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Integrated assessment of groundwater salinity sources and inter-aquifer mixing dynamics in Siwa Oasis, Egypt: A multi-method approach using self-organizing maps, isotopic tracers, and numerical modeling

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Table S1: Climatological data from Siwa meteorological station based on monthly mean of 20 years monitoring.

Month	Mean Temp. °C	Rainfall mm/month	Relative Humidity %	EP mm/Month	ETo (mm/day)
January	11.7	0.8	55	62	3.2
February	13.4	2	45	101	3.9
March	16.4	0.7	44	175	5.6
April	20.85	0.9	37	229	7.4
May	25.55	1.5	33	274	8.7
June	28.2	0	35	276	9.3
July	29.25	0	37	283	9.2
August	29	0	40	255	8.4
September	26.55	0	46	192	6.7
October	23.2	0.3	50	151	5.3
November	18.15	0.6	53	100	3.8
December	13.3	2.8	60	67	2.9
Annual mean	21.3	-	45	188.75	74.4
Annual total	-	9.6	-	2265	-

Table S2. All measured parameters used in the current research investigation from different resources

Type	**Range**	**Fe (mg/L)**	**Mn (mg/L)**	**Sr (mg/L)**	**SiO_2 (mg/L)**	**pH**	**Temperature**	**TDS (mg/L)**
Lakes	Min	0.028	0.040	0.061	7.9	7.83	13.5	57216
Lakes	Mean	1.16	0.35	14.77	24.4	8.12	18.73	98229
Lakes	Max	5.241	1.747	30.43	48.9	8.36	27.1	153589
Type	**Range**	**Na^+ (mg/L)**	**K^+ (mg/L)**	**Mg^{2+} (mg/L)**	**Ca^{2+} (mg/L)**	**Cl^-(mg/L)**	**SO_4^{2-} (mg/L)**	**HCO_3^- (mg/L)**
Lakes	Min	3455	6.4	1537	1265	48430	2344	167
Lakes	Mean	22652	11.6	5728	1807	64718	3190	203
Lakes	Max	39500	17.5	12217	2509	94250	5349	287
Type	**Range**	**NO_3^- (mg/L)**	**NH_3 (mg/L)**	**^{14}C (pMC)**	**$\delta^{13}C$ (‰ VPDB)**	**$^{87}Sr/^{86}Sr$**	**δ^2H**	**$\delta\ ^{18}O$**
Lakes	Min	1.4	0	73.66	-9.9	0.7082	-61.712	-7.089
Lakes	Mean	3.03	0.47	78.13	-8.9	0.7083	-43.199	-3.296
Lakes	Max	4.2	1.4	94.72	-7.7	0.7083	-29.724	-0.845
Type	**Range**	**Fe (mg/L)**	**Mn (mg/L)**	**Sr (mg/L)**	**SiO_2 (mg/L)**	**pH**	**Temperature**	**TDS (mg/L)**
Drains	Min	0.006	0.005	3.50	18.4	7.9	18.8	4023
Drains	Mean	0.304	0.026	8.02	53.2	8.1	20.1	7643
Drains	Max	2.069	0.058	16.18	74.7	8.6	21.1	16126
Type	**Range**	**Na^+ (mg/L)**	**K^+ (mg/L)**	**Mg^{2+} (mg/L)**	**Ca^{2+} (mg/L)**	**Cl^-(mg/L)**	**SO_4^{2-} (mg/L)**	**HCO_3^- (mg/L)**
Drains	Min	560	5	267	104	1914	300	126
Drains	Mean	1435	47	493	583	4194.125	678	204
Drains	Max	3750	83	888	1568	9744	1850	275
Type	**Range**	**NO_3^- (mg/L)**	**NH_3 (mg/L)**	**^{14}C (pMC)**	**$\delta^{13}C$ (‰ VPDB)**	**$^{87}Sr/^{86}Sr$**	**δ^2H**	**$\delta\ ^{18}O$**
Drains	Min	1.4	0	56.97	-9.74	0.7082	-75.619	-9.519
Drains	Mean	3.5	0.54	63.67	-9.25	0.7083	-73.201	-8.977
Drains	Max	5.6	1.4	72.27	-8.7	0.7084	-68.957	-7.621
Type	**Range**	**Fe (mg/L)**	**Mn (mg/L)**	**Sr (mg/L)**	**SiO_2 (mg/L)**	**pH**	**Temperature**	**TDS (mg/L)**
NSSA	Min	0.06	0.04	0.042	11.1	6.5	35.5	160
NSSA	Mean	3.23	0.154	0.569	41.6	8.0	39.29	304
NSSA	Max	27.65	0.908	9.507	74.3	8.9	43	929
Type	**Range**	**Na^+ (mg/L)**	**K^+ (mg/L)**	**Mg^{2+} (mg/L)**	**Ca^{2+} (mg/L)**	**Cl^-(mg/L)**	**SO_4^{2-} (mg/L)**	**HCO_3^- (mg/L)**
NSSA	Min	18	13	2	10	41	1.6	90
NSSA	Mean	55	19	16	23	90	33	133
NSSA	Max	280	23	56	65	174	353	185
Type	**Range**	**NO_3^- (mg/L)**	**NH_3 (mg/L)**	**^{14}C (pMC)**	**$\delta^{13}C$ (‰ VPDB)**	**$^{87}Sr/^{86}Sr$**	**δ^2H**	**$\delta\ ^{18}O$**
NSSA	Min	1.4	0	16.13	-11.44	0.709	-80.413	-10.713
NSSA	Mean	4.55	0.203	36.02	-11.44	0.712	-79.110	-10.378
NSSA	Max	18.2	1.4	71.50	-11.44	0.715	-66.333	-8.571
Type	**Range**	**Fe (mg/L)**	**Mn (mg/L)**	**Sr (mg/L)**	**SiO_2 (mg/L)**	**pH**	**Temperature**	**TDS (mg/L)**

Springs	Min	0.029	0.002	1.59	3.3	7.6	17.5	1463
Springs	Mean	4.018	0.672	5.29	33.7	8.0	22.2	11629
Springs	Max	19.07	3.286	9.97	65.1	8.3	25.1	38295
Type	**Range**	**Na^+ (mg/L)**	**K^+ (mg/L)**	**Mg^{2+} (mg/L)**	**Ca^{2+} (mg/L)**	**Cl^-(mg/L)**	**SO_4^{2-} (mg/L)**	**HCO_3^- (mg/L)**
Springs	Min	200	10	113	20	725	5	120
Springs	Mean	2828	43	724	481	7093.4	334	169
Springs	Max	10000	77	2524	1265	24360	700	227
Type	**Range**	**NO_3^- (mg/L)**	**NH_3 (mg/L)**	**^{14}C (pMC)**	**$\delta^{13}C$ (‰ VPDB)**	**$^{87}Sr/^{86}Sr$**	**δ^2H**	**$\delta\ ^{18}O$**
Springs	Min	2.8	0	18.20	-10.26	0.7082	-79.732	-10.519
Springs	Mean	6.51	0.59	18.81	-8.98	0.7082	-73.290	-9.372
Springs	Max	15.4	2.1	20.55	-7.25	0.7083	-63.539	-7.399
Type	**Range**	**Fe (mg/L)**	**Mn (mg/L)**	**Sr (mg/L)**	**SiO_2 (mg/L)**	**pH**	**Temperature**	**TDS (mg/L)**
TCA	Min	0.0029	0.0002	0.008	0.8	6.9	17.7	467
TCA	Mean	2.013	0.256	4.434	36.8	7.9	24.8	4249
TCA	Max	36.23	3.373	9.507	76.2	8.7	37.6	9158
Type	**Range**	**Na^+ (mg/L)**	**K^+ (mg/L)**	**Mg^{2+} (mg/L)**	**Ca^{2+} (mg/L)**	**Cl^-(mg/L)**	**SO_4^{2-} (mg/L)**	**HCO_3^- (mg/L)**
TCA	Min	92	4	9	30	174	23	84
TCA	Mean	852	42	318	237	2404	310	160
TCA	Max	2250	76	860	744	5510	992	329
Type	**Range**	**NO_3^- (mg/L)**	**NH_3 (mg/L)**	**^{14}C (pMC)**	**$\delta^{13}C$ (‰ VPDB)**	**$^{87}Sr/^{86}Sr$**	**δ^2H**	**$\delta\ ^{18}O$**
TCA	Min	1.4	0	15.46	-12.13	0.708	-80.338	-10.624
TCA	Mean	6.18	0.52	23.63	-9.31	0.708	-76.788	-9.911
TCA	Max	29.4	2.1	57.92	-6.25	0.710	-65.634	-8.545

