Supplementary materials

Table S1. A detailed description of the investigated AEZs in Pakistan

Zone	Name	Rainfall (mm/month)	Agricultural activity	Dominant activities	Condition
1	Dry Western Plateau	~30	fruit crops, vegetables, and wheat	Deserts /arid region	Natural
2	South Irrigated Plain	40-60	Cotton, wheat and sugar cane, and rice	Human and agricultural abstraction (S+G)*	Human-disturbed
3	Sandy Desert	~300	grazing	agricultural abstraction(R)*	Natural
4	Northern Irrigated Plain	300-500	wheat, rice, sugar cane, cotton, maize	Human and agriculture abstraction (S+G)	Human-disturbed
5	Suleiman Piedmont	~20	Wheat, millet, and gram	agricultural abstraction from floods of the hill torrents	Natural
6	Barani-Rainfed	50-200	wheat, millet, oilseed, and pulses	agricultural abstraction (R)	Natural
7	Wet Mountains	~200-300	rained agriculture and forest	Mixed influences (water transfer+ abstraction)	Natural+Human-disturbed
8	Northern Dry Mountains	20-75	grazing	Water Transfer, Dams	Natural
9	Western Dry Mountains	60-95	Wheat, fruit crops, and grazing	Water transfer, Dams	Natural
10	Indus Delta	~70	Rice, sugar cane	Human and agricultural abstraction (S)	Human-disturbed

* S, G, and R stand for surface water, groundwater, and rained irrigation

Table S2. Results of the Mann–Kendall (Z value) test for 5 main crops grown in 10 different AEZs during 1981-2017. *Note: Values of Z greater than 1.96 and less than -1.96 represent a significant trend.

Crop	Agro-Ecological Zones									
	DWP	SIP	SD	NIP	SPD	BRR	WM	NDM	WDM	ID
Wheat	0.00	3.93	0.00	6.98	6.87	4.29	5.02	5.46	1.60	3.74
Rice	4.89	3.06	5.65	6.19	0.46	5.92	-2.24	-1.14	1.11	0.79
Sugarcane	2.07	1.45	5.21	3.50	3.77	0.71	6.19	-5.95	-2.13	-2.32
Cotton	3.88	3.50	3.85	-0.28	-1.70	-1.63	3.55	1.56	-1.63	-2.49
Maize	1.93	-5.64	3.07	7.09	5.64	5.34	0.99	4.56	2.19	3.01

DWP (Dry Western Plateau); SIP (South Irrigated Plain); SD (Sandy Dessert); NIP (Northern Irrigated Plain); SPD (Suleiman Piedmont); BRR (Barani-Rainfed); WM (Wet Mountains); NDM (Northern Dry Mountains); WDM (Western Dry Mountains); ID (Indus Delta).

