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Enhanced hydrological modeling with the WRF-Hydro lake–reservoir module at a convection-permitting scale: a case study of the Tana River basin in East Africa

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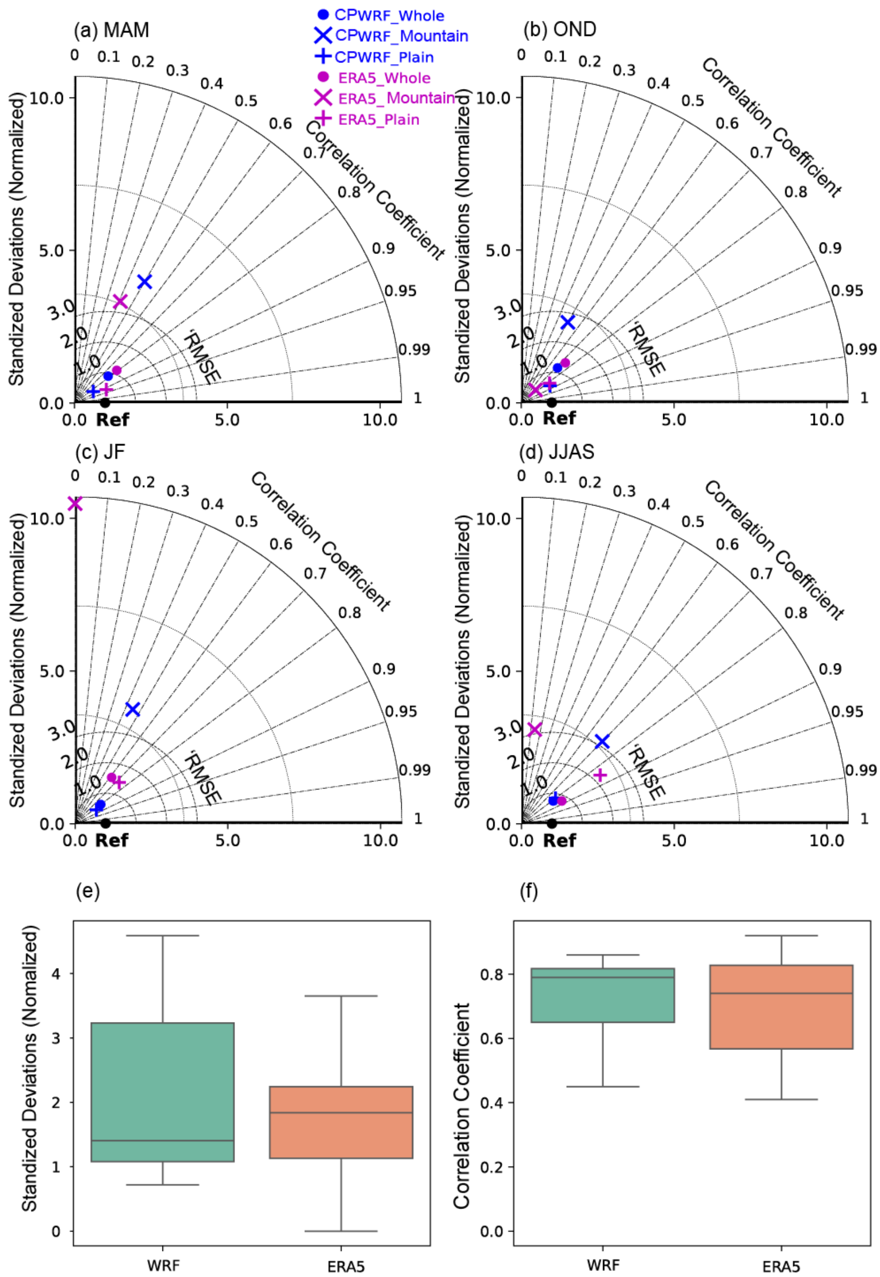

Fig. S1. Taylor diagram for seasonal precipitation over the whole basin, mountainous area, or plain area, from CPWRF simulation with ERA5 as reference. Panel (a, b, c, d) donates results from MAM (March-May), OND (October-December), JF (January-February), and JJAS (Jun-August). The normalized standardized deviation (indicating the spatial variance), and correlation coefficient (indicating the spatial correlation), are calculated based on the spatial precipitation of CPWRF (or ERA5) against IMERG. Panel (e) or (f) indicates the statistical summary of normalized standardized deviation or correlation coefficient from panel a-d. In the box plots, the upper and lower bounds of the boxes are the first (Q1) and third (Q3) quartiles, respectively, the bar in the middle shows the median (Q2), and the whiskers show the upper (2.5Q3-Q1) and lower (2.5Q1-1.5Q3) limbs.

