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Supplement of

How to identify groundwater-caused thermal anomalies in lakes based on multi-temporal satellite data in semi-arid regions

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SUPPLEMENT:

Sect. S1: Recording and atmospheric parameter for applied data (Trans = Transmissivity, Up = Upwelling Radiances [$W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$], Down = Downwelling Radiances [$W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$])

No	Date of Recording	Time (GMT)	Season	Lat	Lon	Trans	Up	Down
1	15.02.2000	08:04	Winter	31.8	35.4	0.83	1.12	1.84
2	03.04.2000	08:03	Winter	31.8	35.4	0.87	0.99	1.64
3	21.05.2000	08:03	Summer	31.8	35.4	0.89	0.88	1.47
4	22.06.2000	08:03	Summer	31.8	35.4	0.81	1.54	2.52
5	25.08.2000	08:02	Summer	31.8	35.4	0.66	2.84	4.41
6	28.10.2000	08:01	Summer	31.8	35.4	0.79	1.52	2.47
7	31.12.2000	08:01	Winter	31.8	35.4	0.88	0.78	1.30
8	21.03.2001	08:01	Winter	31.8	35.4	0.85	1.08	1.81
9	24.05.2001	08:01	Summer	31.8	35.4	0.86	1.08	1.85
10	25.06.2001	08:00	Summer	31.8	35.4	0.79	1.74	2.78
11	11.07.2001	08:00	Summer	31.8	35.4	0.78	1.84	2.97
12	13.09.2001	07:59	Summer	31.8	35.4	0.72	2.26	3.55
13	19.01.2002	08:00	Winter	31.8	35.4	0.92	0.53	0.89
14	08.03.2002	08:00	Winter	31.8	35.4	0.93	0.53	0.90
15	24.03.2002	08:00	Winter	31.8	35.4	0.86	1.04	1.73
16	09.04.2002	08:00	Winter	31.8	35.4	0.86	0.99	1.63
17	14.07.2002	08:00	Summer	31.8	35.4	0.69	2.56	4.01
18	18.10.2002	07:59	Summer	31.8	35.4	0.68	2.39	3.76
19	19.11.2002	07:59	Winter	31.8	35.4	0.94	0.46	0.78

Sect. S2: Comparison of Recording Dates, Rainfall Events and minimum values of SRT-CAT – grey-shaded are all images that are indicated as surface discharge influenced by exhibiting at least one value below the threshold of -0.053 - Abbreviations: TD – Time difference [days], TR – Total amount of rain per event [mm], ED – Event duration [days], MI – Maximum intensity [mm], Min IF – Minimum value after SRT-CAT

No	Date of recording	Date of last rain	TD	TR	ED	MI	Min IF
1	15.02.00	14.02.00	1	47.5	3	41.1	-0.104
2	03.04.00	30.03.00	4	-*	-*	12	0.020
3	21.05.00	21.03.00	17	0.8	1	0.8	0.006
4	22.06.00	21.03.00	49	0.8	1	0.8	0.018
5	25.08.00	21.03.00	31	39.9	1	39.9	-0.021
6	28.10.00	26.10.00	2	7.2	4	4.1	-0.135
7	31.12.00	30.12.00	1	-*	-*	3	-0.318
8	21.03.01	16.03.01	5	-*	-*	1	0.019
9	24.05.01	17.05.01	7	-*	-*	1	-0.019
10	25.06.01	03.05.01	29	50	1	50	-0.076
11	11.07.01	03.05.01	45	50	1	50	0.007
12	13.09.01	03.05.01	109	50	1	50	-0.040
13	19.01.02	18.01.02	1	-*	-*	1	-0.149
14	08.03.02	07.03.02	1	-*	-*	5	0.020
15	24.03.02	22.03.02	2	-*	-*	2	-0.013
16	09.04.02	06.04.02	3	-*	-*	2	-0.020
17	14.07.02	15.05.02	60	2	1	2	0.012
18	18.10.02	16.10.02	2	-*	-*	10	-0.062
19	19.11.02	18.11.02	1	-*	-*	2	-0.136

