Supplementary information for "Global assessment of how reservoirs and desalination plants enhance human water security"

Corresponding author: Akiko Matsumura (matsumura-ak@n-koei.jp)

Table of Contents:

Supplementary Discussions

Reproducibility of river discharge

To verify whether the model adequately represents the effects of reservoirs and desalinations (RDs), we examined whether incorporating RDs improves the model's ability to reproduce observed streamflow. The analysis focused on 12 basins selected from the top 20 basins where RDs most effectively mitigated water scarcity and for which more than 10 years of monthly discharge observations were available. River discharge data were obtained from the Global Runoff Data Centre (GRDC), 56068 Koblenz, Germany.

For each basin, up to three gauging stations were selected. The selection criteria were as follows: (i) the presence of upstream reservoirs; (ii) the dominance of reservoirs constructed before 1980; and (iii) a preference for stations with smaller discharge bias, defined as the ratio of long-term mean discharge between observations and simulations, when multiple stations were available. Criteria (iii) was adopted because extremely large deviations in observed discharge often indicate problems such as positional discrepancies or the influence of nearby artificial water-intake facilities. Model performance was evaluated using the Kling–Gupta efficiency (KGE)[1] and its three components—correlation, variability, and bias—based on monthly discharge.

The results (Supplementary Fig. 4 and Supplementary Table 3) show that, in most basins, the inclusion of RDs led to higher KGE values, indicating that the model reproduced the observed discharge variability more accurately. Corresponding improvements were found in the individual KGE components when RDs were considered. An exception was the Syr Darya Basin, where the model's baseline performance was already low. Previous studies have suggested that this may be related to issues in the precipitation datasets used for the region[2].

Overall, the model tended to exhibit a positive bias (i.e., overestimation of streamflow), particularly in the Murray–Darling, Godavari, Krishna, and Guadalquivir basins. This overestimation is consistent with the known limitations of global hydrological models reported in previous studies[3]. In several basins, such as Sacramento and Chao Phraya, the simulated peaks remained higher than the observed peaks even when RDs were considered (Supplementary Figs. 5–9). One possible reason is that the reservoir operations in this study did not account for purposes other than water supply, such as hydropower generation, leading to an underestimation of reservoir regulation effects. In the Krishna Basin, the inclusion of RDs improved the simulation of wet-season flows, bringing them closer to the observations. However, it also led to an overestimation of dry-season flows, possibly due to uncertainties in irrigation return flow and evaporation losses (Supplementary Fig. 5).

Despite these basin-specific issues, the overall results demonstrate that the model more accurately reproduces the observed discharge when RDs are incorporated, confirming the importance of explicitly representing reservoir and desalination processes in large-scale hydrological modelling.

Reproducibility of reservoir storage

To verify reservoir operations, we used in situ reservoir storage records of reservoirs in the Murray River Basin provided by the Australian Breau. of Meteaorology[4]. This basin was chosen for the validation study because it is a basin where reservoirs play a major role in water supply and because of the availability of quality-controlled data for this basin. Among the reservoirs in the basin, 13 reservoirs with a water supply capacity greater than 50 million cubic meters and an observation period covering the years 1980–2019 were selected. Four metrics were used for comparison: the relative root mean square error (rRMSE, calculated as the RMSE normalized by the mean of the observed reservoir storage), the correlation coefficient of monthly reservoir storage (CC-M), the correlation coefficient of mean monthly reservoir storage (CC-MM), and the correlation coefficient of annual reservoir storage (CC-A).

Supplementary Table 4 shows good agreement between the observed and simulated reservoir storage values, with CC-M values exceeding 0.6 in 10 of the 13 reservoirs, CC-A values exceeding 0.6 in 9 reservoirs, and CC-MM values exceeding 0.8 in 12 reservoirs, indicating high reproducibility of the seasonal variation. The time series of observed and simulated monthly reservoir storage for reservoirs in good agreement are shown in Supplementary Figs. 10--11.

Each reservoir with poor agreement, as shown in Supplementary Fig. 12, was considered to have different factors. For Blowering, the underestimation of storage variability in the simulation may be attributed to the underestimation of river flow into the reservoir. The simulated average river flow at the reservoir was approximately 16 m^3/s, whereas the observation was approximately 46 m^3/s (the value of river flow at the "Tumut River at Oddys bridge"[4] just downstream of the Blowering Dam), nearly three times greater than the simulation. The Waranga Basin provides off-river storage, and water is diverted from surrounding rivers via canals[5]. The underestimation of storage variability in the simulated reservoir may be attributed to the underestimation of inflows to the reservoir because the interbasin or intertributary canals were not implemented in the simulation. The Yarrawonga weir works to increase the water level in the river Murray so that water can be diverted via channels to irrigate land[6]. This function is completely different from that of a dam, and the poor reproducibility of seasonal variations may be explained by the fact that this was a weir.

Overall, despite the limitations of our methodology in reservoir operation models (see Methods in main), time series of reservoir storage correlate well with observations in most of the water supply reservoirs in the Murray River Basin. For reservoirs with poor reproducibility in the Murray River Basin, the issues were outside the reservoir operation model. To address issues in such reservoirs, improving the reproducibility of river flows, incorporating canals associated with reservoirs, and distinguishing weirs that operate differently from reservoirs would be effective.

Supplementary Tables

Supplementary Table 1: Global hydrological fluxes, human water requirements, and deficits in available water resources, with and without infrastructure. Evaluated under climatic conditions from 1980–2019 and social conditions in approximately 2015. Drylands and humid lands are evaluated on the basis of the aridity index (see Extended Data Fig. 3 in the main text).

Run name	**Natural**	**woRD**		**woRDwD**			**wRD**		
Unit	**km^3 year^{-1}**	**km^3 year^{-1}**	**(%) a)**	**km^3 year^{-1}**	**(%) b)**	**(%) b) - a)**	**km^3 year^{-1}**	**(%) c)**	**(%) c) - a)**
Precipitation	**114,145**	**114,145**		**114,145**			**114,145**		
Evapotranspiration	**68,397**	**68,959**		**68,959**			**68,959**		
River discharge	**45,468**	**45,021**		**45,025**			**44,859**		
HWRs (Global)	-	**4,100**		**4,100**			**4,100**		
Domestic		475		475			475		
Industrial		662		662			662		
Agricultural		2,962		2,962			2,962		
Water deficit (Global)	-	**1,526**	**37.2**	**1,522**	**37.1**	**-0.10**	**1,304**	**31.8**	**-5.42**
Chronic deficit		590	14.4	586	14.3	-0.10	583	14.2	-0.16
Temporal deficit		936	22.8	937	22.8	0.00	721	17.6	-5.26
HWRs (Drylands)	-	**2,198**		**2,198**			**2,198**		
Domestic		191		666			666		
Industrial		223		885			885		
Agricultural		1,784		4,746			4,746		
Water deficit (Drylands)	-	**1,120**	**51.0**	**1,116**	**50.8**	**-0.18**	**978**	**44.5**	**-6.45**
Chronic deficit		561	25.5	557	25.3	-0.19	555	25.2	-0.29
Temporal deficit		559	25.4	559	25.4	0.00	424	19.3	-6.16
HWRs (Humid lands)	-	**1,902**		**1,902**			**1,902**		
Domestic		284		284			284		
Industrial		439		439			439		
Agricultural		1,178		1,178			1,178		
Water deficit (Humid lands)	-	**406**	**21.4**	**406**	**21.4**	**0.00**	**326**	**17.1**	**-4.23**
Chronic deficit		29	1.5	29	1.5	0.00	28	1.5	-0.02
Temporal deficit		378	19.9	378	19.9	0.00	297	15.6	-4.21

a)-c) indicate percentages relative to the total HWRs within each region (global, drylands, humid lands).

