Answer to the reviewer 1

We first thank the reviewer for the detailed and rigorous comments provided. It will help to improve the quality of the paper, especially concerning the error budget. The main concern of the reviewer 1 is that the results presented in the paper can not be discussed or used for quantitative interpretation as the signal to noise ratio of the relative gravity measurements is too low. The reviewer is true in a sense as the error budget of the relative gravimeter used (a CG5 from Scintrex) is not well known. Most of the error: linearity of the drift, stability of the calibration, sensibility to environmental parameters (temperature, vibration, transport, tilt,…) are mainly and poorly described with empirical law.

But the gravity measurements presented in the paper are from field experiments especially designed to minimized all possibles errors and presented in details below following the comments of the reviewer 1. Moreover the gravity results presented in the paper show a clear coherency with previous studies, the geological and meteorological settings and additional geophysical observations (more details at the end of the comments). In details, all comments of the reviewer 1 about the low signal to noise ratio are discussed below:

- calibration : to limit the errors due to the calibration effect, only one CG5 is used (#167). The calibration factor of the #167 CG5 is monitored since 2006 with stability since 2009 (later detailed with a figure).

- environmental parameters: the gravity measurements are done in a natural cave where the temperature stability is better than one degree C and with a very low seismological noise.

- relaxation : a new strategy has been used with long gravity measurement duration (more than 30 minutes in general). Therefore the gravity readings are taken outside of the relaxation period which is clearly seen in the figure 4 looking at the gravity residuals (differences between t1-2 and t3-4-5). We agree with the reviewer that it could be discussed more in details. It is a choice of the authors to present the added values gravity measurements to quantify vadose zone water storage and not to focus on the methodological issues.

- duration of the field experiment: the gravity S2D field experiment extend during on year and half which equivalent to the previous study by Jacob. Extend the field experiment period during 6 or 7 years as suggested by the reviewer could certainly confirm the results but the scientific added values for such a paper is not clear: the paper do not focus on the inter-annual seasonal groundwater storage variations but more on the geological or geomorphological influence on the seasonal groundwater storage.

Another important point is that the gravity results are in accordance with previous or different gravity measurements nearby (such as absolute gravity measurements published by Jacob or continuous superconducting gravimeter published by Fores). We agree with the reviewer that the comparison with other gravity measurements is lacking and it has be added in the revised version of the paper. The gravity results are also in accordance with other geophysical dataset. A MRS sounding has been done twice in 2011 (in Deville PhD *https://tel.archives-ouvertes.fr/tel-00829346/document*). The results on the inversion show significant groundwater content only in the first meters of the soil as seen in the gravity results (figure 2 below) but the MRS in not accurate enough (unlike gravity!) to monitor the temporal variations of the groundwater content. Moreover in depth where the MRS estimate a small water content (~ 1 %), no significant gravity variations are measured. The MRS profile can be seen as an indirect confirmation of the gravity significant signal to noise ratio. The figure has been added in the figure 6 and is used to enhance the discussion.