Table S3. The stable isotopes concentrations in all water resources of Siwa Oasis

Sample ID	Aquifer	δ^2H	$\delta^{18}O$	Sample ID	Aquifer	δ^2H	$\delta^{18}O$
1	TCA	-78.44	-9.95	110	TCA	-77.77	-9.82
3	TCA	-77.72	-10.14	117	TCA	-78.06	-10.31
7	TCA	-77.70	-10.26	118	TCA	-78.48	-10.12
8	TCA	-79.24	-10.19	121	TCA	-76.20	-9.81
9	TCA	-78.21	-9.98	123	TCA	-76.90	-9.50
10	TCA	-78.63	-10.22	124	TCA	-79.32	-9.84
11	TCA	-77.58	-9.38	127	TCA	-73.94	-9.69
12	TCA	-76.89	-9.91	128	TCA	-72.38	-8.45
15	TCA	-76.47	-9.93	129	TCA	-78.31	-10.12
16	TCA	-76.64	-9.61	130	TCA	-74.50	-9.86
17	TCA	-65.79	-8.55	131	TCA	-76.78	-9.91
19	TCA	-73.23	-9.41	132	TCA	-78.76	-10.22
20	TCA	-65.63	-8.55	133	TCA	-78.83	-10.62
21	TCA	-66.71	-8.58	139	TCA	-79.65	-10.30
30	TCA	-68.27	-8.79	140	TCA	-78.94	-10.18
31	TCA	-79.38	-10.15	142	TCA	-76.88	-10.27
32	TCA	-79.37	-10.12	144	TCA	-78.14	-10.03
33	TCA	-79.01	-10.22	145	TCA	-80.34	-9.99

34	TCA	-73.70	-8.88	146	TCA	-78.97	-9.89
37	TCA	-78.79	-9.91	147	TCA	-79.52	-9.47
40	TCA	-79.04	-10.35	148	TCA	-77.16	-10.58
41	TCA	-78.51	-10.04	151	TCA	-77.00	-10.56
43	TCA	-78.24	-10.11	152	TCA	-77.23	-9.76
45	TCA	-78.83	-10.10	153	TCA	-76.76	-9.29
46	TCA	-77.31	-9.93	4	NSSA	-79.58	-10.42
47	TCA	-79.05	-10.27	24	NSSA	-66.33	-8.57
48	TCA	-78.66	-10.21	29	NSSA	-79.96	-10.48
49	TCA	-78.10	-10.09	35	NSSA	-80.00	-10.71
52	TCA	-76.69	-10.07	38	NSSA	-79.69	-10.29
53	TCA	-75.76	-9.68	39	NSSA	-79.31	-10.29
54	TCA	-78.17	-10.02	55	NSSA	-79.71	-10.52
58	TCA	-79.23	-10.35	56	NSSA	-79.94	-10.36
60	TCA	-78.94	-10.24	57	NSSA	-79.56	-10.58
61	TCA	-78.92	-10.29	59	NSSA	-79.28	-10.42
62	TCA	-79.04	-10.22	79	NSSA	-79.94	-10.09
63	TCA	-78.97	-10.16	83	NSSA	-79.08	-10.59
65	TCA	-79.47	-10.27	88	NSSA	-80.09	-10.38
66	TCA	-77.21	-9.78	89	NSSA	-79.98	-10.65
68	TCA	-78.59	-10.30	91	NSSA	-80.02	-10.40
69	TCA	-78.30	-10.18	113	NSSA	-79.14	-10.47
70	TCA	-78.90	-10.23	122	NSSA	-79.98	-10.56
72	TCA	-78.05	-10.03	134	NSSA	-80.41	-10.60
73	TCA	-78.40	-10.08	135	NSSA	-79.78	-10.43
77	TCA	-75.22	-9.88	5	Springs	-74.61	-10.06
78	TCA	-73.62	-9.91	6	Springs	-77.92	-10.36
80	TCA	-78.34	-10.27	14	Springs	-73.47	-9.32
81	TCA	-69.49	-8.91	22	Springs	-64.94	-8.35
82	TCA	-69.86	-9.26	23	Springs	-79.73	-10.52
84	TCA	-75.35	-10.17	90	Springs	-63.54	-7.40
85	TCA	-71.18	-9.21	13	Drains	-74.18	-9.02
86	TCA	-72.30	-9.53	18	Drains	-74.61	-9.27
87	TCA	-76.04	-9.95	28	Drains	-69.56	-8.76
93	TCA	-75.53	-9.84	44	Drains	-68.96	-7.62
94	TCA	-73.97	-9.41	50	Drains	-75.62	-9.52
95	TCA	-75.54	-10.02	149	Drains	-73.86	-9.12
96	TCA	-74.93	-9.55	2	Lakes	-61.71	-7.09
101	TCA	-78.21	-10.04	27	Lakes	-30.00	-0.90
104	TCA	-77.31	-9.85	75	Lakes	-29.72	-1.05
108	TCA	-78.10	-10.27	92	Lakes	-32.77	-0.85
109	TCA	-76.69	-9.96	125	Lakes	-43.27	-2.81

Table S4. The concentration of isotopic tracers used for mixing models and age correction of groundwater.