Abbreviations:

HWRs: Human Water Requirements, Natural: naturalized conditions (without human intervention)

woRD: without Reservoirs and Desalinations, woRDwD: with Desalinations, wRD: with Reservoirs and Desalinations

Supplementary Table 2: Top 20 basins where RDs most effectively reduced water scarcity. The basins included in the rankings have areas larger than 50,000 km² and an average natural flow exceeding 20 m³/s. The values for RFAs, type, and the reduction in the CDTD due to RDs correspond to those shown in Fig. 4 in the main text.

			Basin water scarcity indexes			Flow alterations by RDs				Hydrological conditions								
No.	Name (river/basin)	Country	CDTD (woRD)	Chronic Deficit (% of total deficit)	ΔCDTD by RDs	a) Total RFA (%)	b) Inter-annual RFA (%)	b) % of a)	Type	Area (km^2)	c) Average water resources (m^3 s^{-1})	d) Average human water requirements (m^3 s^{-1})	d) % of c)	Aridity Index	e) CV of monthly river discharge	f) CV of annual river discharge	f) % of e)	Number of reservoirs
		*							**		***				***	***		
1	Krishna	India	42.7	11.5	25.2	37.1	4.3	11.6	A	257,187	2,377	2,018	84.9	0.39	1.39	0.26	19.0	62
2	Sacramento	USA	24.6	0.0	21.2	17.5	4.3	24.4	B	71,377	1,354	213	15.8	0.66	1.37	0.45	33.0	50
3	Narmada	India	51.9	0.0	20.7	25.4	2.1	8.2	A	96,371	1,883	733	38.9	0.56	1.66	0.29	17.2	12
4	Syr Darya	see List A*	39.9	24.5	20.4	25.7	6.5	25.5	B	355,877	781	614	78.6	0.28	0.93	0.31	33.3	13
5	Chao Phraya	Thailand	60.1	27.4	19.3	27.0	4.2	15.7	A	160,313	2,005	1,849	92.2	0.71	1.17	0.28	24.1	10
6	Red	China, Vietnam	25.8	0.0	19.0	6.6	0.3	5.1	A	140,962	3,040	285	9.4	1.24	1.07	0.15	14.1	20
7	Godavari	India	39.1	1.8	18.9	13.1	1.7	13.3	A	308,639	5,354	1,413	26.4	0.57	1.46	0.26	17.6	56
8	Guadalquivir	Spain	30.6	0.0	18.0	20.7	8.6	41.5	C	57,272	316	126	39.8	0.41	1.73	0.75	43.2	37
9	Tigris Euphrates	See List B*	42.0	27.3	17.9	24.7	4.9	20.0	B	772,774	2,540	1,517	59.7	0.17	0.87	0.39	45.0	50
10	Colombia	USA	28.3	9.2	17.2	7.7	1.0	12.8	A	650,913	6,106	913	15.0	0.62	0.62	0.22	35.9	124
11	Hooghly	India	37.4	0.0	16.0	16.7	1.4	8.2	A	81,065	1,800	802	44.6	0.86	1.33	0.27	20.0	8
12	Balsas	Mexico	38.8	0.0	14.5	5.8	0.5	8.8	A	112,977	968	160	16.6	0.54	1.16	0.26	22.0	15
13	Moulouya	Morrocco	22.9	0.0	14.5	18.2	8.0	43.8	C	54,604	44	14	32.3	0.17	1.47	0.79	53.9	3
14	Tapti	India	36.9	0.0	14.1	9.6	1.0	10.2	A	64,457	778	200	25.8	0.45	1.73	0.37	21.4	8
15	Murray-Darling	Australia	31.2	42.3	13.7	14.3	5.0	35.1	C	931,506	1,426	467	32.7	0.24	0.94	0.47	49.5	54
16	Save	See List C*	18.2	0.0	12.1	5.5	1.9	34.2	C	101,682	384	30	7.9	0.34	2.27	0.83	36.5	23
17	Mahanadi	India	42.2	0.0	11.9	10.0	1.1	11.1	A	135,089	3,279	1,117	34.1	0.73	1.49	0.22	15.0	22
18	Tagus	Spain	14.2	0.0	11.6	14.3	5.0	35.1	C	84,988	565	155	27.5	0.46	1.37	0.50	36.7	48
19	Mekong	See List D*	28.4	0.0	11.0	4.0	0.2	5.9	A	777,152	17,727	1,677	9.5	0.98	0.90	0.12	13.8	38
20	Yaqui	Mexico	26.3	0.0	10.8	17.0	6.3	37.0	C	72,457	119	37	30.7	0.32	1.28	0.45	35.1	3

Abbreviations) RD: Reservoirs and Desalinations, woRD: without Reservoirs and Desalinations, CDTD: Cumulative Deficit to Demand, RFA: Relative Flow Alteration, CV: Coefficient of Variance

*) List A: [Kyrgyzstan, Uzbekistan, Tajikistan, Kazakhstan], List B: [Turkey, Syria, Iraq, Iran, Kuwait], List C: [Zimbabwe, Mozambique], List D: [Cambodia, China, Lao PDR, Myanmar, Thailand, Vietnam]

**) Type A: seasonal reallocator, Type B: moderate interannual buffer, Type C: strong interannual buffer, Type D: freshwater augmenter

***) Evaluated under naturalized conditions (i.e., without human intervention)

Supplementary Table 3: Validation results for monthly discharge based on the Kling-Gupta Efficiency (KGE) and its three components. The results are shown for 25 stations across 12 basins.

GRCD ID	River discharge station metadata							woRD simulation				wRD simulation			
	Basin name	Station name	Latitude	Longitude	Catchment area (km^2)	Altitude (m)	Availability (year)	KGE	r	α	β	KGE	r	α	β
2854180	Krishna	YADGIRI	16.737	77.127	69,863	350	29.7	-0.77	0.76	1.88	2.52	-0.17	0.80	1.34	2.10
2854400	Krishna	BAWAPURAM	15.8831	77.9569	67,180	272	37.2	-2.20	0.73	2.75	3.67	-1.47	0.79	2.07	3.22
4146281	Sacramento	VERONA, CA	38.7743	-121.5983	55,040	-1	40.0	-1.86	0.84	3.72	1.87	-1.45	0.87	3.29	1.85
4146270	Sacramento	FAIR OAKS, CA	38.6355	-121.2277	4,890	22	40.0	-0.04	0.66	1.90	1.40	0.20	0.72	1.64	1.40
2416850	Syr-Darya	UCH-KURGAN	41.17	72.1	58,400	498	11.0	-0.30	-0.04	0.60	0.32	-0.66	-0.33	0.28	0.32
2964100	Chao-Phraya	NAKHON SAWAN	15.67	100.12	110,569	17	14.3	-1.50	0.72	3.29	1.96	-0.39	0.72	2.08	1.82
2964150	Chao-Phraya	UTHAI THANI	15.3797	100.0353	3,865	-999	15.9	-1.45	0.73	3.18	2.08	-0.40	0.73	2.05	1.88
2856500	Godavari	MANCHERIAL	18.83444	79.4517	102,900	124	38.3	-2.35	0.68	2.44	4.01	-1.94	0.72	1.88	3.79
2856550	Godavari	ASHTI	19.685	79.789	50,990	137	40.0	0.04	0.91	1.59	1.75	0.15	0.92	1.46	1.70
2856900	Godavari	POLAVARAM	17.252	81.6525	299,320	-999	39.9	-0.24	0.89	1.80	1.93	-0.08	0.89	1.61	1.89
6217100	Guadalquivir	ALCALA DEL RIO	37.51844	-5.97639	46,134	10	15.8	-2.89	0.92	3.44	4.02	-2.48	0.92	2.62	4.08
6217135	Guadalquivir	CORDOBA	37.87936	-4.77485	24,704	86	15.8	-2.58	0.83	4.12	2.73	-1.12	0.80	2.36	2.61
4115200	Colombia	THE DALLES, OR	45.6073	-121.1734	613,830	-999	40.0	0.47	0.78	1.44	0.79	0.57	0.78	1.29	0.77
4115080	Colombia	CASTLE ROCK, WA	46.2748	-122.9146	5,796	6	32.8	0.18	0.85	1.80	1.14	0.18	0.85	1.80	1.14
4115101	Colombia	PORTLAND, OR	45.5185	-122.6679	29,008	0	40.0	0.60	0.95	1.38	1.13	0.64	0.96	1.34	1.13
4355225	Balsas	CAIMANERA, MICH.	18.5	-100.9	-999	234	22.9	-1.14	0.93	2.60	2.43	-1.05	0.93	2.51	2.39
5204101	Murray-Darling	D/S MAUDE WEIR	-34.4776	144.301	57,700	80	37.0	-2.30	0.78	3.14	3.50	-1.64	0.80	2.37	3.25
5304140	Murray-Darling	BELOW WAKOOL JUNCTION	-34.8472	143.342	116,393	64	39.0	-1.51	0.66	2.80	2.71	-0.71	0.78	1.98	2.38
6113050	Tagus	ALMOUROL	39.461	-8.375	67,482	19	37.3	0.17	0.93	1.57	1.61	0.29	0.94	1.36	1.61
6113110	Tagus	ALBUFEIRA DE BELVER (R.E.)	39.48	-7.998	61,540	39	29.6	-0.25	0.91	1.89	1.87	-0.06	0.92	1.61	1.86
2969220	Mekong	KAENG SAPHU TAI (DOWNSTREAM)	15.24	105.2483	116,000	105	14.0	-0.05	0.91	1.68	1.79	0.14	0.91	1.50	1.70
2969200	Mekong	UBON	15.2217	104.8617	104,000	105	14.0	-0.18	0.87	1.69	1.95	0.03	0.87	1.47	1.84
2969150	Mekong	YASOTHON	15.7817	104.1417	43,100	117	13.0	-0.44	0.83	2.05	1.98	0.06	0.83	1.46	1.80
4353015	Yaqui	EL CUBIL	29.216667	-109.233333	-999	350	30.0	0.71	0.79	0.81	1.04	0.69	0.78	0.79	1.04
4353020	Yaqui	EL CUBIL, SON.	29.2	-109.233333	-999	350	24.3	0.59	0.65	1.17	1.14	0.60	0.64	1.12	1.13