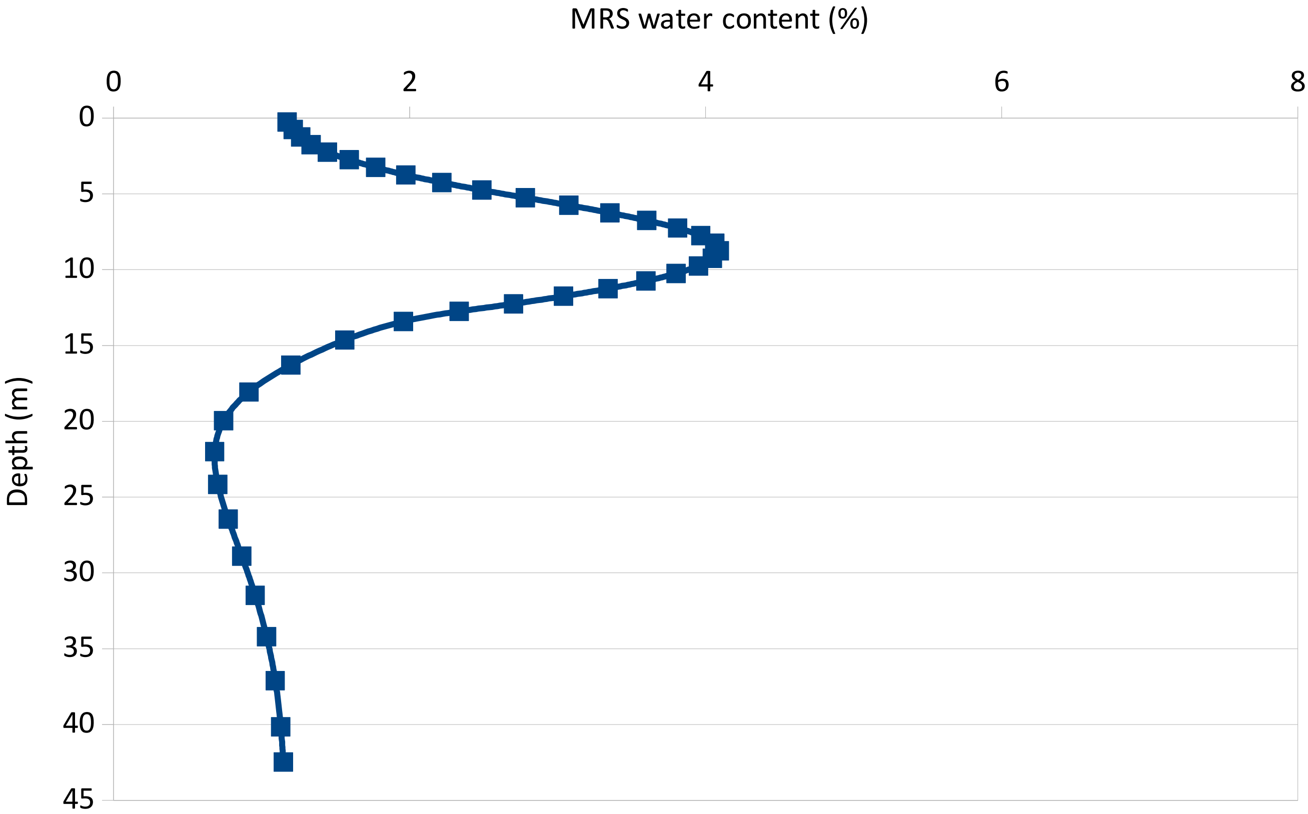


Figure 2: Water content vertical profile from MRS inversion at site BESS

The suggestion of the reviewer to focus the paper on the threshold above which groundwater content variations could be measured by relative gravity measurements is attractive. But we think that it is not possible rigorously from our knowledge as not physical model of the CG5 measurements errors is available. Moreover it is not in the scope of the study which is the variability of seasonal groundwater storage in karst hydrosystem. The idea of the paper is to provide a relative gravity dataset as accurate as possible, taken advantage of natural caves (stable environment and common mode rejection as detailed below) to quantify seasonal transient water storage in the epikarst in different geological context. Such a study of the variability of the vadose zone water storage is not common, even in non-karstic hydro-systems as finally noticed by the reviewer 2.

Finally, the conclusion from the reviewer is that “the paper does not provide convincing results” but the methodology. As the reviewer is not convinced by the gravity measurements, he does not provides any comments about the discussion and the interpretation of the gravity field experiment results. In fact, to our knowledge, only one published paper from Jacob presents surface to depth gravity field experiments in karst caves (and the recent phd of A. Watlet in Rochefort). The paper of Jacob present the methodology, the comparison with surface gravity measurements only on one site during one season and half. In the present study, we first improve the methodology. We also added in two others karstic sites: one with a similar meteorological and geological context and one in a different context. Moreover, the surface to depth gravity measurements where in one cave at different depths. This is the first time that the thickness of the epikarst (or of the subsurface karst reservoir) is quantified and confirm by a MRS profile. Finally a comparison of the geological and geomorphological settings allows to suggest a clear influence of the lithology on the capacity of the epikarst reservoir. For one of the first times in a karst hydrosytem and in vadose zone, it is quantify at an intermediate scale well suited for numerical modeling.

Specific comments

-Figures 1-2: Add a regional map showing the 4 sites (i.e., include Jacob (2009) and Fores (2017) ones) altogether. Then discuss to which extent the results of Fores (2017) and present measurements of the flux tower and of the superconducting and absolute gravimeters can be used to improve the knowledge of the crop coefficient. For example, is the crop cover similar on the 3 sites? Given that all sites are located in a same Mediterranean area, one may expect that using the results from the superconducting gravimeter and the flux tower, one can provide an estimate of evapotranspiration parameters that is certainly better than the poor estimates used here and more generally, in hydrogeology. Then, the paper may be modified as a function of improved estimates of ET.

Incidentally, in Table 1, I do not understand why at BESS and SEOU, the cumulative evapotranspiration values reach such low levels, actually comparable to winter ones and much lower than at the BEAU site, which, if I'm right, experiences similar climatic conditions (I'd even expect warmer and possibly drier conditions at SEOU, located at much lower altitude than BESS and BEAU; anyway, elaborate, please).

Figure 1-2: On a larger map, BESS and BEAU are on the same position in a corner and SEOU is in the opposite corner; That's why we do not include such a map.

Seasonal crop coefficient from Fores (2017) have been used to evaluate more accurately the actual evapo-transpiration (ETa) from the potential one (ETP). The crop coefficients vary from 0,55 during the summer period where less water is available in the soil to 1,20 during the winter. The annual ETa with seasonal crop coefficient is similar to the ETa with a constant one but more consistent with a Mediterranean climate. The final NWI estimate changes significantly especially during the discharge period. As highlight in the paper and in Fores (2017), an accurate and local measurement is needed to interpret small gravity temporal variations, even with a "calibrated" crop coefficient. Therefore the paper still focus on the recharge periods where the ETa amount is not equivalent to the precipitation amount.

The comparison between the ETa at BEAU site and at BESS and SEOU sites can not be done directly as the time period are not exactly the same. With the new evaluation of the ETa, ETa during the summer are now equivalent

-L280: "stations are measured many times": do you mean: occupations? Is it exactly the same protocol as applied by Jacob?

