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Interactive comment on "Time-lapse gravity and levelling surveys reveal mass loss and ongoing subsidence in the urban subrosion prone area of Bad Frankenhausen/Germany" *by* Martin Kobe et al.

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Dear Prof. Braitenberg,

We much appreciate your comprehensive discussion of our manuscript and thank you for the overall positive comments as well as for the critical notes. All attached comments and suggestions will help to further improve our manuscript. After shortly summarizing the manuscript, the review recognizes the great care that was bestowed on the measurements. Our conclusion, that mass transport induced by subrosion pro-

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cesses can be identified by repeated gravity surveys, is approved.

1. Hydrology

The review mainly concentrates on the hydrological aspects. First, we want to point out and clarify some important facts:

(a) The anti-correlation between the soil water content taken from the GLDAS model and the temporal changes of the gravity differences is not an exclusive anti-correlation as the sign of the correlation depends on the sequence of the calculation of the gravity differences (delta g (PA-PB) = -delta g (PB-PA)).

(b) The correlation between the gravity differences and the soil water variation shows that the amplitude of the hydrological effect on the observed gravity values differs at points PA and PB. Reasons can be differences in soil parameters, local topography, soil sealing, and perhaps the depth of local aquifers, which must not mandatorily be related to karst phenomena and the observed mass loss. If both points are affected to the same degree, no hydrological effect would be observed in the gravity difference between the points.

(c) For an observation of the mass loss caused by subrosion, we are mainly interested in the long-term trend of gravity differences. We agree that uncertainties in the gravity differences affect the calculated long-term trend, even if they occur only in one measurement campaign. For this reason, we developed the correction approach. However, the longer the time-series becomes, the less important is the uncertainty resulting from one single campaign.

However, the correlation between these hydrological variations and gravity differences in the seasonal range is less clear for the years 2014-2015. One reason could be that in 2014/2015 the accuracy of the gravity measurements is lower, because also older LCR gravimeters were used. In the following years, more gravimeters with higher precision (Scintrex CG5 and ZLS Burris) were in use and thus, leading to a higher

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precision in the adjustments of the gravity network. On the other hand, there is always the possibility that the global model GLDAS (0.25°x0.25°) does not well represent the local situation in all details. In addition, and since the local ground water variations are unknown, we cannot exclude an additional hydrological effect, especially in extremely dry or wet years (2015 = dry), which is not included in the GLDAS model (only soil water variations). This means, that the suspicious signal in 2014/2015 is not an artifact, but it presents an additional unknown hydrological effect, which induced a further signal in the gravity measurements. We will rethink the wording in the manuscript.

In order to avoid a misunderstanding, we want to respond to the comment "The important concurring mass variation stems from hydrology": We need to distinguish between the gravity changes due to pure hydrological mass changes (e.g. seasonal soil water variations), which need to be corrected first, and the mass changes caused by dissolution/erosion, which are the aim of our measurements – we have to separate them. Therefore, the correlation between hydrological variations and changes in the gravity differences is firstly assumed to occur in the seasonal range. Thus, the regression factor is determined and applied in this range. Indeed, the correction would also affect the long-term variations in the gravity differences, if the model GLDAS showed long-term changes in the soil water content. However, we assume that in longer time series of many years there would be no long-term hydrological variations. After correction of the hydrological effect there is a trend left, which is interpreted as mass loss from dissolved/eroded and finally transported material, thus as "real mass change". We think that the suitability of the hydrological correction is convincing because after the correction, there are several gravity differences that do not exhibit any long-term trend and thus, no mass changes. This holds especially for gravity differences between points which are located outside of the subrosion areas.

Using rainfall observations as input data for a simulation of the total water storage could be a possibility. However, the pure integration of rainfall is not appropriate. In fact, the authors tested a simple model: The integrated precipitation was reduced by the calculated (estimated) evaporation by applying the simple model of Haude (1955) or the more complicated model after Penman-Monteith (1975). Both approaches reveal a remaining strong trend in the reduced data and thus, a contribution of other effects, which makes it impossible to identify the smaller seasonal variations. Unfortunately, the estimation of run-off and percolation is extremely complicated. Additionally, the separation of soil water and ground water is not simple to model. Thus, our simple modelling approach did not yield satisfying results. Additionally, we do not have the experience, data, and capacities to develop a realistic hydrological modelling for a greater region. Therefore, we decided to use the well-known model GLDAS. The correlation between temporal changes in the gravity differences and hydrological variations from GLDAS was better. Of course, also other hydrological models could be applied. In this step, the application of the hydrological data/model is only used for correction purpose.