Station name, latitude, longitude, catchment area, and altitude are obtained from the Global Runoff Data Centre (GRDC), 56068 Koblenz, Germany.
Availability indicates the number of years for which observational data are available between 1980 and 2019.
"-999" denotes undefined (missing) values.
KGE, r, α, and β represent the Kling–Gupta efficiency and its three components: the correlation coefficient (r), the ratio of standard deviations (α), and the mean bias ratio (β).
woRD: without Reservoirs and Desalinations, wRD: with Reservoirs and Desalinations

Better : wRD performs better than woRD.
Same : no difference between wRD and woRD.
Worse : wRD performs worse than woRD.

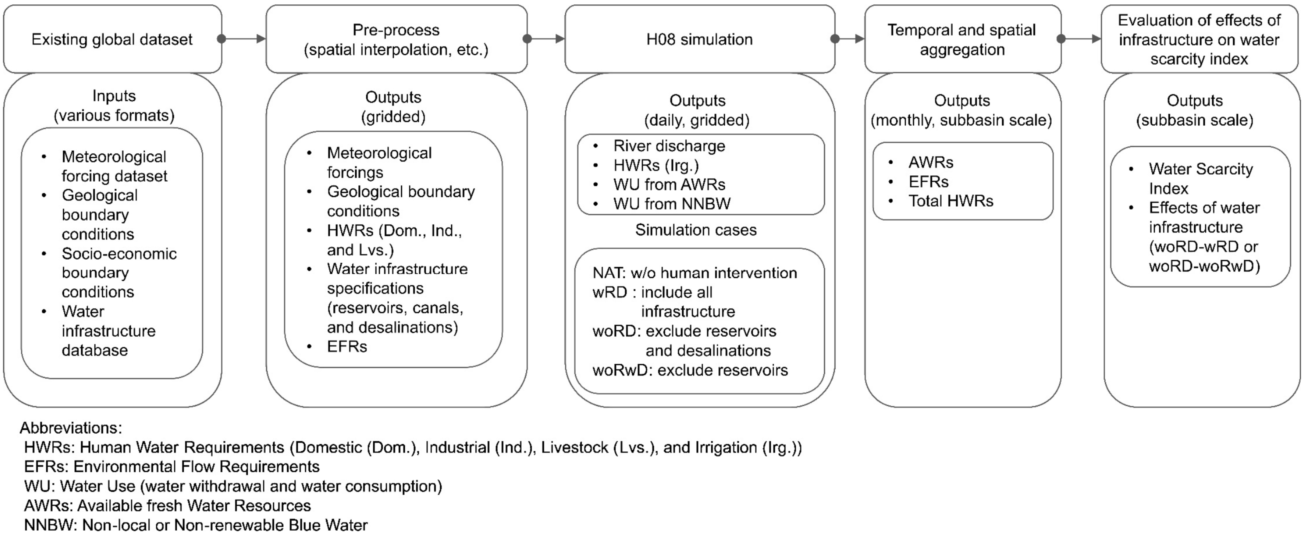
Supplementary Table 4: Validation results for monthly reservoir storage in the Murray River Basin.

ID	Name	Capacity (million m^3 s^{-1})	Catchment area (km^3)	rRMSE (%)	CC-M (-)	CC-MM (-)	CC-A (-)
6605	Wyangala	1,220	8,217	34.6	0.897	0.865	0.916
6643	Eppalock	312	2,053	31.8	0.885	0.958	0.904
6653	Eildon	3,390	3,881	49.4	0.841	0.846	0.886
6628	Hume	3,038	15,312	45.5	0.820	0.944	0.830
6649	Tullaroop	74	720	39.0	0.818	0.875	0.777
6637	Dartmouth	4,057	3,559	38.8	0.792	0.929	0.809
6647	Cairn Curran	148	1,630	41.6	0.766	0.876	0.729
6621	Corin	75	194	26.7	0.762	0.813	0.796
6613	Burrinjuck	1,026	13,112	35.0	0.731	0.968	0.714
6619	Googong	125	897	33.2	0.627	0.846	0.653
6618	Blowering	1,628	1,622	62.8	0.360	0.964	0.369
6635	Waranga Basin	411	110	60.4	0.121	0.944	0.037
6626	Yarrawonga Weir	118	26,108	24.5	-0.013	-0.700	0.073