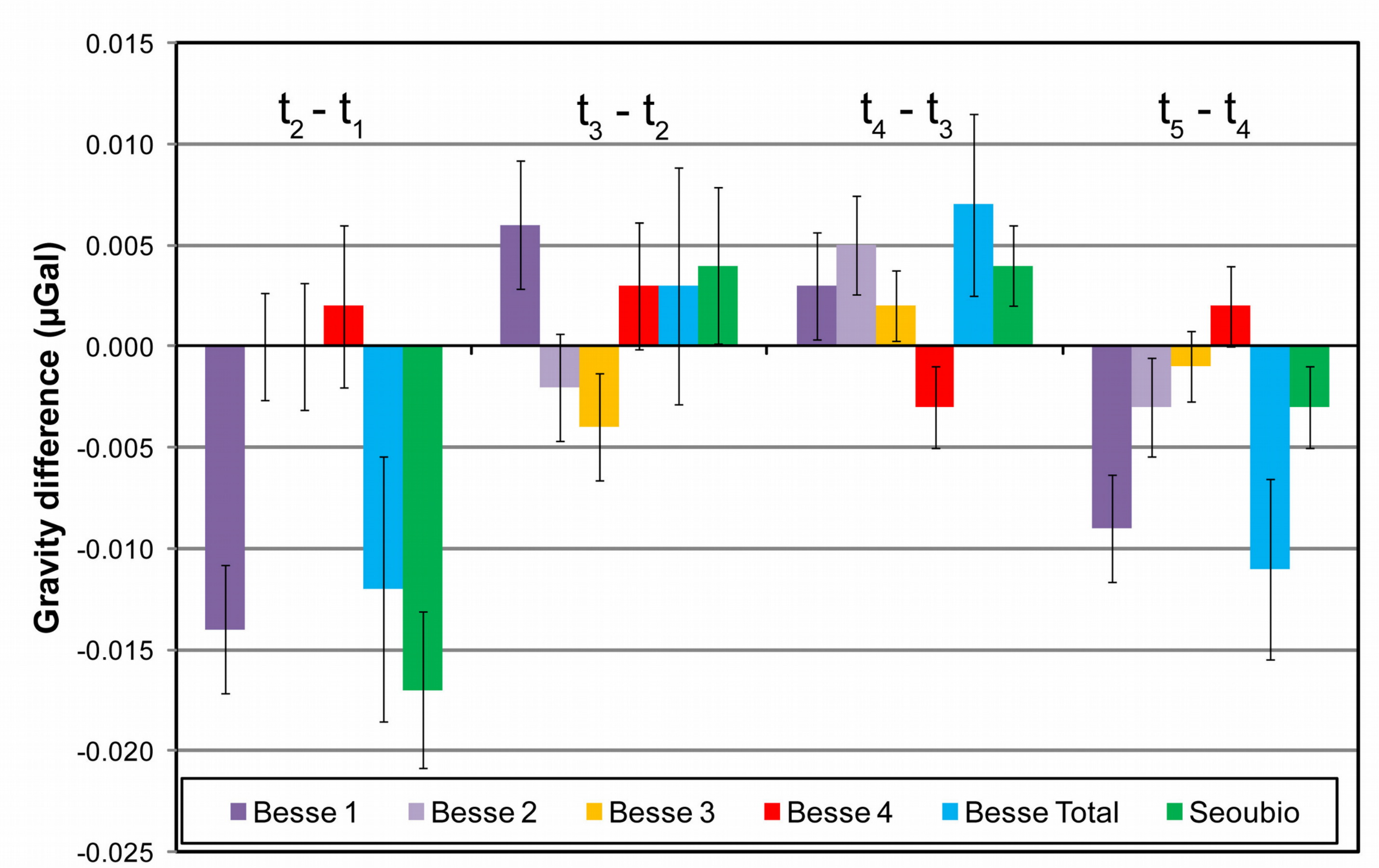
Yes, the strategy used is almost the same as Jacob (for t1 and t2). The only difference is that the transportation of CG5 was done with a rope "cable-car" at BEAU. At BESS and SEOU sites, the CG5 was transported by hand or in a "back-pack".

-Table 1: I do not understand why at BESS site, the differences for all depth have been added, as below 12 m results are not significant –according to the authors themselves- and hence, random signals and associated errors are summed rather than actual geophysical values. Why not taking the difference 0-12 m and then arguing that no significant gravity changes could be measured at greater depths?

Only the measurements between 0 and 12 m depth are now presented in the table 1.

-Why are measurements at t3 never discussed in the paper (however, it supports the discussion on the protocol)?

For the clarity of the table 1 and for the interpretation, the gravity measurements are summed by seasons. All the measurements can be found in the annex with the recharge period in gray as in the table 1. The figure *below present the t3 gravity survey. On the figure, a clear difference is seen between the recharge and discharge period.*



-How do you compute the final error? Is it the RMS of the STDs at each ti ? Hence, according to Annex 1, I would expect, for example at SEOU, Dgt1-Dgt2 = -17+/-3.9 µGal (3.9 = sqrt(1.42 +3.62)). I assume that the errors provided in Annex 1 take into account the error due the calibration factor (1 µGal in Jacob), is it? Elaborate. Same comment for BEAU: considering the sigma_STD of Jacob (Table 1) I obtain 2.1 rather than 1.6.

