Reply to Reviewer 2:

We want to thank Reviewer 2 for the thoughtful contributions and comments to our manuscript that underline the careful reading for which we are really grateful. In the following we will comment on a point-by-point basis on the given comments (reviewers comments are given in bold and answers are given in italic).

ABSTRACT:

The use of in-situ in the abstract made me think that you were making in-situ measurements, but such measurements are not adequately presented and used in the paper.

The use of "in-situ" is used in the abstract during the introduction sentences, which puts the study in its general semantic context. Nevertheless, previously obtained in-situ data concerning SGD and spring water samples are mentioned as well throughout the manuscript. In our understanding the latter is used and presented adequately. However, we reworked some of the passages concerning obtained in-situ data to improve its presentation.

Page 1 Line 2 - "...measurements may provide" - not all in situ measurements are made to determine continuous temporal changes as implied by the sentence.

We agree. The statement was too general. Thus, we changed the text according to the reviewer's suggestion.

INTRODUCTION:

Page 2 Line 21 – can reference Tamborski papers and Kelly papers.

One paper of Tamborski and Kelly was added as reference.

MATERIALS AND METHODS:

Why is there no materials and methods text below the 2 heading on page 3 and then a duplicate heading of 2 Material and Methods on page 7 with lots of text below it that looks more like results?

To our best knowledge, there is no need to have text below main headings. However, we reorganized the text and separated "study area" and "material and method" in individual sections. The separation leads the general alternation of heading and text. In regard to the duplicate heading and a partial numbering chaos, we agree to the reviewer. During the conversion to the HESS format, we must have caused the chaotic conditions that we will correct in the revised version and double-check prior to resubmission.

Also, I think Tamborski should be referenced within the section 2 text starting on page 7.

We added the reference: Tamborski, J. J., Rogers, A. D., Bokuniewicz, H. J., Cochran, J. K., and Young, C. R.: Identification and quantification of diffuse fresh submarine groundwater discharge via airborne thermal infrared remote sensing, Remote Sensing of Environment, 171, 202-217, 2015

In general, the methods section could benefit from more references and better explanation of software packages and processes used.

We agree, in the manuscripts current state, it is hard to reproduce the method. In the revised manuscript, we brought in more clarity, and additionally we included an offer to distribute the code written in Matlab to any researcher upon request.

Section 2.1 is a one sentence paragraph that was lacking in critical information about the study area. At the very least, please add information about the number of known springs in the study area and perhaps the volume of water they discharge. Is there seasonality to the discharge volumes?

Information on number of springs is indirectly given in Figure 1. We decided against giving absolute numbers in the text out of several reasons.

1. *During the last years, we repeatedly observed several locations along the western coast and recognised a highly dynamic system of coming and leaving springs, on- and offshore.*
2. *We found and investigated the 8 submarine springs given in Figure 1 and a lot more in the near vicinity, but this number is only a fraction of focused submarine springs in the wider area, not to speak of the entire coastline that we are not able to tell.*
3. *It is unclear how long springs (both terrestrial and submarine) exist in the investigated area, due to the observed continuously changing groundwater flow systems, as a consequence of changing hydraulic gradients due to the falling Dead Sea and the associated groundwater levels and the heterogeneity of the sedimentary body, acting as aquifer.*

Thus, giving an absolute number would be valid for the moment and the area of investigation, but certainly not in general terms.

Section 2.1.1 the last sentence proposes a connection between groundwater discharge and the maturity of the karst system. It seems like this is the hypothesis that is set out to be tested in the paper, but the authors never come back to this thought in the discussion or conclusion sections.

It is not really a hypothesis to be tested, since we cannot really test it. We merely proposed one possible and very likely explanation, resulting from the observation of burst-like discharge events from diffuse springs in the thermal infrared data. The proposed explanation (maturity of the karst system) presented, which is certainly not the final one, is already introduced in the section "hydrogeological section" and also linked to the discussion and conclusion sections, e.g. p13L 22f "[…] Discharge behaviour in this case depends on the maturity and geometric formation of the conduit network, is therefore highly anisotropic, heterogeneous, and features a rapid flow (Surić et al., 2015) […]" or p14L32ff "[…] And lastly we are able to reveal a short-term periodicity in the order of 20 to 78 seconds for diffuse SGD which we attribute to an interplay of conduit maturity/geometry and wave setup […].