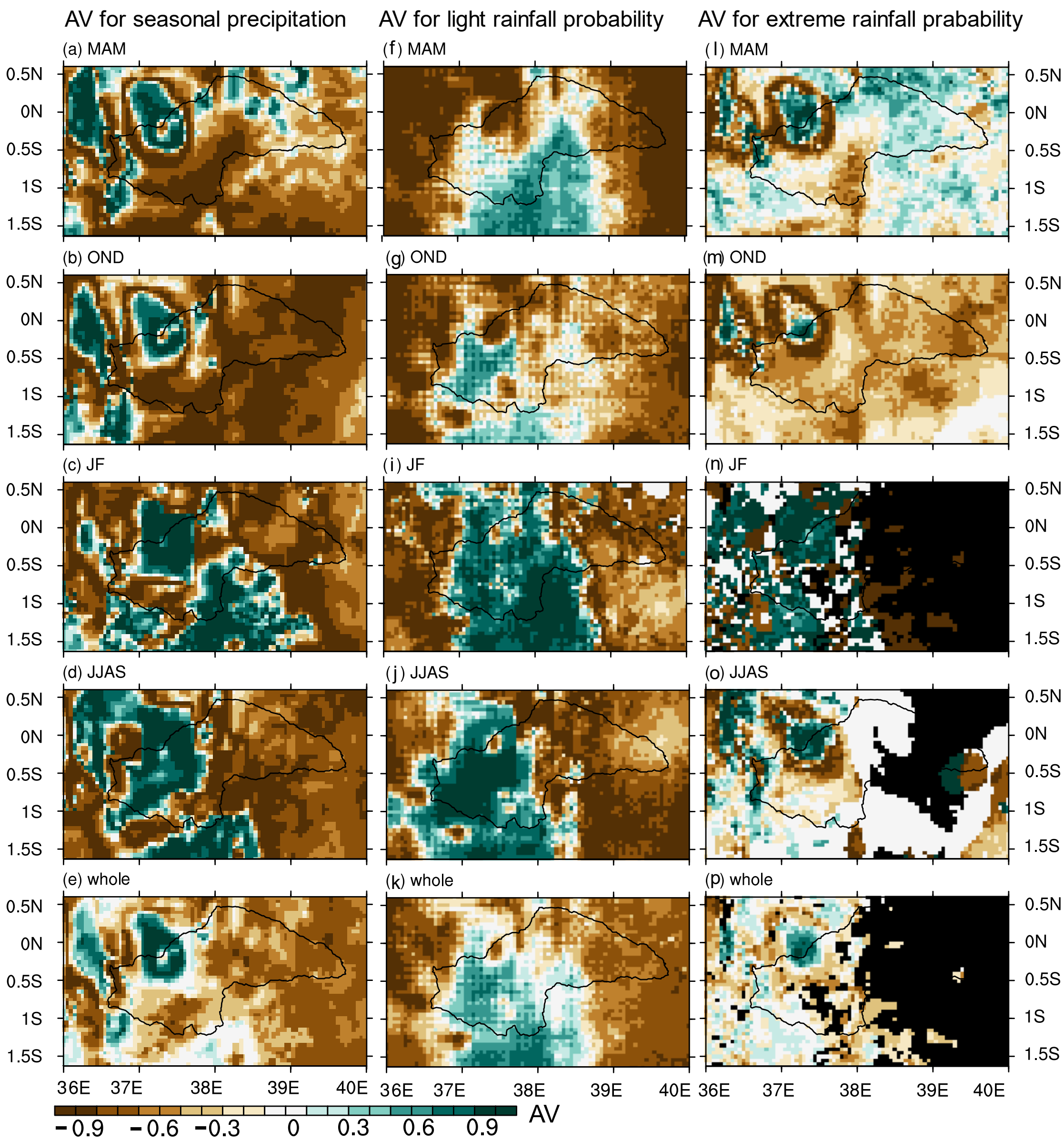

Fig. S2. The spatial distributions of added value (AV) of convection-permitting WRF simulation (CPWRF) with respect to ERA5, over seasonal precipitation (PCP) amount, light rainfall probability, and extreme rainfall probability, for MAM (March-May), OND (October-December), JF (January-February), JJAS (June-August), and the whole year. The light or extreme rainfall indicates a frequency of daily precipitation with 1-15 mm day^{-1} or > 20 mm day^{-1}. In panels (n-p), the black indicates an invalid value which is due to the zero as a divisor for calculating AV.

