Supplementary Information

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Elevated Fe and Mn concentrations in groundwater in the Songnen Plain, Northeast China, and the factors and mechanisms involved

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Table S1. Methods for determining water quality indicators and the corresponding detection limits.

Test indicator	Unit	Test site	Test method	Detection limit
pH	—	Field	Portable multi-parameter rapid water quality analyzer (HANNA-HI9828)	—
TDS				1
TH			EDTA titration method	1
K	mg/L	Lab	Inductively coupled plasma optical emission spectrometry	0.07
Ca				0.03
Na				0.02
Mg				0.02
Fe				0.004
Mn				0.0005
As				0.001
TP			Ammonium molybdate spectrophotometry	0.01
HCO_3^-			Neutralization titration method	5
COD_{Mn}			Acidic permanganate method	0.5
Cl^-			Ion Chromatography	0.007
SO_4^{2-}				0.046
NH_4^+				0.025
NO_3^-				0.016
NO_2^-				0.016

TDS: total dissolved solids; TH: total hardness (calculated as $CaCO_3$); TP: total phosphorus.

Table S2. Data sources used in the study.

Variables	Data sources	Organization
Map of annual meteorological precipitation Map of average meteorological temperature Map of soil types Map land use types	https://www.resdc.cn/Default.aspx	Resource and Environment Science and Data Center

Table S3. Statistical data for the Fe and Mn concentrations in the groundwater.

	Number of samples	Number of samples with elevated Fe/Mn	Percentage of samples with elevated Fe/Mn	Min (mg/L)	Median (mg/L)	Max (mg/L)	Mean (mg/L)	Standard Deviation
Fe	1332	697	52.3%	<DL	0.340	48.930	1.873	4.71
Mn	1332	776	58.3%	<DL	0.1800	10.4600	0.4976	0.86

samples

DL: detection limit.

Table S4. Summary of the Fe and Mn concentrations in the groundwater samples grouped by the influencing factors.

Influencing factors		Fe (mg/L)						Mn (mg/L)					
		Number of samples	Number of samples with Fe>0.3	Percentage of samples with Fe>0.3	Min	Median	Max	Number of samples	Number of samples with Mn>0.1	Percentage of samples with Mn>0.1	Min	Median	Max
Annual meteoric precipitation (mm)	(300,400]	99	39	39.4%	<DL	0.190	48.930	99	43	43.4%	<DL	0.0800	4.1300
	(400,500]	516	284	55.0%	<DL	0.390	47.980	516	336	65.1%	<DL	0.2100	8.1130
	(500,600]	678	349	51.5%	<DL	0.323	48.760	678	374	55.2%	<DL	0.1579	10.4600
	(600,700]	39	25	64.1%	<DL	0.574	9.530	39	23	59.0%	<DL	0.2478	2.3990
Annual average meteoric temperature (°C)	(1,3]	75	25	33.3%	<DL	0.117	18.540	75	29	38.7%	<DL	0.0410	1.9730
	(3,5]	304	149	49.0%	<DL	0.267	41.700	304	151	49.7%	<DL	0.0924	10.4600
	(5,6]	471	280	59.4%	<DL	0.510	48.760	471	313	66.5%	<DL	0.3160	8.1130
	(6,7]	482	243	50.4%	<DL	0.310	48.930	482	283	58.7%	<DL	0.1604	8.0150
Altitude (m)	(0,140]	250	201	80.4%	<DL	1.360	48.930	250	205	82.0%	<DL	0.3555	7.8400
	(140,160]	414	231	55.8%	<DL	0.412	43.310	414	288	69.6%	<DL	0.2516	10.4600
	(160,180]	224	103	46.0%	<DL	0.255	14.260	224	122	54.5%	<DL	0.1950	8.0150
	(180,400]	444	162	36.5%	<DL	0.140	21.650	444	161	36.3%	<DL	0.0369	4.0400
Distance to the nearest river (km)	(0,5]	252	149	59.1%	<DL	0.532	13.310	252	156	61.9%	<DL	0.2050	10.4600
	(5,10]	199	116	58.3%	<DL	0.548	47.980	199	118	59.3%	<DL	0.2100	7.8400
	(10,40]	533	293	55.0%	<DL	0.400	48.930	533	316	59.3%	<DL	0.2100	6.3880
	(40,150]	348	139	39.9%	<DL	0.210	22.990	348	186	53.4%	<DL	0.1300	8.0150