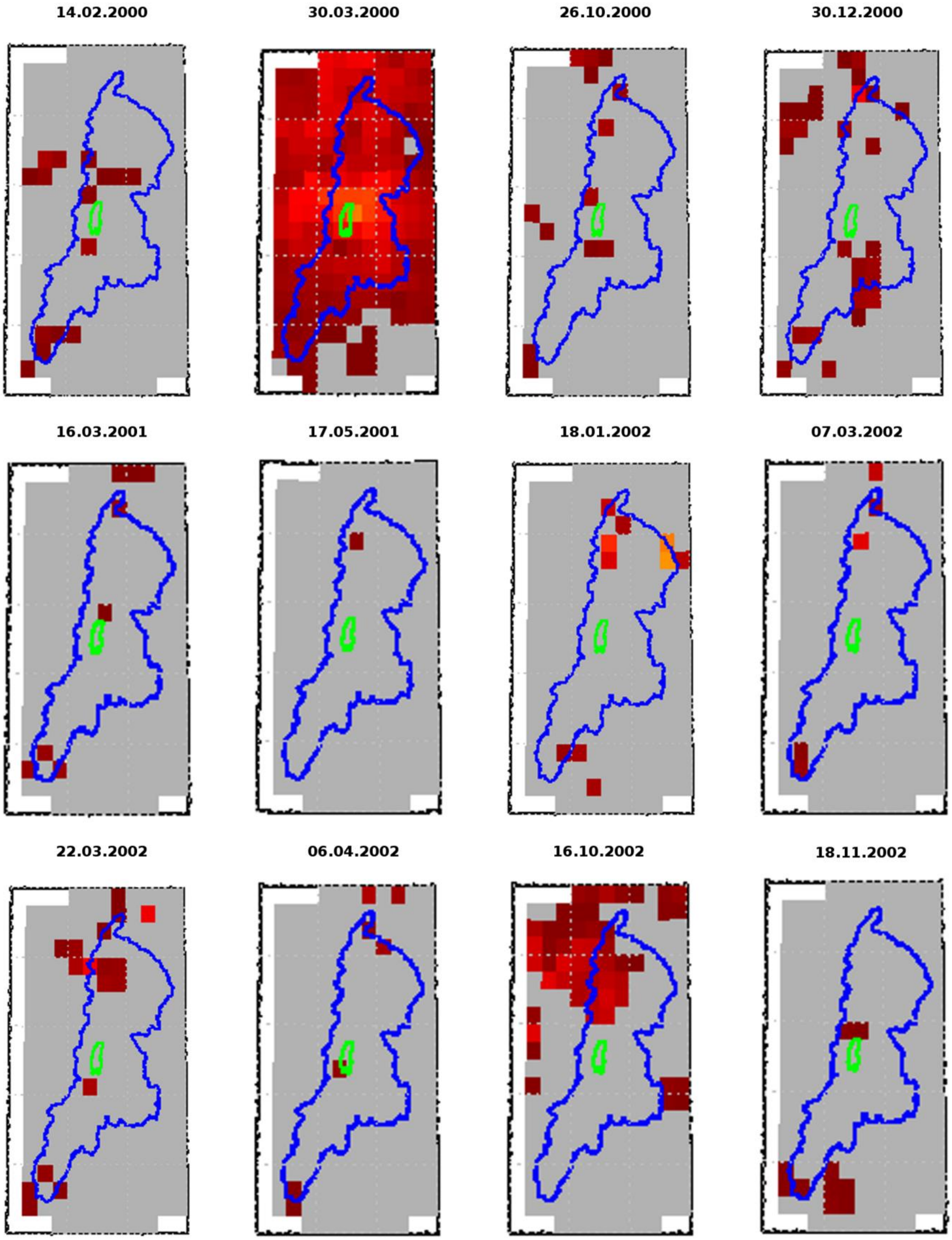
* Information derived from TRMM data where total amount per event and event duration are inappropriate to infer

Sect. S3: Recording dates vs. rain occurrence and intensity for all rain stations and TRMM_34B2 data – Abbreviations: RD – Recording date of image, TD - Time difference between RD and the respective station/TRMM [days], MI - maximum intensity of the rain event [mm]