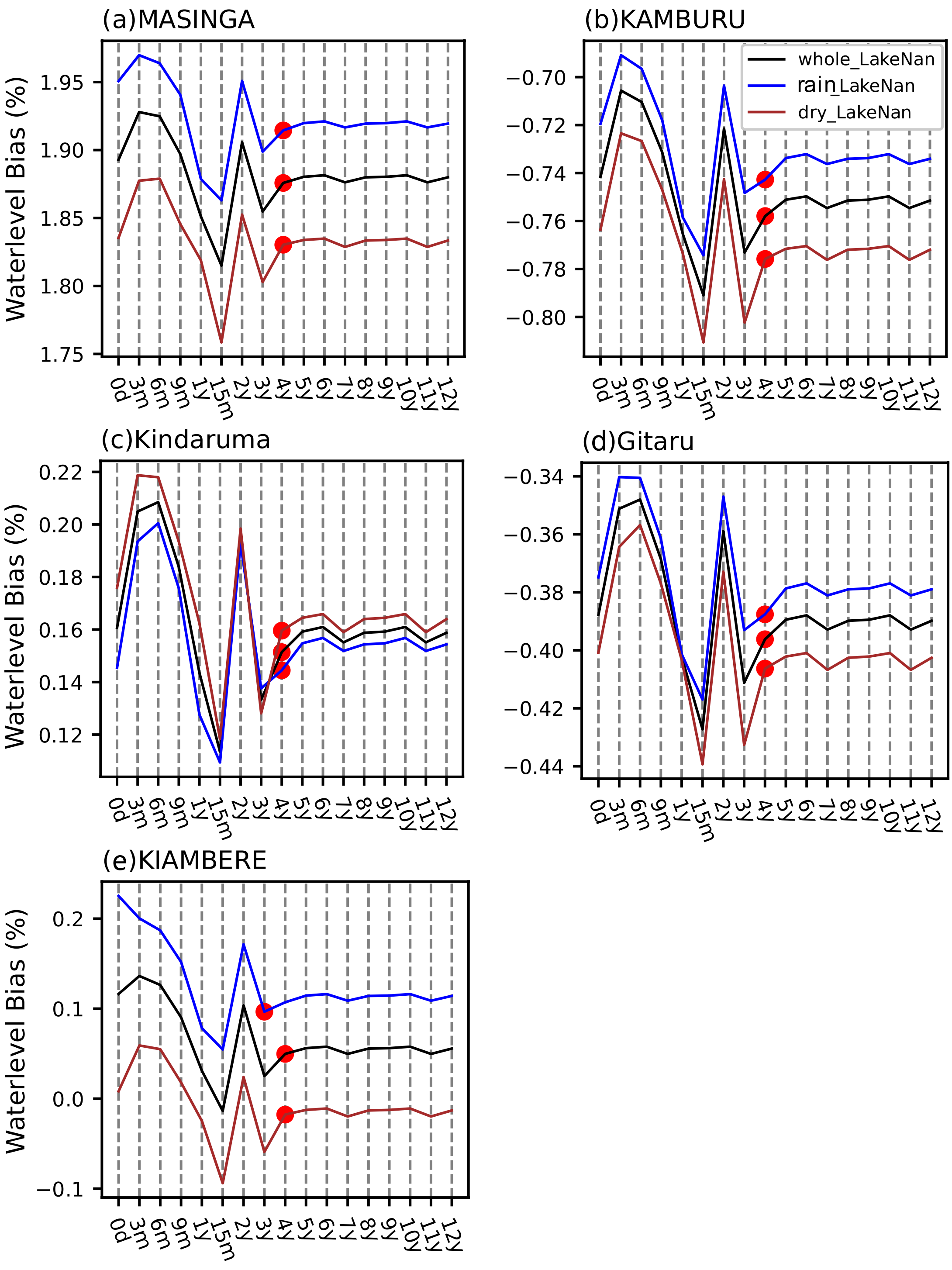

Fig. S3. The bias of simulated water level from lakes of MASINGA (a), KAMBURU (b), GITARU(c), KINDARUMA(d) and KIAMBERE (e) with the increase of spin-up time from LakeRaw Model for the whole year (black line), rainy season (March-May and October-December, red line) and dry season (January-February and June-August, blue line). The red dots highlight the minimum necessary spin-up time to reach equilibrium from WRF-Hydro modelling with the lake module (LakeRaw).

