SUPPLEMENTARY MATERIALS

Appendix A. Supplementary descriptions of global hydrological models

Appendix A.1. Summary of specifications

To supplement Section 2.2 and Table 2, model specifications and analysis settings are summarized in Table A1. Note that because LPJmL also supports the biome calculation, it requires a longer spin-up to stabilize initial conditions.

Table A1. Hydrological models used in this study. See also Table 2. Abbreviations for meteorological input variables: (T) daily mean air temperature, (Tmx) daily maximum air temperature, (Tmn) daily minimum air temperature, (Prcp) precipitation, (RH) relative humidity or specific humidity of the air, (rsds) shortwave downward radiation, (rlds) longwave downward radiation. [1]Rain/snow discrimination for PGFv2 and GSWP3 was calculated using Yasutomi *et al* (2011). [2]Because LPJmL also supports the biome calculations, a longer spin-up is required to stabilize initial conditions. [3]For calculation of evapotranspiration (no potential evapotranspiration is calculated). [4]Batjes (2012). [5]Batjes (2005).

GHM	Input meteorological variables	Soil info (Number of soil layers)	Potential evapotranspiration formula	Snowmelt	Spin-up	Land-use change (croplands or vegetation)
DBH	T, Tmx, Tmn, Prcp, Pres, RH, rsds, rlds, Wind	FAO (3)	Soil-vegetation-atmosphere transfer scheme[3]	Energy balance	1951-1970	varied
H08	T, Rain[1], Snow[1], Pres, RH, rsds, rlds, Wind	N/A (1)	Bulk formula	Energy balance	1901-1970	varied
LPJmL	T, Prcp, rsds, rlds,	HWSD[4] (5)	Priestley-Taylor	Degree-day	5000 years[2]	varied
PCR-GLOBWB	T, Prcp	FAO+ISRIC-WISE[5] (2)	Hamon	Degree-day	1901-1970 (and another 100 years of spin-up beforehand)	varied
WaterGAP	T, Prcp, rsds, rlds	FAO+ISRIC-WISE[5] (1)	Priestley-Taylor	Degree-day	1901-1970	varied irrigation area only

Appendix A.2. Dam location adopted in each GHM

GRanD covers global 6,862 dams, whose location is given in geographical coordinates. For hydrological simulation at the resolution of $0.5° \times 0.5°$, each dam must be assigned at one of land cells. Each GHM adopted one of three types of gridded dam location data as we listed in Table A2.

Table A2. Dam location data adopted by GHMs. 'GRanD-ISIMIP' means dam location data which were gridded into $0.5° \times 0.5°$ land cells from the original GRanD data and provided by ISIMIP for ISIMIP2a simulations. [1] For PCR-GLOBWB, dam locations were additionally modified from the standard 'Gridded GRanD' data (details are indicated in brackets).

Dam location data	GRanD-ISIMIP	LPJmL	WaterGAP
GHMs adopted	DBH, H08, PCR-GLOBWB[1]	LPJmL	WaterGAP
Resolution	$0.5° \times 0.5°$	$0.5° \times 0.5°$	$0.5° \times 0.5°$
River network	DDM30	DDM30	DDM30
Dams used in simulations	6,862 (same as GRanD)	—	1109 grid cells with reservoir outflow cells of GRanD with capacity > 0.5 km^3 or reservoir area > 100 km^2 are handled with reservoir algorithm, the others from GRanD as lakes
Dam location adjustment			
Type	Conditional adjustment [+Manual adjustment[1]]	Manual adjustment	Manual adjustment
Dams to be adjusted	(1) upstream area $> 10,000$ km^2 in GRanD and (2) upstream area realized with DDM30 is deviated $> 50\%$ from that listed in GRanD	Capacity > 1 km^3	All dams manually checked according location in DDM30
How to relocate dams	Relocated to one of eight neighboring land cells such that the deviation in upstream area is smallest among them [Most consistent with geographic information (e.g., river, near city) provided with GRanD [1]]	To be located in correct river stretches	To be consistent with map information, upstream area and location in the drainage network
Commissioning year	Same as in GRanD	—	Some data are updated
References	ISIMIP (2015), Müller Schmied et al. (2016), [Wada et al. (2014)[1]]	Müller Schmied et al. (2016)	Müller Schmied et al. (2016)

Appendix A.3. Dam operation scheme by Hanasaki et al (2006)

According to the dam operation scheme proposed by Hanasaki *et al* (2006), the outflow from a dam R m^3/y with a capacity of C m^3 is given by a function of the mean annual inflow I_{mean} m^3/y, the dam water storage at the beginning of the operational year S_{init} m^3 and the water demand (dams for irrigation purposes only). If the water demand for irrigation is neglected for simplicity, R is given by

$$R = \frac{S_{init}}{0.85C} I_{mean}. \tag{A.1}$$

Thus, for a certain dam (i.e., C is fixed), R increases with I_{mean} while S_{init} can be assumed to be invariant, as in temperate climates.