Influencing factors		Fe (mg/L)						Mn (mg/L)					
		Number of samples	Number of samples with Fe>0.3	Percentage of samples with Fe>0.3	Min	Median	Max	Number of samples	Number of samples with Mn>0.1	Percentage of samples with Mn>0.1	Min	Median	Max
Soil type	Dark-brown earths	14	4	28.6%	<DL	0.120	1.902	14	6	42.9%	<DL	0.0670	1.0200
	Black soils	263	145	55.1%	<DL	0.408	48.760	263	153	58.2%	<DL	0.1833	10.4600
	Chernozems	343	172	50.1%	<DL	0.310	48.930	343	197	57.4%	<DL	0.1996	5.1730
	Castanozems	19	10	52.6%	<DL	0.315	7.257	19	11	57.9%	<DL	0.1500	0.4400
	Aeolian sandy soils	150	78	52.0%	<DL	0.326	32.840	150	95	63.3%	<DL	0.1800	8.0150
	Meadow soils	444	238	53.6%	<DL	0.374	43.310	444	256	57.7%	<DL	0.1846	8.1130
	Bog soils	24	13	54.2%	<DL	0.532	16.920	24	13	54.2%	<DL	0.1256	0.5617
	Solonchaks	11	5	45.5%	<DL	0.280	11.850	11	7	63.6%	<DL	0.2100	0.7700
	Solonetzs	29	16	55.2%	<DL	0.460	14.280	29	20	69.0%	<DL	0.1700	3.4100
	Paddy soils	15	5	33.3%	<DL	0.180	9.041	15	4	26.7%	<DL	0.0400	1.26400
	Water body	16	9	56.3%	<DL	0.870	47.980	16	11	68.8%	<DL	0.2100	7.8400
Soil texture	Sand	72	38	52.8%	0.01	0.325	16.490	72	46	63.9%	<DL	0.1800	8.0150
	Loam	407	189	46.4%	<DL	0.250	43.310	407	228	56.0%	<DL	0.1600	8.1130
	Clay	849	467	55.0%	<DL	0.410	48.930	849	500	58.9%	<DL	0.1960	10.460
Land use type	Paddy field	92	57	62.0%	<DL	0.646	43.310	92	57	62.0%	<DL	0.3139	8.1130
	Dryland	782	387	49.5%	<DL	0.2778	48.930	782	436	55.8%	<DL	0.1600	10.4600
	Forest land	37	17	45.9%	<DL	0.259	48.760	37	19	51.4%	<DL	0.1400	1.3310
	Grassland	113	52	46.0%	<DL	0.266	11.330	113	64	56.6%	<DL	0.1715	6.3880