Ground water or percolation is surely an important factor for the development of sinkholes, not only in Bad Frankenhausen. The ground water level is known to vary between 2.5 m in the south of the city up to 10-20 m in the northern part of our monitoring network, thus with topography, and possibly with very local deviations which are not known well enough. Ground water level observations are only available from wells outside the city of Bad Frankenhausen, at about 5 to 10 km distance. Fig.1 shows one example for the well in Oldisleben-Esperstedt that is located southeast of the city of Bad Frankenhausen (upper aquifer about 2.5 m below surface). In comparison with the soil water content from GLDAS the agreement in the seasonal range seems good while other wells seem to be disturbed by anthropogenic activities, like e.g. pumping (see fig. 2).

A detailed investigation of the subsurface water flow that causes the mass changes by dissolution was not aim of the current project. It could be a future task to better understand the subrosion processes and thus, the development of sinkholes. However, just the analysis of the water influx from the local rivers will not be successful. The influx from the very small river “kleine Wipper” is not significant and, even more, no data is available. In contrast, flow measurements from the spring in the 'Quellgrund' could be valuable for the interpretation of subrosion effects, especially since natural salt water is used for the nearby swimming pool. Such data can only be provided by the city of Bad Frankenhausen but, unfortunately, to our knowledge no data is available. Up to now, we can state that we can observe a certain mass loss. Any more sophisticated interpretations that consider also the observed height changes and hydrological variations will be subject of further investigations, e.g. a gravimetric modelling of the subsurface structures and density changes is intended. Numerical modelling of the sinkhole development was intended within the junior research group at LIAG but is still pending. Additionally, longer time series are needed.

2. Quantitative interpretation

A second major point in the review strikes the quantitative interpretation of the observed gravity changes. We much appreciate the suggestion to discuss the observed gravity changes and the interpreted propagation of an existing cave in relation to published erosion rates of different lithologies. As reported in our manuscript, the maximum observed gravity decrease amounts to 8 μGal. This can be roughly explained by a cavity with its roof at 15 m depth, that propagates 1 m towards the Earth's surface within the four years of the gravity monitoring – the horizontal extent of the cavity is assumed to be 8 m in each direction, the density of the leached material is 2600 kg/m3.

Such erosion rates of 0.25 m/a appear to be large, also for the authors, but are still in the range of the erosion rates known from literature. Whereas for limestone erosion rates in the order of only 0.1 mm/a are reported (Waltham et al., 2005; Gabrovsek and Stepišnik, 2005), for gypsum rates are reported, that can even reach 0.5 m to 1.0 m/a (Waltham, 2005) under favourable conditions. From a 458 m deep research well (nearby the leaning church and, hence, our discussed levelling profile "church") it is known, that the drilled lithology between ca. 6.5 m and 74 m consists of several anhydrite and gypsum layers and at least 10 smaller cavities (pers. communication, Schmidt, TLUG). Hence, the drilled lithologies generally provide favourable conditions

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for increased erosion rates; the erosion itself is proven by the existence of cavities.

As shortly discussed in the manuscript, the quantitative interpretation is subjected to ambiguity and, most probably, the assumption of a single layer of 1 m thickness as source of the gravity decrease is too simple. From Fig. 11 in the manuscript it can be seen, that the same propagation of a cavity by 1 m, that is located only at 10 m depth rather than at 15 m, would cause a gravity signal in the order of 13 μGal. Hence, the required thickness of the dissolved material and the erosion rates would decrease by about 50 percent. Moreover, most probably the observed signal is not only caused by dissolution at one depth but is the superimposed signal that results from mass loss at different depths. Mass changes at different depths would result in “gravity anomalies” of different wavelength. Unfortunately, as also discussed in the manuscript, the layout of the monitoring at its current state does not allow a more precise differentiation of sources at different depth.

Finally, it can be discussed if the mass loss is only due to the slow-acting leaching of the material, or if the propagation of a roof collapse can result in a larger rate of mass loss, i.e. breccia.

3. Line-related comments

We are fully convinced that also the minor remarks will help to further clarify some aspects of the manuscript:

a) C. Braitenberg:

Page 2, L. 21: not clear what is intended with "projects in problematic karst regions“. Please give an explanatory sentence.

Answer & Changes:

We agree that the term ‘problematic’ is not well chosen and that it can cause some confusion. Here, just karst regions are meant that are affected by subrosion and where anthropogenic engineering projects were undertaken. Gutiérrez & Lizaga (2016) report about “Sinkholes, collapse structures and large landslides in an active salt dome submerged by a reservoir,” in Iran; and Milanovic (2002) deals with “human activities and engineering constructions in karst“.

