Supplement

Table S1. Evaluation metrics of root mean square error (RMSE) and correlation coefficients (R) for soil moisture and evapotranspiration during 2016-2018 in open-loop (OL) and univariate assimilation scenarios of soil moisture (SM_DA and SM_DA_PAR) and groundwater level (GWL _DA and GWL _DA_PAR).

Year	Variable	OL	SM_DA	SM_DA_PAR	GWL _DA	GWL _DA_PAR
2016	SM (RMSE, cm^3/cm^3)	0.11	0.06	0.05	0.12	0.12
2017		0.10	0.05	0.04	0.10	0.11
2018		0.09	0.05	0.04	0.10	0.11
2016-2018		0.10	0.05	0.05	0.10	0.11
2016	SM (R)	0.62	0.85	0.85	0.50	0.47
2017		0.63	0.88	0.88	0.58	0.43
2018		0.61	0.89	0.90	0.56	0.46
2016-2018		0.62	0.87	0.88	0.55	0.46
2016	ET (RMSE, mm/day)	0.76	0.72	0.71	0.76	0.76
2017		0.79	0.77	0.77	0.79	0.79
2018		0.73	0.75	0.75	0.73	0.73
2016-2018		0.76	0.74	0.74	0.76	0.76
2016	ET (R)	0.82	0.80	0.81	0.82	0.82
2017		0.86	0.86	0.86	0.86	0.86
2018		0.83	0.82	0.82	0.83	0.83
2016-2018		0.84	0.83	0.83	0.84	0.84

Table S2. Root mean square error (RMSE) values of groundwater level (m) from 2016 to 2018 for the open-loop (OL) and univariate assimilation scenarios of groundwater level (GWL_DA and GWL_DA_PAR) and soil moisture (SM_DA and SM_DA_PAR).

Year	Distance	OL	GWL _DA	GWL _DA_PAR	SM_DA	SM_DA_PAR
2016	0	7.30	3.40	2.04	7.39	7.92
2017		7.24	2.77	2.05		
2018		7.24	2.50	2.05		
2016-2018		7.26	2.89	2.05		
2016	0-0.5km	7.27	6.51	3.66	8.43	7.96
2017		6.98	4.43	3.87		
2018		6.77	3.83	3.56		
2016-2018		7.01	4.92	3.70		
2016	0.5-2.5km	6.49	6.49	5.55	7.84	7.69
2017		6.45	5.84	5.69		
2018		6.31	5.52	5.52		
2016-2018		6.42	5.95	5.59		
2016	2.5-5km	7.12	6.89	5.92	7.89	7.86
2017		7.10	6.29	5.82		
2018		6.92	6.05	5.89		
2016-2018		7.05	6.41	5.88		

Table S3. Root mean square error (RMSE) values of groundwater level (m) from 2016 to 2018 for the open-loop (OL) and multivariate assimilation scenarios (FC_DA, FC_DA_PAR, WC_DA, WC_DA_PAR,

WC_DA_r and WC_DA_r_PAR). Note: "0 km" indicates assimilation locations; validation sites are grouped by distance from these points: <0.5 km, 0.5-2.5 km, and 2.5-5 km.

Year	Distance	OL	FC_DA	FC_DA_PAR	WC_DA	WC_DA_PAR	WC_DA_r	WC_DA_r_PAR
2016	0	7.30	3.36	3.27	3.17	2.17	3.25	2.38
2017		7.24	4.29	3.19	2.93	1.98	3.02	2.05
2018		7.24	3.64	3.32	3.38	2.03	2.62	2.15
2016-2018		7.26	3.76	3.26	3.16	2.06	2.96	2.19
2016	0-0.5km	7.27	4.73	4.55	4.11	4.24	4.40	4.52
2017		6.98	4.00	3.71	3.92	4.60	4.25	3.46
2018		6.77	3.15	3.70	3.85	3.56	3.93	3.58
2016-2018		7.01	3.96	3.98	3.96	4.13	4.19	3.85
2016	0.5-2.5km	6.49	6.53	6.01	5.66	8.00	5.82	5.65
2017		6.45	5.84	5.74	5.55	5.68	5.72	5.58
2018		6.31	5.44	5.75	5.53	5.60	5.72	5.55
2016-2018		6.42	5.93	5.83	5.58	6.43	5.75	5.59
2016	2.5-5km	7.12	6.55	6.18	6.09	8.54	7.92	6.20
2017		7.10	6.03	5.91	5.99	6.18	7.46	8.17
2018		6.92	5.77	5.92	6.01	5.92	6.37	5.91
2016-2018		7.05	6.12	6.00	6.03	6.88	7.25	6.76

Table S4. Evaluation metrics of root mean square error (RMSE) and correlation coefficients (R) for soil moisture and evapotranspiration during 2016-2018 in open-loop (OL) and multivariate assimilation scenarios of soil moisture (FC_DA, FC_DA_PAR, WC_DA, WC_DA_PAR, WC_DA_r and WC_DA_r_PAR).

Year	Variable	OL	FC_DA	FC_DA_PAR	WC_DA	WC_DA_PAR	WC_DA_r	WC_DA_r_PAR
2016	SM (RMSE, cm^3/cm^3)	0.11	0.05	0.05	0.07	0.05	0.06	0.05
2017		0.10	0.07	0.06	0.05	0.04	0.05	0.04
2018		0.09	0.08	0.05	0.07	0.04	0.05	0.04
2016-2018		0.10	0.07	0.05	0.06	0.04	0.05	0.05
2016	SM (R)	0.62	0.85	0.87	0.75	0.90	0.74	0.88
2017		0.63	0.74	0.81	0.85	0.89	0.86	0.88
2018		0.61	0.69	0.85	0.71	0.92	0.88	0.89
2016-2018		0.62	0.76	0.84	0.77	0.90	0.83	0.88
2016	ET (RMSE, mm/day)	0.76	0.71	0.71	0.71	0.71	0.71	0.71
2017		0.79	0.77	0.77	0.77	0.77	0.77	0.77
2018		0.73	0.75	0.75	0.75	0.75	0.75	0.75
2016-2018		0.76	0.74	0.75	0.74	0.74	0.74	0.74
2016	ET (R)	0.82	0.81	0.81	0.81	0.81	0.81	0.81
2017		0.86	0.86	0.86	0.86	0.86	0.86	0.86
2018		0.83	0.82	0.82	0.82	0.82	0.82	0.82
2016-2018		0.84	0.83	0.83	0.83	0.83	0.83	0.83