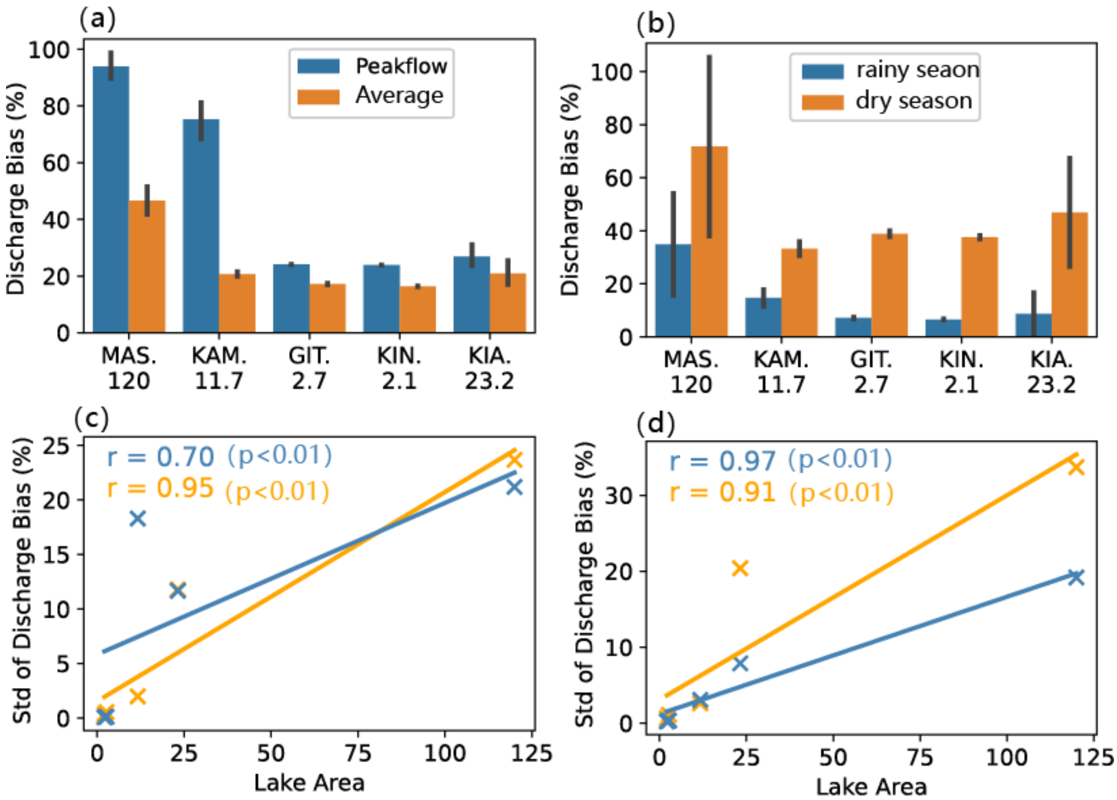

Fig. S4. Sensitivity comparison of lake-related parameters among different lakes, including MASINGA (MAS.), KAMBURU (KAM.), GITARU (GIT.), KINDARUMA (KIN.), KIAMBERE (KIA.) with areas of 120, 11.7, 2.7, 2.1 and 23.2 km^2, respectively. (a) shows the model-data bias of Peak-Flow (on December 3, 2011, when the daily discharge was the highest during 2011-2014 in the 12-year spin-up experiment) and average discharge (calculated over January 2011-December 2014, Allmean). (b) indicates the model-data bias of dry-season and wet-season flow. The error bar indicates the one standard deviation. (c or d) displays a scatter plot illustrating the relationship between the standard deviation and lake area. Here, the standard deviation indicates the impact of lake-related parameter changes on discharge, which measures the parameter sensitivity of a lake.

