Supplementary Material for

Revealing joint evolutions and causal interactions in complex eco-hydrological systems by a network-based framework

Lu Wang[1], Yue-Ping Xu[1*], Haiting Gu[1], Li Liu[1], Xiao Liang[1], Siwei Chen[1]

[1] Institute of Water Science and Engineering, Zhejiang University, Hangzhou, 310058, China

* Correspondence to: yuepingxu@zju.edu.cn

S1 Introduction of Mann-Kendall test

The Mann-Kendall (MK) test searches for a trend in a series without specifying whether the trend is linear or nonlinear. Given a series $x(t)$ with the length of n, the null hypothesis of no trend assumes that the series $x(t)$ is independently distributed. The MK test is based on the test statistic S:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x(j) - x(i)) \qquad \text{(Eq. S1.1)}$$

with

$$\begin{cases} \operatorname{sgn}(x) = 1 \;\; if \;\; x > 0 \\ \operatorname{sgn}(0) = 0 \\ \operatorname{sgn}(x) = -1 \;\; if \;\; x < 0 \end{cases} \qquad \text{(Eq. S1.2)}$$

A positive (negative) value of S indicates an upward (downward) trend. It is found that the statistic S is approximately normally distributed when n>8. The standardized test statistic Z follows the standard normal distribution:

$$Z = \begin{cases} (S-1)/\sqrt{Var(S)} \;\; if \;\; S > 0 \\ \operatorname{sgn}(0) = 0 \\ (S+1)/\sqrt{Var(S)} \;\; if \;\; S < 0 \end{cases} \qquad \text{(Eq. S1.3)}$$

The null hypothesis of no trend is rejected if the absolute value of Z is bigger than the theoretical value $Z_{1-\alpha/2}$, where α is the statistical significance level concerned.

S2 Datasets

Table S1. Brief description of datasets used in the study

Type	Abbreviation	Variables	Data sources	Temporal resolution	Unit
Hydrological variables	R	Runoff	National Hydrological Yearbook	Monthly	m^3/s
	SL	Sediment load			kg/s
	SMSA	Soil moisture storage anomaly	GLDAS-v2.1-Noah	Monthly	mm
	SWSA	Surface water storage anomaly	GLDAS-v2.1-Noah	Monthly	mm
	TWSA	Terrestrial water storage anomaly	GRACE/GRACR-FO CSR	Monthly	mm
			GRACE/GRACR-FO GSFC		mm
			GRACE/GRACR-FO JPL		mm
	SCA	Snow cover area	MODIS-based snow cover product	Monthly	km^2
Ecological variables	NDVI	Normalized difference vegetation index	MOD13A3.061	Monthly	/
	GPP	Gross primary productivity	MOD17A2H.061	Monthly	gC m^{-2}
	WUE	Ecosystem water use efficiency	MOD17A2H.061 MOD16A2.061	Monthly	C/kg H_2O
Meteorological data (Auxiliary data)	P	Precipitation	China Meteorological Administration	Monthly	mm
	T	Temperature		Monthly	°C
Human activity (Auxiliary data)	RSC	Reservoir storage change	National Hydrological Yearbook	Monthly	10^8 m^3
	WW	Water withdrawals	Water Resources Bulletin of the Yellow River	Annual	m^3

S3 Multi-year mean values of ecohydrological variables

Table S2. Multi-year mean values of eco-hydrological variables (in the growing season)