Influencing factors		Fe (mg/L)						Mn (mg/L)					
		Number of samples	Number of samples with Fe>0.3	Percentage of samples with Fe>0.3	Min	Median	Max	Number of samples	Number of samples with Mn>0.1	Percentage of samples with Mn>0.1	Min	Median	Max
Land use type	Water body	73	43	58.9%	<DL	0.6700	47.980	73	47	64.4%	<DL	0.2384	7.8400
	Construction land	58	38	65.5%	<DL	0.455	18.160	58	35	60.3%	<DL	0.1500	2.6760
	Unutilized land	175	102	58.3%	<DL	0.460	30.240	175	118	67.4%	<DL	0.2151	4.3990
Groundwater type	Fissure water	73	43	58.9%	<DL	0.710	41.700	73	35	47.9%	<DL	0.3368	48.9300
	Pore water	1156	603	52.2%	<DL	0.337	48.930	1156	671	58.0%	<DL	0.1000	3.438
Depth of groundwater level	(0,5)	707	370	52.3%	<DL	0.340	47.980	707	400	56.6%	<DL	0.1710	10.4600
	(5,10]	503	257	51.1%	<DL	0.320	48.930	503	302	60.0%	<DL	0.1900	8.1130
	(10,20]	99	63	63.6%	<DL	0.510	48.760	99	63	63.6%	<DL	0.2800	4.3310
COD_{Mn}	≤1	475	156	32.8%	<DL	0.140	47.980	475	168	35.4%	<DL	0.0200	8.1130
	1-2	467	265	56.7%	<DL	0.441	37.120	467	317	67.9%	<DL	0.2853	6.3880
	>2	390	276	70.8%	<DL	0.893	48.930	390	291	74.6%	<DL	0.3000	10.4600
NH_4^+	≤0.5	1082	472	43.6%	<DL	0.210	37.120	1082	542	50.1%	<DL	0.1011	10.4600
	0.5-1	130	114	87.7%	<DL	2.185	48.930	130	124	95.4%	<DL	0.7450	6.3880
	>1	118	111	94.1%	<DL	3.222	48.760	118	110	93.2%	<DL	0.4750	8.1130
NO_3^-	≤1	393	302	76.8%	<DL	1.471	48.760	393	321	81.7%	<DL	0.4500	8.1130
	1-10	351	227	64.7%	<DL	0.576	48.930	351	255	72.6%	<DL	0.2900	7.8400
	10-50	213	68	31.9%	<DL	0.126	21.650	213	90	42.3%	<DL	0.0500	6.3880
	>50	375	100	26.7%	<DL	0.120	18.540	375	110	29.3%	<DL	0.0268	10.4600

Influencing factors		Fe (mg/L)						Mn (mg/L)					
		Number of samples	**Number of samples with Fe>0.3**	**Percentage of samples with Fe>0.3**	**Min**	**Median**	**Max**	**Number of samples**	**Number of samples with Mn>0.1**	**Percentage of samples with Mn>0.1**	**Min**	**Median**	**Max**
Total phosphorus	≤0.02	163	39	23.9%	<DL	0.086	32.840	163	64	39.3%	<DL	0.0351	10.4600
	0.02-0.1	202	74	36.6%	<DL	0.137	36.020	202	73	36.1%	<DL	0.0528	3.4930
	0.1-0.4	190	126	66.3%	<DL	0.637	48.760	190	129	67.9%	<DL	0.2228	8.1130
	>0.4	174	157	90.2%	<DL	3.062	41.700	174	155	89.1%	0.0086	0.7345	4.3990

DL: detection limit.