	Gilgal		Jerusalem		Amman		TRMM_3B42	
RD	TD	MI	TD	MI	TD	MI	TD	MI
15.02.00	1	10	1	41.1	1	8.9	1	2
03.04.00	13	3	10	21.1	10	7.9	4	12
21.05.00	61	3	58	21.1	17	0.8	-*	-*
22.06.00	93	3	90	21.1	49	0.8	-*	-*
25.08.00	157	3	154	21.1	31	39.9	-*	-*
28.10.00	3	4	n/a	n/a	2	4.1	2	6
31.12.00	7	4	6	24.1	6	7.6	1	3
21.03.01	12	4	12	3	25	0.8	5	1
24.05.01	21	9	22	0.8	22	5.1	7	1
25.06.01	53	9	43	0.8	29	50	-*	-*
11.07.01	69	9	59	0.8	45	50	-*	-*
13.09.01	133	9	123	0.8	109	50	-*	-*
19.01.02	9	23	9	64	7	23.1	1	13
08.03.02	11	1	10	1.3	10	0.8	1	5
24.03.02	3	6	2	6.1	3	17	2	2
09.04.02	6	4	5	33.8	4	70.1	3	2
14.07.02	60	2	101	33.8	100	70.1	-*	-*
18.10.02	2	3.5	4	0.8	54	50	2	10
19.11.02	14	15	29	0.5	15	3	1	2

* Information derived from TRMM data where total amount per event and event duration are inappropriate to infer

Sect. S4: Last rain occurrence according to TRMM prior to Landsat data recording



Sect. S5: Explanation of Volume calculation

Processing steps	Description
Data basis:	geo-referenced aerial photographs (2007) – GSD: 1 m
Determination of fan area:	manual digitalisation using the cliff as western boundary and the DS as eastern boundary
Volume calculation:	1. creating an upper plane representing the current topographical surface by extracting the before determined fan area from the ASTER GDEM 2. creating a tilted lower plane by applying the calculation: X_iY_i – (X_iY_i –Min) on the upper plane 3. calculating the volume using the “Cut Fill” function of ArcGIS. using upper and lower plane as input parameter

Sect. S6: Parameter used for pore runoff calculation

Parameter	Value	Parameter	Value
V_{total}	$14.07 \cdot 10^6$	h_a	-384
n_{pores}	30% *	h_b	-420
Material	Gravel	L	1000
Kf	10^{-2} *	A	$33 \cdot 10^3$

*Values after Hölting and Coldewey 2005

Sect. S7: Detailed explanation of travel time calculation of submarine spring discharge

Travel time equation for round buoyant jets after Lee and Chu, 2003:

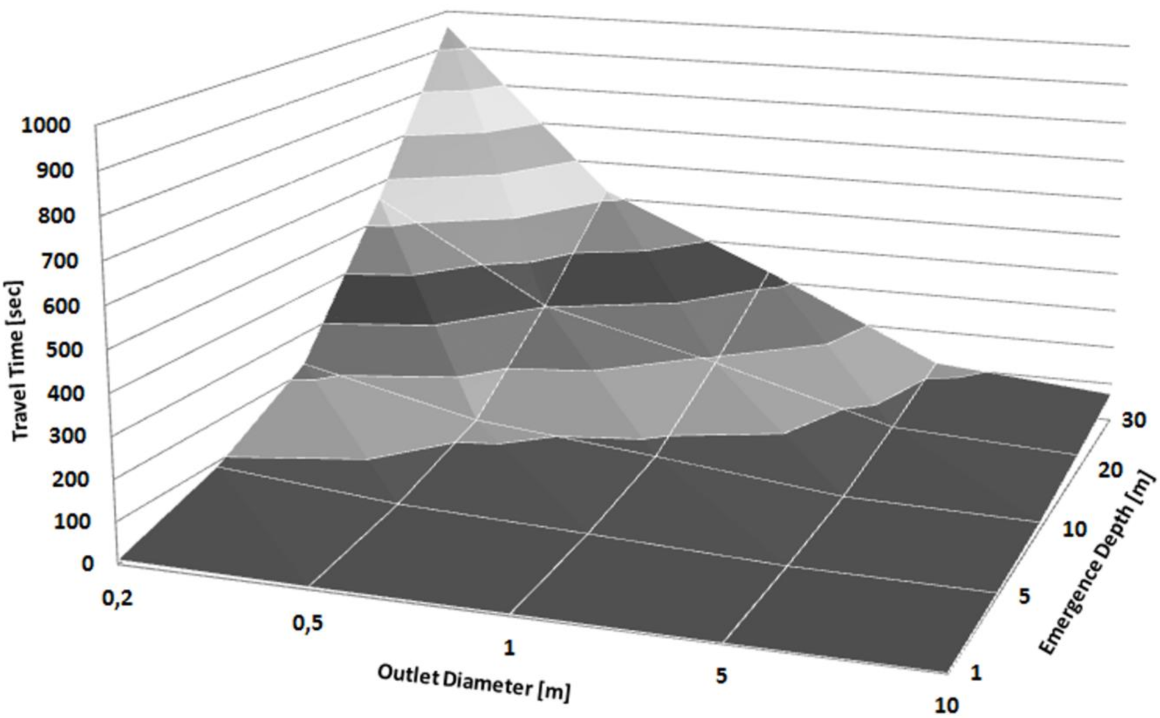
$$t(z) = z\left(A\left(\frac{\Delta\rho}{\rho_0}\frac{\pi}{4}D^2\omega_0\right)^{\frac{1}{3}} z^{-\frac{1}{3}}\right)^{-1}$$