-Table 1: why are the gravity differences divided by a factor 2, which is not applied to Figure 6?

We thanks the reviewer for his rigorous and careful reading of the table 1. Gravity S2D differences are presented with the associated errors. For the errors of BEAU, the table 1 was wrong. The computation of the final error is similar to Jacob paper. The only difference is that the error computation is even more conservative as 2 uGal are added to account the calibration and non-linear drift error. It has been corrected. Concerning the final error at SEOU, as half of the Bouguer plate effect was reported in the table 1, half of the final error was written. To be more consistent, the measured double Bouguer plate effect is now reported with the final error calculated from the RMS of the STD at each ti.

Figure 6 is now in EqW to remove potential ambiguities in the gravity values.

-Figure 6: does “recharge” stand for t2-t4 and discharge for t4-t5? Mention it, and, in that case, one should read (a) +9, +3, -2, 0 µGal according to Annex 1.

The text and the table 1 have been modified to clearly show the recharge (t2 – t1 and t4 - t5) and discharge (t2-t3-t4) periods. Figure 6 has been corrected also.

-The reasoning leading to equation (7) repeats what was written by Jacob. Hence, section 3 can be significantly shortened by just referring to Jacob et al., 2009.
Section 3 has been reduced by just referring jacob et al., 2009. Equation 3,4,5 have been removed in particular.

-L526: the mentioned 30 m are not significant; they belong to the error bars given in Table 1.
It has been corrected, below 12 m in BESS, no significant water storage can be measured by the MRS and gravity.

-L602: not only absolute measurements: this should be possible by performing continuous, relative gravity measurements both at the surface and in caves.
This is true. It will be added in the revised version. It remains that continuous measurements in natural caves are quite difficult to set up except in particular site such as Rochefort in Belgium (Watlet, 2017).

-What about possible aliasing effects? What would be the influence of a strong rainfall just before a gravity survey? Can you rule out this artifact, .e.g., based on meteorological series and on the way the superconducting gravimeter behaves in the Larzac (closeby BEAU site)? The numerous outstanding AG measurements may help as well.
The AG and SG measurements are now included in the discussion. The gravity survey (except the first one in SEOU) have not be done just after a strong rainfall to reduce the aliasing effect. In SEOU for the first survey just after strong rainfall, it seems that a significant amount of the rain water is still in the epikarst (and then measured by the gravimeter). The aliasing effect is more clearly discussed in the revised version.

-What is the role of the saturated zone? At SEOU, underground water is pretty close the gravimeter when it is measuring in the cave, hence, it may be much more sensitive to that water changes than the surface site, hence biasing the results. This depends on the spatial extension of the water table; this should be modeled and discussed.
In BESS, the saturated zone is far from the surface and the impact is not significant in the gravity measurements. The water level of a small lake was monitored in SEOU cave but the impact on the S2D is difficult to model as the voids are hardly known. The water table in this part of the karst is difficult to defined as small lake are seen in caves at different altitudes. As the gravity survey were not directly after rainfall, the impact of the water table should be reduced (water level measured in a small underground lake is presented below in figure 3). During the gravity survey, except the first as discussed in the paper, the water level is stable). It has been included in the discussion.