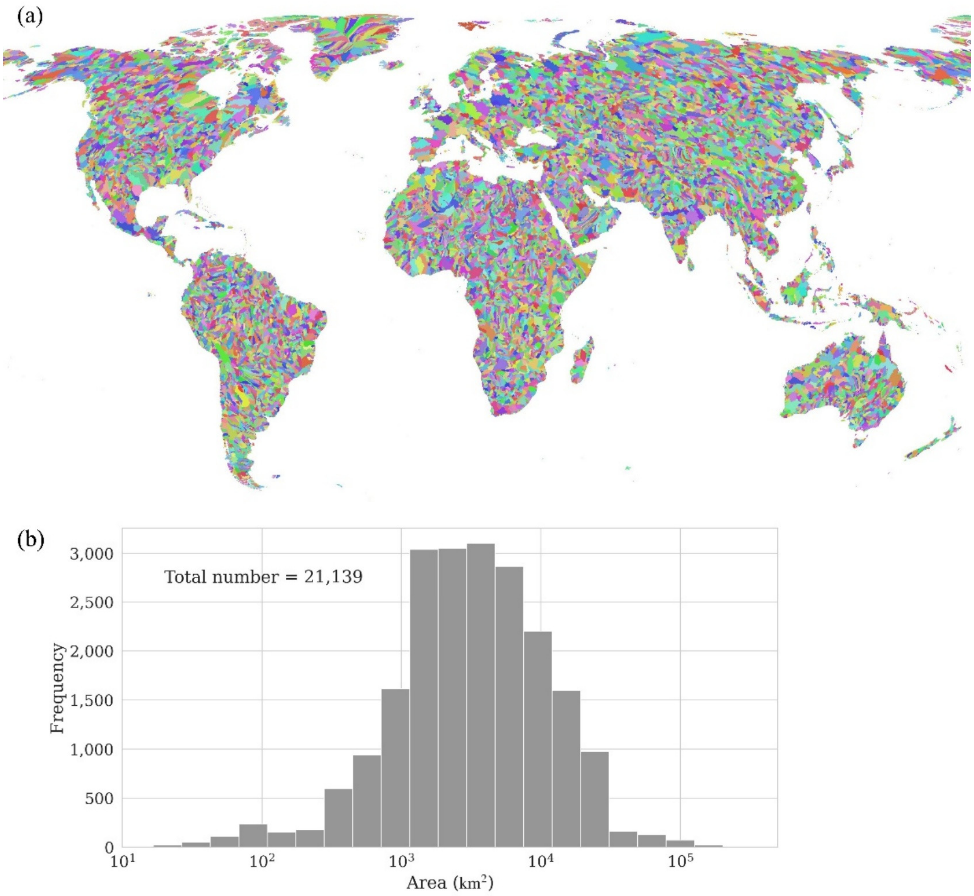
The ID, Name, Capacity, and Catchment area were obtained from the GRanD database.
rRMSE: relative Root Mean Square Error
CC-M: Correlation Coefficient of Monthly reservoir storage
CC-CM: Correlation Coefficient of Monthly reservoir storage
CC-A: Correlation Coefficient of Annual reservoir storage

Correlation Coefficient	
(blue)	0.8-1.0
(green)	0.5-0.8
(grey)	< 0.5

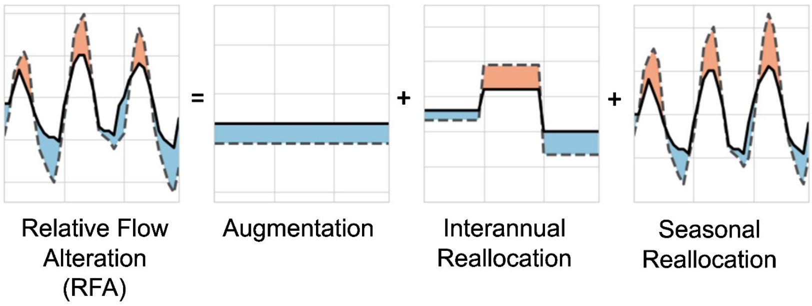
Supplementary Figures



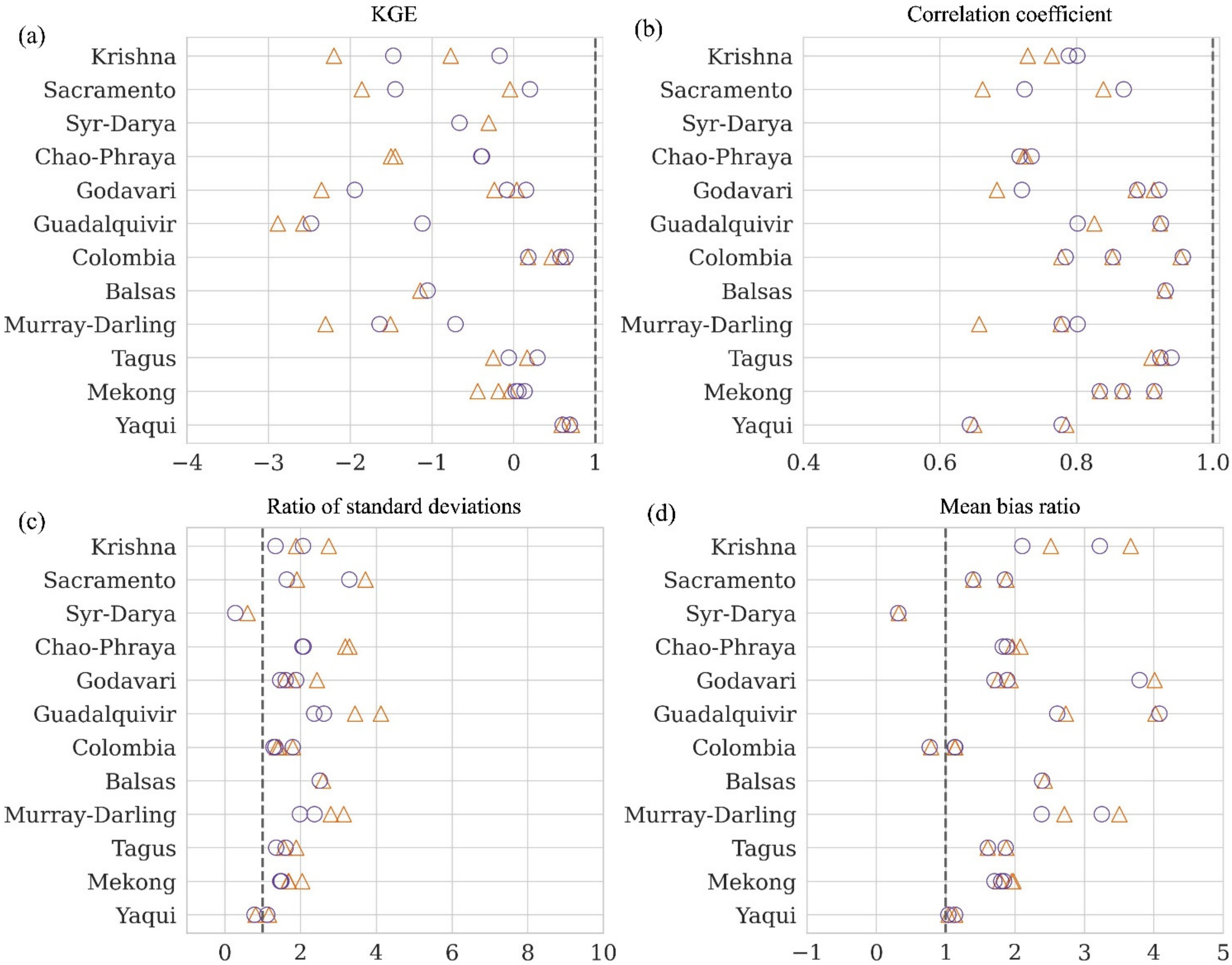
Supplementary Fig. 1. Flow diagram of the methodology of this study.