Appendix A.4. Dams and gauge stations used in this study

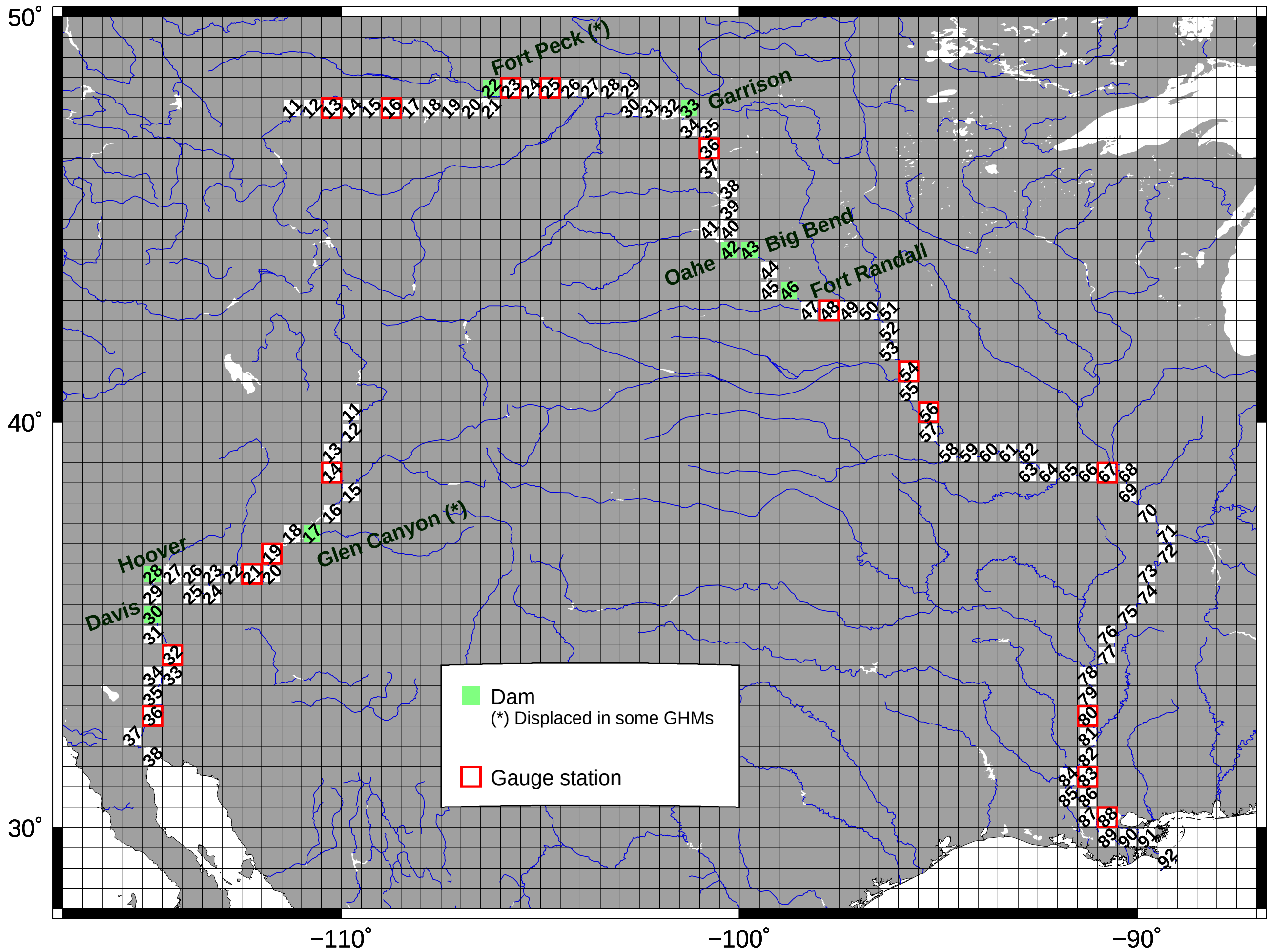

Figure A1. Map of dams and gauge stations used in this study. Note that some GHMs shifted dam location in their simulations (see Tables A3 and A5).

Table A3. Major dams in the Missouri River. SCN is short for the sequential cell number from the uppermost reach, corresponding to the number indicated on the channel map in Figure 1. Note that the locations in this table were provided as standard input data by ISIMIP at a geographical resolution of 0.5° × 0.5°. That is, they do not necessarily coincide with the actual geographical coordinates. Catchment areas in brackets are the original numbers in GRanD. † Fort Randall Dam is not in the standard list of dams for ISIMIP2a. ‡ The construction year of Fort Peck Dam varies among references. This value is according to GRanD. ∗ Big Bend Dam was not included in the WaterGAP simulations. ∗∗ Fort Peck Dam was relocated to SCN 21 (106.25W, 47.75N) in the LPJmL and WaterGAP simulations.