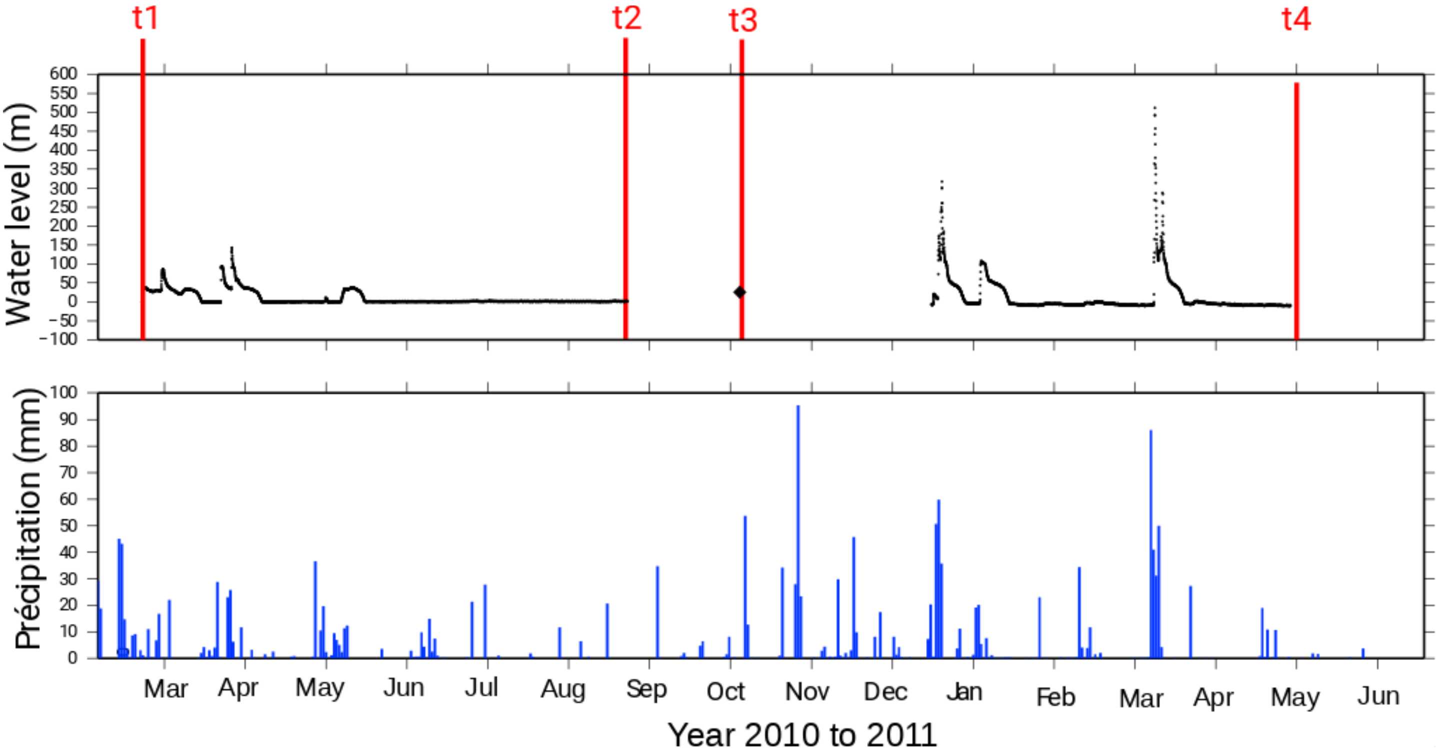


Figure 3: Water level measurements in a nearby (a few meters) lake in SEOU.

-Annex 1: why is the calibration factor around 0.9995, while being at 1.0005 in Jacob for CG5#1687? Slow evolution as evidenced by e.g., Meurers, 2017 https://doi.org/10.1016/j.geog.2017.02.009)? Or artifact ? Does gravity at experimental sites belong to the gravity ranged along the calibration line? If not, what would be the consequence? An error of 0.001 on the calibration factor would result in a 4 μGal error at SEOU, and nearly 6 at BEAU. Incidentally, I do not understand Table 1/Figure 4 of Jacob: on Figure 4 the calibration factor changes continuously by 800 ppm (from 400 to 1200) between t0 and t5 (first and last grey lines), whilst the calibration corrections mentioned on Table 1 randomly fluctuate from 1.0003 to 1.00065, i.e. 350 ppm. But, 800 ppm on a gravity difference of 6000 μGal as in BEAU would mean an error of about 5 μGal.

The gravity at the experimental sites belong to the gravity range along the calibration baseline (between about 30m in Montpellier and around 1560m in Aigoual summit). The changes of the calibration value between Jacob and our paper is due to Scintrex calibration which changes the Gcal1 value. As the calibration value is expressed with respect of the current Gcal1 value, each Scintrex calibration creates an offset in the calibration value. Nevertheless, when we report all the calibration factor respectively to the first GCal1 value, the calibration factor changes can be monitored. The figure 4 below present the calibration value since 2006. A clear evolution is seen with significant variations during the Jacob paper and our study. Around the measurement period, a slow increase of the calibration value is measured and it as been taken into account by interpolation.

