33 parameters included in the Morris screening method

No.	Parameter	Input file extension	Description	Range	Method	Reference
1	SFTMP	.bsn	Snowfall temperature (°C)	[-5, 5]	Replace	(Khorashadi Zadeh et al., 2017; Li et al., 2021; Muleta, 2012; Neitsch et al., 2011; Zhang et al., 2013)
2	SMTMP	.bsn	Snowmelt base temperature (°C)	[-5, 5]	Replace	(Li et al., 2021; Neitsch et al., 2011; Zhang et al., 2013)
3	SMFMX	.bsn	Melt factor for snow on June 21 (mm H_2O/°C-day)	[0, 20]	Replace	(Li et al., 2021)
4	SMFMN	.bsn	Melt factor for snow on December 21 (mm H_2O/°C-day)	[0, 20]	Replace	(Li et al., 2021)
5	TIMP	.bsn	Snowpack temperature lag factor	[0.01, 1]	Replace	(Li et al., 2021; Neitsch et al., 2011; Zhang et al., 2013)
6	SURLAG	.bsn	Surface runoff lag coefficient	[0.05, 24]	Replace	(Li et al., 2021; Zhang et al., 2013)
7	GW_DELAY	.gw	Groundwater delay time (days)	[0, 500]	Replace	(Hernandez-Suarez and Nejadhashemi, 2022; Jeong et al., 2024; Mao et al., 2024)
8	ALPHA_BF	.gw	Base flow alpha factor	[0, 1]	Replace	(Hernandez-Suarez and Nejadhashemi, 2022; Khorashadi Zadeh et al., 2017; Li et al., 2021; Mao et al., 2024; Zhang et al., 2013)
9	GWQMN	.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O)	[0, 5000]	Replace	(Hernandez-Suarez and Nejadhashemi, 2022; Jeong et al., 2024; Li et al., 2021)
10	GW_REVAP	.gw	Groundwater “revap’’ coefficient	[0.02, 0.2]	Replace	(Jeong et al., 2024; Li et al., 2021; Neitsch et al., 2011; Zhang et al., 2013)

11	REVAPMN	.gw	Threshold depth of water in the shollow aquifer for ‘‘revap’’ or percolation to the deep aquifer to occur (mm H_2O)	[0, 1000]	Replace	(Hernandez-Suarez and Nejadhashemi, 2022; Jeong et al., 2024)
12	RCHRG_DP	.gw	Deep aquifer percolation fraction	[0, 1]	Replace	(Jeong et al., 2024; Khorashadi Zadeh et al., 2017; Li et al., 2021; Neitsch et al., 2011; Zhang et al., 2013)
13	GW_SPYLD[a]	.gw	Specific yield of the shallow aquifer (m^3/m^3)	[0, 0.4]	Replace	
14	SLSUBBSN[b]	.hru	Average slope length (m)	[0.75, 1.25]	Factor	(Zhang et al., 2013)
15	HRU_SLP[b]	.hru	Average Slope steepness (m/m)	[0.75, 1.25]	Factor	(Mao et al., 2024)
16	OV_N[b]	.hru	Manning’s “n” value for overland flow	[0.75, 1.25]	Factor	(Mao et al., 2024)
17	LAT_TTIME	.hru	Lateral flow travel time (days)	[0, 180]	Replace	(Jeong et al., 2024; Zhang et al., 2013)
18	CANMX	.hru	Maximum canopy storage (mm H_2O)	[0, 100]	Replace	(Jeong et al., 2024; Li et al., 2021; Zhang et al., 2013)
19	ESCO	.hru	Soil evaporation compensation factor	[0.01, 1]	Replace	(Hernandez-Suarez and Nejadhashemi, 2022; Li et al., 2021; Mao et al., 2024; Neitsch et al., 2011; van Griensven et al., 2006)
20	EPCO	.hru	Plant uptake compensation factor	[0.01, 1]	Replace	(Hernandez-Suarez and Nejadhashemi, 2022; Li et al., 2021; Mao et al., 2024; Neitsch et al., 2011; van Griensven et al., 2006)
21	BIOMIX	.mgt	Biological mixing efficiency	[0, 1]	Replace	(Hernandez-Suarez and Nejadhashemi, 2022; Khorashadi Zadeh et al., 2017; Zhang et al., 2013)

22	CN2[b]	.mgt	Runoff curve number multiplicative factor	[0.75, 1.25]	Factor	(Hernandez-Suarez and Nejadhashemi, 2022; Zhang et al., 2013)
23	CH_N2	.rte	Manning's "n" value for the main channel	[0, 0.3]	Replace	(Mao et al., 2024)
24	CH_K2	.rte	Effective hydraulic conductivity in main channel alluvium (mm/hr)	[0, 500]	Replace	(Hernandez-Suarez and Nejadhashemi, 2022)
25	ALPHA_BNK	.rte	Baseflow alpha factor for bank storage (days)	[0, 1]	Replace	(Zhang et al., 2013)
26	SOL_Z[b]	.sol	Soil profile total depth multiplicative factor	[0.75, 1.25]	Factor	(Hernandez-Suarez and Nejadhashemi, 2022; Zhang et al., 2013)
27	SOL_BD[b]	.sol	Moist bulk density (Mg/cm^3)	[0.75, 1.25]	Factor	(Zhang et al., 2013)
28	SOL_AWC[b]	.sol	Available water capacity multiplicative factor	[0.75, 1.25]	Factor	(Zhang et al., 2013)
29	SOL_K[b]	.sol	Saturated hydraulic conductivity multiplicative factor	[0.75, 1.25]	Factor	(Mao et al., 2024; Zhang et al., 2013)
30	SOL_ALB[b]	.sol	Moist soil albedo.	[0.75, 1.25]	Factor	(Zhang et al., 2013)
31	TLAPS	.sub	Temperature lapse rate (°C/km)	[-10, 10]	Replace	(Khorashadi Zadeh et al., 2017; Li et al., 2021)
32	CH_K1	.sub	Effective hydraulic conductivity in tributary channel (mm/hr)	[0, 300]	Replace	(Phetanan et al., 2024)
33	CH_N1	.sub	Manning's "n" value for the tributary channels	[0.01, 30]	Replace	(Phetanan et al., 2024)

[a]The parameter GW_SPYLD is not active in the SWAT model but was included as a dummy parameter to validate the effectiveness of Morris method.

[b]Parameters adjusted using a multiplicative factor are denoted as the "Factor method" to account for spatial variability. All other parameters were adjusted by direct replacement of old values with new ones, denoted as the "Replace method".

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