Dam	SCN	Corresponding land cell		Storage	Construction year	Catchment area	
		Longitude	Latitude	10^6 m^3		10^5 km^2	
Fort Peck	22∗∗	106.25W	48.25N	23560	1957 ‡	2.07	(1.47)
Garrison	33	101.25W	47.75N	30220	1953	4.69	(4.63)
Oahe	42	100.25W	44.25N	29110	1966	6.37	(6.13)
Big Bend∗	43	99.75W	44.25N	2344	1963	6.39	(6.28)
Fort Randall†	46	98.75W	43.25N	6680	1954	6.78	-

Table A4. Gauge stations along the main stem of the Missouri-Mississippi River used in this analysis. SCN means the sequential cell number from the uppermost reach, corresponding to the number indicated on the channel map in Figure 1. Some of the observation periods include gaps. Note that the locations in this table were used in the hydrological simulations of this study at a geographical resolution of 0.5° × 0.5°. Abbreviations for station names: (nr.) near, (c.) city.

Station Name	GRDC ID	USGS ID	SCN	Corresponding land cell		Observation period
				Longitude	Latitude	
Virgelle	4120902	06109500	13	110.25W	47.75N	1935–
Nr. Landusky		06115200	16	108.75W	47.75N	1934–
Nr. Wolf Point		06177000	23	105.75W	48.25N	1928–
Nr. Culbertson	4120900	06185500	25	104.75W	48.25N	1941–
Bismarck		06342500	36	100.75W	46.75N	1927–
Yankton	4121800	06467500	48	97.75W	42.75N	1930–1997
Omaha		06610000	54	95.75W	41.25N	1928–
Nebraska C.	4122650	06807000	56	95.25W	40.25N	1929–
Hermann	4122900	06934500	67	90.75W	38.75N	1928–
Nr. Arkansas C.	4127500	07265450	80	91.25W	32.75N	1928–1980
Vicksburg	4127800	07289000	83	91.25W	31.25N	1931–
Tarbert Landing	4127930	07295100	88	90.75W	30.25N	1965–1991

Table A5. Same as Table A3 but for the Green-Colorado River. SCN means the sequential cell number from the uppermost reach of the Green River, corresponding to the number indicated on the channel map in Figure 1. ∗ Davis Dam was not included in the WaterGAP simulations. ∗∗ Glen Canyon Dam was relocated to SCN 18 (111.25W, 37.25N) in the WaterGAP simulations and to SCN 19 (111.75W, 36.75N) in the LPJmL simulations.

Dam	SCN	Corresponding land cell		Storage	Construction year	Catchment area	
		Longitude	Latitude	10^6 m^3		10^5 km^2	
Glen Canyon	17∗∗	110.75W	37.25N	25070	1963	2.76	(2.79)
Hoover	28	114.75W	36.25N	36700	1935	4.21	(4.24)
Davis∗	30	114.75W	35.25N	2243	1952	4.26	(4.26)

Table A6. Same as Table A4 but for the Green-Colorado River. SCN means the sequential cell number from the uppermost reach of the Green River, corresponding to the number indicated on the channel map in Figure 1. Abbreviations for station names: (nr.) near, (blw.) below.

Station Name	GRDC ID	USGS ID	SCN	Corresponding land cell		Observation peric
				Longitude	Latitude	
Green River	4152550	09315000	14	110.25W	38.75N	1894–
Lees Ferry	4152450	09380000	19	111.75W	36.75N	1921–
Nr. Grand Canyon		09402500	21	112.25W	36.25N	1922–
Nr. Topock		09424000	32	114.25W	34.25N	1917–1982
Blw. Yuma Main Canal	4152050	09521100	36	114.75W	32.75N	1963–

Appendix B. Meteorological characteristics

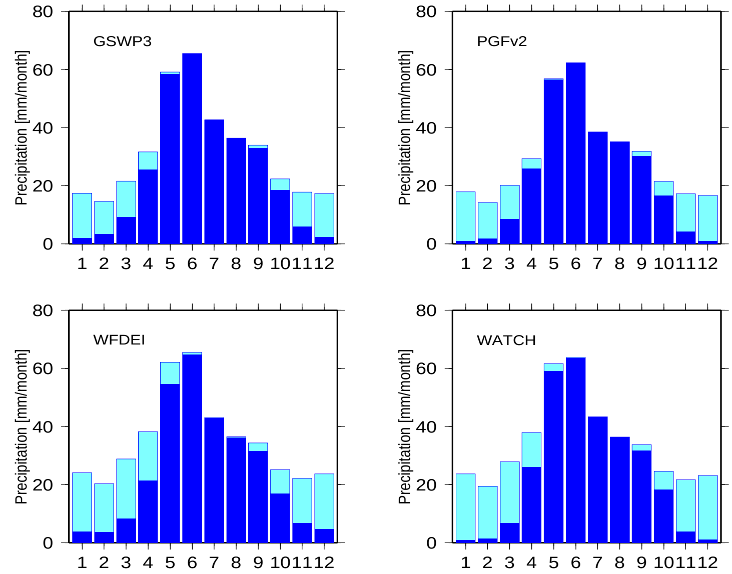

Figure B1. Monthly rain-snow ratio over the catchment area of Fort Peck Dam. Blue and light cyan bars show rainfall and snowfall, respectively.