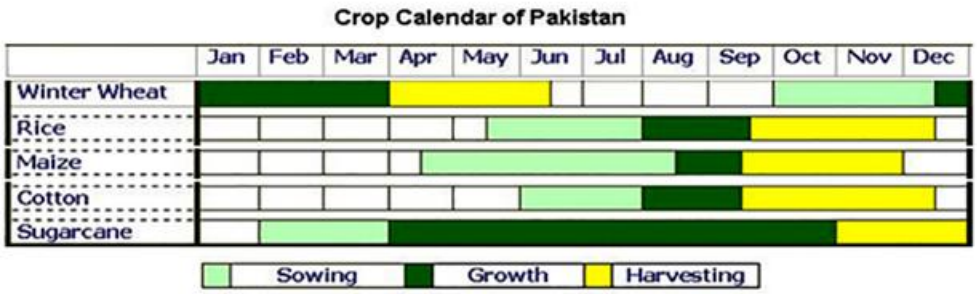


Figure S1. Cropping calendar for major crops in the study region

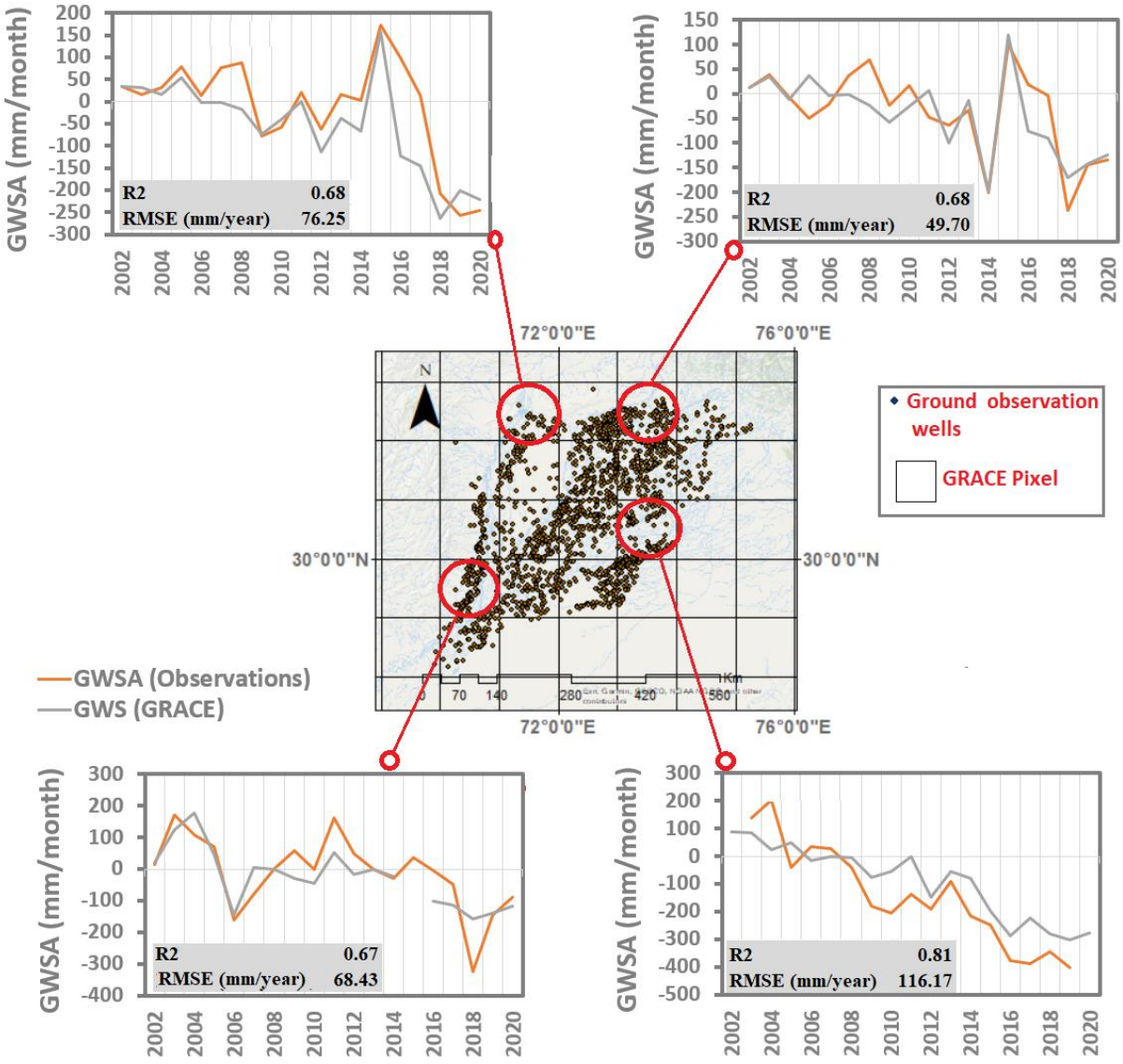


Figure S2. Comparison of GRACE-based GWSA and observational wells (Note: these data are compared on a seasonal basis since measurements are only available for June and October in each year. The number of measurements existing in each GRID cell was averaged).

Estimation of normalized difference vegetation index (NDVI):

The digital number of Landsat spectral bands (NIR and RED) was first converted into spectral radiance (L_λ) (Chen *et al.*, 2006; Pan, 2016).

$$L_\lambda = \frac{L_{max} - L_{min}}{(Qcal_{max} - Qcal_{min})} \times (Qcal - Qcal_{min}) + L_{min} \qquad \text{(S1)}$$

where $\boldsymbol{L_\lambda}$ is the spectral radiance (W/m^2 sr^{-1} $\mu m - 1$), Q_{cal} is the quantized calibrated pixel value (DN), $Qcal_{max}$ is the maximum quantized calibrated pixel value (DN), $Qcal\ _{min}$ is the minimum quantized calibrated pixel value (DN), L_{max} is the spectral radiance scaled to $Qcal_{max}$, L_{min} is the spectral radiance scaled to $Qcal\ _{min}$. Spectral radiance of NIR and RED spectral bands is converted into reflectance using the following relation:

$$r = \frac{\pi \times L_\lambda \times d^2}{E_{sun} \times Cos\theta} \quad \text{(S2)}$$

where r is planetary reflectance (dimensionless), $\boldsymbol{L_\lambda}$ is the spectral radiance at the sensor aperture (watt m^{-2} ster^{-1} μm^{-1}), and d is the square of the Earth–Sun distance (astronomical unit). E_{sun} represents the mean solar atmosphere irradiances (watt m^{-2} m^{-1}), θ is the solar zenith angle (degree), θ = (90 - B), and B represents the Sun's elevation angle. Information regarding all constant parameters for NIR and RED bands was obtained from the LANDSAT metadata header file. Finally, spectral reflectance of NIR and RED bands was used to compute the normalized difference vegetation index (NDVI):