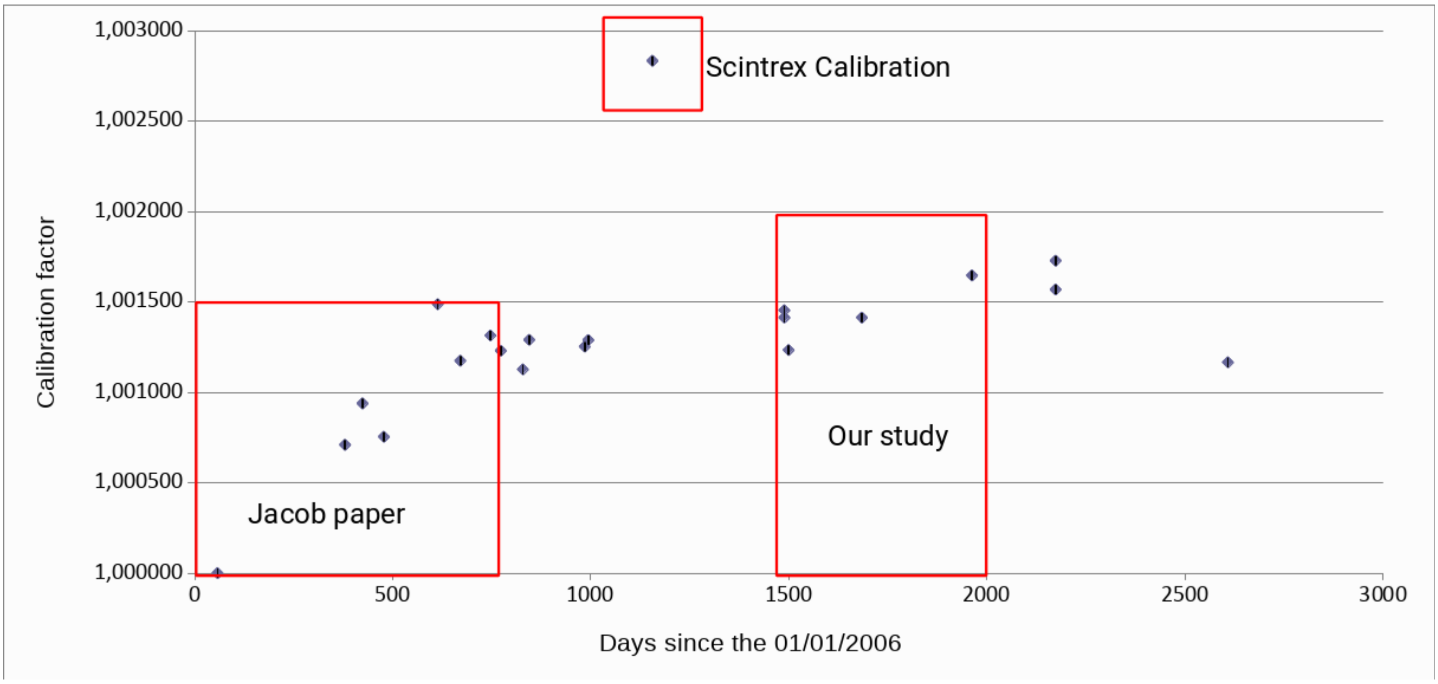


Figure 4: evolution on the calibration factor of CG5 #167 since 2006 with respect to the first GCal1 Scintrex parameter. One can note the poor consistency of the Scintrex calibration due to the smaller calibration line used.

Technical corrections
-Missing spaces between several numerical values and unit symbol (e.g.,https://physics.nist.gov/cuu/pdf/sp811.pdf)
Corrected

-Table 1: according to Jacob, Sep07-Feb08 should be 12.9 (*2?) instead of 13.0 (*2?) µGal.
Corrected

-Table 1: for a better legibility make use of colors or gray background to evidence recharge and discharge periods; provide also an additional column providing the ratio EqW/NW1, which is discussed in the manuscript.
The Table 1 have been completed by the ratio EqW/NWI and the different period have a better legibility with the use of gray background.

-Figure 4: provide the dates corresponding to each ti; invert (a) and (b) such that SEOU and BESS appear in a same order in the whole manuscript. How do those histograms compare with Jacob? As all authors of Jacob and this paper have belonged to the same lab, you may compute the histograms from Jacob's data directly, and include it in the discussion.
SEOU appears first in the whole manuscript. Jacob was measuring only 5 times for each occupation and each station was occupied 3 or 4 times. The number of the data was significantly different from our gravity survey (at least 50%) and the operators have changed. Even the transport of the CG5 was different ("cablecar" for Jacob and backpack for this study). Even if the CG5 was the same, it was send to Scintrex in between the two studies for a complete servicing. Too many parameters are different to clearly compare the histograms.

Avoid useless repetitions, especially about the vulnerability of karst aquifers (introduction, L521-545).
L521-545 have been rewritten to be more specific and highlight the impact of water storage in the epikarst for groundwater transfer.

Deville et al., 2012, in press: published in 2013.
Corrected

Answer to the Reviewer 2

We first thank to the reviewer 2 for the detailed comments which provide a lot of points to enhance the quality of the paper. About the release of the dataset, it will be available after publication in the SNO H+ database (http://hplus.ore.fr/en/) or upon demand by email. We believe that such an unusual dataset should be supported by a publication to be rigorously used in others studies.

The main concern of the reviewer 2 is that such micro-gravity experiment is “no longer novel and that some unique aspect are lacking”. As finally noticed by the reviewer, only a few studies (thanks for the additional review of reports from USGS especially) focus on the micro-gravity applied to karst hydro-systems. Among them, only two deals with surface and subsurface measurements. The idea of the paper is to provide a relative gravity dataset as accurate as possible, taken advantage of natural caves (stable environment and common mode rejection as detailed below) to quantify seasonal transient water storage in the epikarst in different geological context. Such a study of the variability of the vadose zone water storage is not common, even in non-karstic hydro-systems. To enhance the quality of the paper, a MRS profile has been added (in the Figure 6) for comparison and interpretation with the gravity data. The results of the inversion clearly show water content only in the first meters as seen in the gravity results but the MRS is not accurate enough to monitor the temporal variations of the groundwater content (contrary to the gravity). Such a comparison of gravity and MRS data is not usual in the geophysical literature from our knowledge.

The reviewer 2 (as the reviewer 1) suggest also than the comparison of the two strategies of measurement is minimal. It is a choice of the authors to present the added values gravity measurements to quantify vadose zone water storage and not to focus on the methodological issues (which is not a main thematic of HESS). As suggested by the reviewer, a side by side comparison in a site with an easy access tunnel of the two strategies have been already done. The main difference is that the transportation of the CG5 was done by bike. It could be added as a supplement material. Only a small loop of three points was used. It was published in french in the S. Deville phd (in french: *https://tel.archives-ouvertes.fr/tel-00829346/document*). I copy and paste below a figure with the histograms of the residuals between the two different strategies.