In a revised version we will reformulate the sentence, e.g, as following: Subrosion and the development of sinkholes can be inïňĆuenced by numerous anthropogenic factors such as mining (Brady and Brown, 2006; Mesescu, 2011), tunnelling (Song et al., 2012), water abstraction (Bell, 1988; Aurit et al., 2013), water impoundment (Hunt et al., 2013), and other hydrological projects in karst regions, which enhance the natural process of dissolution (Milanovic, 2002; Gutiérrez and Lizaga, 2016).

b) C. Braitenberg:

Page 3, L.2-5: here different geophysical methods that are useful to deïňĄne morphology of cavities and sinkhole ïňĄlls are mentioned, but the gravity method is lacking. Please include it, for instance with Braitenberg et al. 2016, and Pivetta et al.2015.

Answer & Changes:

The previous role of structure-imaging gravity in sinkhole investigations is mentioned in L13-L18. Furthermore, the previous application of time-lapse gravity investigating underground mass redistribution is mentioned starting on L19.

In a revised manuscript, we will add this information. We are aware of the fact that some (mirco-) gravity surveys were conducted in the past to derive information about cave morphologies or to map sinkholes, e.g. in the Dead Sea region (Rybakov et al. 2001).

Rybakov, M., Goldschmidt, V., Fleischer, L., Rotstein, Y.: Cave detection and 4-D monitoring: A microgravity case history near the Dead Sea, The Leading Edge, 8, 896-900, 2001.

c) C. Braitenberg:

Page 3, L. 19-23: for hydrologic monitoring in karst I suggest to include the recent paper of Campollion et al 2018 and the work of Van Camp et al. 2006.

Answer & Changes:

In a revised manuscript, we will cite these papers – especially as they are related to water storage changes in karst regions and make use of gravity surveys.

d) C. Braitenberg:

Page 5, L. 6:" Karst Trail". Not clear what is meant: is it a touristic trail or you mean something else? Please reformulate or add a few words.

Answer & Changes:

Actually, this is a touristic trail. In a revised version, this fact will be explained, or the entire sentence will be reformulated.

e) C. Braitenberg:

Page 5, L.10:" structures regional scattered": check Grammar.

Answer & Changes:

We agree that this sentence is not well written. It and its citation can be replaced by: Proven by salt springs and about 20,000 subrosion structures, which shape the landscape south of the Harz Mountains (Knolle et al., 2017), the Upper Permian provides the solvable material in the near surface (Kugler, 1958), especially along the KSM Fault, where the southward-draining groundwater from the Kyffhäuser hill range ascends (Reuter,1962).

Knolle, F., Kempe, S., Vogel, B. and Rupp, H. (2017): World-Wide Largest Biosphere Reserve On Sulphate Karst And The Schlotten Caves – Endangered Geo- And Biodivesity Hotspots In the South Harz, Germany; Proceedings of the 17th International Congress of Speleology, Sydney, July 22-28, 2017.

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f) C. Braitenberg:

Page 15: Least Square Adjustment of Network: it would be of interest to see the mathematical equations of the process. Maybe you could add it to the Appendix.

Answer:

The software, which was used for the last squares adjustment, is cited in the text (GNLSA; Wenzel, 1985, 1993); furthermore, we also refer to the methodological approach (Wolf, 1972). Hence, we suggest refraining from submitting a more detailed appendix. The equation is published several times (Fig. 3; cited by Naujoks, 2008).

Naujoks, M. (2008): Hydrological information in gravity: observation and modelling; PhD thesis, Friedrich Schiller University Jena, 2008.

g) C. Braitenberg:

Page 17, L.1: GLDAS produces artifacts before February 2016. Do you know whether the data assimilated in the model have changed in 2016? How does the GLDAS series compare to the groundwater measurements in the well you have? Please also show the groundwater well that exists. Show also the rainfall and an integrated rainfall function. Discuss whether it is useful for the observed gravity changes.

Answer:

GLDAS etc.: see discussion above. GLDAS data contain the soil water, not exactly comparable to ground water as groundwater mostly is delayed. The authors would like to point out that the record of precipitation/rain is not very helpful, as it is of quite high frequency compared to the quarterly measuring campaigns and their results. A ground water well in the city of BF would be of extreme higher value although we have to be aware of the high variability in the small city.

h) C. Braitenberg:

Page 18, L. 5: “add up to 0.1..”: units missing?

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Answer & Changes:

Yes, the unit 'μGal over 4 years' is missing and will be added.

i) C. Braitenberg:

Page 18, L. 7: "It is not mandatory that gravity values on installed benchmarks are stable over time": please add a few words, to make this point clearer.

Answer & Changes:

We agree that this statement might need some more explanation in a revised manuscript, e.g. in the following way: For gravity investigations, it is not mandatory that gravity values for installed benchmarks are stable over time (Weise et al., 2018). The careful selection of the benchmark locations prior to the installation of the monitoring network is based upon the expectation of favourable noise and environmental conditions at these points. However, during the operation time of the network, these assumptions can turn out to be wrong or not sustainable, e.g. due to unknown/changing hydrological conditions in soil or ground water or construction work. Hence, the possibility of temporal gravity changes at these benchmarks must be properly considered during interpretation and discussion of results.