$$\text{NDVI} = \frac{NIR - RED}{NIR + RED} \quad \text{(S3)}$$

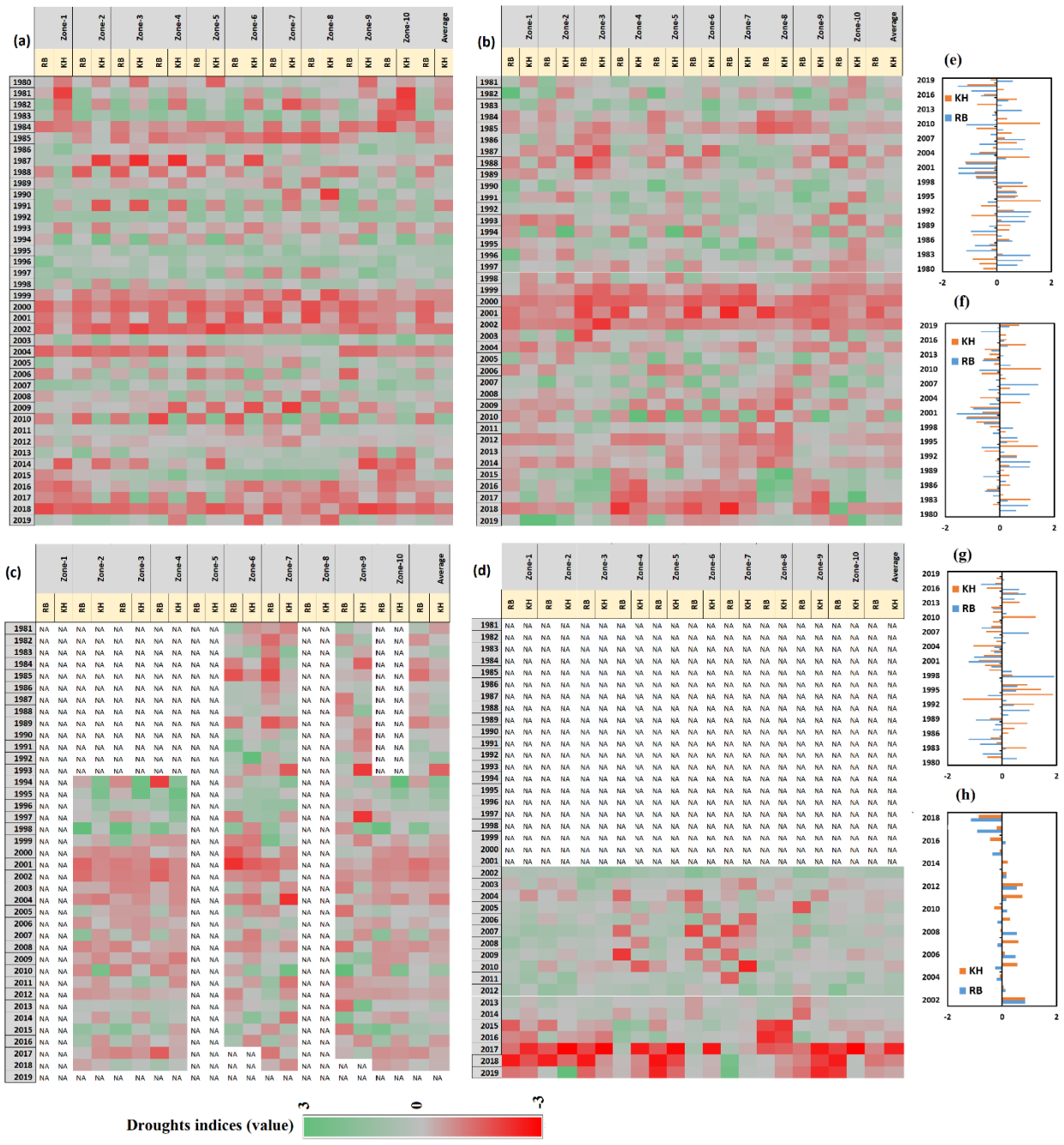


Figure S3. a, b, c, and d represent the seasonal distribution of hydro-metrological conditions based on a 6-month timescale for SPEI, STWSI, SSFI, and SGWI over 10 different agro-ecological zones, and e, f, g, and h represent the average seasonal conditions of SPEI, STWSI, SSFI, and SGWI for all zones from 1980 to 2019. RB represents the Rabi season and KH represents the Kharif season.

References

Pan J. 2016. Area delineation and spatial-temporal dynamics of urban heat island in Lanzhou City, China using remote sensing imagery. J Indian Soc Remote Sens. 44(1):111–127.

Chen X-L, Zhao H-M, Li P-X, Yin Z-Y. 2006. Remote sensing image-based analysis of the relationship between urban heat island and land use/cover changes. Remote Sens Environ. 104(2):133–146