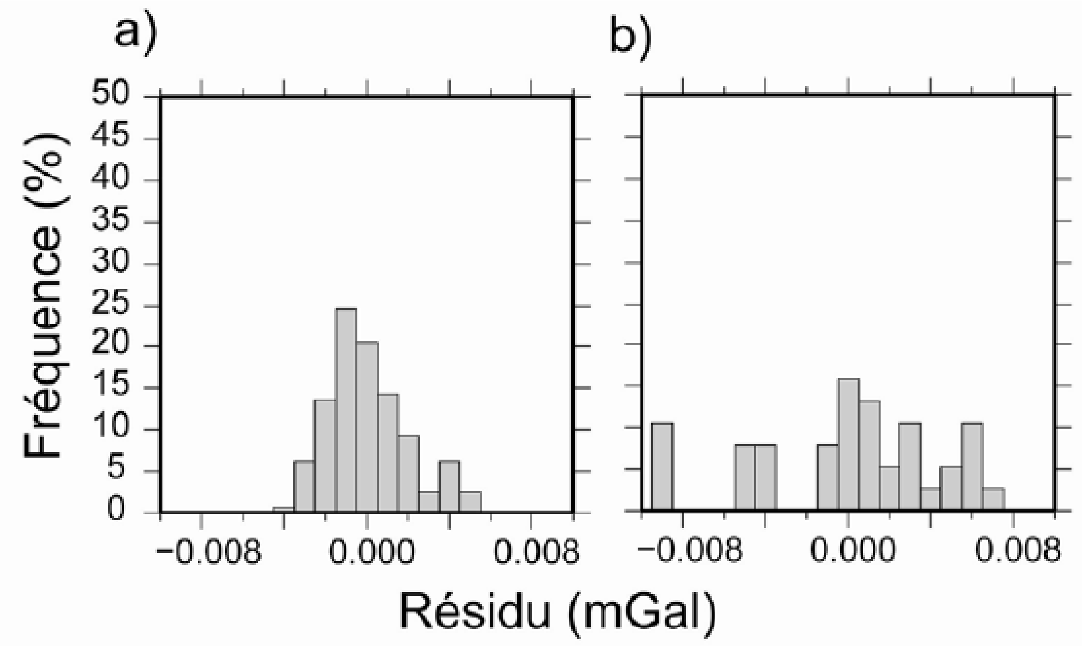


Figure 1: a) long time strategy b) short time classical strategy

The figure 1 is interpreted as a clear example of the impact transportation on the gravity readings. Transportation by bike induced tilting and vibrations. After transportation, a relaxation of the CG5 can be seen. The main problem is that no model of the relaxation is available currently. The only way not to be influenced by the relaxation is to wait until the end of the relaxation (around 30 minutes with the CG5 #167). That is the main idea of the so called in the paper long time strategy.

Detailed comments

Introduction: The main characteristics of gravity measurements has be also added in the introduction (and in the discussion). Indeed gravity is a unique method to directly monitor the groundwater budget with some advantage (integration of the small scale heterogeneities, accuracy, sensibility to the vadose zone, potential of both time lapse and spatial variations) and drawback (mainly the absence of vertical resolution and the non sensibility to water fluxes).

S2D field experiments in natural caves:
As suggested by the reviewer, more details have been added in the discussion to present the advantages and disadvantages of S2D experiments in natural caves : stable environment (low noise, stable temperature) versus accessibility (ropes are needed in BESS and SEOU) and moreover the common mode rejection (below and upper the gravity measurements). Its is an important point of the paper and should more discussed as suggest by reviewer 2

L. 69: Better to present as a circular area
Corrected

L. 70-72: "As surface gravity..." This sentence doesn't make sense to me. I think further elaboration/clarification of gravimeter sensitivity of above-ground and below-ground measurements, including discussion of common-mode rejection, is warranted. Also, The concept that storage increases above a gravity-station cause a decrease in gravity.
The presentation of the gravity from surface and from depth addressed now this points in the introduction and in the discussion.

L. 164: How representative are these gauges? There must be much more spatial uncertainty than measurement error, suggest focusing on the former. Can you state the similarities and differences between the two study areas?
Spatial uncertainty of gauges have described by Jacob at the seasonal temporal scale and Fores at the event scale. The conclusion are that the spatial uncertainty are not significant at the seasonal scale and quite large at event scale. The climate similarities between the two sites have been added in the paper.

L. 205: You need to describe the CG-5 first, specifically, that it is used to measure the relative difference in gravity between two locations. You should mention that all of the gravity values in the paper have large (~980000 mGal) offsets relative to the absolute-gravity value. In some places, it's CG5, in others it's CG-5.
CG5 is now used in all places.
The paragraph about the gravity experiment have been reformat and the concept of relative gravity measurements is now introduced.

L. 227: "Stable during the studied period." – does that mean the continually increasing calibration factor for this meter in Jacob (2009) from 2006-2009 is no longer observed?
A long discussion (with a figure) about the stability of the calibration factor can be find in the answer to the reviewer 1. In a few words, the calibration factor of the #167 seems nearly stable now.