Variables	$R_{\_modulus}$	TWSA	SMSA	GWSA	NDVI	GPP
Units	$\times 10^3\ m^3/km^2$	mm	mm	mm	/	$g*C/m^2$
Region I	84.98	5.15	12.87	-7.84	0.45	339.95
Region II	84.39	-1.65	4.28	-5.58	0.49	476.17
Region III	-57.36	-22.18	2.88	-24.79	0.27	260.19
Region IV	-	-31.56	4.39	-35.71	0.22	219.51
Region V	10.47	-49.90	4.32	-52.96	0.41	419.59
Region VI	13.64	-42.48	-8.08	-32.85	0.55	632.47
Region VII	81.19	-99.62	-11.70	-83.28	0.65	731.21
Region VIII	-217.58	-152.81	-34.91	-117.67	0.59	623.75
Variables	WUE	$SL_{\_modulus}$	SCA	P	T	ET
Units	$C/kg\ H_2O$	$\times 10^3\ kg/km^2$	km^2	mm	°C	mm
Region I	0.98	66.94	7900	449.64	7.3	346.2
Region II	1.57	21.09		400.74	11.7	302.59
Region III	1.86	105.42		229.08	18.3	139.80
Region IV	2.02	-		276.84	18.4	108.54
Region V	2.14	601.29		407.88	18.8	194.82
Region VI	1.98	741.25		442.92	19.3	318.96
Region VII	2.05	-3778.52		521.22	21.4	356.61
Region VIII	1.75	2307.59		930.18	20.0	356.29