Figure captions

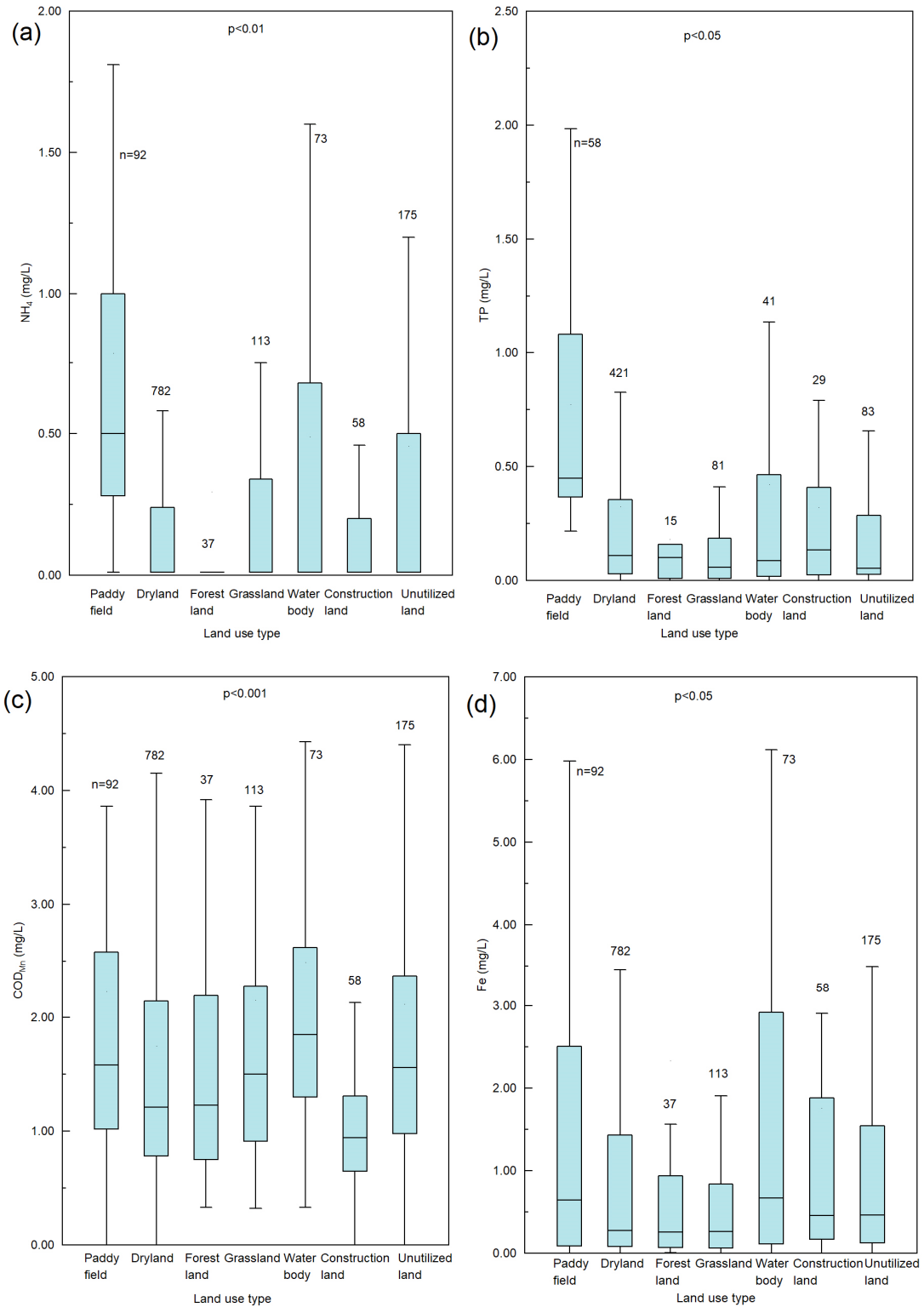
Figure S1. NH_4^+ concentrations, total phosphorus (TP) concentrations, and chemical oxygen demand (COD_{Mn}) compared with the Fe and Mn concentrations in groundwater in areas with different land use types.

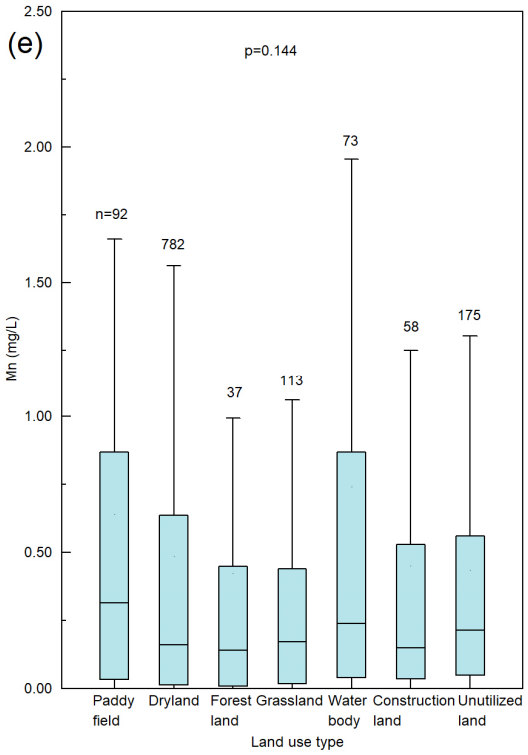
Figure S2. Overlay of the sampling points with high NH_4^+ concentrations, total phosphorus (TP) concentrations, and chemical oxygen demand (COD_{Mn}) in groundwater on a land use map.