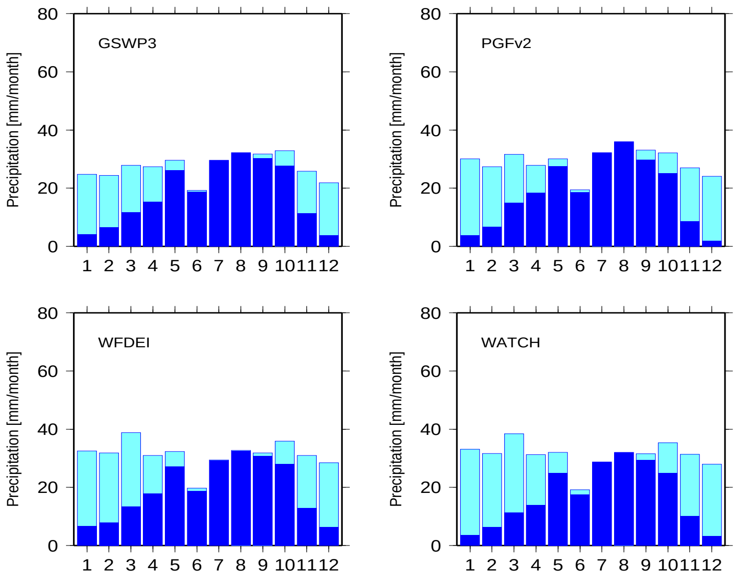

Figure B2. Same as Figure B1 but over the catchment area of Glen Canyon Dam.

Appendix C. Supplementary results

Table C1. Seasonal fraction of simulated river discharge in comparison with that observed one at gauge stations along the Missouri-Mississippi River. For each model, the simulated fraction and closeness (Cls.) to the observed fraction are shown. Closeness is judged by the deviation D from the observation: $*$ for $|D| < 0.1$, $**$ for $|D| < 0.05$, and $***$ for $|D| < 0.02$. Gauge stations at each SCN are listed in Table A4.