S4 Evolution trend of snow cover area

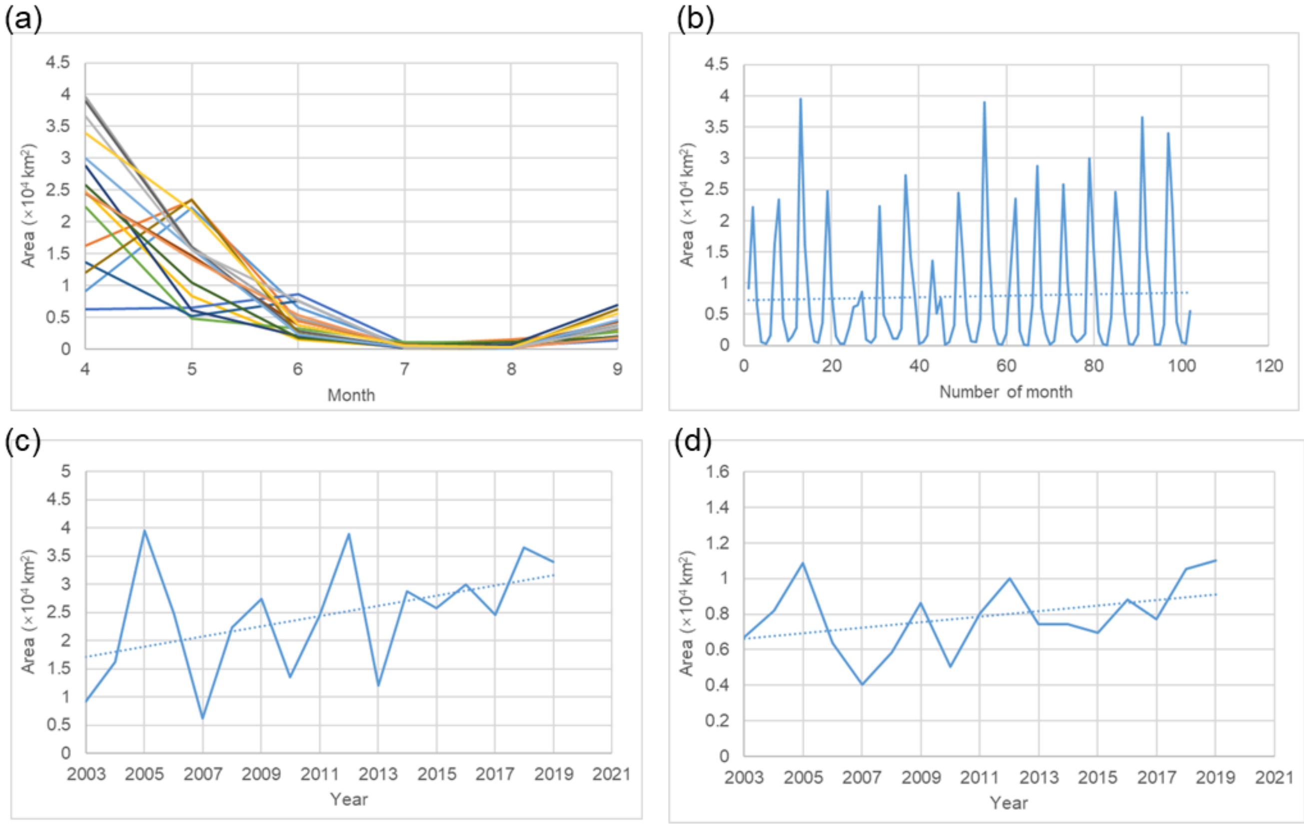

Figure S1. SCA during 2003-2019 in the source region of the YRB. (a) The intra-annual variation; (b) The monthly data. (c) The inter-annual variation (April). (d) The inter-annual variation (growing season average).

S5 Annual WUE evolutions across the YRB

Figure S2. Annual WUE evolutions during 2003-2019 across the eight subregions of the YRB.