Section 2.1.2 I don't consider diffuse flow to be onshore springs, but the title of the section says that there are onshore springs. What and where are the onshore springs

that are meant to be described in this section? This becomes very important for understand the information presented in section 2.5

Neither do we consider onshore springs to be explicitly diffuse in discharge, nor does the heading state it. Instead the heading reads as "Submarine groundwater discharge and onshore spring characteristics". Yet, we agree that the formulation, particularly in the last paragraph, can cause the impression that onshore springs are occurring as diffuse springs. Thus, we changed that passage, describing onshore springs characteristics separately and referring to Fig. 1d in which the spring-locations are shown.

Section 2.1.3 What about ambient warming of shallow areas compared to deeper areas? How do you address this issue? It seems like your data may have been collected at night. If so, say so.

First, we need to express our sincere gratitude to reviewer 2 who pinpointed at a typo with severe understanding-consequences. Although we state the investigation time to be 12:43 a.m., we meant to write 12:43 ***p.m****. Thus, it was not during night, which would not be allowed, but during noon. We changed it accordingly. Second, shallow areas are certainly more warmed compared to deeper areas with more incoming radiation. Yet, since we do not investigate absolute SSTs but the SST variability of a time span of less than 3minutes, this fact is not of relevance. It would be of relevance, if we would compare data covering a longer time span, say for a day, during which the warming would play a major role, but for three minutes the warming effect is certainly negligible.*

Page 5 Line 1 With data acquisition between what times? Your UAV was airborne between 12:43 and 12:50 AM, but when were the data actually collected. You present fewer minutes of data than advertised here.

With time needed for take-off and landing, the actual recording time is from 12:45 to 12:48 pm. We added the recording time in the revised version of the manuscript.

Figure 2 is not necessary because the text adequately describes what the authors did

Quite frankly, although we somewhat agree with reviewer, who apparently is from the field of remote sensing and thus familiar with camera characteristics, we still think it is beneficial to keep Fig. 2 especially for readers with a non-remote sensing background. The figure shows nicely in how far frames relate to recording time and what is meant with master and slave images.

What program did you use to co-register your images?

All image processing steps (co-registering, cropping, extraction of focused and diffuse SGD, spatiotemporal analysis) were conducted within Matlab. We added the software to the section and tried to refine the description regarding the image processing as it was also noted by Reviewer 1 that this section is not reproducible. Since the processing requires knowledge on image processing, which some research may not possess, we also offer to distribute the Matlab code upon request in the revised version of the manuscript.

Why did you choose 150 pixels? I have seen very small-sized focused SGD flows (much smaller than 150 pixels) and very large focused SGD flows.

The threshold of 150 is subjective with the aim to focus on larger patterns only. Admittedly, smaller areas (<150 pixels as connected area) which also fulfil the temperature variance criterion of being smaller than 0.019 do also exist. Yet, all of these areas are due to stones that were not masked especially close to the shoreline. Other areas which might provoke the

assumption of being below the variance threshold of 0.019 are in fact above 0.025 and thus, do not reflect focused SGD.

Page 6 Lines 18-19 I'm confused about using frame 210, which you say is not shown, and then reference the first image in Figure 3 later on in the same sentence. I don't understand what is happening here.

We agree that it is a bit confusing. Frame 210 showed the clearest picture with the largest extent of thermal anomaly caused by diffuse SGD and was therefore chosen to determine the transect length. Although comparable, the visible anomaly extents shown in frame 1 are smaller, but already indicate the general anomaly/discharge picture. Therefore and due to its position as first frame, the first frame was chosen to be shown instead of frame 210. To ease the reading and understanding, we changed the lines which reads now: "As a consequence we delineate diffuse SGD from a single frame (frame 210 – not shown) in which thermal radiation patterns and maximum spatial extents induced by high discharge rates are unequivocally detectable (a comparable single image is shown in Fig. 3-upper left image)."

What software did you use to do the inverse modelling?

The inverse modelling was pursued with Phreeqc 3.2 applying thermodynamic database Pitzer.dat. Although already included, we rewrote the passage to make it clear.

Page 6 Line 26 – you say single SGDs, are these point source or diffuse or both?