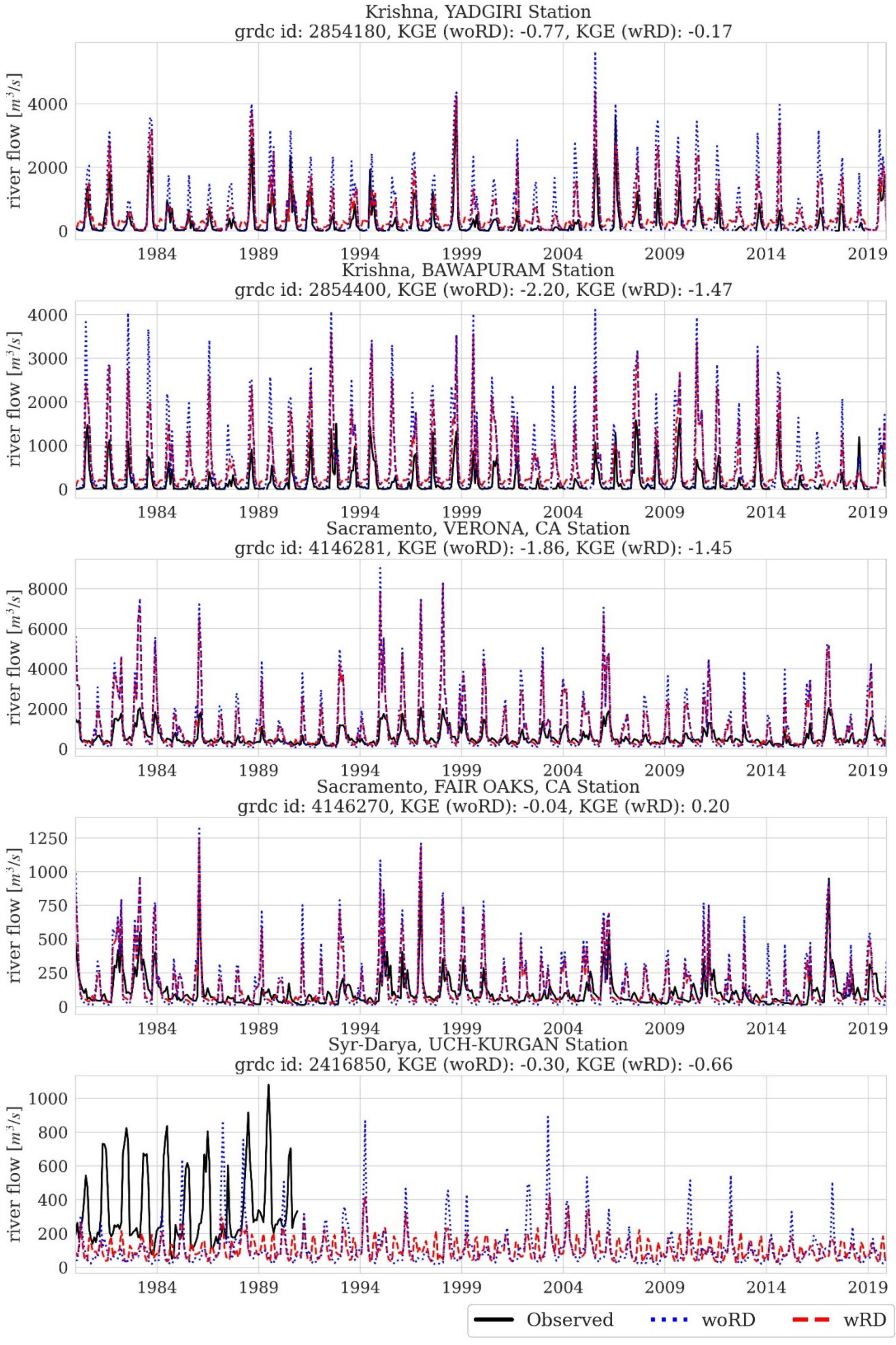
Supplementary Fig. 2. Map and area distribution of the subbasins developed in this study. (a) Global distribution of subbasins, with adjacent basins shown in different colors. (b) Frequency distribution of subbasin areas on a logarithmic scale.



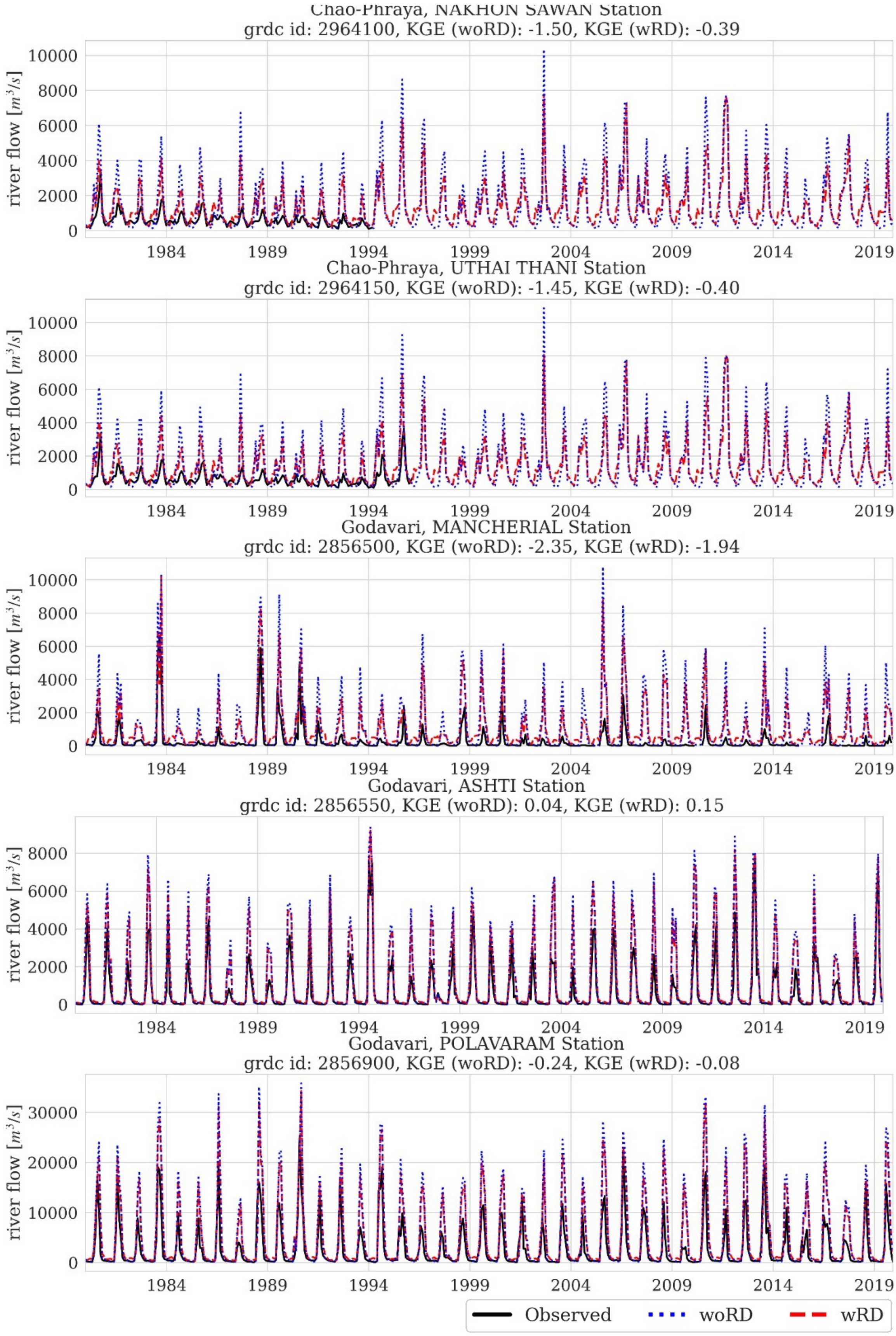
Supplementary Fig. 3. Conceptual diagram of relative flow alteration and its decomposition into augmentation, interannual reallocation, and seasonal reallocation. The black solid and dotted lines represent water availability with and without infrastructure, respectively. The shaded area shows the difference between the two conditions: periods when water availability with infrastructure exceeds that without infrastructure are shown in blue, while periods when the opposite occurs are shown in red.