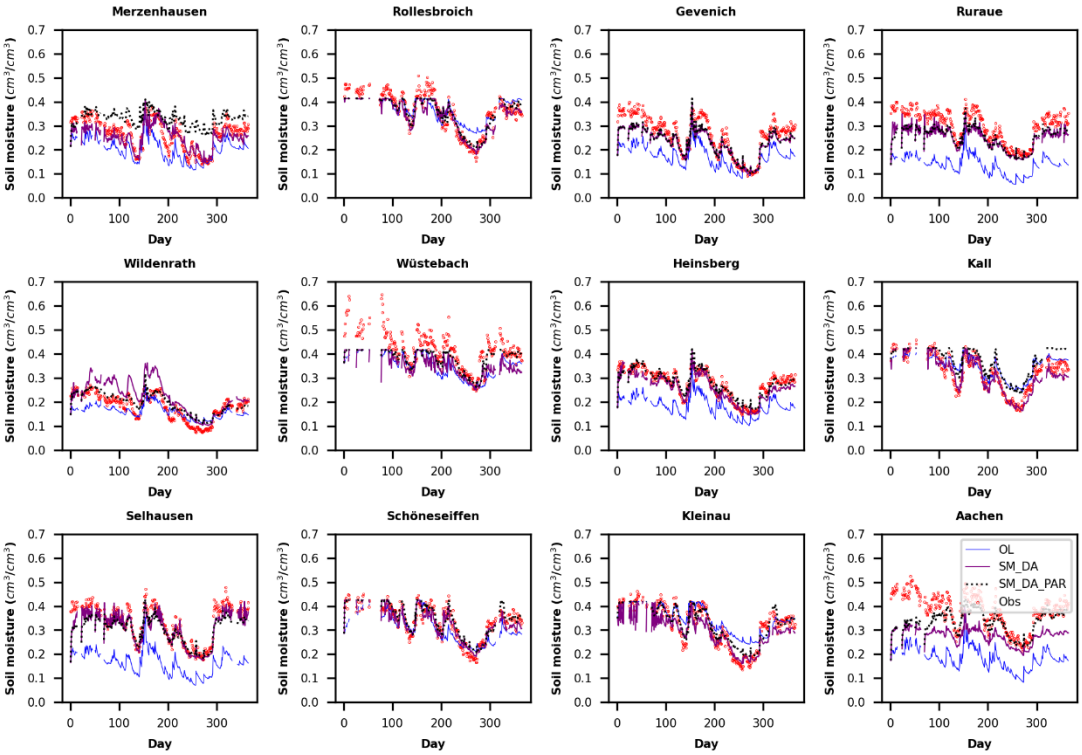

Figure S1. The soil moisture dynamics during 2016 were estimated using the OL (blue), SM_DA (green), and SM_DA_PAR (black) scenarios and compared with field data obtained from CRNS instruments (red). Vertical weighting was applied to the simulated soil moisture to accurately represent the soil profile.

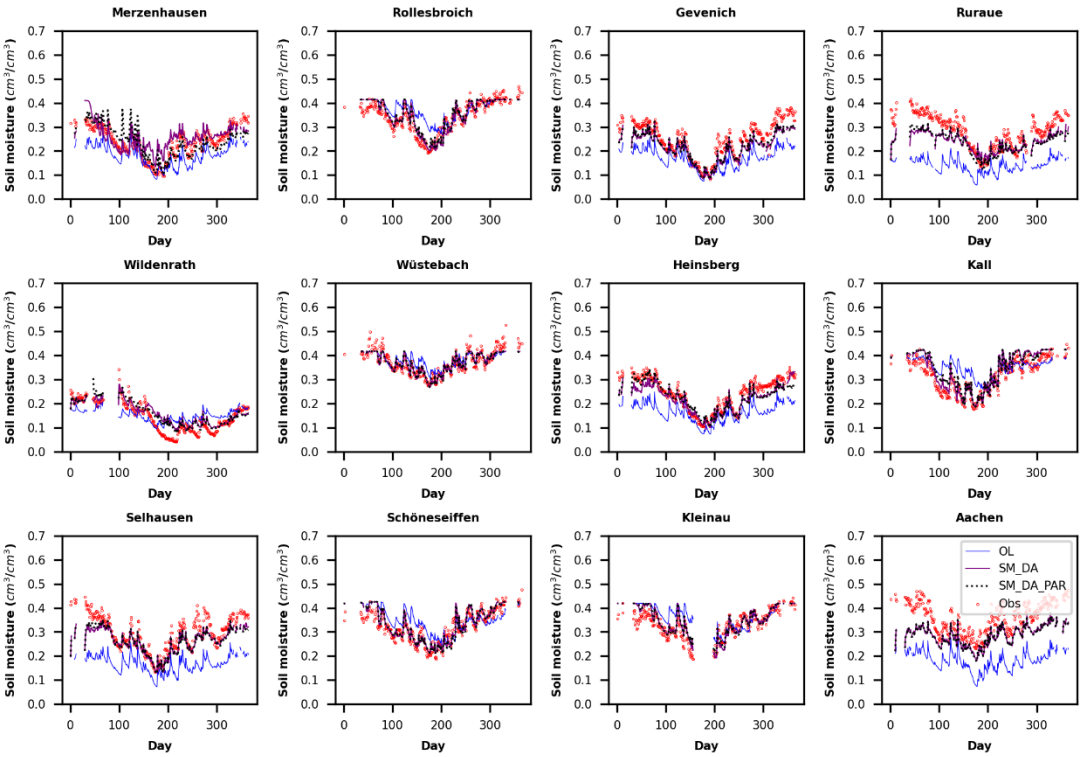

Figure S2. The soil moisture dynamics during 2017 were estimated using the OL (blue), SM_DA (green), and SM_DA_PAR (black) scenarios and compared with field data obtained from CRNS instruments (red). Vertical weighting was applied to the simulated soil moisture to accurately represent the soil profile.