Figure S3. Overlay of the sampling points with high NH_4^+ concentrations, total phosphorus (TP) concentrations, and chemical oxygen demand (COD_{Mn}) in groundwater on a map of the distributions of the Fe and Mn concentrations in groundwater.

Figure S4. Annual meteorological precipitation in 2015 in the study area.

Figure S5. Annual average meteorological temperature in 2015 in the study area.


(a)
p<0.01
NH_4 (mg/L)
2.00
1.50
1.00
0.50
0.00
n=92
782
37
113
73
58
175
Paddy field
Dryland
Forest land
Grassland
Water body
Construction land
Unutilized land
Land use type
(b)
p<0.05
TP (mg/L)
2.50
2.00
1.50
1.00
0.50
0.00
n=58
421
15
81
41
29
83
Paddy field
Dryland
Forest land
Grassland
Water body
Construction land
Unutilized land
Land use type
(c)
p<0.001
COD_{Mn} (mg/L)
5.00
4.00
3.00
2.00
1.00
0.00
n=92
782
37
113
73
58
175
Paddy field
Dryland
Forest land
Grassland
Water body
Construction land
Unutilized land
Land use type
(d)
p<0.05
Fe (mg/L)
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
n=92
782
37
113
73
58
175
Paddy field
Dryland
Forest land
Grassland
Water body
Construction land
Unutilized land
Land use type



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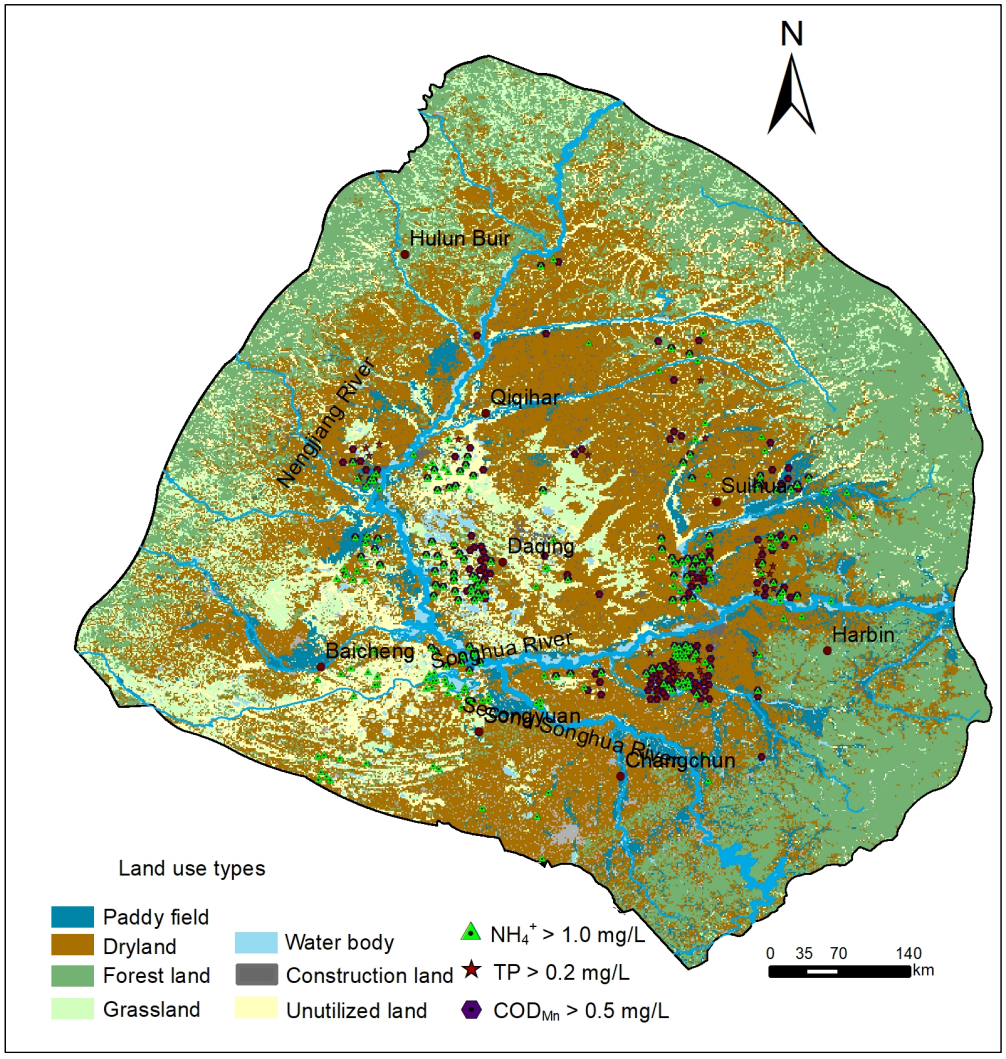

