Table S1: Geophysical and vegetative characteristics (CaMa-Flood slope and Noah-MP soil and land cover types) of the selected global river basins

Basin	Drainage area (km^2)	Mean Slope (%)	Dominant Soil Texture	Dominant Land Cover
Yukon	824794.7	1.0	Loam	Evergreen Needleleaf Forest
Mackenzie	1698403.9	0.7	Sandy Loam	Evergreen Needleleaf Forest
Fraser	216563.0	2.0	Loam	Evergreen Needleleaf Forest
Columbia	652359.5	1.9	Silt Loam	Evergreen Needleleaf Forest
Mississippi	2918820.0	0.4	Silt Loam	Grasslands
Pearl	16920.2	0.1	Sandy Loam	Woody Savannas
Orinoco	821894.3	0.7	Clay Loam	Evergreen Broadleaf Forest
Amazon	4671461.8	0.7	Loam	Evergreen Broadleaf Forest
Tocantins	759793.1	0.4	Clay	Savannas
Parnaiba	298405.3	0.5	Sandy Clay Loam	Savannas
Parana	2520777.8	0.5	Loam	Savannas
Uruguay	242692.5	0.5	Clay	Grasslands
Ebro	84016.4	1.3	Loam	Croplands
Rhone	92923.2	1.8	Loam	Croplands
Rhine	159337.8	0.9	Loam	Mixed Forests
Po	72020.4	1.9	Clay Loam	Croplands
Elbe	131118.4	0.5	Loam	Croplands
Danube	777784.1	0.8	Loam	Croplands
Onega	63044.8	0.2	Silt Loam	Mixed Forests
Severnaya Dvina	343794.8	0.2	Silt Loam	Mixed Forests
Volga	1366093.1	0.2	Loam	Mixed Forests
Don	380598.0	0.2	Loam	Croplands
Chelif	44326.5	0.9	Loam	Open Shrublands
Niger	2061636.3	0.3	Loam	Barren or Sparsely Vegetated
Lake Chad	601365.3	0.3	Loam	Savannas
Congo	3619085.4	0.4	Sandy Loam	Woody Savannas
Okavango	229666.2	0.3	Sandy Loam	Savannas
Limpopo	258770.3	0.5	Sandy Loam	Savannas
Orange	784762.9	0.5	Sandy Loam	Open Shrublands
Ob	2454226.9	0.4	Loam	Mixed Forests

Yenisey	2431664.8	0.8	Silt Loam	Mixed Forests
Lena	2458634.9	0.7	Silt Loam	Deciduous Needleleaf Forest
Indigirka	304905.7	1.0	Loam	Wooded Tundra
Kolyma	422146.8	0.7	Silt Loam	Open Shrublands
Anadyr	106004.5	0.6	Loam	Wooded Tundra
Amur	1877929.1	0.5	Loam	Mixed Forests
Amu Darya	282058.5	3.6	Loam	Grasslands
Yellow	293382.1	1.5	Loam	Grasslands
Ganges	941568.4	1.3	Loam	Croplands
Irrawaddy	361561.6	1.6	Clay Loam	Evergreen Broadleaf Forest
Mekong	637746.5	1.3	Clay Loam	Evergreen Broadleaf Forest
Yangtze	1677763.7	1.8	Clay Loam	Mixed Forests
Murray-Darling	754963.3	0.4	Sandy Clay Loam	Open Shrublands