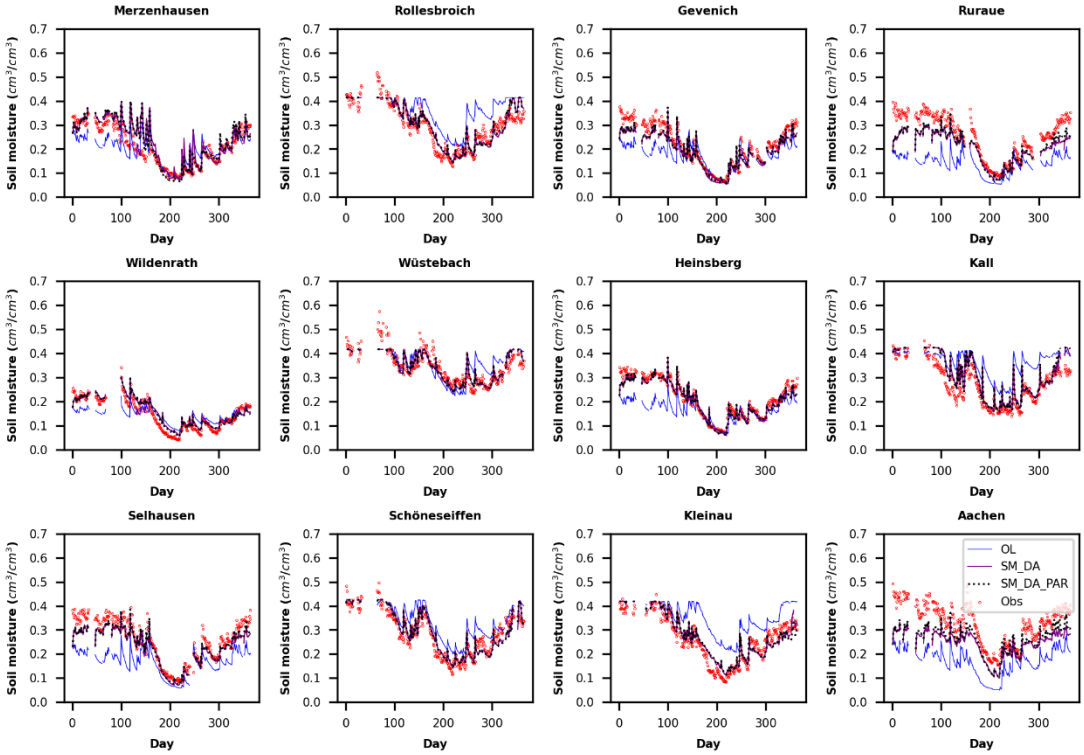

Figure S3. The soil moisture dynamics during 2018 were estimated using the OL (blue), SM_DA (green), and SM_DA_PAR (black) scenarios and compared with field data obtained from CRNS instruments (red). Vertical weighting was applied to the simulated soil moisture to accurately represent the soil profile.