Sample ID	Sr (mg/L)	^{14}C (pMC)	±1σ (pMC)	δ^{13}C (‰ VPDB)	^{87}Sr/^{86}Sr	±1σ
ES_2	14.9	94.72	0.27	-9.91	0.708319	0.000016

ES_4	0.036	34.98	0.99		0.714266	0.000016
ES_6	2.2	18.31	1.00	-10.26	0.708263	0.000016
ES_10	2.2	21.83	0.94	-12.00	0.708329	0.000016
ES_11	2.2	17.36	1.02	-11.61	0.708274	0.000016
ES_13	10.3	68.48	0.59	-9.74	0.708283	0.000016
ES_14	4.1	20.55	0.96	-7.25	0.708272	0.000015
ES_18	8.4	56.97	0.64	-9.12	0.708241	0.000016
ES_20	10.1	16.48	0.98	-9.57	0.708218	0.000016
ES_22	8.3	18.20	0.94	-8.15	0.708229	0.000016
ES_24	0.033	24.39	1.02		0.713643	0.000016
ES_27	20.5	73.66	0.51	-8.80	0.708243	0.000016
ES_28	14.9	72.27	0.56	-8.95	0.708247	0.000016
ES_29	0.044	19.73	1.19		0.711898	0.000016
ES_30	7.5			-9.09	0.708172	0.000016
ES_32	2.1	21.39	1.04	-8.62	0.708316	0.000016
ES_34	1.4	28.38	1.10	-9.84	0.708544	0.000015
ES_35	0.089	16.13	0.76	-11.44	0.708513	0.000016
ES_38	0.051	28.72	1.39		0.714561	0.000016
ES_40	1.1	20.80	1.00	-10.63	0.708400	0.000016
ES_41	2.0	16.23	0.91	-6.91	0.708293	0.000016
ES_44	10.7			-8.70	0.708399	0.000016
ES_52	5.0	20.79	1.05	-8.89	0.708244	0.000016
ES_56	0.045				0.711857	0.000016
ES_57	0.073	22.16	0.90		0.710653	0.000016
ES_58	0.133	17.73	0.74	-12.13	0.709733	0.000016
ES_75	29.9	77.88	0.44	-7.70	0.708294	0.000016
ES_78	8.1	22.23	0.99	-6.46	0.708244	0.000016
ES_82	8.2	19.96	1.03	-8.41	0.708135	0.000016
ES_83	0.050	61.11	0.65		0.711986	0.000016
ES_85	5.6	24.32	0.89	-6.25	0.708229	0.000016
ES_89	0.046	42.56	1.20		0.713835	0.000017
ES_91	0.028	71.50	1.33		0.711877	0.000016
ES_92	30.2	74.86	0.45	-8.71	0.708297	0.000016
ES_93	6.7	19.59	0.90	-7.94	0.708234	0.000016
ES_95	5.7	16.78	1.00	-9.85	0.708254	0.000016
ES_104	5.8	57.92	0.92	-9.08	0.708239	0.000016
ES_108	5.5	19.18	1.11	-10.12	0.708198	0.000016
ES_113	0.076	67.29	0.47		0.710335	0.000016
ES_117	3.3	17.80	2.89	-10.23	0.708249	0.000016
ES_121	4.1	20.65	0.91	-11.34	0.708226	0.000016
ES_122	0.122	29.89	0.74		0.710013	0.000016
ES_124	3.8	42.51	1.15	-6.45	0.708234	0.000016
ES_125	28.1	73.97	0.34	-8.37	0.708251	0.000016
ES_132	3.4	18.70	0.84	-6.25	0.708235	0.000016
ES_133	4.4	16.69	1.03	-12.12	0.708214	0.000016
ES_135	0.0	33.68	0.67		0.710563	0.000016
ES_139	2.9	15.46	0.93	-10.87	0.708270	0.000016

ES_140	3.2	41.98	1.00	-9.57	0.708250	0.000016
ES_144	2.4	24.12	0.87	-8.78	0.708239	0.000016
ES_147	2.6			-8.49	0.708257	0.000016
ES_152	5.2	40.09	0.97	-7.17	0.708250	0.000016

Table S5. The results of the NETPATH model, after adjustment for isotopic changes related to the calcite phase, demonstrated a high degree of accuracy in age correction.

Aquifer type	Final Water sample	Isotopic Exchange (calcite)	Isotopic exchange (CO_2)	Computed ^{13}C	Observed ^{13}C	Computed ^{14}C	Observed ^{14}C	Age (year)	EV factor (NETPATH)
TCA	78	1.082		-6.46	-6.46	30.87	22.22	2717	16.35
TCA	20	0.291		-9.57	-9.57	83.76	16.48	13438	1.66
TCA	95	0.336		-9.85	-9.85	68.64	16.77	11647	14.29
TCA	108	0.323		-10.12	-10.12	72.82	19.18	11029	8.36
TCA	133	0.11		-12.12	-12.12	84.15	16.68	13375	21.92
TCA	121	1.35		-11.34	-11.34	43.06	20.65	6076	19.69
TCA	41	1.04		-6.91	-6.91	51.71	16.22	9581	2.85
TCA	140	0.348		-9.57	-9.57	65.9	41.9	3739	14.9
TCA	139	0.196		-10.87	-10.87	79.6	15.45	13551	9.7
TCA	11	0.127		-11.61	-11.61	84.02	17.36	13035	11.93
TCA	34	0.311		-9.84	-9.84	67.21	28.37	7128	9.69
TCA	58	1.09		-12.13	-12.13	66.98	17.73	10988	1.48
TCA	82	0.507		-8.41	-8.41	58.3	19.96	8860	14.12
TCA	93	0.774		-7.94	-7.94	60.53	19.58	9328	3.05
TCA	85	0.799		-6.25	-6.25	35.39	24.32	3102	31.9
TCA	52	0.53		-8.88	-8.89	69.98	20.79	10033	3.17
TCA	104	0.47		-9.07	-9.08	65.01	57.91	955	7.56
TCA	132	0.981		-6.25	-6.25	33.02	18.69	4703	17.67
TCA	17	0.284		-10.23	-10.23	71.61	17.8	11507	15.42
TCA	124	0.462		-6.45	-6.45	45.93	42.5	640	3.03
TCA	144	0.5		-8.78	-8.78	72.4	24.11	9088	2.6
TCA	32	0.513		-8.62	-8.62	73.08	21.38	10158	1.93
TCA	10	0.08		-12	-12	88.07	21.83	11529	8.69
TCA	40	0.2		-10.62	-10.63	81.84	20.8	11324	4.96
spring	14	0.58		-7.25	-7.25	45.88	20.54	6642	21.18
spring	6	0.19		-10.26	-10.26	79.48	18.3	12138	10.49
spring	22	0.705		-8.15	-8.15	72.22	18.19	11396	1.35
NSSA	35	0.031	0.2	-11.44	-11.44	58.97	16.12	10720	1.5
NSSA	89	0.152	0.001	-11.44	-11.44	71.55	42.55	4296	1.75
NSSA	57	0.898	0.001	-11.44	-11.44	72.91	22.16	9845	1.04
NSSA	38	1.26	0.2	-11.44	-11.44	68.64	28.72	7202	2
NSSA	24	0.867		-11.44	-11.44	76.01	24.39	9397	1.67
NSSA	29	1.36		-11.44	-11.44	67.62	19.72	14184	1.35
NSSA	135	0.28	0.2	-11.44	-11.44	86.27	33.68	7775	1.15

Elmaraqi lake	125	0.34		-8.37	-8.37	44.57	73.96	recent	486.67
Siwa lake	92	0.34		-8.71	-8.71	69.36	74.86	recent	14.54
Aghormi lake	75	0.47		-7.7	-7.7	46.78	77.88	recent	72.77
Zeitun lake	27	0.47		-8.8	-8.8	45.63	73.66	recent	86.89