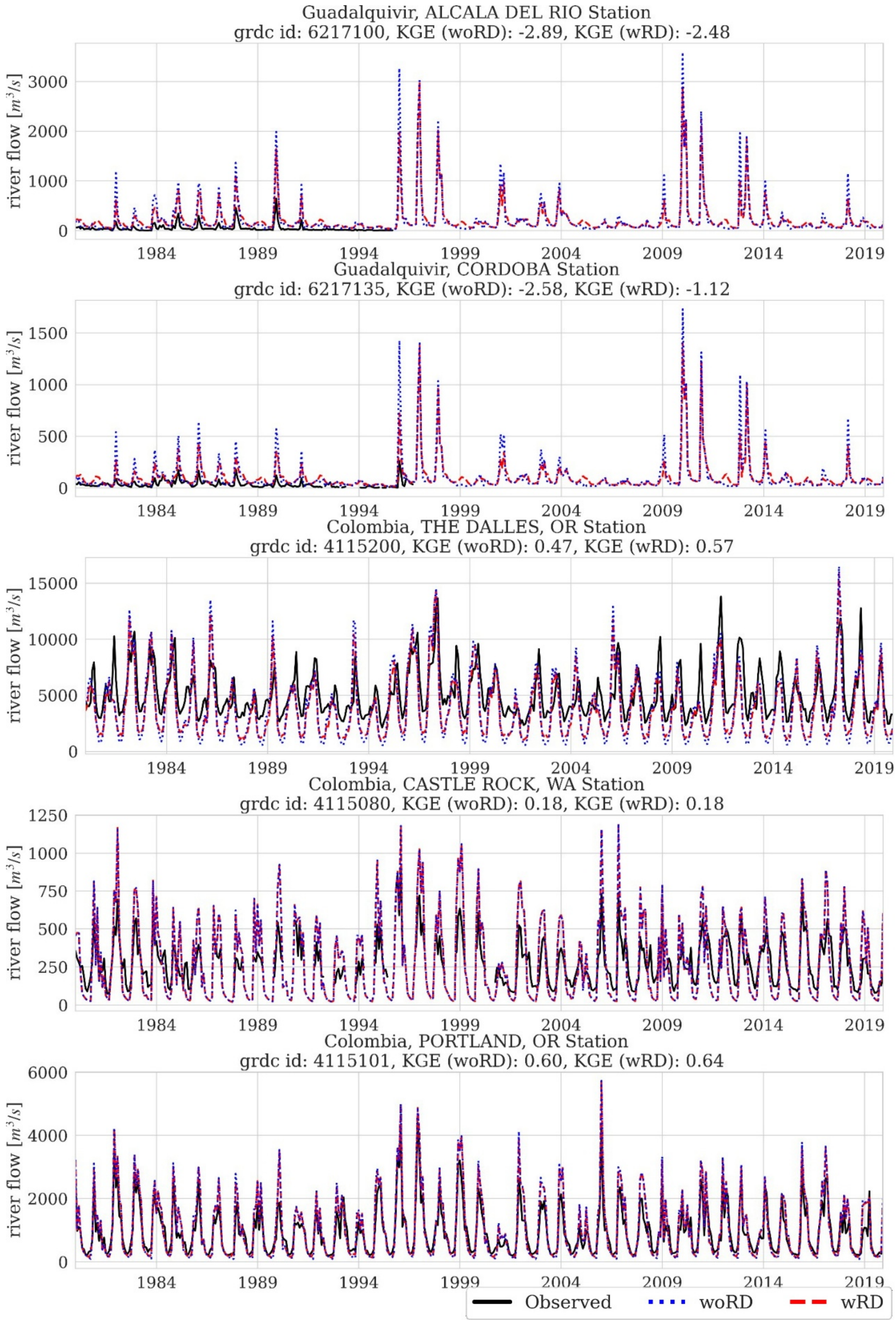
Supplementary Fig. 4. Validation results for monthly discharge based on the Kling-Gupta Efficiency (KGE) and its three components (corresponding to Supplementary Table 3). Scatter plots showing (a) the Kling–Gupta Efficiency (KGE), (b) the correlation coefficient, (c) the ratio of standard deviations, and (d) the bias ratio (comparing the mean values of the simulated and observed flows). The results are shown for 25 stations across 12 basins. The circles indicate simulations with reservoirs and desalinations (wRD), and the rectangles indicate simulations without reservoirs and desalinations (woRD). The dashed lines denote the most accurate reference values.



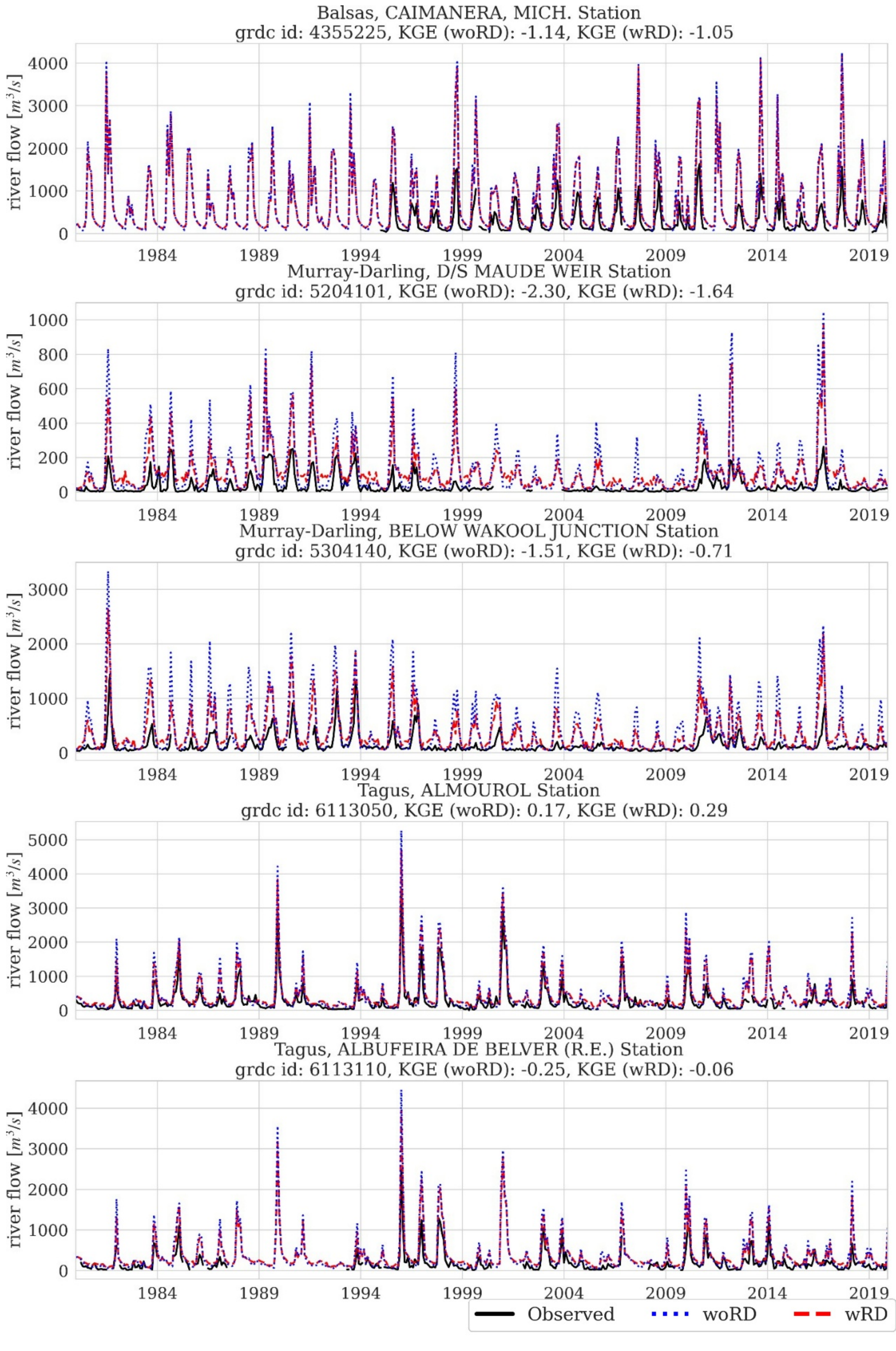
Supplementary Fig. 5. Time series of monthly discharge at 25 selected observation stations (1--5)