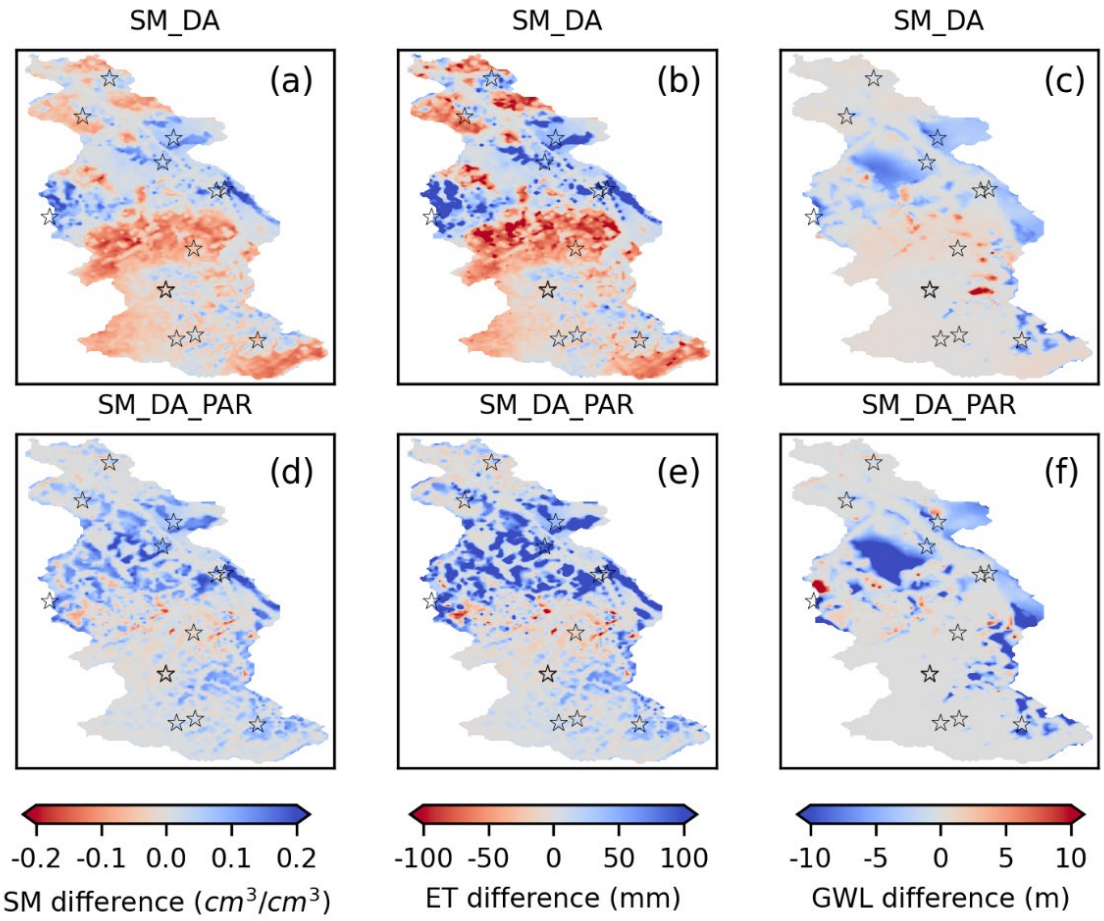

Figure S4. Spatial variations in annual soil moisture (0-80 cm), evapotranspiration, and groundwater level for 2016 are presented in panels (a)-(c), illustrating differences between SM_DA and OL simulations (SM_DA - OL). Panels (d)-(f) display similar contrasts between SM_DA_PAR and OL (SM_DA_PAR - OL). Black pentagrams indicate the locations of the CRNS monitoring stations.

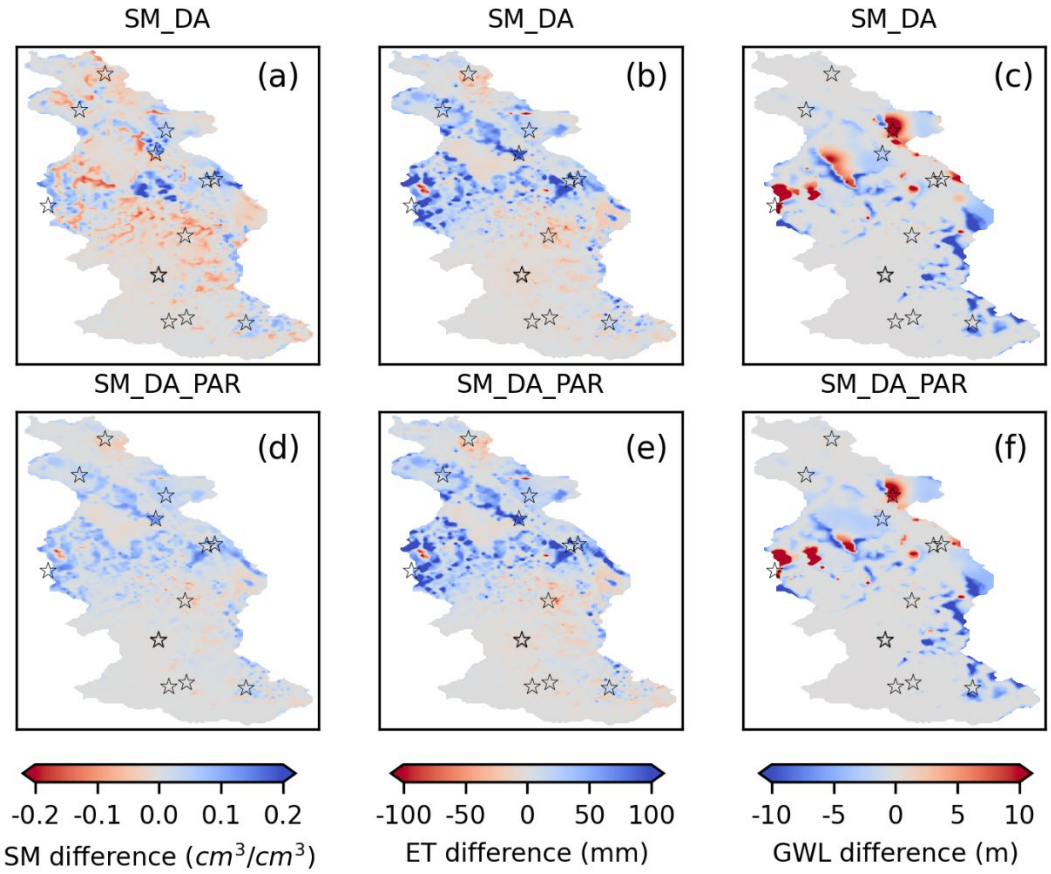

Figure S5. Spatial variations in annual soil moisture (0-80 cm), evapotranspiration, and groundwater level for 2017 are presented in panels (a)-(c), illustrating differences between SM_DA and OL simulations (SM_DA - OL). Panels (d)-(f) display similar contrasts between SM_DA_PAR and OL (SM_DA_PAR - OL). Black pentagrams indicate the locations of the CRNS monitoring stations.