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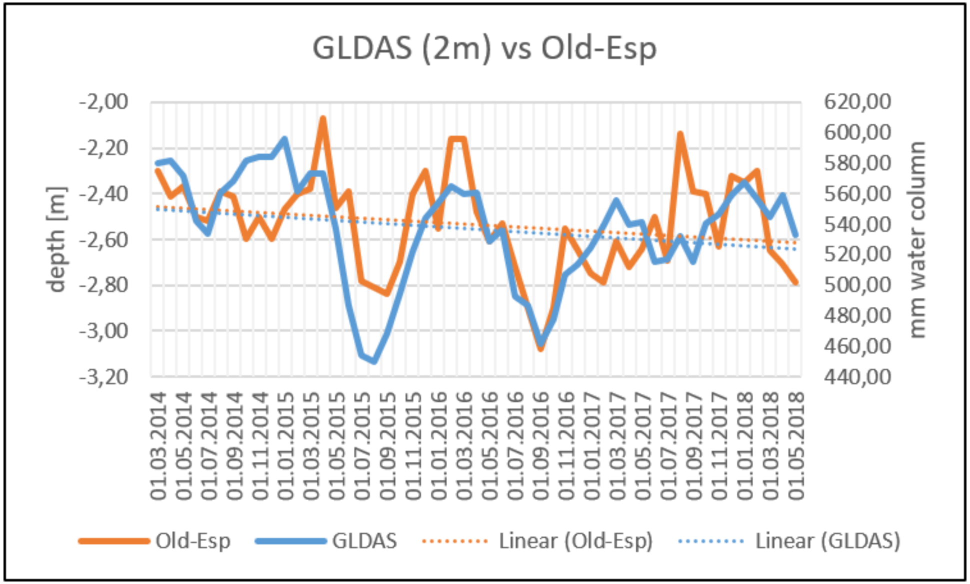

Fig. 1. Groundwater level recorded at Oldisleben-Esperstedt and compared to soil water content from GLDAS, monthly samples.

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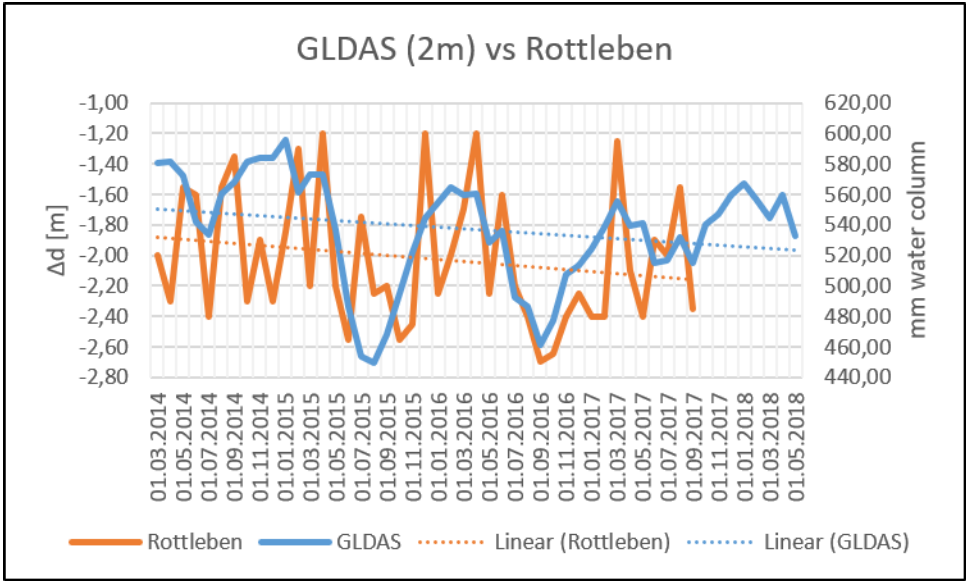

Fig. 2. Groundwater level recorded at Rottleben and compared to soil water content from GLDAS, monthly samples.

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$$v_{i,j} = (\overline{g}_i - \overline{g}_j) - (g_i - g_j) + D(t_i - t_j) \qquad (3.1)$$

with the adjusted gravity difference $(\overline{g}_i - \overline{g}_j)$ between the stations i and j, the observed gravity difference $(g_i - g_j)$ between i and j, a linear drift coefficient D over the observation time $t_i - t_j$, and the residual $v_{i,j}$.

Fig. 3. Least squares technique: Residual equation for one gravity difference.

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