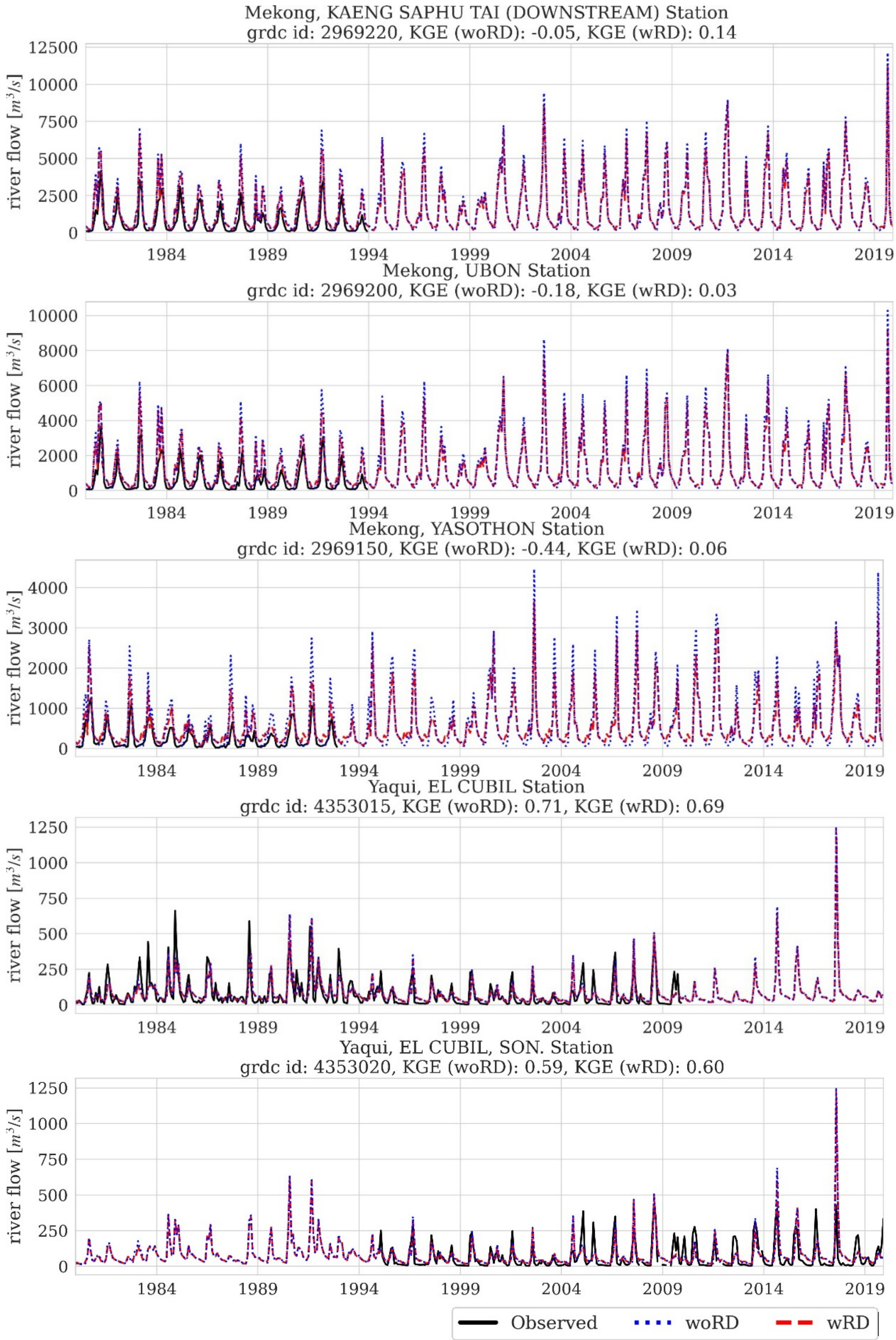
Supplementary Fig. 6. Time series of monthly discharge at 25 selected observation stations (6--10)



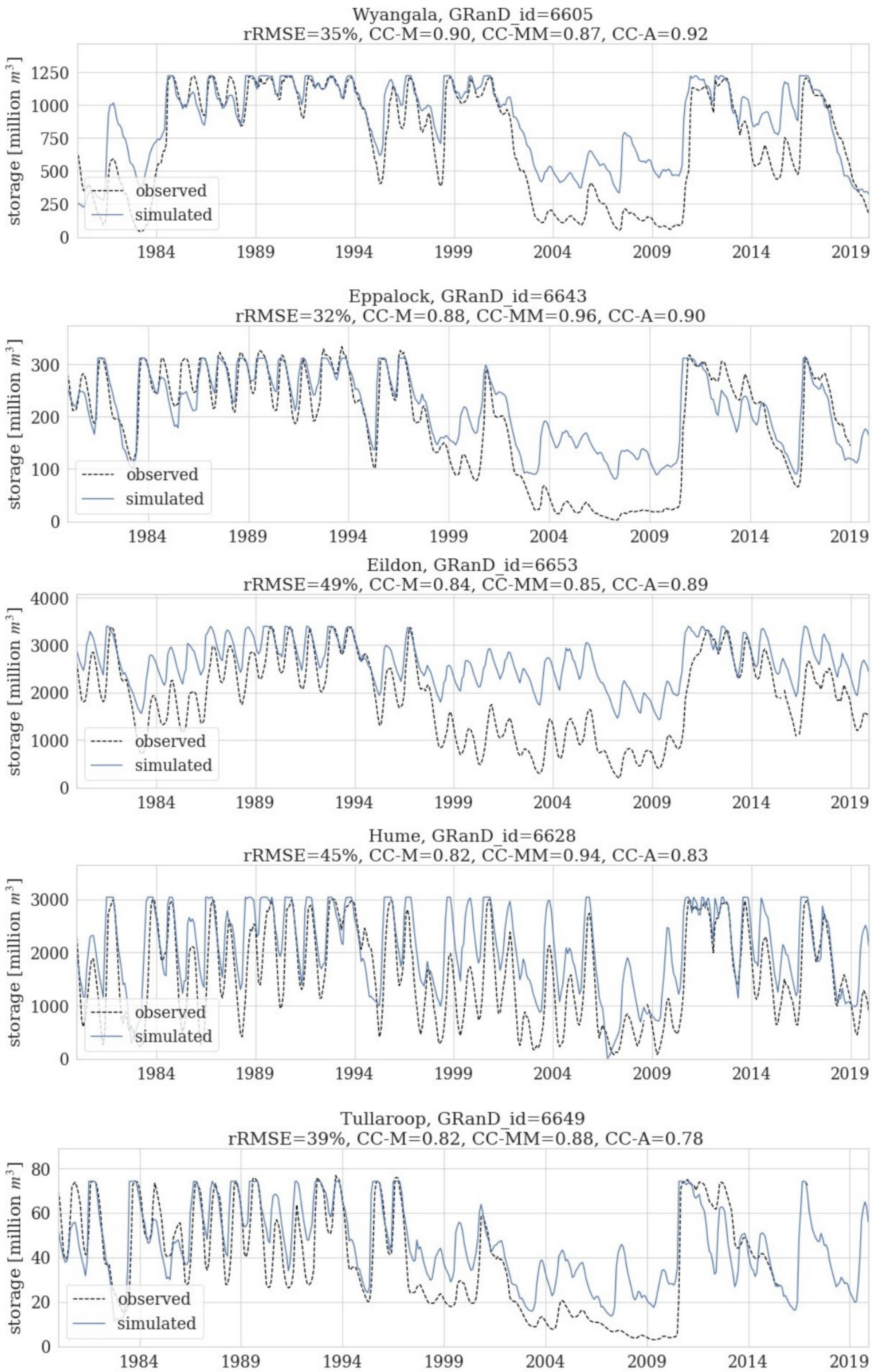
Supplementary Fig. 7. Time series of monthly discharge at 25 selected observation stations (11--15)