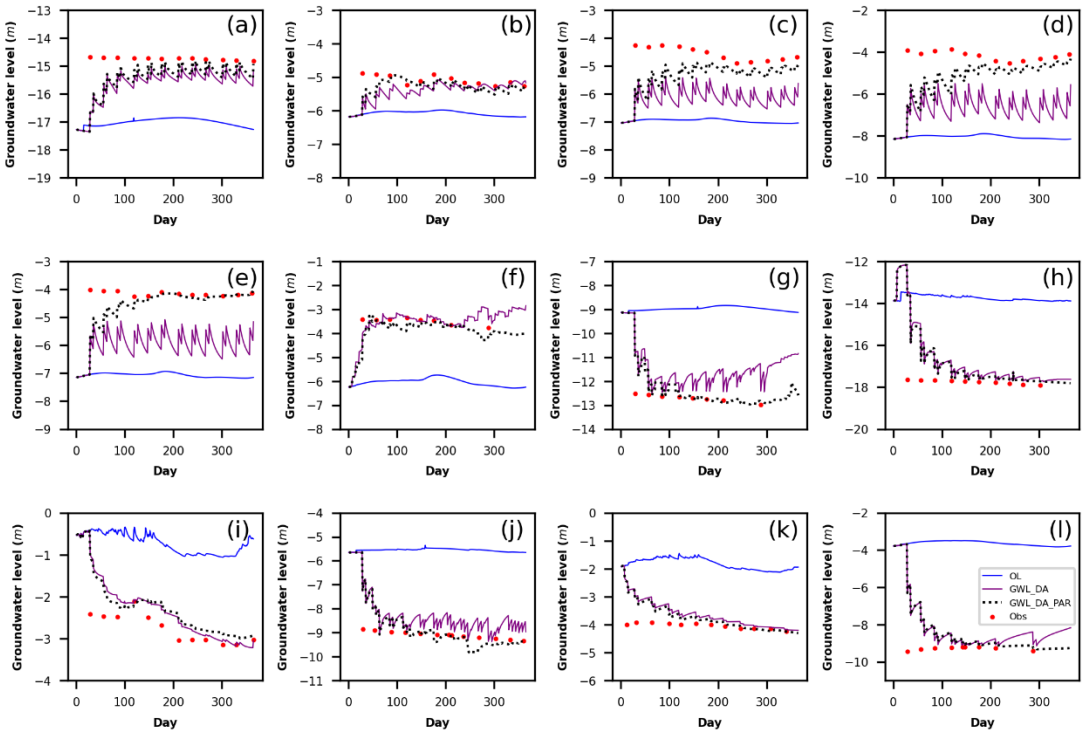

Figure S6. The groundwater level dynamics during 2018 were estimated using the OL (blue), GWL_DA

(green), and GWL_DA_PAR (black) scenarios and compared with field data obtained from 12 selected assimilated groundwater wells (red).

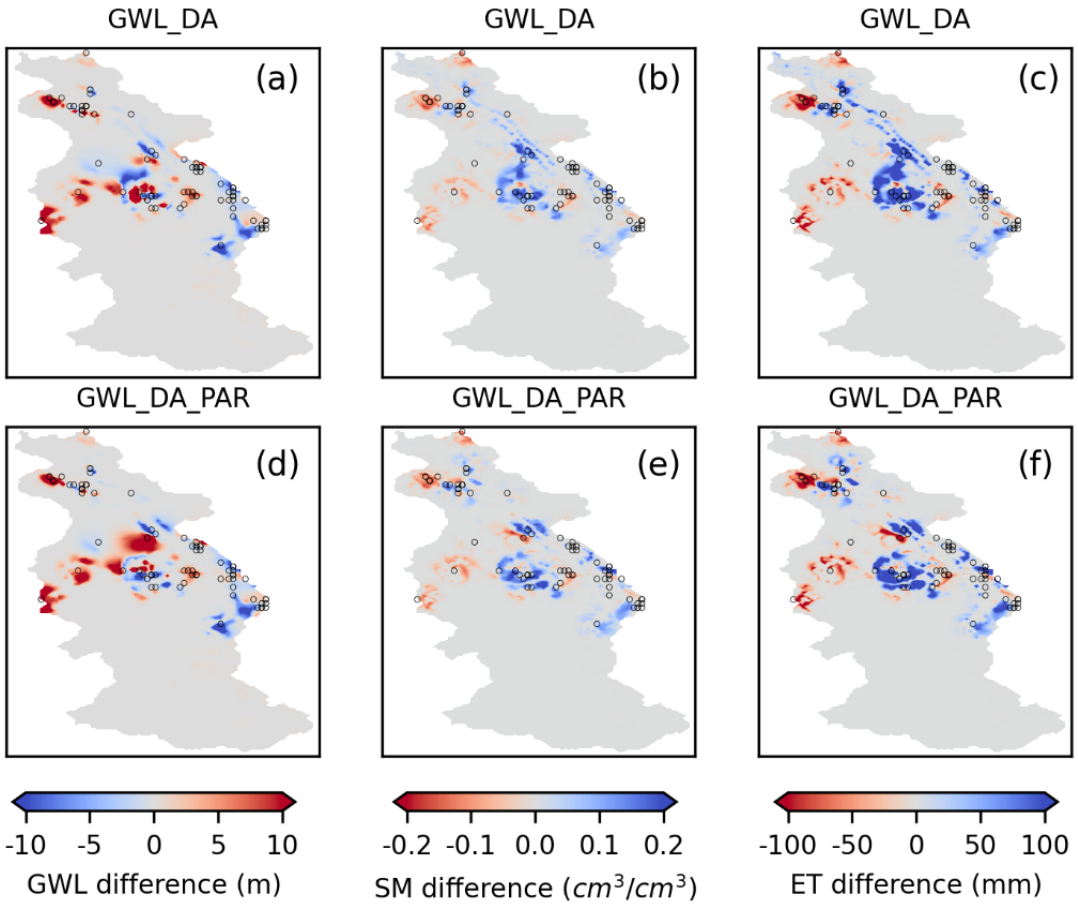

Figure S7. Spatial variations in annual groundwater level, soil moisture (0-80 cm), and evapotranspiration for 2016 are presented in panels (a)-(c), illustrating differences between GWL_DA and OL simulations (GWL_DA - OL). Panels (d)-(f) display similar contrasts between GWL_DA _PAR and OL (GWL_DA _PAR - OL). Black circles indicate the locations of the groundwater monitoring sites.