SCN	DBH		H08		LPJmL		PCR-GLOBWB		WaterGAP		Ensemble mean		Observation
	Fraction	Cls.	Fraction	Cls.	Fraction	Cls.	Fraction	Cls.	Fraction	Cls.	Fraction	Cls.	
DJF													
13	0.0651		0.2114	**	0.2646	*	0.0997	*	0.2039	**	0.1689	***	0.1805
16	0.0642		0.2013	**	0.2434	*	0.0980	*	0.1934	***	0.1601	***	0.1747
23	0.0566		0.2506	***	0.2053	**	0.0942		0.2290	***	0.1671	*	0.2442
25	0.0551		0.2442	***	0.1897	*	0.0939		0.2252	**	0.1616	*	0.2456
36	0.0683		0.2450	***	0.2223	***	0.1115		0.2177	***	0.1729	*	0.2351
48	0.1599	***	0.2576		0.2171	*	0.1070	**	0.2244	*	0.1932	**	0.1524
54	0.1416	***	0.2543		0.1857	**	0.0969	*	0.2158	*	0.1789	**	0.1490
56	0.1406	**	0.2522	*	0.1823	***	0.1512	***	0.2151	*	0.1883	**	0.1638
67	0.1568	**	0.2641	*	0.1763	***	0.1257	*	0.2391	*	0.1924	***	0.1851
80	0.1897	*	0.2837	***	0.2333	**	0.2164	*	0.2782	***	0.2403	**	0.2815
83	0.1967	*	0.2807	***	0.2371	**	0.2283	*	0.2774	***	0.2440	**	0.2807
88	0.2104	*	0.2805	***	0.2451	**	0.2286	*	0.2761	***	0.2481	**	0.2824
MAM													
13	0.2588	*	0.4641		0.4086	*	0.3832	*	0.3486	**	0.3727	*	0.3158
16	0.2424	*	0.4711		0.4246	*	0.3802	*	0.3623	**	0.3761	**	0.3279
23	0.2149	**	0.2539	***	0.3597	*	0.3668		0.2847	**	0.2960	**	0.2641
25	0.2066	*	0.2647	***	0.3799		0.3642	*	0.2969	***	0.3025	**	0.2789
36	0.1816	*	0.2640	***	0.2980	**	0.3492	*	0.2857	**	0.2757	**	0.2522
48	0.1581	*	0.2703	**	0.2971	*	0.3463		0.2784	*	0.2700	**	0.2221
54	0.1939	*	0.3104	*	0.3463	*	0.3462	*	0.3075	*	0.3009	**	0.2510
56	0.1979	*	0.3127	**	0.3439	*	0.3178	**	0.3115	**	0.2968	**	0.2700
67	0.2152		0.3288	**	0.3291	**	0.3560	***	0.3151	**	0.3088	**	0.3522
80	0.2831	*	0.4114	**	0.3604	**	0.3627	**	0.3527	**	0.3541	**	0.3828
83	0.2791	*	0.4104	**	0.3613	***	0.3674	***	0.3534	***	0.3543	***	0.3718
88	0.2705		0.4004	**	0.3562	**	0.3671	***	0.3547	**	0.3498	**	0.3768
JJA													
13	0.4324	*	0.1860		0.1772		0.3282	***	0.2536	*	0.2755	*	0.3338
16	0.4471		0.1921		0.1926		0.3338	***	0.2586	*	0.2848	**	0.3332
23	0.4672		0.2478	**	0.2388	**	0.3577	*	0.2642	***	0.3151	**	0.2840
25	0.4712		0.2464	**	0.2419	**	0.3611	*	0.2584	***	0.3158	**	0.2699
36	0.4615		0.2480	**	0.2586	**	0.3385	*	0.2809	***	0.3175	**	0.2862
48	0.3837	*	0.2349	*	0.2693	**	0.3530	**	0.2778	**	0.3037	***	0.3060
54	0.3775	*	0.2095	*	0.2571	**	0.3571	*	0.2668	**	0.2936	***	0.2982
56	0.3716	*	0.2047	*	0.2579	**	0.2695	***	0.2565	**	0.2720	***	0.2823
67	0.3379		0.1905	**	0.2586	**	0.3125	*	0.2240	***	0.2647	**	0.2269
80	0.2973		0.1788	***	0.2082	**	0.2483	*	0.2002	***	0.2265	**	0.1839
83	0.2963		0.1874	***	0.2065	***	0.2382	**	0.2036	***	0.2264	**	0.1944
88	0.2934	*	0.2021	***	0.2045	***	0.2388	**	0.2068	***	0.2291	**	0.1942
SON													
13	0.2437	*	0.1384	**	0.1496	**	0.1889	***	0.1938	**	0.1829	***	0.1699
16	0.2463	*	0.1355	**	0.1395	**	0.1880	**	0.1858	**	0.1790	***	0.1642
23	0.2614	*	0.2477	**	0.1962	***	0.1814	**	0.2220	***	0.2217	***	0.2078
25	0.2671	*	0.2447	**	0.1885	***	0.1808	**	0.2195	***	0.2201	***	0.2056
36	0.2886	*	0.2431	***	0.2212	***	0.2008	**	0.2157	***	0.2339	***	0.2265
48	0.2982	**	0.2372	*	0.2164		0.1937		0.2194		0.2330	*	0.3195
54	0.2869	***	0.2258	*	0.2110	*	0.1998		0.2099	*	0.2267	*	0.3018
56	0.2899	***	0.2304	*	0.2159	*	0.2614	**	0.2169	*	0.2429	**	0.2839
67	0.2901	*	0.2166	***	0.2361	***	0.2058	**	0.2218	***	0.2341	***	0.2358
80	0.2300	*	0.1260	**	0.1981	**	0.1726	**	0.1689	***	0.1791	**	0.1518
83	0.2279	*	0.1215	**	0.1951	**	0.1660	***	0.1656	***	0.1752	**	0.1530
88	0.2257	*	0.1170	**	0.1942	**	0.1654	***	0.1624	***	0.1729	**	0.1466

Table C2. Same as Table C1 but along the Green-Colorado River. Gauge stations at each SCN are listed in Table A6.

