Supplementary Information for

Soil Moisture to Runoff (SM2R): A Data-Driven Model for Runoff Estimation Across Poorly Gauged Asian Water Towers Based on Soil Moisture Dynamics

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Introduction

This Supplementary Information provides comparisons between runoff estimated from the SM2R model and that from two other runoff products (Supplementary text, Tables S1 to S2, and Figure S1). Final parameters as well as iterations of the SM2R model for each drainage basin are also listed (Table S3).

1 Supplementary text: Comparisons between SM2R and multi-model simulated runoff

We added comparisons with two other runoff products to further evaluate the performance of SM2R-derived runoff. The supplemented runoff estimates include: (1) the China Natural Runoff Dataset (CNRD; https://doi.org/10.6084/m9.figshare.13185410), and (2) the ensemble mean of 16 simulations from the second phase of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP 2b; https://data.isimip.org/). The CNRD data set was generated by the Variable Infiltration Capacity (VIC) land surface model, and calibrated and validated with runoff observations from 200 gauges across Mainland China during 1961–2018 [*Gou et al.*, 2021]. As for the ISIMIP data set, we use the ensemble mean of four model simulations, including two hydrological models (i.e., H08 and WaterGAP2), one land surface model (i.e., MATSIRO), and one dynamic vegetation model (i.e., LPJml), which are widely used as references for runoff analysis [*Gou et al.*, 2021; *Satoh et al.*, 2022]. Each model is forced by four meteorological forcings, i.e., GFDL, Hadgem, IPSL, and Miroc5 during the historical period (1981–2005).

In general, performance between SM2R and CNRD-derived runoff is comparable at most gauges (Table S1 and Figure S1). Although CNRD-derived runoff shows high accuracy at the Luning gauge, we find better performance of SM2R than CNRD at the Lazi gauge. In particular, at the Gongshan, Zhimenda, Tangnaihai, and Maqu gauges where SM2R does not perform as well as other gauges across the Asian water towers, the VIC model-derived CNRD product cannot improve the simulation accuracy, either. This further indicates challenges in runoff simulations over basins with a complex rainfall-runoff relationship caused by frozen soil degradation. ISIMIP runoff data seem to perform poorly over the Asian water towers with 13/19 gauges having *NSE* < 0 (Table S2). Overall, the SM2R model shows comparable performance with the VIC land surface model that is calibrated by in situ observations, both of which are much more accurate than ISIMIP model simulations.

2 Supplementary tables

Table S1 Specific values of *NSE*, *logNSE*, *CC*, *NRMSE*, and *KGE* for evaluating CNRD-derived runoff (1981–2018) based on observations from 13 gauges. Note that only gauges located in China are shown because of data availability of the CNRD product.

Water tower	Gauge	Observations (months)	*CC*	*NRMSE*	*KGE*	*NSE*	*LogNSE*
Brahmaputra	Lazi	132	0.81	0.18	0.44	0.48	0.05
	Nugesha	181	0.90	0.11	0.66	0.75	0.50
	Lhasa	181	0.92	0.10	0.84	0.83	0.76
	Yangcun	169	0.92	0.10	0.79	0.83	0.75
	Nuxia	456	0.96	0.08	0.65	0.82	0.88
Salween	Jiayuqiao	448	0.97	0.12	0.66	0.79	0.87
	Gongshan	182	0.70	0.24	0.61	0.21	0.34
Mekong	Changdu	456	0.95	0.10	0.71	0.78	0.81
	Liutongjiang	76	0.95	0.12	0.75	0.81	0.88
Yangtze	Zhimenda	444	0.94	0.24	-0.26	-0.69	0.03
	Luning	240	0.97	0.05	0.93	0.94	0.88

Yellow	Tangnaihai	456	0.93	0.16	0.21	-0.03	0.41
	Maqu	336	0.93	0.17	0.09	-0.24	0.46

Table S2 Specific values of *NSE*, *logNSE*, *CC*, *NRMSE*, and *KGE* for evaluating runoff derived from multi-model mean of the ISIMIP data set during the historical period (1981–2005) based on observations from 19 gauges. Note that the Liutongjiang gauge does not have observed data during 1981–2005, and was therefore removed from this table.

Water tower	Gauge	Observations (months)	*CC*	*NRMSE*	*KGE*	*NSE*	*LogNSE*
Indus	Besham Qila	300	0.12	0.98	-2.16	-14.27	-1.25
	Shatial Bridge	96	0.08	1.07	-2.22	-14.37	-1.21
	Partab Bridge Bunji	276	0.08	0.74	-1.28	-7.80	-0.75
	Skardu Kachura	288	0.12	0.64	-0.94	-5.87	-0.48
Ganges	Asaraghat	300	0.80	0.20	0.15	-0.41	0.33
	Kali Khola	141	0.90	0.23	0.39	0.37	0.74
	Chatara	284	0.90	0.11	0.74	0.78	0.81
Brahmaputra	Lazi	72	0.63	0.42	0.09	-0.48	-1.61
	Nugesha	72	0.72	0.33	0.38	-0.18	0.34
	Lhasa	49	0.85	1.41	-3.47	-21.38	-0.93
	Yangcun	72	0.84	0.44	-0.24	-1.39	0.57
	Nuxia	300	0.85	0.21	0.61	0.46	0.82
Salween	Jiayuqiao	292	0.85	0.26	0.22	-0.17	0.79
	Gongshan	54	0.81	0.47	-0.04	-1.16	0.26
Mekong	Changdu	300	0.82	0.18	0.75	0.57	0.73
Yangtze	Zhimenda	300	0.65	0.20	0.65	0.32	0.76
	Luning	240	0.83	0.32	0.19	-0.31	0.56
Yellow	Tangnaihai	300	0.65	0.20	0.65	0.32	0.76
	Maqu	300	0.69	0.28	0.35	-0.33	0.65

Table S3 Optimized parameters of the SM2R model in each study basin.