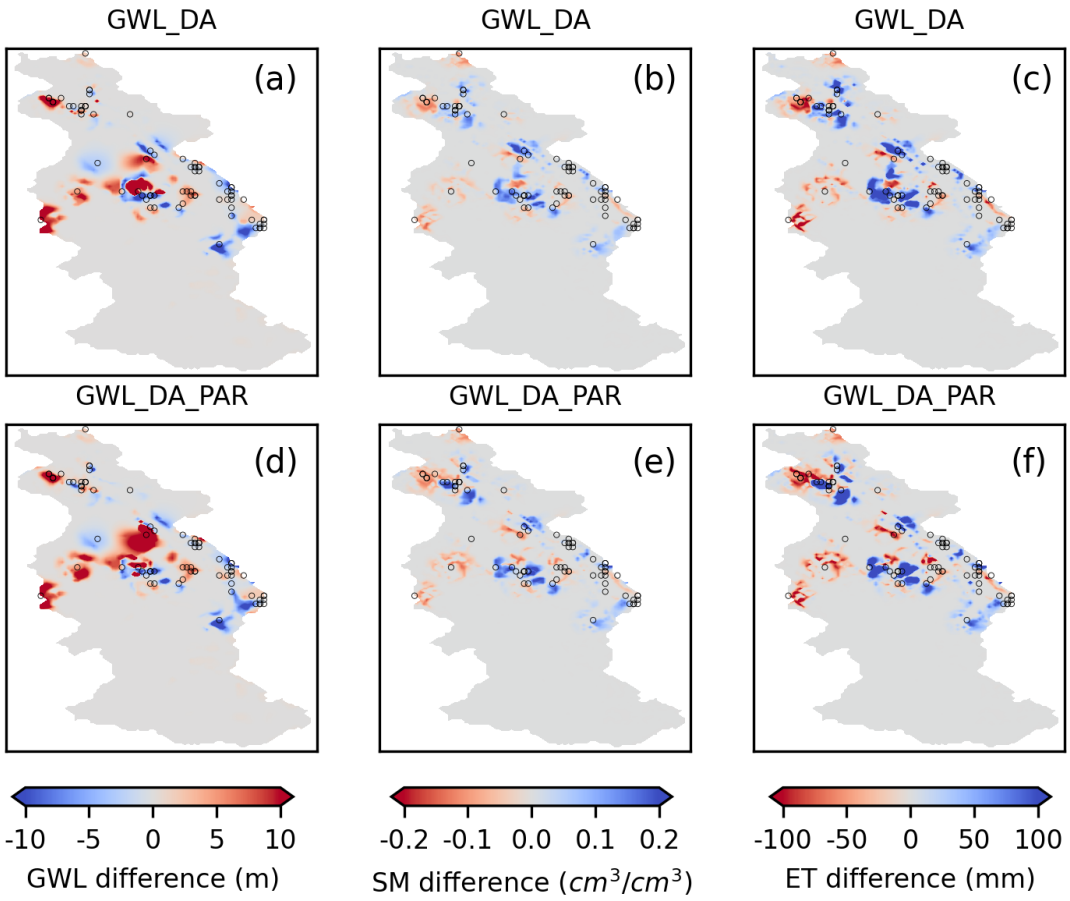

Figure S8. Spatial variations in annual groundwater level, soil moisture (0-80 cm), and evapotranspiration for 2017 are presented in panels (a)-(c), illustrating differences between GWL_DA and OL simulations (GWL_DA - OL). Panels (d)-(f) display similar contrasts between GWL_DA _PAR and OL (GWL_DA _PAR - OL). Black circles indicate the locations of the groundwater monitoring sites.

