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Determining groundwater degradation from irrigation in desert-marginal northern China

Electronic Supplementary Material

Table ESM1 Location of water quality sampling sites and field measurements for groundwaters from Chahaertan. See Figure 3, main text, for sample locations.

Site No	Site Name	Long. E	Lat. N	Elevation m asl	Irrig-ated[1]	Well depth m bgl	Sample date	Temp °C	pH	Diss. O2 mg/L	SEC µS/cm
1	Zhang Zhong	105.7188	39.2910	1195	I	120	07-Sep-06	16.1	7.70	8.50	822
2	Chen Qinglai & Si Chunyuan	105.7216	39.2827	1205	I	120	07-Sep-06	16.5	7.46	8.31	888
3	Sumuto No. 3 Well	105.7158	39.3006	1200	I	120	07-Sep-06	15.9	7.39	9.39	1768
4	Power Station Pumping Well	105.7373	39.3100	1191	I		07-Sep-06	16.2	7.61	11.50	679
5	Dong Feng No. 2	105.7078	39.3021	1193	I	120	08-Sep-06	17.0	7.59	9.68	893
6	Wang Guoyao	105.7048	39.2499	1226	I	132	08-Sep-06	15.9	7.55	9.85	861
7	Water Management Stn Well	105.7073	39.2597	1228	I	120	08-Sep-06	16.4	7.98	8.50	840
8	Shang Yuchang	105.7043	39.2818	1227	I	110	08-Sep-06	17.0	7.60	9.10	823
9	Zi Leishui	105.7188	39.3205	1185	I	105	08-Sep-06	15.7	7.65	9.18	765
10	Hu He Xing No. 4	105.7152	39.3147	1191	I	110	09-Sep-06	15.8	7.66	9.49	745
11	Hu He Xing No. 2	105.7145	39.3254	1182	I	95	09-Sep-06	17.8	7.65	6.20	1802
12	Wu Da Mu No. 20	105.7156	39.3474	1175	I	100	09-Sep-06	15.2	7.41	10.32	2800
13	Wu Da Mu No. 15	105.7200	39.3427	1168	I	100	11-Sep-06	15.7	7.69	11.49	705
14	Wu Da Mu No. 2	105.7268	39.3453	1169	I	105	11-Sep-06	15.0	7.63	8.04	1330
15	Wu Da Mu No. 7	105.7159	39.3295	1187	I	110	11-Sep-06	16.0	7.68	11.75	1025
16	Nowgan Tone No. 2	105.7248	39.3295	1185	I	100	11-Sep-06	16.3	7.80	11.30	656
17	Yu Chang	105.7267	39.3601	1171	I	60	11-Sep-06	15.7	7.69	8.54	1274
18	Drinking Water Well, L. Chah.	105.6465	39.4706	1094	I	>90	12-Sep-06	21.6	8.04	6.50	527
19	Fu Qing Dui No. 1, L. Chah.	105.6495	39.4608	1096	I	100	12-Sep-06	15.6	8.03	6.40	462
20	Lu Xing Jun Homestay	105.6762	39.6150	1046	N-I	70	12-Sep-06	18.2	8.22	1.78	606
21	Salt Mine Factory	105.7462	39.7428	1012	N-I		12-Sep-06	19.1	8.63	0.00	662
22	Xilingaole Naoertao G. No. 3	105.7957	39.3663	1186	N-I	145	13-Sep-06	17.4	7.80	8.34	673

[1] Irrig: I – Irrigated; N-I – Non irrigated

Table ESM2 Analyses of major and minor inorganic species in groundwaters from the Chahaertan area, with calculated saturation indices (SIs) with respect to calcite and gypsum, and pH for comparison. See Figure 3, main text, for sample locations.