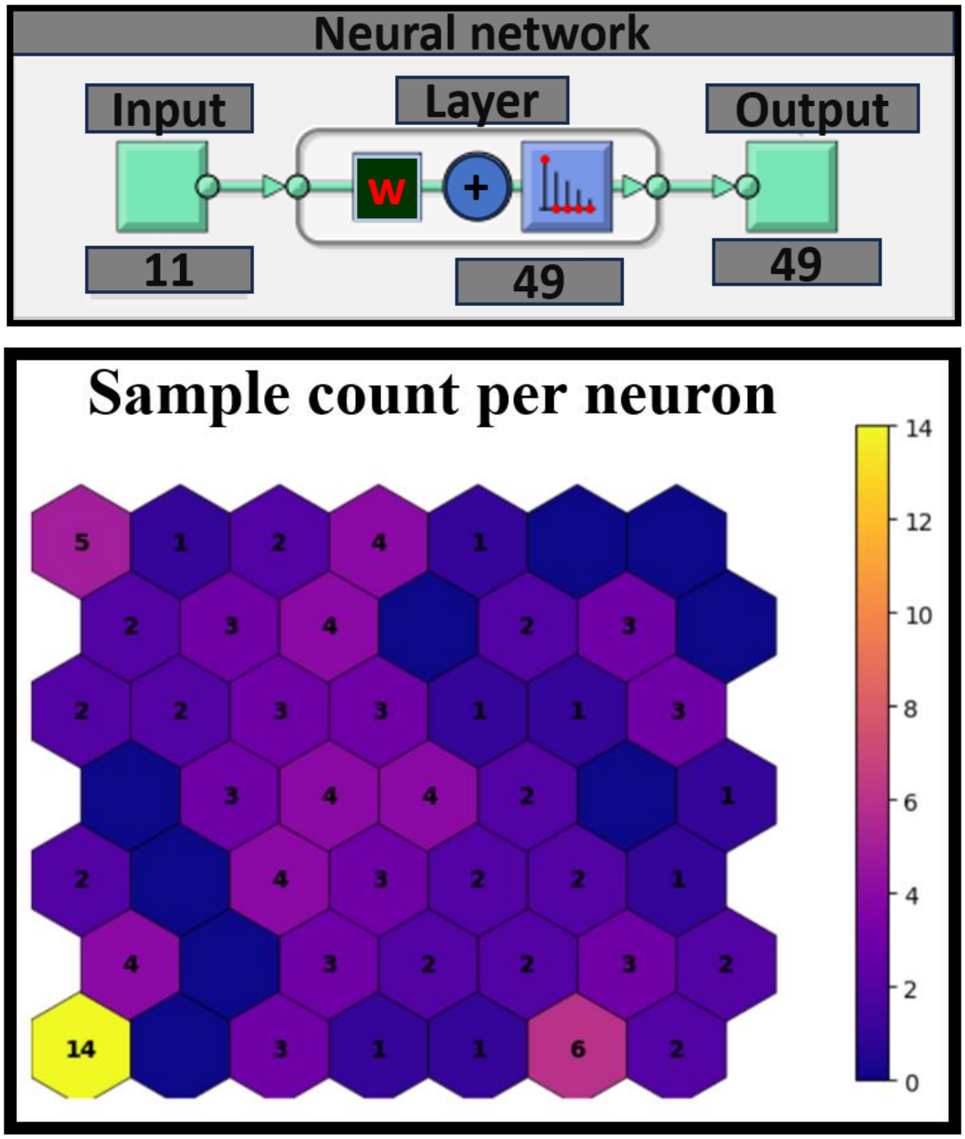


Figure S1. 2D maps represent the architecture of SOM, neighbor weigh distance, weight positions, and sample hits

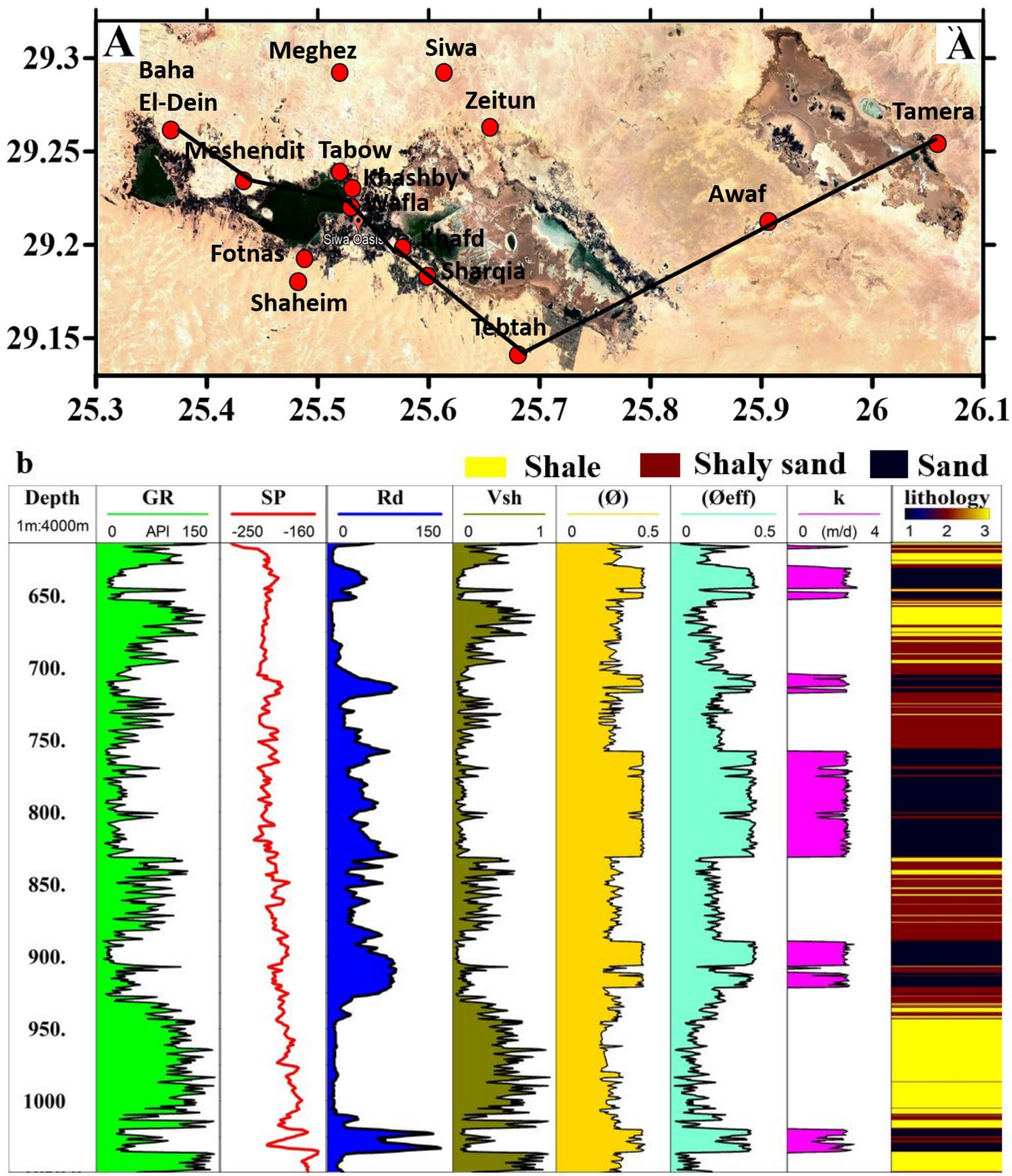


Figure S2. (a) Distribution of well log's location in Siwa Oasis, **(b)**Vertical panel shows the response of well logs, Vsh, Ø, $Ø_{eff}$, K, and lithological clusters