Figure S2. Overlay of the sampling points with high NH_4^+ concentrations, total phosphorus (TP) concentrations, and chemical oxygen demand (COD_{Mn}) in groundwater on a land use map.

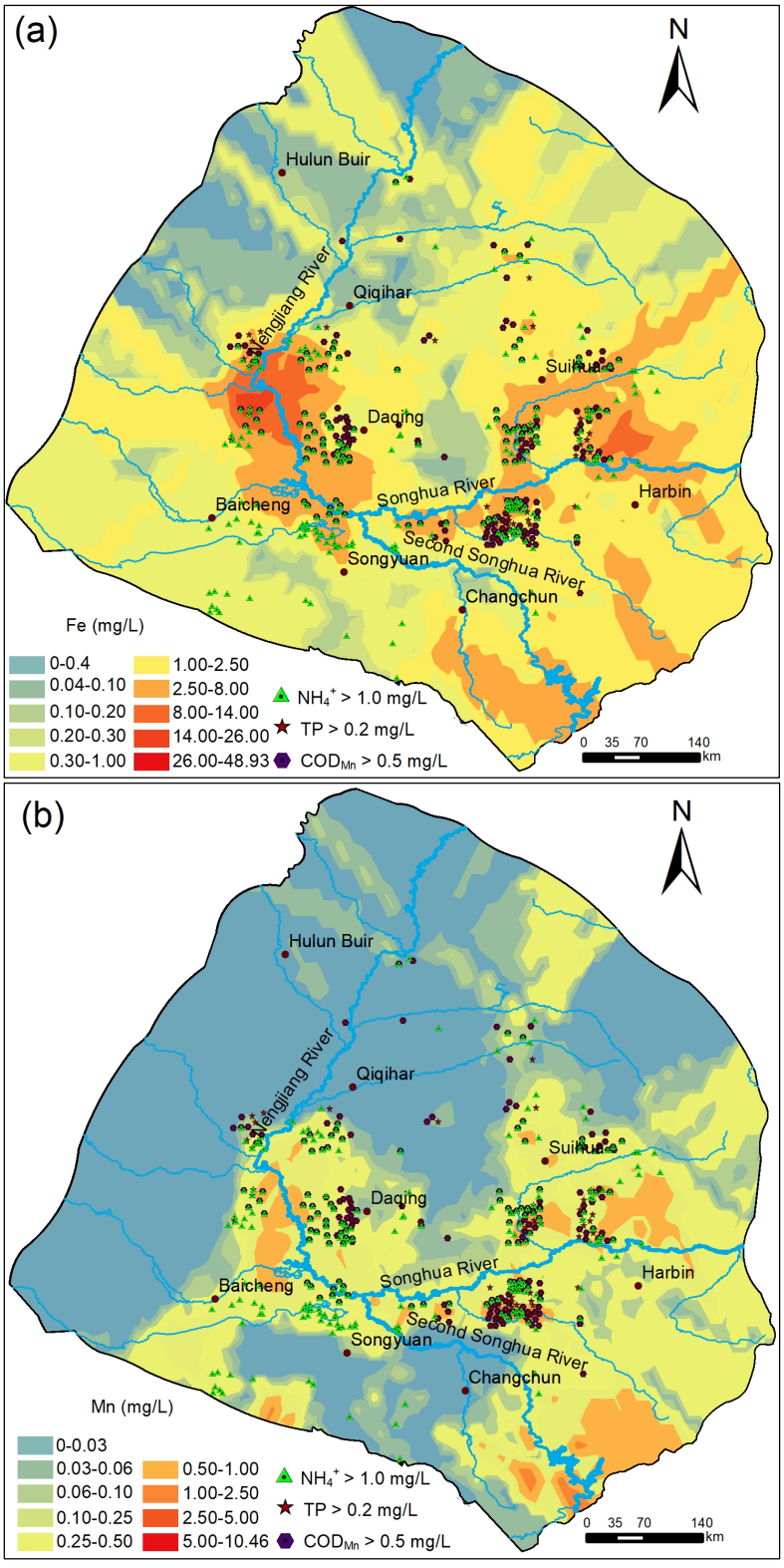

Figure S3. Overlay of the sampling points with high NH_4^+ concentrations, total phosphorus (TP) concentrations, and chemical oxygen demand (COD_{Mn}) in groundwater on a map of the distributions of the Fe and Mn concentrations in groundwater.