At locations where it is not specifically stated as diffuse or focused SGD both are meant. As the reviewers' questions points at an unclear statement, we clarified it.

Section 2 (with text) Does the last sentence of the last paragraph of the section refer to known spring locations? Can these be provided in one of the figures or referenced in the sentence?

Yes, they refer to the known springs (focused SGD and onshore) as you need in-situ water samples to apply the inverse modelling. All spring characteristics included in the modelling are given in Table 2 and spring locations are shown in Fig. 1. We added references at appropriate positons in the text.

RESULTS:

Section 3.1 What assumptions did you make to arrive at the statement "we expect here the most pristine patterns representative for each spot"?

The assumption behind relates to the interplay of active forces, or more specific, the discharge momentum vs. any external influence such as waves, currents etc. Only at the maximum extent, we assume the external influence to be lowest compared to any other location along the thermal anomaly. Thus, here we can observe anomaly patterns best which reflect temporal SGD behaviour with least external influence.

Section 3.1.1 does the 1st focused SGD spot correspond to one of the springs labelled in Figure 1? If so, please say so in the sentence. Same thing for the 2nd and 3rd focused SGD spots.

Yes, it does and is revealed in the result section p8L2ff and p8L10ff. However, we added the corresponding sampled spring numbers in section 3.1.1.

Section 3.1.2 Where are the diffuse SGD spots relative to Figure 1? I don't typically think of diffuse SGD as being a "spot-like" and circular feature; rather, diffuse SGD is typically patchy and spread out over fairly large areas that do not have to be circular features. Perhaps diffuse SGD locations may be better than diffuse SGD spots?

We too thought diffuse SGD to be patchy and observed it in the same way in the field due to the development of schlieren. Based on the patchy and areal observation we show diffuse SGD as area in Figure 1 instead of discrete symbols. The area is 20-25m long as described in section 2.1.2. However, in the present case, the two forms, diffuse and spot-like or focussed discharge, seem to co-exist in the same area. TIR images confirm the observation showing elevated and patchy SSTs in that area along the coastline. Yet, TIR images also reveal spot like discharge within the diffuse SGD area, evoking a CVP (counter rotating vortex pair) and thus suggesting a lateral, pulse-like discharge at the coastline (in contrast to SGD emergence at the sea bottom which induces a buoyancy driven vertical ascend of SGD-water and as a consequence circular pattern on the sea surface). Thus, we all should possible change our spatial thinking in the way as to think of SGD either in the form of focused or diffuse but to consider a possible spatial co-existence of both forms at the same spot/location.

Section 3.2 What does temporally mostly pristine mean? What software was used for the temporal autocorrelation analysis?

"Temporally pristine" means that the true temporal signal of SGD will be most pronounced in the centre (focused SGD) or at the midpoint of the transect (diffuse SGD). In other locations the temporal behaviour will be more influenced by external influences such as waves or currents. The autocorrelation analysis was conducted using Matlab. The latter fact is now included in the revised version of the manuscript.

Section 3.2.2 Why reference Figure 4 in line 18? Also what does "ones" refer to in line 20 and in line 24?

Reference to Fig. 4 is irrelevant and was deleted. The "ones" refer to SGD spots (the first "ones" to diffuse SGD spots 1 and 2 and the second "ones" to all diffuse SGD spots). To increase clarity, both "ones" were exchanged with the respective naming of the SGD spots.

Section 4.1 Line 15 the 3rd SGD spot refers to focused, SGD, correct? If so, why does the very next sentence starting with "This" refer to diffuse SGD? What is "This" referring to? There is an awkward transition here. Also, why reference Figure 4 in a sentence that talks about diffuse SGD?

Correct, but the reviewer seems to miss the context. In the indicated passage we talk about the shape of the SGD patterns and possible causes. In all three focused SGD cases the shape is elliptic and northward oriented, which is more pronounced for the 1st compared to the 2nd and 3rd focused SGD spot. We hypothesise the cause for shape and the deflection trend to be the diffuse discharge or the discharge momentum induced by the burst-like discharge events from, diffuse SGD. The "this" refers to the deflection. The reference to Fig. 4 is wrong and should refer to Fig. 3. We clarified the "this"-misunderstanding and the wrong reference in the revised version.