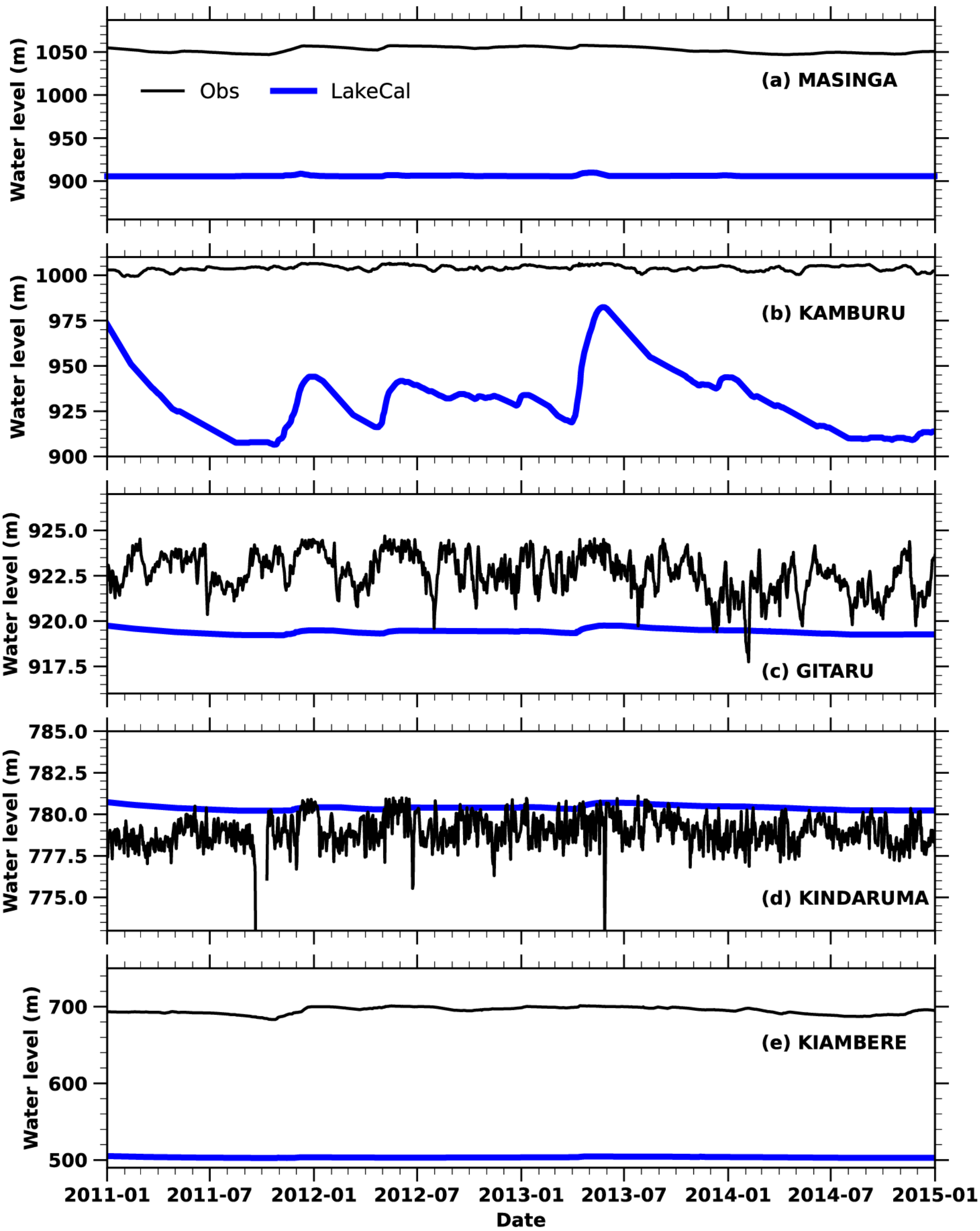

Fig. S5. The simulated daily water level evolution from the well-calibrated WRF-Hydro simulation with lake/reservoir module (LakeCal) against the observation (Obs). The water levels involve five lakes: MASINGA (a), KAMBURU (b), GITARU(c), KINDARUMA(d), and KIAMBERE (e).

Table S1. Evaluation of monthly precipitation over TRB from CPWRF and ERA5.

Index	whole		Mountain area		Plain area	
	CPWRF-IMERG	ERA5-IMERG	CPWRF-IMERG	ERA5-IMERG	CPWRF-IMERG	ERA5-IMERG
r^2	0.45	0.82	0.71	0.21	0.04	0.82
Bias (mm/mon)	-17(-37%)	9(14%)	18(15%)	57(58%)	-26(-86%)	-6(-11%)

Note: coefficient of determination (r^2), (root-mean-square error) RMSE, Bais was calculated over the simulated monthly precipitation during 2011-2014 regionally averaged over TRB against the IMERG.

Tables S2-S6

In all the following tables, Nash-Sutcliffe Efficiency (NSE), coefficient of determination (r^2), bias (Bias, unit: %), and Kling-Gupta Efficiency (KGE) are calculated based on the simulated daily discharge at Garissa (or water levels of a given lake) against the observations during 2011-2014. The terms “whole period”, “rainy season”, and “dry season” refer to the data used for calculating these indices, representing the entire year, January-February and July-September, and March-May and October-December, respectively.