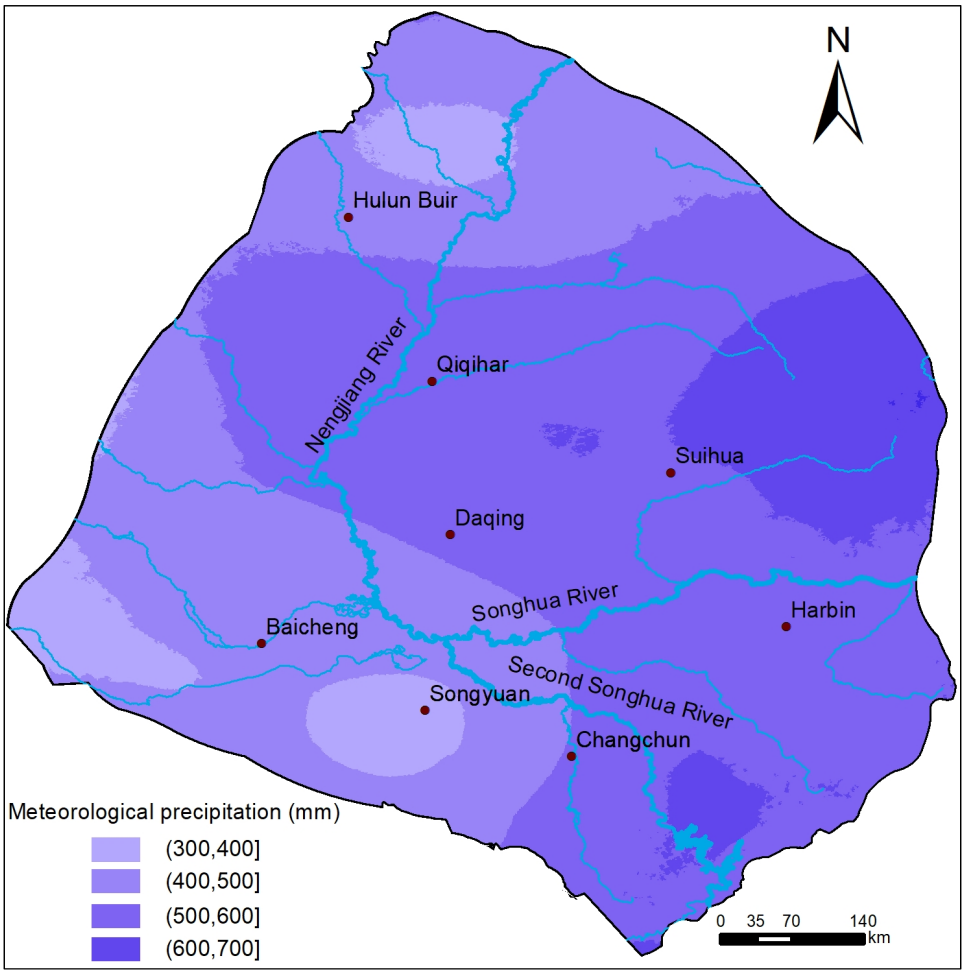

Figure S4. Annual meteorological precipitation in 2015 in the study area.