SCN	DBH		H08		LPJmL		PCR-GLOBWB		WaterGAP		Ensemble mean		Observation
	Fraction	Cls.	Fraction	Cls.	Fraction	Cls.	Fraction	Cls.	Fraction	Cls.	Fraction	Cls.	
DJF													
14	0.0913	∗	0.1919	∗∗	0.1585	∗ ∗ ∗	0.1377	∗ ∗ ∗	0.1467	∗ ∗ ∗	0.1452	∗ ∗ ∗	0.1554
19	0.0876		0.2361	∗ ∗ ∗	0.2262	∗ ∗ ∗	0.1424	∗	0.2053	∗∗	0.1795	∗	0.2364
21	0.1046		0.2709	∗∗	0.2415	∗ ∗ ∗	0.1509	∗	0.2179	∗ ∗ ∗	0.1972	∗∗	0.2291
32	0.1334	∗ ∗ ∗	0.2334	∗	0.2456		0.1960	∗	0.2364	∗	0.2090	∗	0.1416
36	0.1682	∗	0.2594	∗∗	0.2763	∗∗	0.2233	∗ ∗ ∗	0.2838	∗	0.2422	∗ ∗ ∗	0.2332
DJF													
14	0.2665	∗	0.4899		0.5973		0.4211	∗	0.5570		0.4664		0.3442
19	0.2530	∗∗	0.2737	∗	0.3199		0.3886		0.3381		0.3147	∗	0.2196
21	0.2378	∗ ∗ ∗	0.2787	∗∗	0.2979	∗	0.3779		0.3287	∗	0.3042	∗	0.2296
32	0.2035		0.2580	∗	0.2929	∗∗	0.3673	∗∗	0.2445	∗	0.2732	∗	0.3233
36	0.2065	∗	0.2859	∗∗	0.2617	∗ ∗ ∗	0.3474	∗	0.1434		0.2490	∗ ∗ ∗	0.2619
DJF													
14	0.3855	∗∗	0.1654		0.1055		0.2380		0.1741		0.2137		0.3645
19	0.4086		0.2546	∗	0.2265	∗	0.2626	∗∗	0.2514	∗	0.2807	∗∗	0.3083
21	0.3983	∗	0.2310	∗	0.2252	∗	0.2621	∗∗	0.2533	∗	0.2740	∗∗	0.3084
32	0.3891	∗∗	0.2729	∗	0.2269		0.2364		0.2948	∗∗	0.2840	∗	0.3425
36	0.3489		0.2490	∗ ∗ ∗	0.2137	∗∗	0.2244	∗ ∗ ∗	0.2931	∗	0.2658	∗∗	0.2369
DJF													
14	0.2567		0.1528	∗ ∗ ∗	0.1387	∗ ∗ ∗	0.2032	∗	0.1221	∗ ∗ ∗	0.1747	∗∗	0.1360
19	0.2509	∗ ∗ ∗	0.2355	∗ ∗ ∗	0.2275	∗ ∗ ∗	0.2063	∗∗	0.2052	∗∗	0.2251	∗ ∗ ∗	0.2357
21	0.2593	∗∗	0.2194	∗ ∗ ∗	0.2354	∗ ∗ ∗	0.2091	∗∗	0.2001	∗∗	0.2247	∗ ∗ ∗	0.2329
32	0.2739	∗	0.2357	∗∗	0.2346	∗∗	0.2002	∗ ∗ ∗	0.2243	∗∗	0.2337	∗∗	0.1926
36	0.2764	∗ ∗ ∗	0.2057	∗	0.2483	∗ ∗ ∗	0.2048	∗	0.2797	∗ ∗ ∗	0.2430	∗∗	0.2680