Table S2. Model evaluation from LakeRaw, LakeNan, and LakeCal.

Experiment		KGE	Bias (%)	r^2	NSE
LakeNan simulation driven by CPWRF-precipitation	whole	0.16	-53	0.30	-1.09
	rainy season	0.13	-41	0.27	-1.23
	dry season	-0.24	-78	0.00	-4.81
LakeRaw simulation driven by CPWRF-precipitation	whole	0.35	40	0.33	0.01
	rainy season	0.45	22	0.29	0.14
	dry season	-0.30	81	0.12	-4.34
LakeCal simulation driven by CPWRF-precipitation	whole	0.70	9	0.59	0.57
	rainy season	0.74	-2	0.59	0.58
	dry season	0.36	34	0.22	-0.73
LakeCal simulation driven by ERA5-precipitation (LakeCal-ERA5)	whole	0.46	42	0.45	0.04
	rainy season	0.62	21	0.47	0.28
	dry season	-0.08	89	0.19	-5.81

LakeNan: the calibrated WRF-Hydro system without lake/reservoir module.

LakeRaw: WRF-Hydro system integrated with lake/reservoir module based on the parameters from LakeNan. Therein, the default value of lake-related parameters is obtained from the WRF-Hydro GIS pre-processing toolkit.

LakeCal: the well-calibrated WRF-Hydro system integrated with lake/reservoir module.

Whole: the whole year

Dry season: January-February and July-September

Rainy season: March-May and October-December

Table S3. Evaluation of Sensitivity Experiments for MannN.