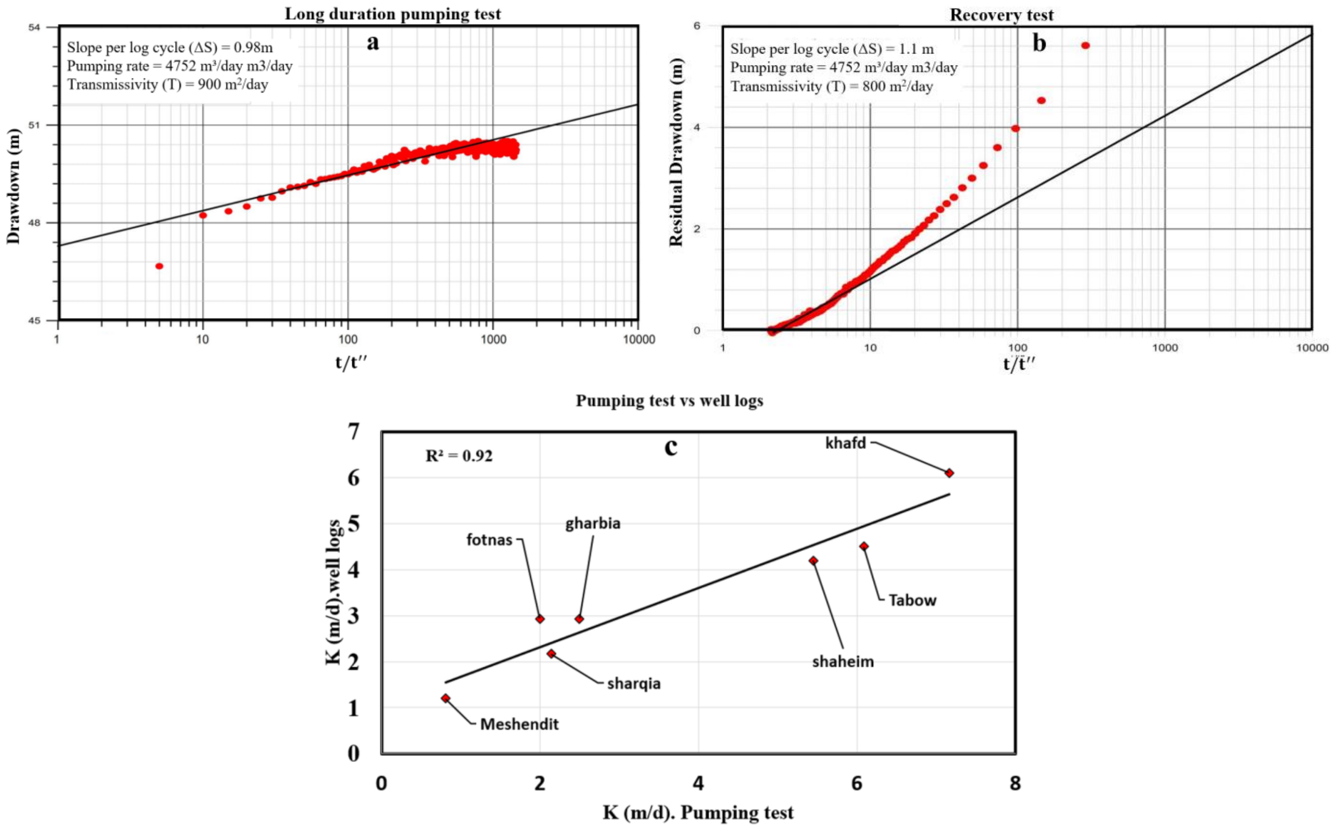


Figure S3. The relationship between drawdown and time for long duration pumping test (a) and recovery test (b) and calibration curve of hydraulic conductivity estimated from well logs vs pumping test

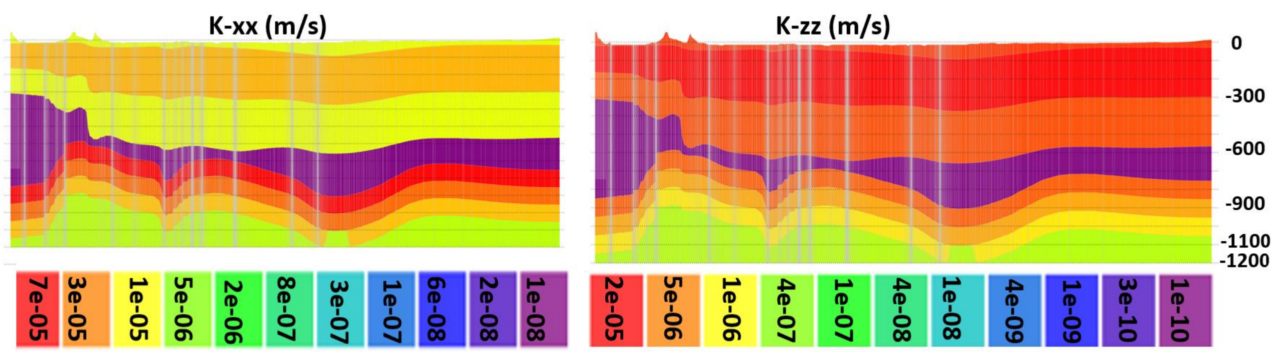


Figure S4. The final horizontal and vertical hydraulic conductivity used for the calibrated numerical flow model