where t=travel-time [s], z=depth of emergence [m], A=specific dimensionless constant with a value of 4.2 after Pantokratoras [2001], Δρ=difference of densities between DS water and groundwater [$g \cdot cm^{-3}$], ρ_0= density of DS [$g \cdot cm^{-3}$], D= outlet diameter [m], ω_0=velocity at outlet [$m \cdot s^{-1}$].

Parameter	Value	Source	Comment
z	1, 5, 10, 20, 30	Ionescu et al. (2012)	All depths were applied iteratively
Δρ	0.05	Own measurement	As reference we applied the density of brackish spring water of 1.19 $g \cdot cm^{-3}$
ρ_0	1.24	Own measurement	
D	0.2, 0.5, 1, 5, 10	Ionescu et al. (2012)	All diameters were applied iteratively based on findings of Ionescu et al. 2012
ω_0	$10^{-3} m \cdot s^{-1}$	Yechieli et al., 2010	number presumably represents a minimum, own measurements in open channels exhibit velocities of 10^{-3}-$10^{-1} m \cdot s^{-1}$

Explanation: Accounting for the variables *D* and *z* we calculate the travel-times for varying depths and diameters that represent minimum values as both outlet velocity and density difference can approach larger values (see Fig. below).

Travel-times remain below 100 sec for i) small outlets (diameter: <1 m) with a shallow emergence of <10 m and ii) for larger outlets (diameter: >5 m) with an emergence depth of up to 30 m (black colour in Fig. 8). Although these travel-times are only an approximation assuming a constant velocity and neglecting velocity-reducing influence of e.g. lateral deceleration through currents, it gives an indication on the rapidity of groundwater mass transport towards the sea-surface. Within the open water, a stable thermocline that affects the vertical flow exists between April and August in a depth of 25-28 m below the DS-level (Gertman and Hecht, 2002). Consequentially, groundwater that emerges below this depth might be influenced in terms of velocity and heat transfer, but not in the general density-driven vertical flow. Due to the complexity a detailed analysis of velocity fields and heat transfer is beyond the scope of this study. However, because of the short travel-time we suppose the native groundwater temperature does not completely adapt to ambient temperatures. This assumption might not account for small discharge volumes with small outlet diameters at larger emergence depths and for periods of spring and fall, where ΔT approaches zero. In contrast, during winter and summer months ΔT approaches 5-10 °C. We presume that during these times larger discharge volumes that occur at larger outlet diameters, largely maintain native groundwater temperatures until the surface is reached. According to Lee and Chu (2003), as the vertically flowing groundwater reaches the sea-surface, a buoyancy layer forms with a diameter far greater than the original outlet diameter. Hence, it is conceivable that larger discharge volumes are thermally identifiable at least during winter and summer months even on satellite date with a coarse GSD.



Travel-times [s] of submarine springs to the sea-surface for varying outlet diameters and emergence depths.

Sect. S8 Indication of the relationship between area with range values <8.5 °C and spatially according accumulated spring discharge volumes measured by the HIS

Discharge site	Covered area [$10^3 m^2$]	Accumulated discharge volume [$m^3 s^{-1}$]	Ratio (Area/Discharge Volume)
A	54	0.43	125
B*	146	1.33	109
C	34	0.31	110

B* represents the outlined submarine spring and the adjacent area of connected range values of <8.5 °C to the southwest of site B

Sect. S9 Example of the effect evoked by conversion from DN to SST with different emissivity values of fresh groundwater in respect to saline DS water

Emissivity value	DN value (0-255)	Temperature [°C]	Temperature Difference [°C]
0.97	0	-44,0	
0.99	0	-44,2	-0,21
0.97	100	8,6	
0.99	100	7,8	-0,92
0.97	255	58,8	
0.99	255	57,3	-1,49