Water tower	Gauge	a	*b*	*c*	*e*	*f*	*g*	*z*	*Iterations*
Indus	Besham Qila	5.01	25.90	11.30	0.66	2.21	0.19	2890	11
	Shatial Bridge	5.00	25.90	11.30	0.60	2.24	0.17	2890	9
	Partab Bridge Bunji	5.00	25.90	11.30	0.51	1.38	0.13	2890	4
	Skardu Kachura	5.00	25.90	11.30	0.46	1.39	0.11	2890	2
Ganges	Asaraghat	5.25	13.18	15.63	4.05	1.22	0.48	2890	109
	Kali Khola	5.26	13.19	15.62	3.24	1.97	0.44	2890	58
	Chatara	5.15	13.19	15.61	2.62	2.71	0.44	2890	42
Brahmaputra	Lazi	6.24	0.32	28.56	8.07	3.79	2.32	2891	757
	Nugesha	5.99	60.96	9.89	6.94	11.97	2.87	2890	335

	Lhasa	5.70	13.16	15.68	6.96	5.91	1.20	2890	306
	Yangcun	6.15	60.89	10.51	8.25	11.75	3.20	2890	440
	Nuxia	6.03	13.11	15.77	8.52	11.78	3.01	2890	420
Salween	Jiayuqiao	5.62	60.35	11.46	10.96	4.73	1.97	2891	738
	Gongshan	5.54	25.54	12.01	9.40	5.31	1.87	2890	552
Mekong	Changdu	5.78	60.15	12.28	11.94	4.32	2.12	2891	872
	Liutongjiang	5.82	24.91	11.03	10.51	4.97	1.42	2890	606
Yangtze	Zhimenda	6.07	25.57	12.48	8.26	1.04	1.54	2890	477
	Luning	6.15	25.08	12.83	13.10	4.19	2.33	2890	410
Yellow	Tangnaihai	5.76	25.74	11.85	8.42	0.44	1.33	2890	431
	Maqu	5.75	25.82	11.64	6.91	0.74	0.87	2890	355

3 Supplementary figures

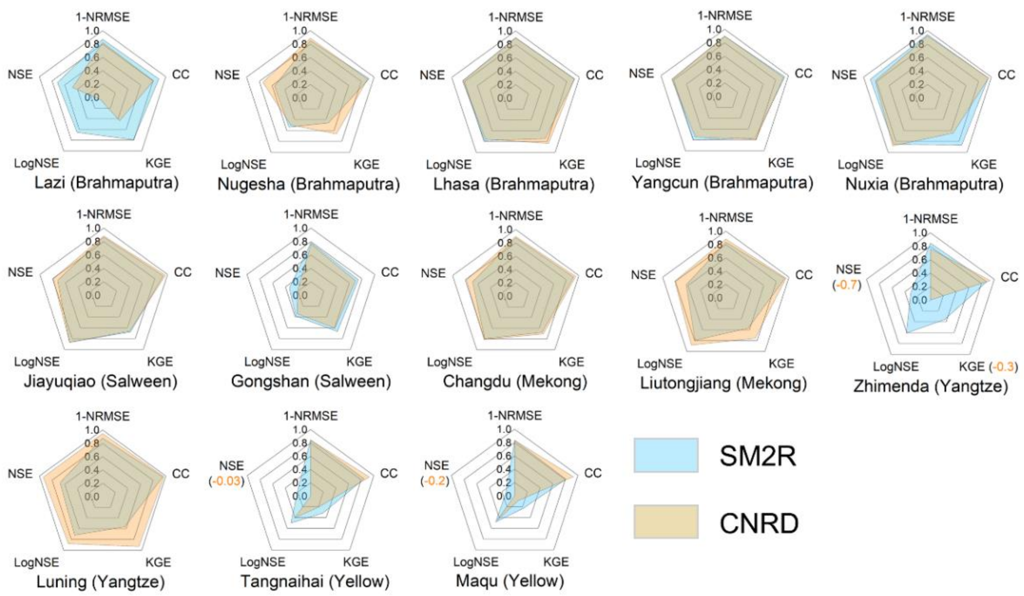

Figure S1 Radar plots of five indices (i.e., *NSE*, *logNSE*, *CC*, *NRMSE*, and *KGE*) evaluating SM2R and CNRD-derived runoff based on observations from 13 gauges in China. Evaluation results from SM2R are shown in blue, whereas those from CNRD are shown in yellow. Indices of CNRD evaluation with values <0 were excluded from the plots but the values are specifically shown in yellow font (at the Zhimenda, Tangnaihai, and Maqu gauges). The *NRMSE* index is shown as (1-*NRMSE*) in the plots, and a perfect fit is indicated by a value of 1 for all indices.

Supplementary references

Gou, J., C. Miao, L. Samaniego, M. Xiao, J. Wu, and X. Guo (2021), CNRD v1.0: A high-quality natural runoff dataset for hydrological and climate studies in China, *Bulletin of the American Meteorological Society*, *102*(5), E929-E947.

Satoh, Y., et al. (2022), The timing of unprecedented hydrological drought under climate change, *Nature Communications*, *13*(1), 3287.