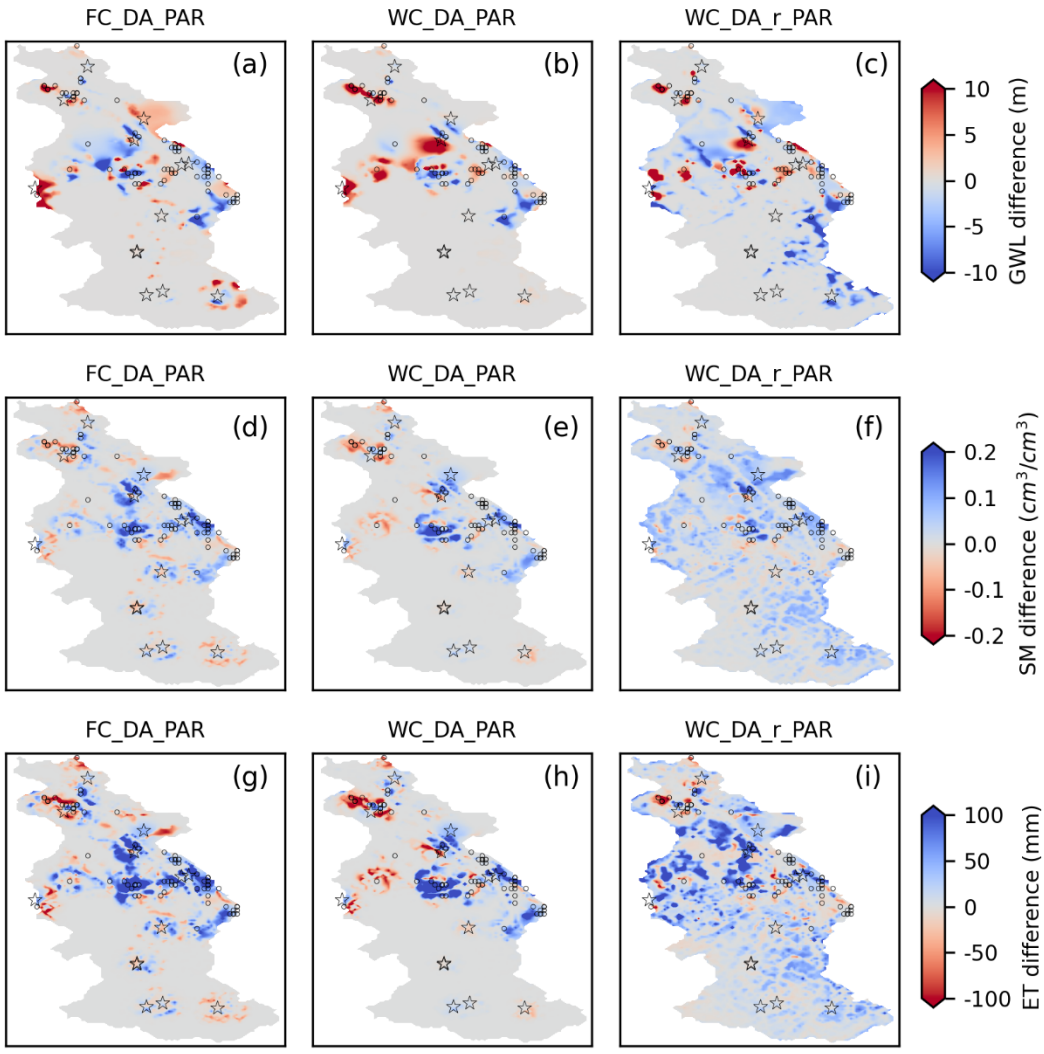

Figure S9. Spatial variations in the 2016 annual differences of groundwater level, 0-80 cm soil moisture, and evapotranspiration are shown in panels (a, d, g), comparing multivariate data assimilation scenarios FC_DA_PAR with the open-loop (OL) run. Panels (b, e, h) and (c, f, i) illustrate the respective differences for WC_DA_PAR and WC_DA_r_PAR scenarios. Locations of CRNS and assimilated groundwater wells are indicated by black pentagrams and circles.

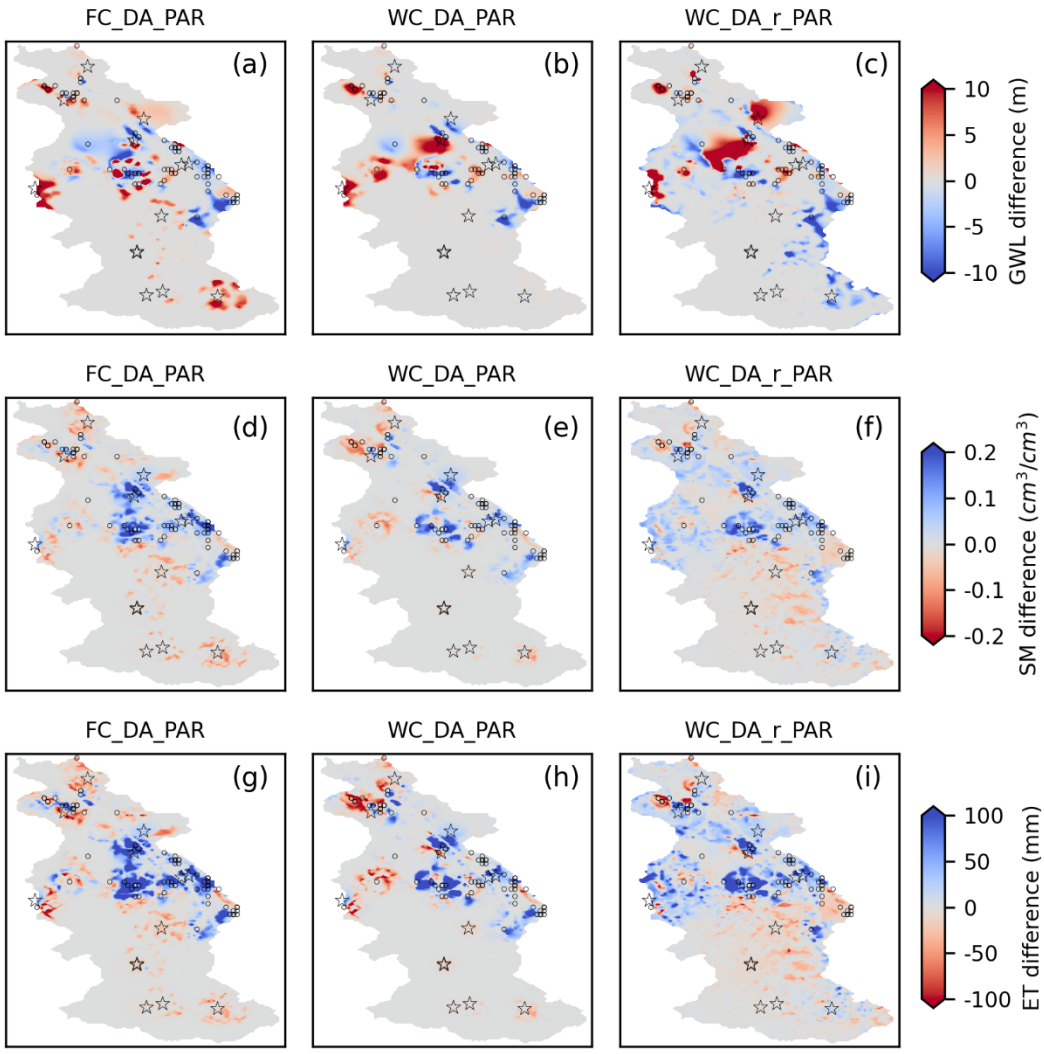

Figure S10. Spatial variations in the 2017 annual differences of groundwater level, 0-80 cm soil moisture, and evapotranspiration are shown in panels (a, d, g), comparing multivariate data assimilation scenarios FC_DA_PAR with the open-loop (OL) run. Panels (b, e, h) and (c, f, i) illustrate the respective differences for WC_DA_PAR and WC_DA_r_PAR scenarios. Locations of CRNS and assimilated groundwater wells are indicated by black pentagrams and circles.