Section 4.2 would benefit from referencing a figure: The variance image (Figure ?) provides...

We agree and added several figure references to Section 4.2.

I'm also not convinced that the higher discharge rates reveal karst conduits (if higher discharge rates is what "it" refers to) close to the shoreline. We know that faults, fractures, paleochannels, and animal burrows can also be conduits of groundwater flow. Just because the area has karst, doesn't mean that karst is the only explanation for the flow patterns. Please justify your assumption of karst conduits more fully. Are you relying on your insitu data? If so, cite it as support in this section.

We reworked the final statements. While paleo-channels are unlikely in the studied part of the sedimentary fan of Wadi Darga as sedimentary conditions derived from close-by drillings suggest, animal burrows can be excluded for the present case as well, as the sedimentary body we are discussing is soaked with brine, and thus at least as saline as the Dead Sea, making it difficult for any macrozoobenthos or larger animal to survive.
On the contrary, faults may play a role in the present setting. Former investigations by Ionescu et al. (2012) show that microbiologically accelerated dissolution of hosted minerals in the sedimentary body occur widely. We assume, fractures and faults, maybe the result of neotectonic activities may form the initial pathways for water flowing eastwards to the Dead Sea and will be widened (in terms of hydraulic aperture) by dissolution.

Section 4.3 Why keep referencing figure 4 throughout this section? Figure 3 The red writing on the figure is very hard to see and read.

The referencing appears to remain from an earlier version of the manuscript and was not correct before the first submission. Thank you for the lead, we changed it in the revised version. Likewise, we changed the red lettering in Fig. 3.

Figure 4 If these spots correspond to spring numbers in Figure 1, please add spring numbers here. It seems like you should be able to do a very rough calculation of the volume of water coming from the springs since you know the water column depth and the size of the surface expression of the thermal plume. Do you have estimates for the volume of water issuing from these springs and how does that volume compare to a rough calculation?

We added the spring number below the graphic as suggested. Concerning the volume calculation, to our best knowledge there is no approach calculating the volume of water or the discharge rate, based on depth and surface area nor is there any measured discharge rate/volume available for the investigated focused SGDs. We believe the reviewer thinks of a conus as first approximation of the SGD plume beneath the water surface, using known principles to calculate the volume of the cone/water plume beneath the surface. Although generally correct, the cone approximation has severe flaws and eventually would not provide any more insight to potential volume/rates deriving from SGD as the simple areal surface expression (For all three focussed SGDs: Area [m²]: 15 / 28 / 4 - Volume [m³]: 71 / 210 / 19).
The SGD plume within the water column is not at all a conus as both theoretical (see works of Jirka et al. or Papanicolaou et al.) and own experimental (not published) works proof. Instead it is rather tube-like in the bottom near area and develops a pronounced funnel near the water surface. The ratio between tube and funnel depends on a diversity of factors including density and temperature gradients, entrainment and momentum (some of factors are even interdependent, making it difficult to determine the dominant factor). Further unknown is the entrainment of ambient water and thus the amount of pure SGD water within a defined water parcel. Thus, when calculating the volume using the conus approximation would give us the volume of water (both SGD and ambient water) within the conus but certainly not a SGD volume. To determine the SGD ratios using the presented approach we currently plan a further experiment along with further in-situ measurements but this is not yet pursued and thus not presented.

Figure 5 should add NTR to middle column so reader is reminded of acronym in text. The read writing in the first column is very hard to read. The caption says red boxes in figure 4, but there are no red boxes in figure 4.

We added the NTR acronym in the caption of figure 5 and 6 to make it easier for the reader to follow and changed the red lettering to facilitate readability. The red boxes are contained in Fig. 3. We corrected the wrong reference.

Figure 6 should add NTR to middle column so reader is reminded of acronym in text. What is the third transect pixel? Is that pixel 3 of the transect, closest to shore?

Concerning NTR, see comment before. The third pixel of the transect is close to the shore. We added a respective statement in brackets in the figure caption.

Table 1 are the peak values statistically different than the non-peak values. It would be very beneficial to do a simple statistical analysis to demonstrate significance.

We will add the test and its results in the revised version.

Table 2 is illegible

We agree and we will change it in the revised version.