Table S2: Correlation Coefficient of Each Experiment Across Different Basins

Basin	EXP1	EXP2	EXP3	EXP4	EXP6	EXP7	EXP8	ERA5-Land
Yukon	0.90	0.91	0.88	0.88	0.88	0.84	0.89	0.69
Mackenzie	0.81	0.67	0.70	0.87	0.87	0.88	0.74	0.62
Fraser	0.91	0.94	0.92	0.93	0.93	0.92	0.81	0.94
Columbia	0.57	0.55	0.55	0.61	0.59	0.56	0.64	0.62
Mississippi	0.81	0.67	0.70	0.87	0.87	0.88	0.74	0.62
Pearl	0.71	0.64	0.65	0.70	0.69	0.65	0.57	0.69
Orinoco	0.79	0.87	0.85	0.83	0.84	0.85	0.68	0.83
Amazon	0.87	0.94	0.93	0.92	0.91	0.93	0.83	0.95
Tocantins	0.84	0.90	0.88	0.86	0.86	0.88	0.63	0.91
Parnaiba	0.83	0.88	0.83	0.88	0.88	0.82	0.70	0.86
Parana	0.67	0.72	0.73	0.70	0.67	0.72	0.54	0.72
Uruguay	0.77	0.79	0.81	0.81	0.81	0.80	0.72	0.82
Ebro	0.41	0.57	0.53	0.62	0.53	0.54	0.32	0.59
Rhone	0.48	0.44	0.46	0.50	0.46	0.47	0.42	0.60
Rhine	0.50	0.51	0.49	0.63	0.56	0.53	0.56	0.69
Po	0.71	0.67	0.65	0.71	0.69	0.67	0.63	0.70

Elbe	0.69	0.75	0.68	0.76	0.69	0.73	0.36	0.73
Danube	0.29	0.23	0.29	0.34	0.27	0.32	0.28	0.34
Onega	0.81	0.70	0.64	0.78	0.79	0.68	0.86	0.53
Severnaya Dvina	0.86	0.69	0.69	0.78	0.79	0.71	0.88	0.56
Volga	0.45	0.42	0.41	0.43	0.45	0.45	0.34	0.29
Don	0.49	0.40	0.39	0.37	0.38	0.41	0.30	0.33
Chelif	0.59	0.61	0.49	0.63	0.66	0.20	0.58	0.63
Niger	0.83	0.81	0.74	0.83	0.84	0.72	0.87	0.81
Lake Chad	0.81	0.85	0.83	0.80	0.81	0.83	0.54	0.84
Congo	0.49	0.46	0.48	0.48	0.44	0.50	0.56	0.50
Okavango	0.68	0.79	0.82	0.78	0.81	0.82	0.32	0.84
Limpopo	0.44	0.45	0.40	0.51	0.55	0.23	0.56	0.56
Orange	0.53	0.62	0.58	0.61	0.56	0.56	0.38	0.61
Ob	0.73	0.50	0.70	0.48	0.53	0.62	0.35	0.30
Yenisey	0.83	0.85	0.83	0.72	0.74	0.72	0.73	0.61
Lena	0.81	0.86	0.87	0.79	0.81	0.75	0.82	0.70
Indigirka	0.62	0.47	0.76	0.80	0.79	0.60	0.76	0.64
Kolyma	0.74	0.70	0.79	0.76	0.79	0.72	0.76	0.74
Anadyr	0.51	0.39	0.53	0.70	0.68	0.66	0.55	0.84
Amur	0.90	0.94	0.76	0.96	0.96	0.87	0.92	0.77
Amu Darya	0.64	0.65	0.63	0.69	0.68	0.67	0.52	0.72
Yellow	0.76	0.75	0.76	0.82	0.83	0.60	0.77	0.73
Ganges	0.89	0.88	0.87	0.89	0.89	0.86	0.89	0.89
Irrawaddy	0.95	0.97	0.97	0.96	0.96	0.97	0.86	0.96
Mekong	0.97	0.95	0.94	0.96	0.94	0.94	0.84	0.97
Yangtze	0.95	0.94	0.95	0.96	0.95	0.93	0.87	0.96
Murray-Darling	0.77	0.71	0.68	0.66	0.63	0.68	0.39	0.76

Table S3: Mean Absolute Error of Each Experiment Across Different Basins

Basin	EXP1	EXP2	EXP3	EXP4	EXP6	EXP7	EXP8	ERA5-Land
Yukon	2824.1	2818.5	1872.1	2066.7	2151.8	2744.2	2625.5	3129.2
Mackenzie	4161.5	3990.4	3153.2	2707.0	2582.2	3019.2	8790.9	3374.7