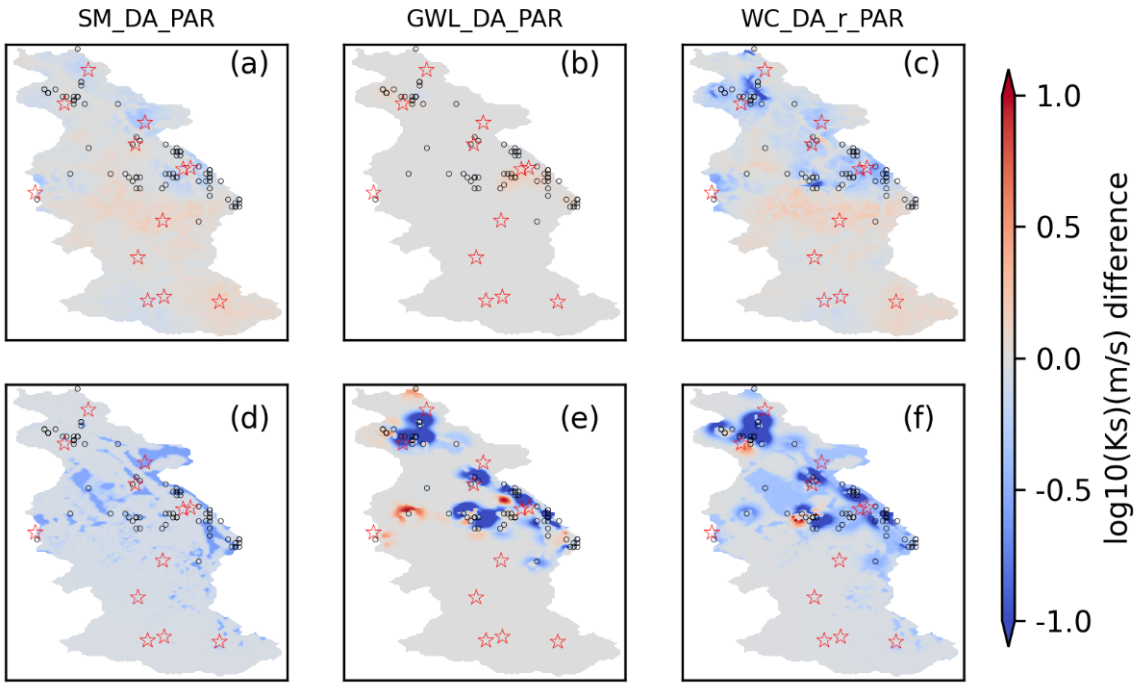

Figure S11. Spatial comparisons of ensemble mean $\log_{10}K_s$ between the open-loop run and multiple data assimilation schemes for the year 2016. Panels (a) and (d) illustrate results from SM_DA_PAR; (b) and (e) display outputs for GWL_DA_PAR; (c) and (f) depict results from WC_DA_r_PAR. The upper panels correspond to measurements at 2 cm soil depth, while the lower panels represent values at 10 m depth. Locations of CRNS measurement sites and assimilated groundwater wells are indicated by red pentagrams and black circles, respectively.

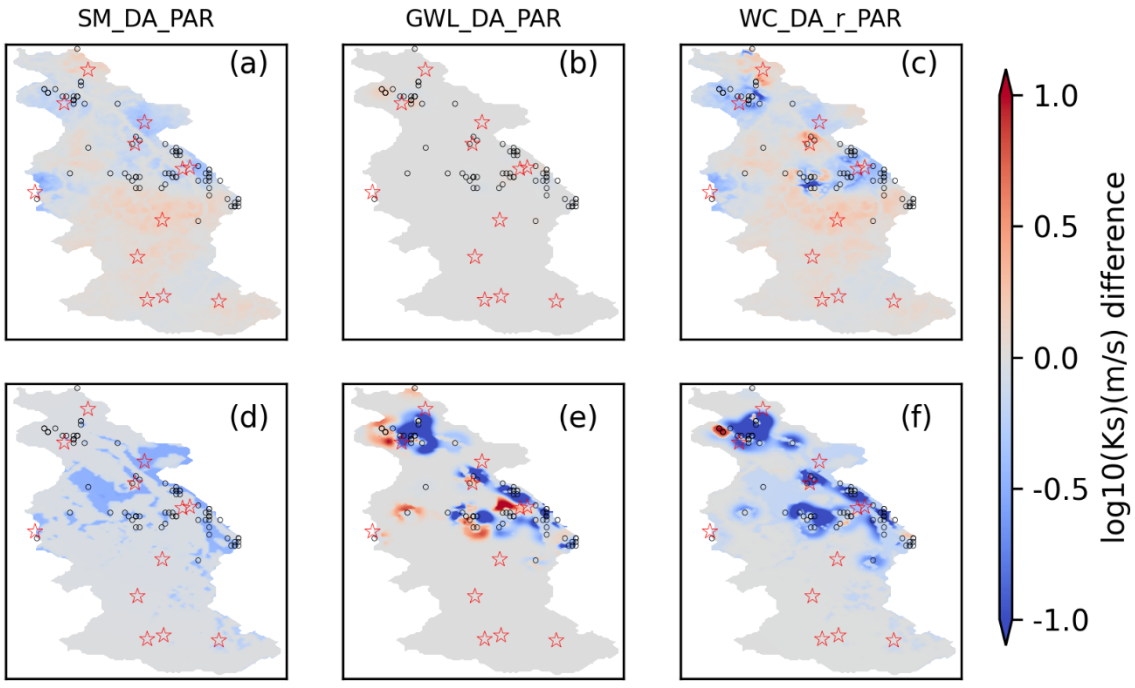

Figure S12. Spatial comparisons of ensemble mean $\log_{10}K_s$ between the open-loop run and multiple data assimilation schemes for the year 2017. Panels (a) and (d) illustrate results from SM_DA_PAR; (b) and (e) display outputs for GWL_DA_PAR; (c) and (f) depict results from WC_DA_r_PAR. The upper panels correspond to measurements at 2 cm soil depth, while the lower panels represent values at 10 m depth. Locations of CRNS measurement sites and assimilated groundwater wells are indicated by red pentagrams and black circles, respectively.