Site No	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	HCO_3 mg/L	Cl mg/L	SO_4 mg/L	NO_3-N mg/L	Si mg/L	Br mg/L	Ba µg/L	Sr µg/L	Fe µg/L	Mn µg/L	B µg/L	pH	Si-calcite	Si-gypsum
1	78.6	24.6	46.2	2.92	140	111	95.4	9.8	6.77	0.157	59.5	0.840	<10	0.15	78	7.70	-0.097	-1.611
2	86.8	24.1	55.7	2.94	142	127	112.0	7.4	6.79	0.165	93.6	0.847	31	0.19	86	7.46	-0.096	-1.517
3	169.0	48.5	75.8	4.05	119	192	166.0	71.7	6.45	0.400	123.0	1.620	<10	0.29	87	7.39	-0.032	-1.2
4	64.7	17.9	35.6	2.63	148	65	89.8	3.6	6.85	0.083	65.6	0.646	12	0.35	61	7.61	-0.029	-1.679
5	83.9	24.2	53.5	3.01	126	109	69.0	28.9	6.87	0.184	92.7	0.870	<10	0.37	101	7.59	-0.012	-1.729
6	84.2	24.0	49.4	3.31	130	121	104.0	8.5	6.44	0.153	66.1	0.854	46	3.7	80	7.55	-0.062	-1.552
7	71.0	22.5	50.5	2.99	140	98	103.0	6.6	6.31	0.132	69.5	0.711	21	0.89	91	7.98	0.335	-1.613
8	78.9	22.7	47.6	3.24	131	108	99.4	10.2	6.40	0.153	79.3	0.815	<10	0.33	82	7.60	-0.013	-1.591
9	73.9	22.1	49.7	2.99	133	107	91.9	9.1	6.54	0.143	72.8	0.774	<10	0.99	86	7.65	0	-1.641
10	66.4	19.8	46.7	2.90	132	102	74.8	6.6	6.72	0.141	62.9	0.697	10	0.74	93	7.66	-0.025	-1.754
11	184.0	54.7	91.1	3.98	115	285	218.0	51.3	6.47	0.423	102.0	1.760	70	1.92	87	7.65	0.254	-1.083
12	281.0	92.1	149.0	5.17	102	369	314.0	137.0	6.28	0.721	80.7	2.890	21	0.43	86	7.41	0.046	-0.857
13	67.2	21.0	51.3	3.03	132	103	83.1	7.4	6.60	0.142	58.7	0.748	<10	0.43	100	7.69	0.004	-1.712
14	150.0	41.3	68.3	3.39	126	248	154.0	23.5	6.33	0.329	89.9	1.420	<10	0.75	82	7.63	0.18	-1.249
15	104.0	31.5	70.5	3.13	130	168	125.0	19.3	6.59	0.229	78.7	1.040	26	0.54	100	7.68	0.134	-1.434
16	65.9	19.3	42.4	2.98	138	90	79.2	4.8	6.42	0.124	62.1	0.679	45	1.07	83	7.80	0.136	-1.732
17	120.0	38.2	70.8	3.34	118	215	137.0	21.0	6.33	0.254	60.7	1.370	19	0.44	82	7.69	0.142	-1.363
18	23.3	12.4	51.0	2.50	138	44	34.8	3.3	6.26	0.053	48.8	0.409	12	0.57	138	8.04	0.051	-2.444
19	28.5	15.4	43.3	2.69	135	51	39.5	3.9	6.22	0.064	45.1	0.511	<10	0.32	133	8.03	0.025	-2.307
20	18.5	10.7	92.7	2.20	125	65	90.0	1.7	5.51	< 0.02	21.2	0.629	<10	0.14	156	8.22	-0.003	-2.167
21	13.3	12.5	111.0	3.30	123	90	92.1	1.2	4.03	0.035	33.5	0.614	136	10.11	168	8.63	0.24	-2.319
22	58.4	23.9	38.8	2.88	124	100	67.9	5.6	6.74	0.137	61.7	0.802	102	12.14	65	7.80	0.06	-1.848

Table ESM3 Analyses of CFCs and stable isotopes in groundwaters from the Chahaertan area. See Figure 3, main text, for sample locations.

Site No	CFC-12	CFC-11	$\delta^{18}O$	$\delta^{2}H$
	pmol/L		‰ VSMOW	
1	0.43	0.21	-11.18	-76.7
2			-11.46	-82.1
3	0.26	0.42	-11.02	-80.8
4	0.70	0.46	-11.04	-78.9
5			-11.55	-82.1
6	0.15	0.13	-10.72	-81.2
7			-10.94	-78.9
8	0.15	0.14	-11.03	-78.1
9	0.15	0.16	-10.94	-75.0
10			-11.08	-77.2
11			-10.84	-77.4
12	0.87	1.31	-11.24	-74.1
13	0.21	0.09	-10.91	-79.3
14			-10.82	-76.9
15	0.33	0.29	-11.25	-77.6
16			-10.99	-78.9
17	0.29	0.33	-11.10	-80.5
18			-12.60	-87.1
19	<0.02	<0.02	-12.02	-83.0
20	<0.02	<0.02	-13.09	-89.9
21	0.38	0.37	-11.94	-82.5
22			-10.88	-79.6