Experiment		KGE	Bias (%)	r^2	NSE
	whole	0.27	39	0.16	-0.31
	rainy season	0.32	20	0.13	-0.26
MannN_1	dry season	-0.40	81	0.03	-4.36
	whole	0.31	40	0.29	-0.03
	rainy season	0.38	22	0.25	0.09
MannN_2	dry season	-0.37	81	0.07	-4.32
	whole	0.36	41	0.28	-0.19
	rainy season	0.44	23	0.25	-0.11
MannN_3	dry season	-0.31	81	0.12	-4.32
	whole	0.36	42	0.37	0.02
	rainy season	0.44	24	0.32	0.16
MannN_4	dry season	-0.24	82	0.15	-4.34
	whole	0.37	41	0.39	0.06
	rainy season	0.48	22	0.35	0.21
MannN_5	dry season	-0.18	82	0.14	-4.42
	whole	0.36	41	0.42	0.10
	rainy season	0.46	23	0.38	0.27
MannN_6	dry season	-0.12	83	0.14	-4.54
	whole	0.38	41	0.45	0.14
	rainy season	0.49	22	0.43	0.32
MannN_7	dry season	-0.09	84	0.14	-4.65
	whole	0.38	41	0.48	0.16
	rainy season	0.50	22	0.45	0.35
MannN_8	dry season	-0.12	83	0.14	-4.54
	whole	0.39	41	0.50	0.18
	rainy season	0.50	22	0.48	0.39
MannN_9	dry season	-0.11	83	0.13	-4.63
	whole	0.39	41	0.52	0.20
	rainy season	0.52	22	0.50	0.40
MannN_10	dry season	-0.12	83	0.14	-4.60

Table S4. Evaluation of Sensitivity Experiments for REFKDT.

Experiment		KGE	Bias (%)	r^2	NSE
	whole	-2.99	131	0.16	-21.76
	rainy season	-3.44	150	0.11	-27.48
REFKDT_1	dry season	-0.22	89	0.03	-5.67
	whole	-0.39	69	0.22	-3.27
	rainy season	-0.52	62	0.18	-4.02
REFKDT_2	dry season	-0.26	84	0.07	-4.66
	whole	0.07	56	0.25	-1.46
	rainy season	0.01	44	0.21	-1.73
REFKDT_3	dry season	-0.28	82	0.09	-4.47
	whole	0.24	50	0.26	-0.84
	rainy season	0.24	37	0.23	-0.94
REFKDT_4	dry season	-0.30	82	0.10	-4.41
	whole	0.33	47	0.28	-0.47
	rainy season	0.37	32	0.25	-0.47
REFKDT_5	dry season	-0.30	82	0.10	-4.39
	whole	0.36	45	0.30	-0.27
	rainy season	0.43	28	0.26	-0.21
REFKDT_6	dry season	-0.30	81	0.11	-4.37
	whole	0.37	43	0.31	-0.15
	rainy season	0.45	26	0.27	-0.06
REFKDT_7	dry season	-0.30	81	0.11	-4.36
	whole	0.37	42	0.32	-0.08
	rainy season	0.46	24	0.28	0.03
REFKDT_8	dry season	-0.30	81	0.11	-4.35
	whole	0.36	41	0.32	-0.03
	rainy season	0.45	23	0.28	0.09
REFKDT_9	dry season	-0.30	81	0.12	-4.34
	whole	0.35	40	0.33	0.01
	rainy season	0.45	22	0.29	0.14
REFKDT_10	dry season	-0.30	81	0.12	-4.34

Table S5. Evaluation of Sensitivity Experiments for the groundwater component option.

Experiment		KGE	Bias (%)	r^2	NSE
GWBASESWCRT_Passthrough	whole	0.35	40	0.33	0.01
	rainy season	0.45	22	0.29	0.14
	dry season	-0.30	81	0.12	-4.34
GWBASESWCRT_Sink	whole 0	0.17	72	0.56	-0.75
	rainy season	0.25	56	0.53	-0.60
	dry season	-0.15	107	0.44	-7.35

GWBASESWCRT_Sink: creates a sink at the bottom of the soil column and water draining from the bottom of the soil column leaves the system into the sink;

GWBASESWCRT_Passthrough: bypasses the bucket model and dumps all flow from the bottom of the soil column directly into the channel.

Table S6. The evaluation of simulated daily water level from WRF-Hydro simulation with lake/reservoir module.

Name	Bias (%)	r^2	NSE	KGE
MASINGA	-14	0.21	-1782.1	0.03
KAMBURU	-7	0.01	-2465.5	-9.86
GITARU	0	0.03	-8.7	-0.20
KINDARUMA	0	0.02	-1.8	-0.23
KIAMBERE	-28	0.25	-1885.8	-0.04

Note: The data used for index calculation are derived from the simulations conducted for calibrating the lake parameters.