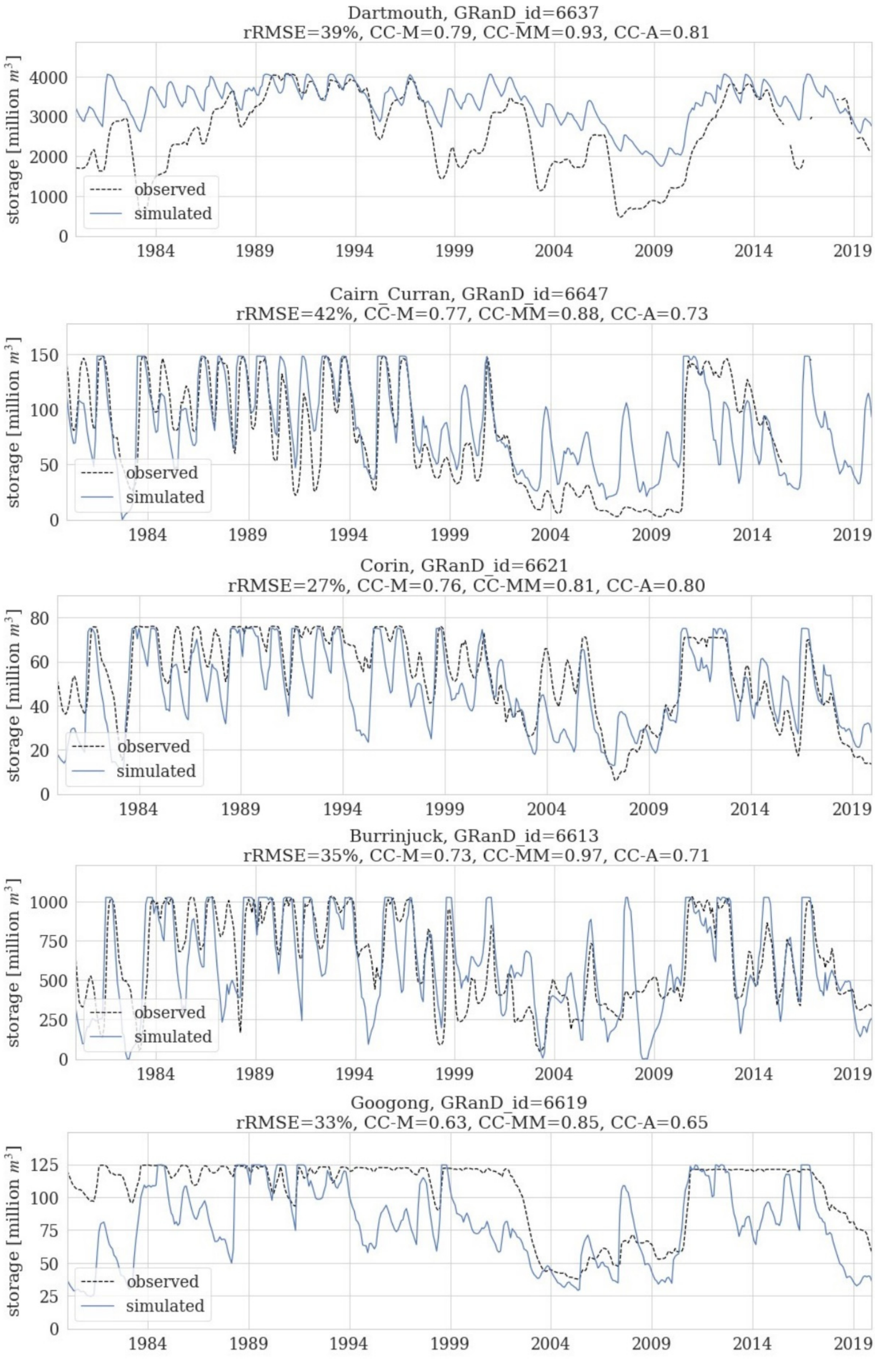
Supplementary Fig. 8. Time series of monthly discharge at 25 selected observation stations (16--20)



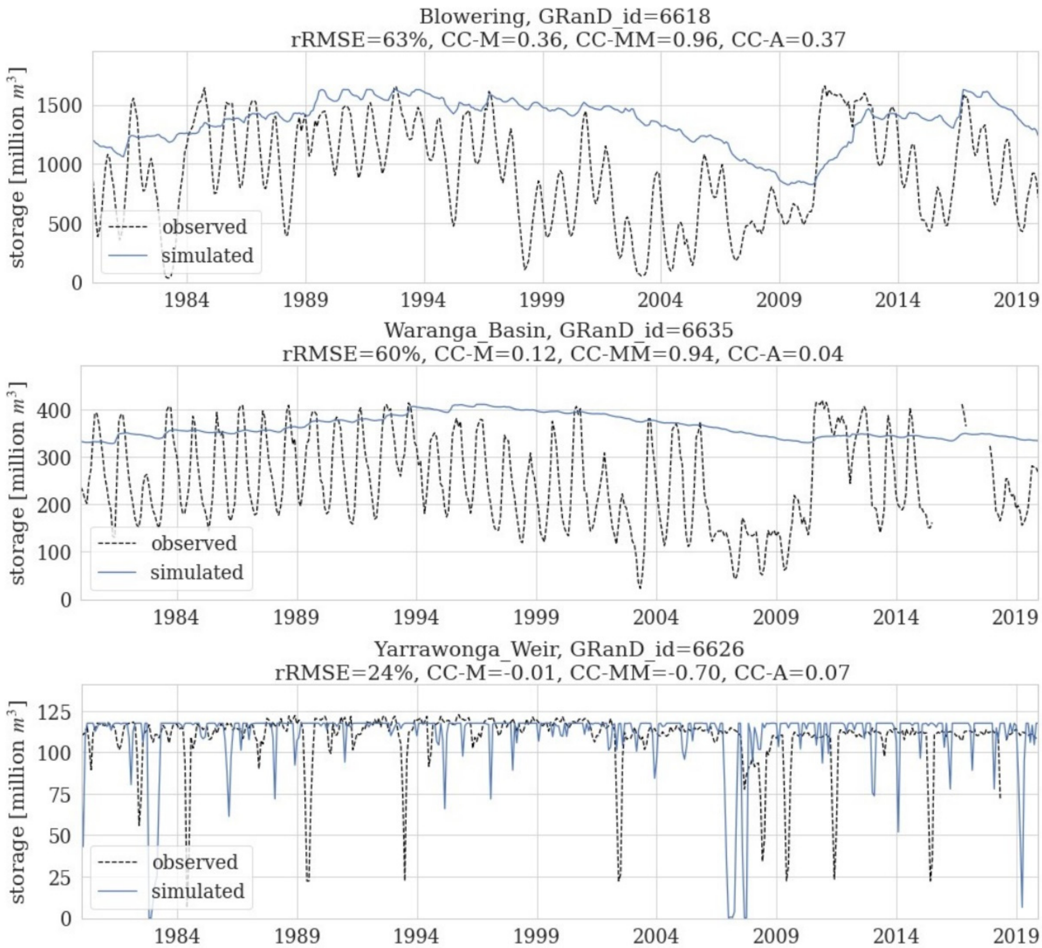
Supplementary Fig. 9. Time series of monthly discharge at 25 selected observation stations (21--25)



Supplementary Fig. 10. Time series of monthly reservoir storage in the Murray River Basin, with good agreement between the observed and simulated values (top 1 to 5).



Supplementary Fig. 11. Time series of monthly reservoir storage in the Murray River Basin, with good agreement between the observed and simulated values (top 6--10).



Supplementary Fig. 12. Time series of monthly reservoir storage in the Murray River Basin, with poor agreement between the observed and simulated values.

Supplementary References

1. Gupta, H. V., Kling, H., Yilmaz, K. K. & Martinez, G. F. Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. *J. Hydrol.* **377**, 80–91 (2009).
2. Marti, B. *et al.* CA-discharge: Geo-Located Discharge Time Series for Mountainous Rivers in Central Asia. *Sci. Data* **10**, 1–21 (2023).
3. Heinicke, S. *et al.* Global hydrological models continue to overestimate river discharge. *Environ. Res. Lett.* **19**, (2024).
4. Australian Bureau of Meteorology. Water Data Online. http://www.bom.gov.au/waterdata/.
5. Goulburn-Murray Water. About Warange Basin. https://www.g-mwater.com.au/water-operations/storages/goulburn/warangabasin.
6. Murray-Darling Basin Authority. Yarrawonga Weir. https://www.mdba.gov.au/water-management/infrastructure/weirs-and-locks/yarrawonga-weir.