Fraser	1206.1	777.0	1077.6	1087.9	971.2	1042.0	2162.8	1076.1
Columbia	4187.6	3491.5	4203.2	4072.5	3720.2	4171.5	5828.1	3738.0
Mississippi	12434.8	9131.1	7933.4	5972.0	6505.8	8560.8	29357.2	5172.6
Pearl	154.3	163.1	158.5	148.7	152.4	159.5	259.8	158.6
Orinoco	11108.0	7928.9	8821.1	9073.9	8979.3	8869.9	13659.5	9352.6
Amazon	40517.6	36792.1	36749.4	28587.2	32665.9	37239.4	40319.2	29266.8
Tocantins	8103.7	6425.9	7366.7	8475.7	7667.3	7725.1	18290.9	7404.4
Parnaiba	493.7	465.9	467.8	428.6	436.1	472.6	783.7	510.9
Parana	5617.5	4787.6	5342.0	9496.3	7762.9	5336.2	29694.7	5648.0
Uruguay	2775.8	2118.2	2001.1	1987.5	1914.8	2114.8	4480.1	1833.5
Ebro	179.9	135.8	145.7	208.8	185.4	147.4	960.6	154.8
Rhone	807.5	720.7	735.5	715.9	738.8	729.1	1249.6	660.3
Rhine	802.7	696.5	688.6	647.8	663.1	670.7	1687.1	695.2
Po	618.4	564.2	555.7	535.7	547.6	541.1	882.5	557.3
Elbe	404.0	250.8	262.1	224.0	222.1	265.4	1284.5	271.8
Danube	2755.0	2554.5	2536.7	2566.7	2522.6	2480.4	7620.4	2508.2
Onega	224.7	273.2	268.5	241.6	237.8	258.3	396.2	375.5
Severnaya Dvina	1196.6	1590.4	1584.5	1422.6	1392.5	1580.3	2318.2	2265.5
Volga	4191.5	3676.9	4096.1	4491.8	4071.1	3933.9	12341.9	4712.1
Don	385.4	322.3	417.0	1038.6	673.7	406.7	3467.2	405.1
Chelif	8.6	26.0	16.9	65.2	54.5	15.7	364.4	8.3
Niger	2418.8	2690.6	2757.3	2590.3	2507.3	2800.2	6657.5	2552.1
Lake Chad	270.0	300.5	268.4	295.4	284.5	261.0	458.4	265.7
Congo	13990.0	14716.1	15854.8	19240.4	16843.2	15612.4	67335.5	19516.3
Okavango	181.8	135.7	156.1	159.6	146.3	157.6	613.8	223.6
Limpopo	141.8	271.9	227.0	431.7	388.6	203.9	1727.0	71.0
Orange	505.1	1105.4	952.8	2095.1	1698.4	803.5	8119.5	304.3
Ob	5623.7	6777.0	5825.9	8640.8	7446.2	6189.2	17824.1	9379.3
Yenisey	8521.4	8666.3	7468.7	7377.4	7463.8	7692.7	14922.4	8718.5
Lena	7760.5	7897.6	5934.9	7514.8	6782.2	8990.6	10389.7	10181.4
Indigirka	1539.4	1525.9	1283.1	1365.6	1342.7	1670.7	1278.5	1432.1
Kolyma	2463.2	2568.0	1961.3	2047.8	1861.8	2419.5	2369.6	2402.7

Anadyr	904.5	975.0	802.7	775.3	784.5	862.2	825.2	685.0
Amur	3998.6	2912.7	3864.8	2525.8	2067.1	4107.0	14174.3	4429.4
Amu Darya	1049.7	1025.3	961.6	916.4	960.0	975.6	988.5	921.5
Yellow	327.3	318.1	314.9	248.8	194.5	282.0	1956.7	375.4
Ganges	3753.2	4817.2	5191.9	6304.0	5241.0	5042.6	11933.1	5050.7
Irrawaddy	3530.6	2449.5	2933.8	3408.3	3179.7	2907.7	6727.8	5001.3
Mekong	3765.6	3504.4	3227.1	2641.9	3296.5	3514.3	8390.6	2658.7
Yangtze	2455.0	3156.9	4330.4	4874.2	3867.9	3698.6	14401.5	7394.9
Murray-Darling	346.7	778.1	687.6	1376.7	1183.1	616.0	3832.2	316.3