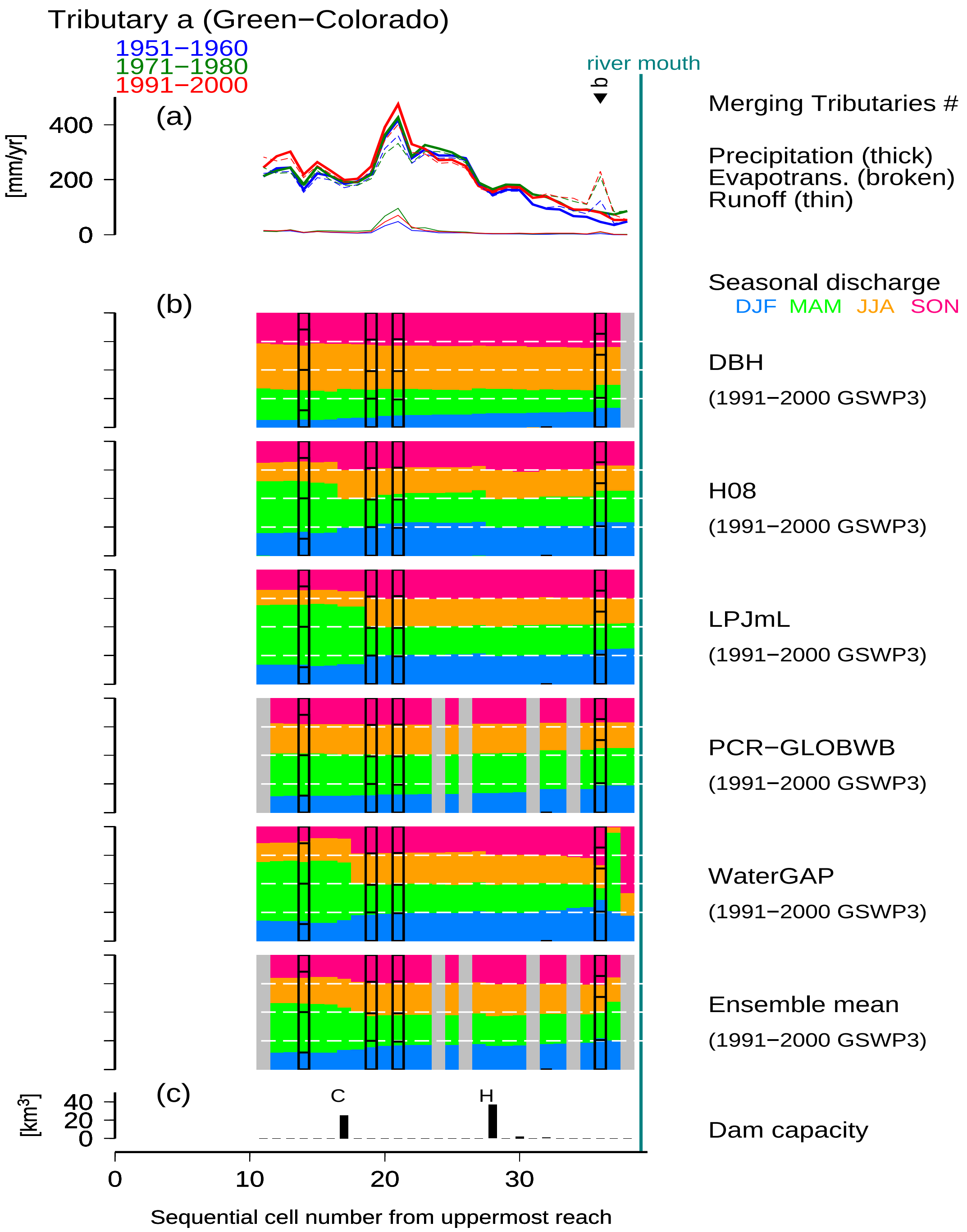

Figure C1. Same as Figure 5 but showing river discharge data for 1991–2000.