S6 Evolutions of precipitation and temperature in Region I

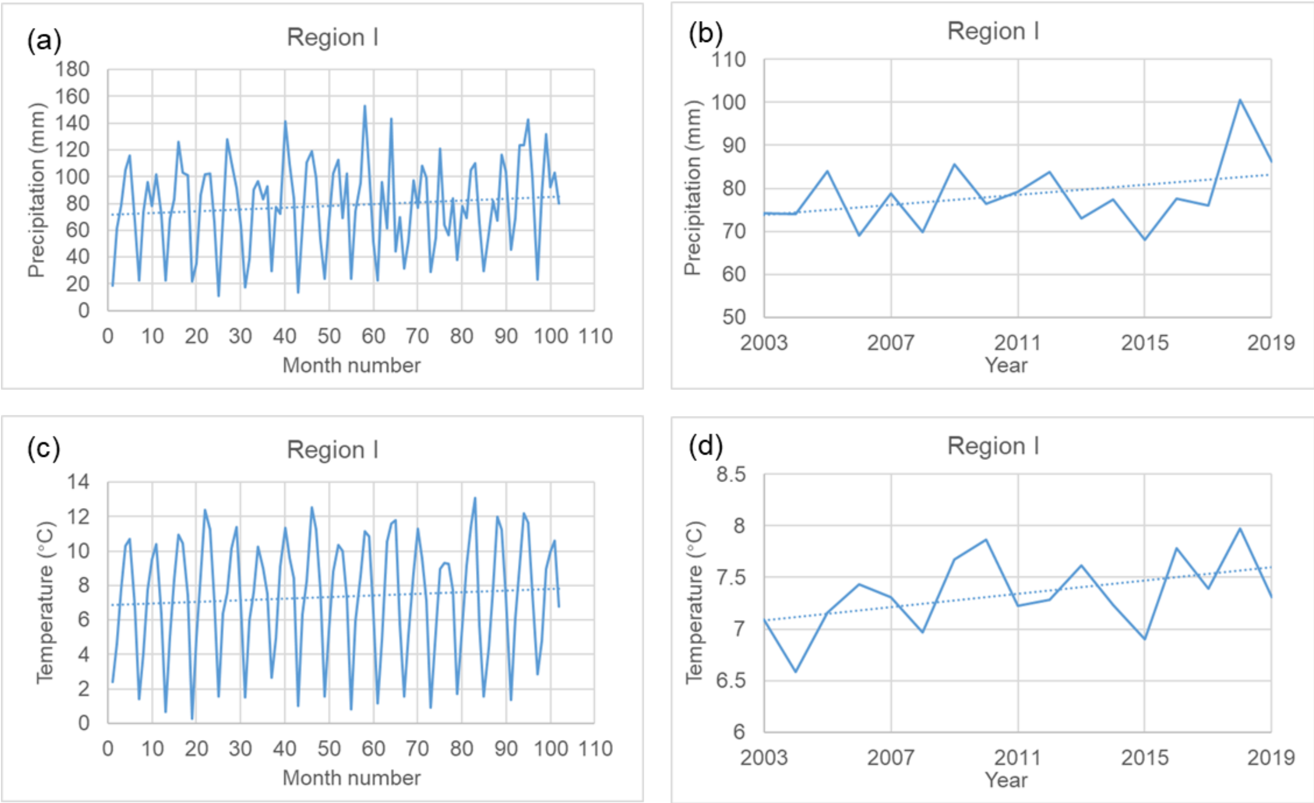

Figure S3. Evolutions of growing season precipitation and temperature in Region I.

S7 Link strength of GPP versus ET to WUE

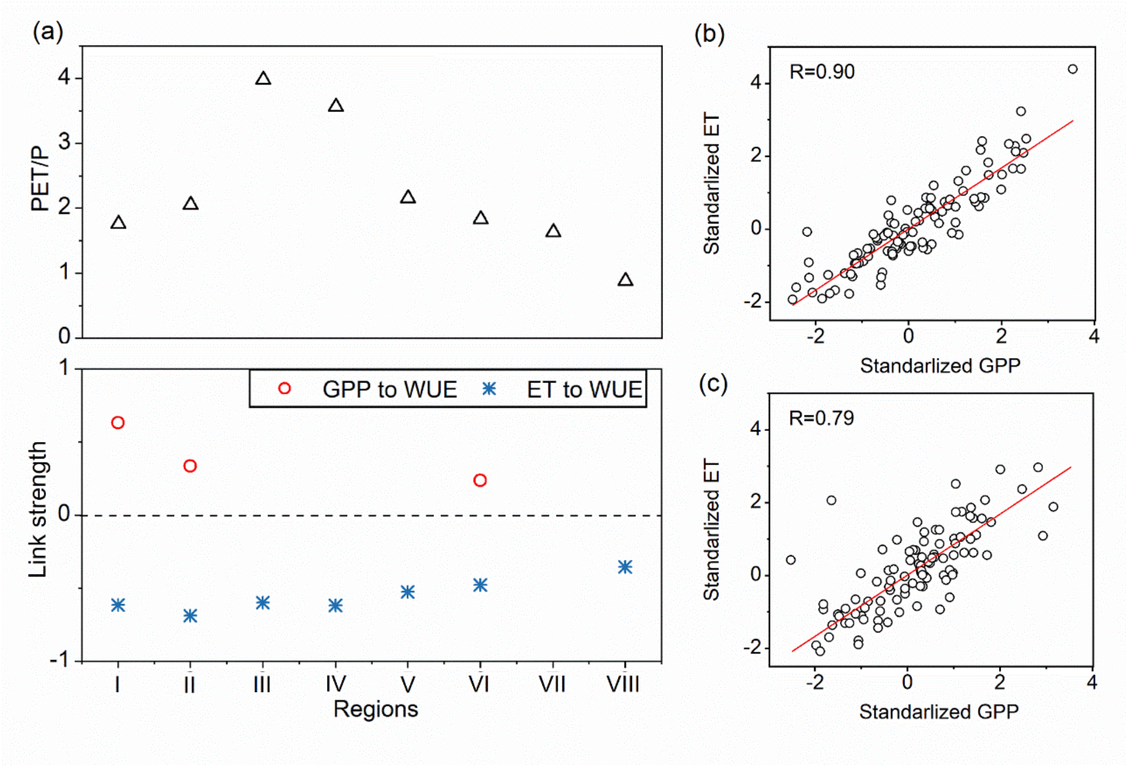

Figure S4. (a) Link strength of GPP versus ET to WUE in the eight subregions in the Yellow River basin. The top plot is the PET/P of each subregion, where the larger the value, the more arid the region. The figure only exhibits significant links. **(b)** Correlations of standardized ET versus GPP in Region VII. **(c)** Correlations of standardized ET versus GPP in Region VIII.