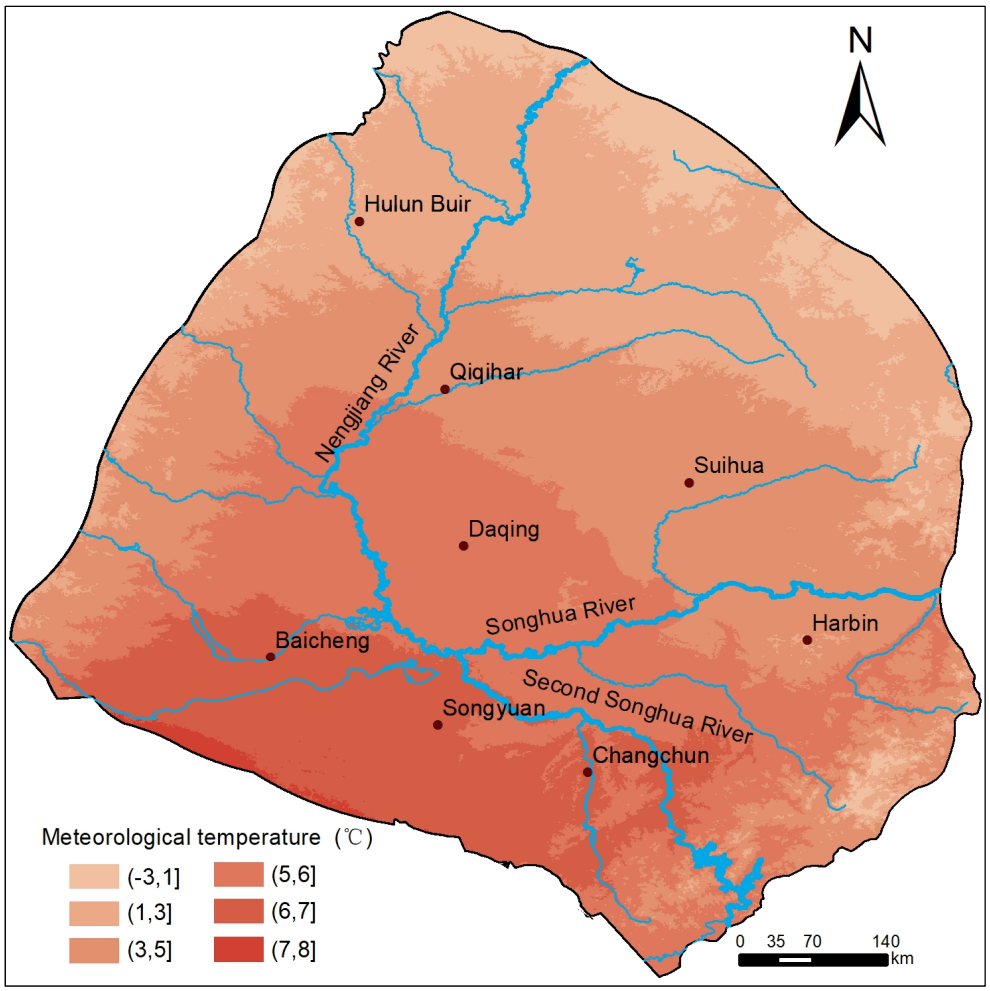

Figure S5. Annual average meteorological temperature in 2015 in the study area.