Table ESM4 Recharge model details

Input data	**Data source**	**Data preparation**
Daily rainfall	Partial dataset of daily rainfall (Chahaertan 2006, Bayanhot and Jilantai 2003-2005). Long term average monthly rainfall at Bayanhot, Jilantai and the Helan Mountains.	A synthetic daily rainfall series for 1 year created by disaggregating long term average monthly rainfall into separate rain events, determined by available data on actual daily rainfall events and by total long term average monthly rainfall .
Monthly evaporation		
Calculation methods		
Distributing rainfall and evaporation	Standard Theissen polygons and spatial distribution of long term average rainfall and evaporation.	
Wetting threshold	Effective precipitation (EP) calculated as difference between rainfall and potential evaporation. If EP > wetting threshold, the remainder is available for runoff and recharge. A proportion is partitioned to runoff, which is routed downhill to adjacent model nodes. If it doesn't subsequently become recharge, runoff is eventually routed to the nearest river node. The remainder after the final runoff partition is recharge.	
Infiltration through wadi beds	Based on a river loss coefficient (see below)	
Irrigation returns	Standard Penman-Grindley approach	
Model boundary		**Illustrated in**
Surface water catchment south of the lake at Jilantai, including northwest flank of Helan Mountains		Figure 12
Model grid		
1000 m square mesh		
Model parameters	**Quaternary aquifer**	**Tertiary rocks**
Wetting threshold	10 mm	3 mm
Runoff coefficient	0.1	0.5
River loss coefficient	0.075	0.01
Model timestep		
Input	Daily	
Output	Monthly	
Calibration data	**Data description**	
River flow	Anecdotal data on the magnitude and duration of river flows; limited qualitative observations of river channel characteristics; empirical estimate of river flows based on Manning equation for open channel flow (20-30 m^3/sec)	
Groundwater flow model groundwater head calculation	Realistic calculation of groundwater heads by groundwater flow model, as shown by groundwater level calibration data (see Table VI).	

Table ESM5. Groundwater flow model parameters

Model boundaries	**Boundary location**		**Illustrated in**
Southeast, south and west boundary	Contact between Quaternary aquifer basin and Tertiary rocks.		Figures 12, 13
East, north and northwest boundary	Surface water catchment boundary.		
Northern boundary	The lake at Jilantai (the main natural groundwater discharge point).		Figures 1, 12
Base	Base of Quaternary deposits overlying Tertiary rocks		Figure 2
Model layering			
Single layer to represent Quaternary basin aquifer, which has no known persistent internal layering (2D model).			
Model grid			
1000 m square mesh			
Steady state model – input data	**Data source**		**Value (range)**
Transmissivity	Groundwater Development and Utilisation Teaching and Research Office 1984, Yuan and Wu 1996.		600 – 1500 m^3/day
Groundwater abstraction	Groundwater Development and Utilisation Teaching and Research Office 1984; Left Banner Water Management and Water Resource Office 1992; data collected during current project.		150 production wells: total abstraction 18.4 Mm^3/a. In steady state model, a constant average daily pumping rate was assigned to each well, ranging from 108-646 m^3/day.
Recharge	Long term average recharge from ZOODRM recharge model		See Table V
Model discharge			
Lake at Jilantai	Leakage nodes allow groundwater to discharge from aquifer, controlled by groundwater head.		
Abstraction through boreholes	See above & below.		
Dynamic balance model – input data	**Data source**	**Time step**	**Value (range)**
Recharge	Recharge model	Monthly	
Storage coefficient	Groundwater Development and Utilisation Teaching and Research Office 1984, Yuan and Wu 1996, data from similar Quaternary aquifers in other areas.		0.1
Groundwater abstraction from production wells	Groundwater Development and Utilisation Teaching and Research Office 1984; Left Banner Water Management and Water Resource Office 1992; data collected during current project.	Monthly	0 (winter) to 1600 m^3/day (peak irrigation months).
Calibration data	**Data description**		
Groundwater levels	Detailed time series of groundwater level data for six monitoring wells within the irrigated area from 1984-1994; limited anecdotal groundwater level data for some production wells; two values outside the irrigated area		
Groundwater discharge	Production well abstraction data; estimate of evaporation from the lake at Jilantai (120 Mm^3/a)		