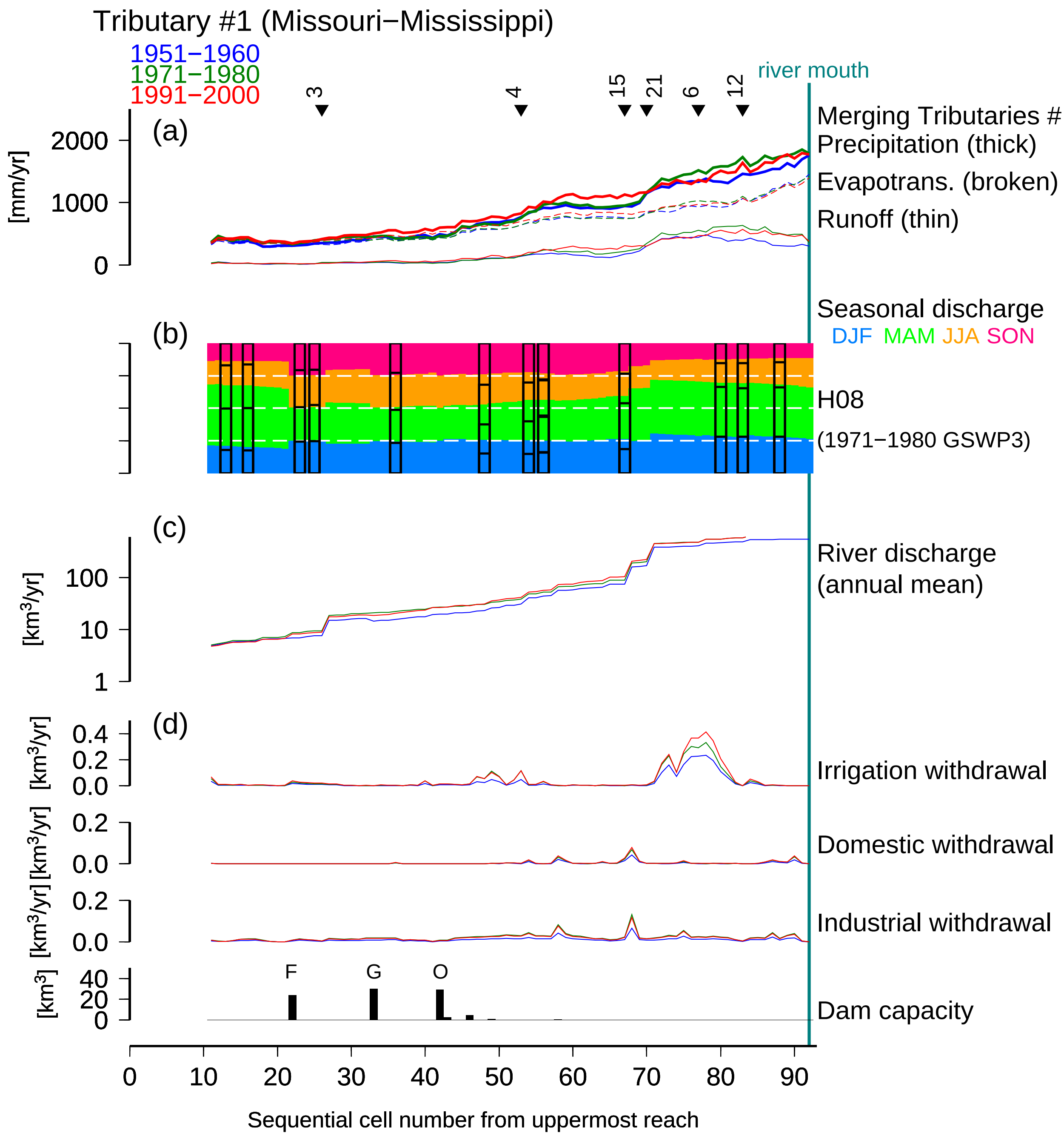

Figure C2. Annual mean river discharge and withdrawals simulated using H08 (varsoc) on a longitudinal section along the Missouri-Mississippi River. For comparison, (a) precipitation and land process and (b) seasonal fraction of river discharge calculated with H08 are shown again (same as Figure 3). Tributaries that meet the Missouri-Mississippi River are indicated by numbers in the top (see also Tributary IDs in Figure 2). The horizontal axis gives the sequential cell number (SCN) from the uppermost reach of the Missouri River (as indicated in Figure 1). (c) Historical changes in annual mean river discharge are shown as blue, green, and red lines for 1951–1960, 1971–1980, and 1991–2000, respectively. (d) Withdrawals for irrigation, municipal and industrial water and dam capacity are indicated in the same colors as (a). Fort Peck (F), Garrison (G), and Oahe (O) Dams are located at SCNs 22, 33, and 42, respectively.

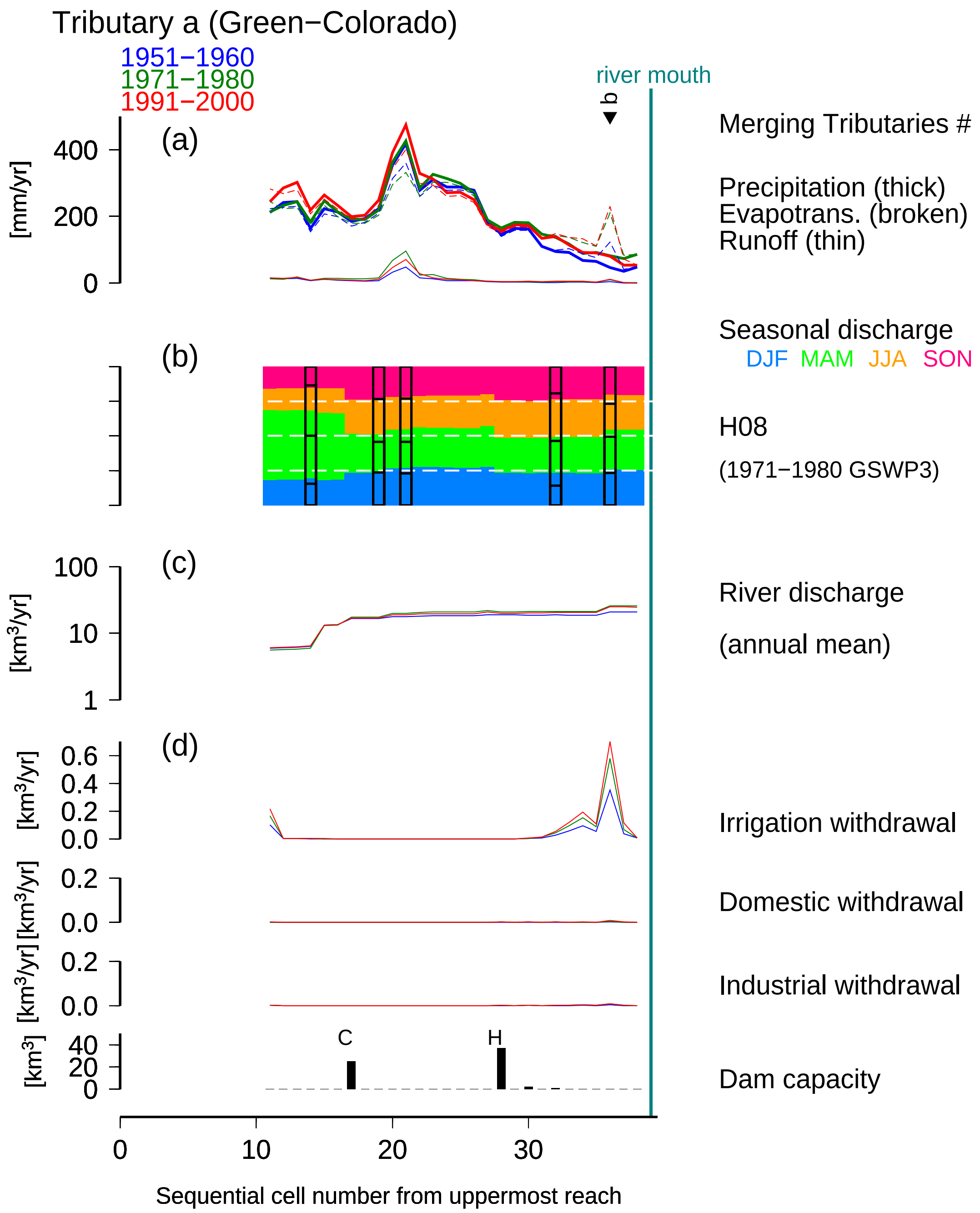

Figure C3. Same as Figure C2 but for the longitudinal section along the Green-Colorado River with river discharge data for 1971–1980. The horizontal axis gives the SCN from the uppermost reach of the Green River (as indicated in Figure 1). Glen Canyon (C) and Hoover (H) Dams are located at SCNs 17 and 28, respectively.

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