Table S4: Root Mean Squared Error of Each Experiment Across Different Basins

Basin	EXP1	EXP2	EXP3	EXP4	EXP6	EXP7	EXP8	ERA5-Land
Yukon	4218.0	4178.4	2891.4	3214.7	3493.1	4054.7	3423.1	4292.4
Mackenzie	5604.8	5886.8	4702.7	3763.6	3961.5	4590.2	9845.7	5081.1
Fraser	1851.7	1233.6	1865.7	1982.5	1712.9	1813.3	3175.8	2012.6
Columbia	5401.1	4636.0	5880.9	6261.6	5398.8	5815.6	8188.3	5796.1
Mississippi	14855.4	11644.0	10397.8	7408.8	8140.6	10854.1	32301.2	6789.8
Pearl	289.5	308.8	294.4	272.5	286.2	293.6	346.5	286.5
Orinoco	13864.2	10622.5	11621.7	11713.8	11550.2	11688.8	18449.0	12958.3
Amazon	51867.0	42683.3	45321.6	37618.6	40467.5	46105.6	44036.7	35919.0
Tocantins	11582.2	9476.9	11150.4	12046.7	10577.7	11546.1	24036.2	11412.1
Parnaiba	588.5	531.0	569.3	512.8	504.4	573.4	1238.7	584.9
Parana	6579.2	5875.5	6670.7	10814.0	9099.2	6582.1	31622.9	6942.4
Uruguay	3811.3	3322.3	3059.8	2716.5	2767.1	3231.9	5360.0	2572.7
Ebro	291.2	228.7	243.3	286.1	272.5	243.5	1330.4	238.6
Rhone	1079.2	1024.1	1046.0	1021.6	1036.3	1030.3	1735.0	935.2
Rhine	1139.5	1047.0	1073.7	924.2	973.6	1032.4	2098.4	940.3
Po	810.8	792.1	826.8	753.5	767.5	797.7	1116.5	776.2
Elbe	536.1	389.5	395.9	296.6	317.4	388.6	1482.9	371.0
Danube	3389.0	3126.4	3134.9	3245.5	3111.9	3074.6	8728.1	3135.8
Onega	450.9	558.1	558.9	458.5	477.9	538.0	526.0	603.1
Severnaya Dvina	2559.2	3466.3	3318.1	2867.1	2973.8	3290.8	2901.3	3679.6

Volga	5610.0	5096.4	5605.3	6352.5	5399.8	5366.2	14665.1	7016.9
Don	461.5	449.4	581.5	1305.4	868.2	564.8	3808.8	564.3
Chelif	26.5	30.4	25.6	76.8	79.2	27.3	571.7	22.0
Niger	3623.4	3611.0	3606.4	3125.3	3182.5	3686.3	8735.6	3953.9
Lake Chad	434.9	435.7	420.9	442.2	437.2	417.7	625.4	443.2
Congo	17360.1	18004.9	19599.2	24039.1	21214.8	19308.4	71054.2	24949.9
Okavango	220.8	165.0	186.2	206.8	177.4	188.3	904.4	250.3
Limpopo	252.8	329.3	299.1	508.1	493.4	294.7	2623.6	221.2
Orange	703.0	1241.0	1132.1	2466.5	2077.3	988.2	11380.1	526.9
Ob	8580.3	9719.9	7877.0	10449.5	9503.8	8724.5	21551.6	10983.4
Yenisey	16931.2	15981.2	12737.2	16505.7	17027.3	18195.0	19439.4	18273.9
Lena	15708.4	14044.2	10521.1	14274.8	14293.4	16450.9	14694.8	16147.4
Indigirka	2625.9	2676.9	2129.5	1970.1	2109.6	2502.0	2083.2	2046.1
Kolyma	4813.5	4697.0	3333.4	3912.8	3995.2	4538.1	3681.7	3789.4
Anadyr	1716.6	1792.6	1621.3	1401.2	1493.5	1541.7	1570.1	1059.3
Amur	5732.7	4235.4	5041.6	3003.9	2677.2	5156.8	18007.6	5198.0
Amu Darya	1280.9	1253.6	1183.0	1127.0	1169.5	1184.7	1283.8	1110.3
Yellow	459.5	434.6	489.7	375.2	304.6	438.9	2835.4	499.6
Ganges	7067.1	7519.6	8449.8	9400.9	8200.2	8456.7	16541.4	7862.2
Irrawaddy	4912.0	3754.5	4502.1	5049.0	4544.7	4455.9	9849.0	7780.2
Mekong	5424.3	5851.0	5206.0	4278.3	5493.5	5558.7	11708.0	3891.8
Yangtze	3598.1	4098.9	5297.3	5673.4	4601.3	4665.4	18168.0	8325.8
Murray-Darling	373.7	823.6	763.8	1471.0	1264.6	699.8	4060.3	364.8