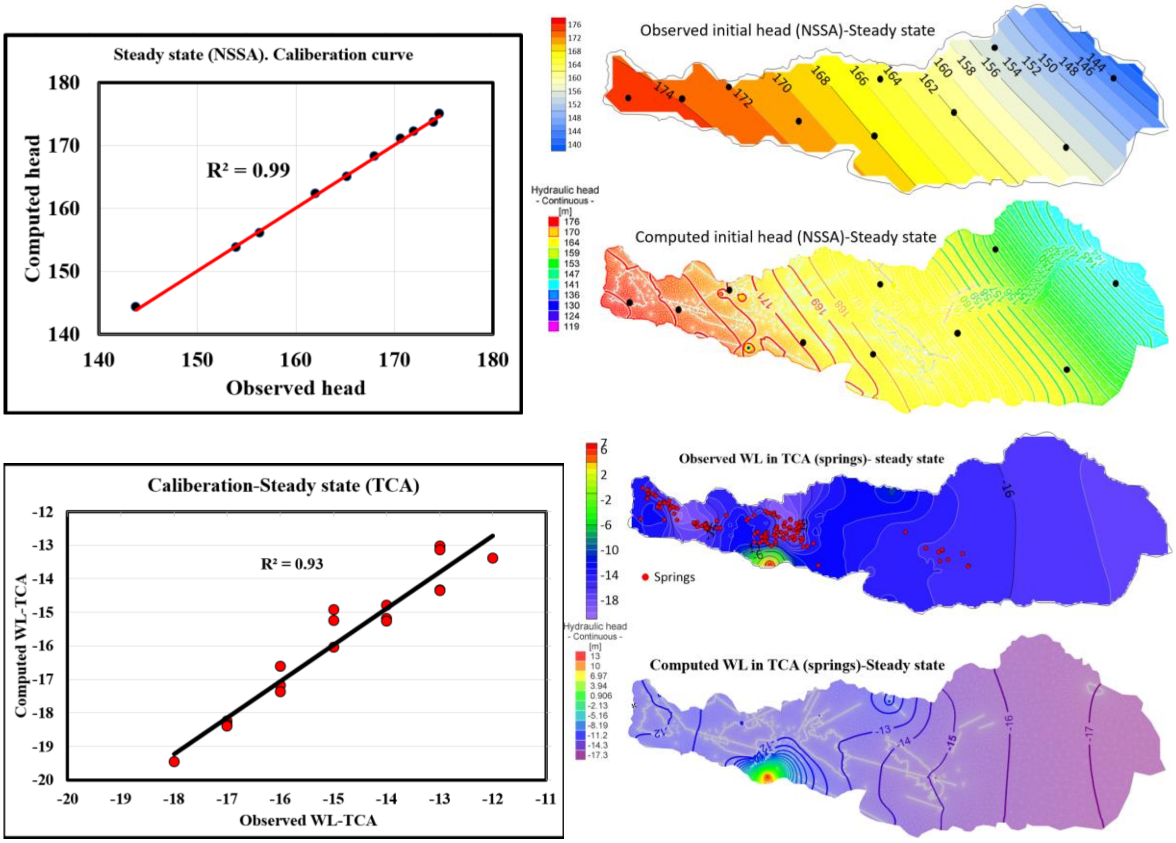


Figure S5. The calibration curve and maps showing the observed and computed initial head in NSSA and springs water level (TCA) in steady state condition.

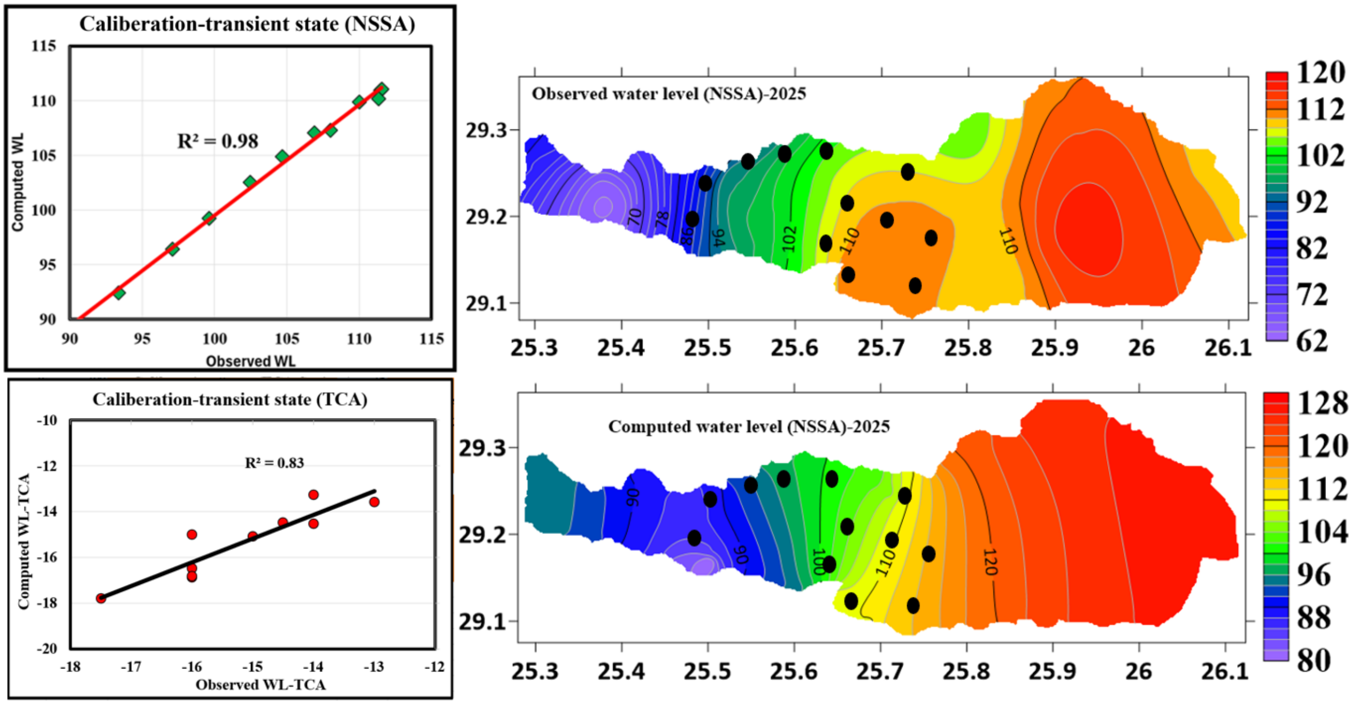
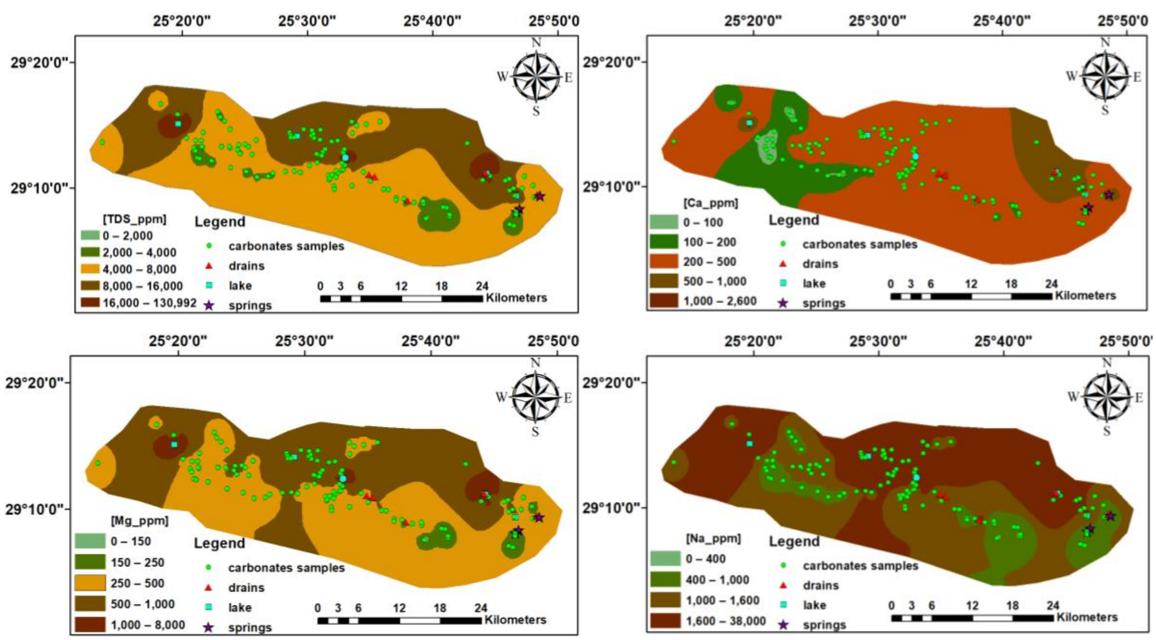


Figure S6. The transient state calibration curve for NSSA and TCA and boreholes distribution map used for calibration of NSSA.



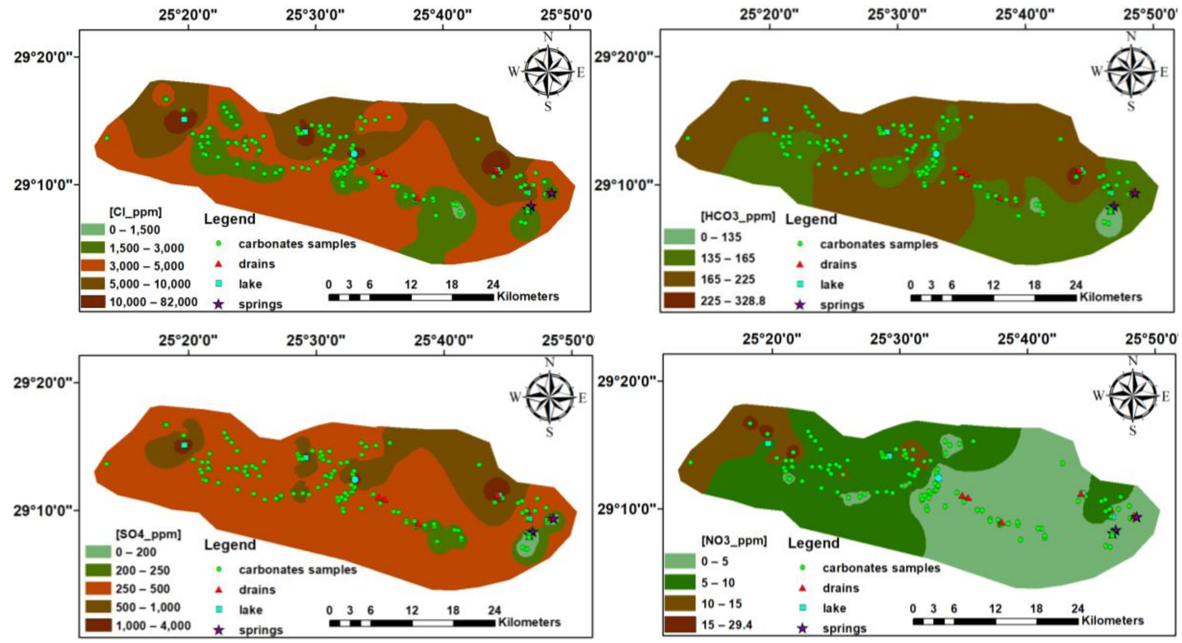
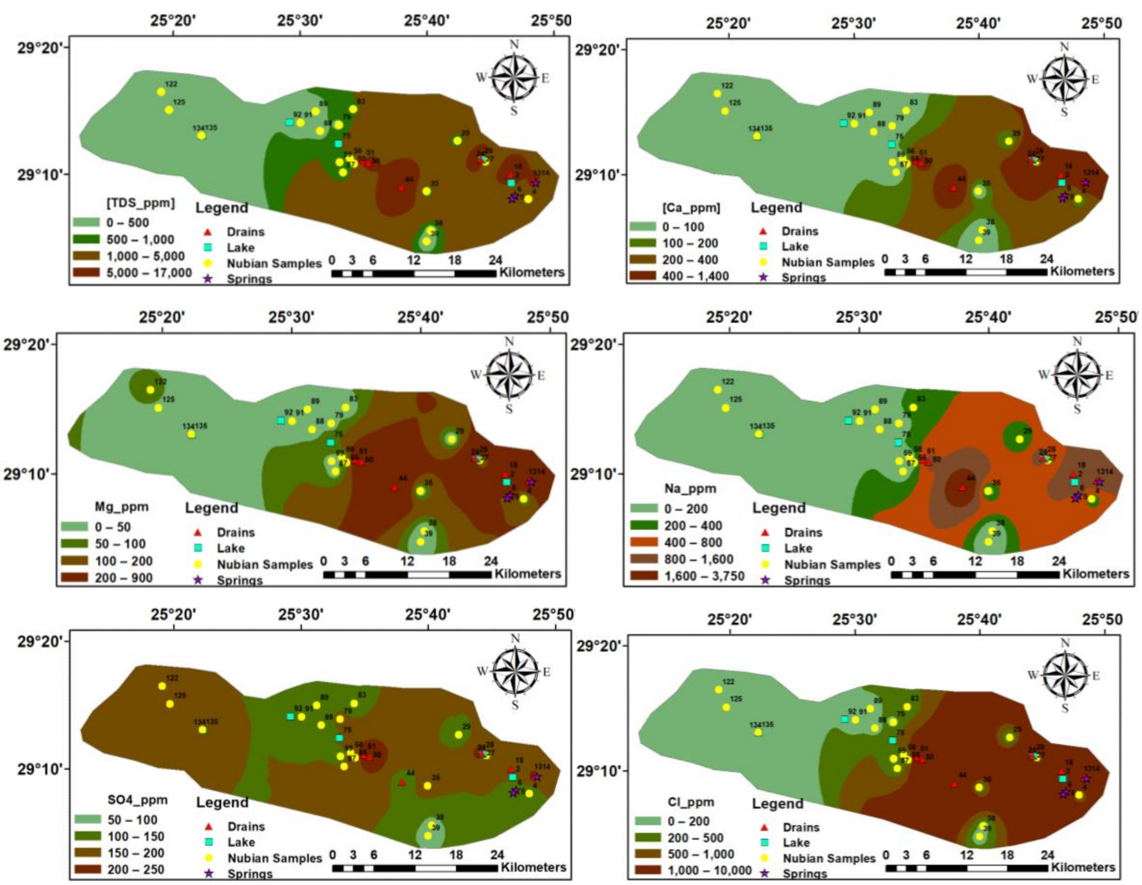


Figure S7. Distribution maps of physicochemical parameters for the TCA, springs, drains and salt lakes.



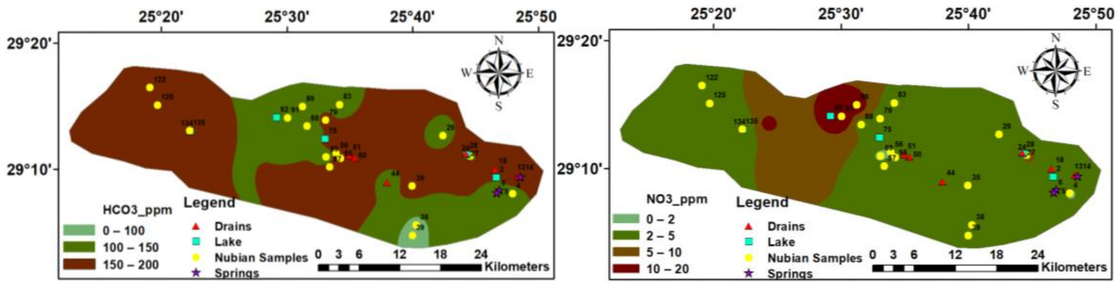


Figure S8. Distribution maps of physicochemical parameters for the NSSA, springs, and drains