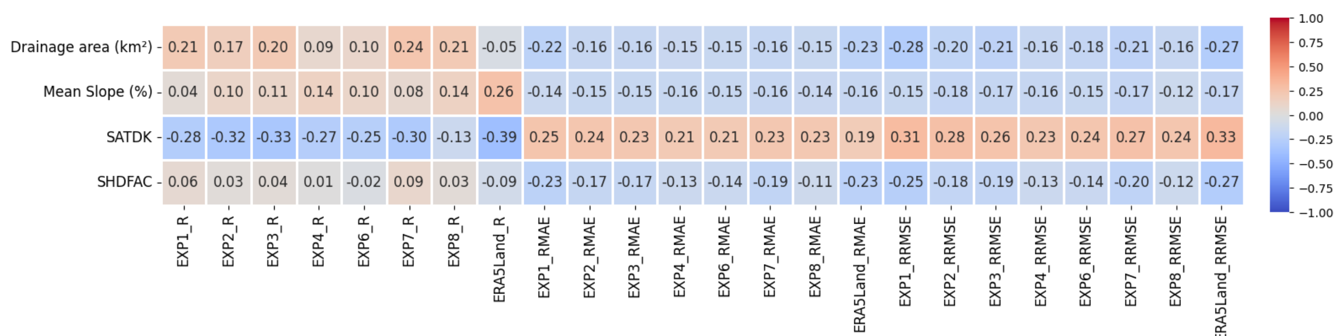

Figure S1: Correlation Heatmap between Experiment Performances (R, RMAE, RRMSE) and Geophysical and Vegetative Properties (Drainage Area, Mean Slope, Saturated Soil Hydraulic Conductivity (SATDK), Vegetation Fraction (SHDFAC)).

To evaluate the correlation between experiment performances and soil/vegetation types, we used saturated soil hydraulic conductivity (SATDK) and vegetation fraction (SHDFAC) as representative quantitative values. This allowed us to perform a meaningful correlation analysis, as soil type and vegetation are typically categorical and not directly correlatable.

Larger basins tend to have higher discharge magnitudes, which can naturally lead to larger MAE and RMSE values. To account for this inherent scaling issue and to provide a more normalized assessment of model performance, Relative Mean Absolute Error (RMAE) and Relative Root Mean Squared Error (RRMSE) were calculated. This normalization is achieved by dividing the MAE and RMSE values by the mean of the observed discharge values for each basin, allowing for a more equitable comparison of model performance across basins of varying scales.

The heatmap illustrates the generally weak correlations between geophysical and vegetative properties and the performance of different runoff experiments. The slightly moderate negative correlation with hydraulic conductivity (SATDK) suggests that in basins with high hydraulic conductivity soils, there is a challenge in capturing the hydrograph shape accurately. This is likely because high hydraulic conductivity increases subsurface runoff at the expense of surface runoff, and the CaMa-Flood routing model does not differentiate between these two types of runoff, affecting the timing and shape of the hydrograph and thus, negatively the R coefficient and positively the bias.

This also supports our previous discussion on CaMa-Flood limitations.