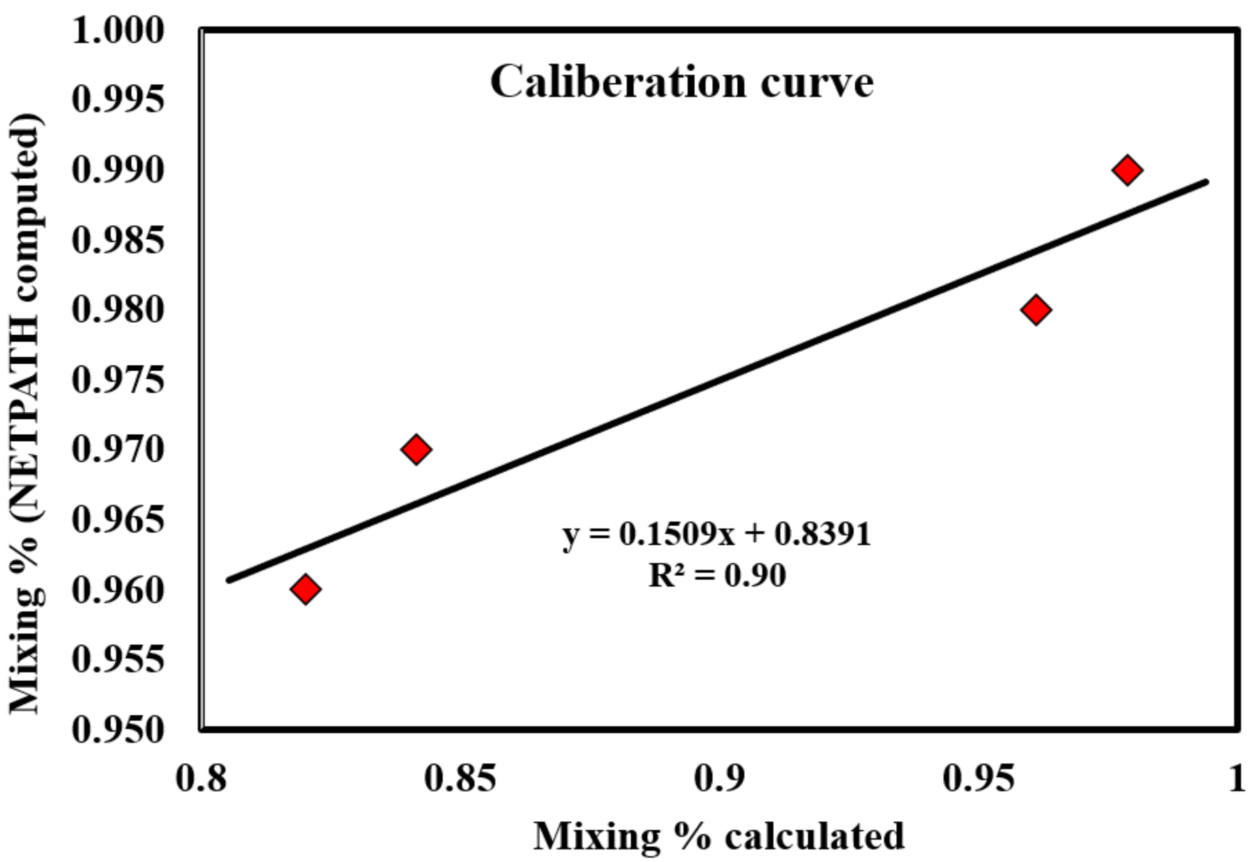


Figure S9. Calibration curve to validate the accuracy of NETPATH model from calculated $\delta^{18}O$ mixing percentages

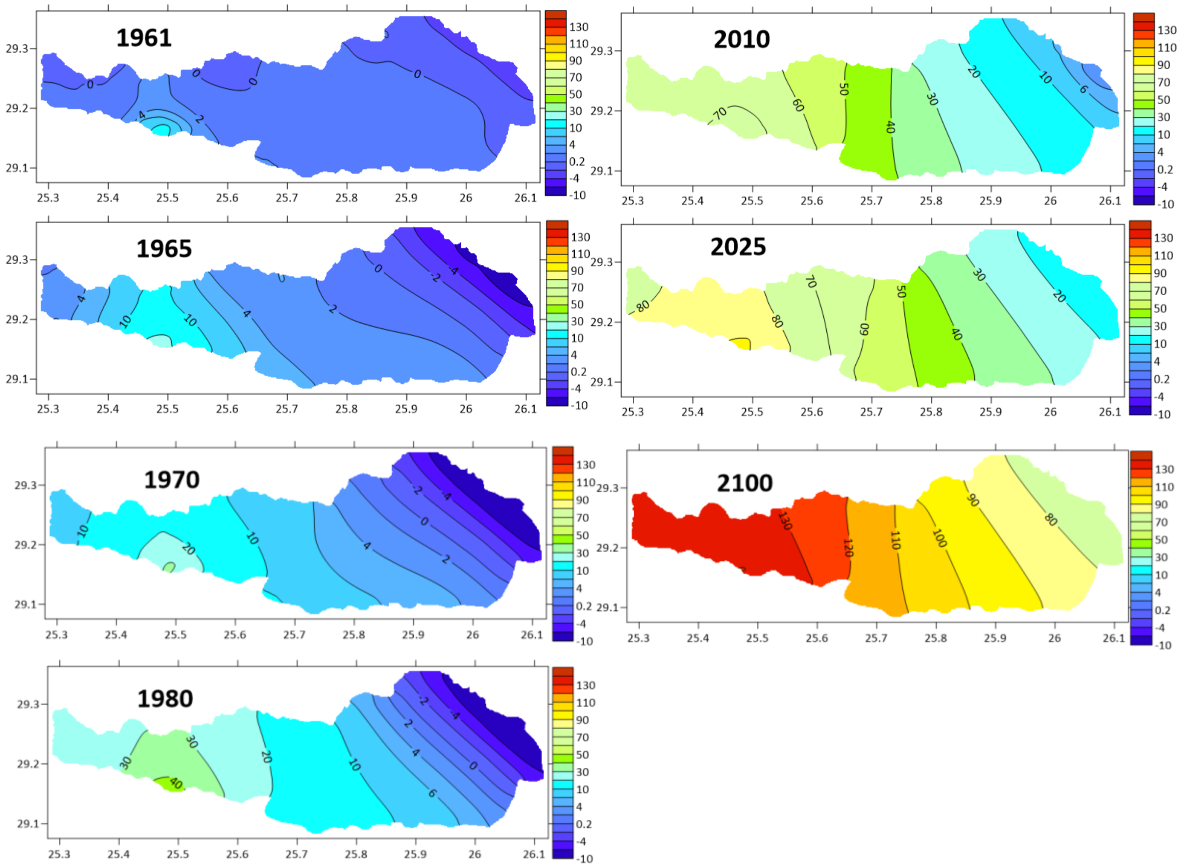


Figure S10. The drawdown in the piezometric head of the NSSA from 1961 to 2100

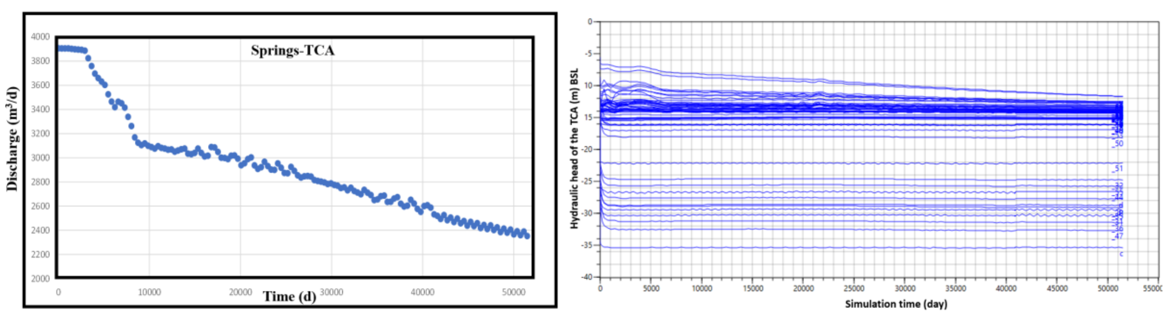


Figure S11. The changes in the discharge rate and hydraulic head of the springs (TCA) from 1960 to 2100 based on the transient model