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L. 238: The concepts of "loops" should be introduced. Were loops observed in order from the surface to depth? If so, is there concern about unequal transport time? The discussion of the "short" and "long" strategies later would also benefit by framing it in terms of loops.
Loops are now introduced. Loops are first observed in depth when it is possible (BESS site). In SEOU and BEAU sites, as ropes must installed, loops begin in surface during the rope installation. The problem of transport is resolved in short term strategy by a first long measurements (at least 30 min) to reach the end of the relaxation. But in the short-time strategy, transportation is not equal between all stations (climbing on the rope is often slower than going down!). That's why the long term strategy has been setup. With the long term strategy, for each station, the end of the relaxation is reached.

L. 258: Please check denominator in equation 2. Isn't the number of gravity readings, m, be larger than the number of gravity stations, n? That would make the denominator negative.
n and m where inverted in the text. n is the number of gravity reading averaged by station occupation, s the number of loops (for drift estimation) and m the number of stations.

Figure 4: Please clarify that these are the residuals of the observed gravity differences vs. the adjusted gravity differences. The labels ("#93 data") are unclear –they are the number of observations, I assume? Suggest "n = 93". Maybe mention the panels which show "short-time" vs "long-time strategy"?
Figure 4 and caption have been clarify. #93 data are the number of observations.

L. 274: To be more precise, I think you'd say error from the relaxation must be accounted for in the error budget (you could potentially not correct for it, but still have a clear error budget).
Corrected.

L. 280: I don't understand "4 and 5 in our case." This means the reference station was observed 4 times, and the other stations 5 times, during each survey? Or 4 loops were observed during some surveys, and 5 during other surveys? It is also confusing in Annex 1. Suggest replacing "4 to 5" and "1 to 2" there with "short" and "long."
4 or 5 is the number of loops during each survey. It has been clarify in the text and in the annex 1.

Could the authors clarify how they end up with, e.g., 140, 248, and 209 observations (for site BESS, long strategy), for a survey with 5 stations? They are including every sample at every station, instead of averaging the samples for any particular station setup? I think this leads to artificially increasing the degrees of freedom (denominator in Equation 2) and underestimating the uncertainty. In other words, there are really only 4 independent measurements (Base-1, Base-2, Base-3, Base-4), not 140+.
The histograms present every sample at every station (see the answer below concerning the shape and interpretation of the residuals). The a-posteriori variance of the equation 2 is used in the MCGRAVI software. In MCGRAVI the gravity readings for each station are averaged before the network adjustment as in every classical network adjustment. So the estimation of the a-posteriori variance use the number of independent measurements. It has been clarify in the equation 2 caption.

L. 289: One disadvantage of the long strategy, as I understand it, is that with a single loop drift can't be separated from possible tares (offsets).
When only one occupation of the base station is done, this statement is true. One need to have multiple occupations (which is the case here) of the base station to separate drift from tares.

L. 297: I would guess the better residuals with the long-term strategy is primarily a consequence of having fewer observations to adjust. If the observations at each station were averaged prior to the network adjustment, with a single loop and allowing for drift, all of the observations could be matched exactly during the adjustment and the residuals would be zero.
This is partially true but the base gravity station is occupied 3 three times during the single loop. If the drift was really not linear, residuals will not be centered on zero. Relaxation due to the transport could also produce significant residuals. The "long-term" strategy allows to remove the relaxation but is possible only when the CG5 has a small and linear drift. That's why histograms center on zero and narrows confirm the long-term strategy.

L. 309: If it's known there was a gravity jump (you can know this because there were multiple loops?), why not correct for that?
The jump is known from multiple loops. The correction of the jump will not change the results as it represent a few percentage of the measurements. As no physical or instrumental explanations are found, we prefer to keep all the data.

L. 321: Annex 1 presents a summary of the adjustments, not "all raw gravity data." The row labels in Annex 1 aren't visible.
Annex 1 have been reformated and clearly presented.

L. 340: I think it's sufficient to state "terrain, gradients, latitude, and depth aren't changing over time" and jump straight to equation 6. Equations 3 and 4 already excludes Earth tide and ocean loading effects that have been accounted for (with zero uncertainty).
Equation have been removed as its straightforward deduced from eq. 3 and 4.

L. 370-372: "Moreover, the large scale heterogeneities..." this statement is unclear.
The large scale heterogeneities (> 100 m) are negligible as the large scale heterogeneities have an equivalent impact on the gravity measurements in surface and in depth. It has been rewritten in the revised version of the paper

L. 374-375: Neither the capacitive function nor fast transfer have been explained.
Capacitive function is equivalent to the storage function and the fast transfer is at the flood or rainfall event scale. The sentence has been completed for clarity

L. 365, 378: times not time's
Corrected

L. 387-388: I'm unclear what storage variations are discussed here: variations at the land surface, above the elevation of the surface station? It would make sense to discuss these in terms of admittance factors ("the admittance factor due to rainfall stored at the surface is xx µGal/mm, at 12 m depth it is xx µGal/mm, etc.)
In this part, only the terrain correction are discussed and more in detail the impact of groundwater on the terrain correction which is small (Jacob et al., 2009). The sentence has been rewritten for clarity. On another point of view, as the gravity measurements are not done immediately after rainfall, the admittance factor is probably not useful in this case.

L. 404: 23.8 mm of water = 1 µGal is approximately the Bouguer slab approximation (41.9 µGal = 1 m of water). As stated on line 394, shouldn't this be twice the Bouguer attraction (23.8 mm = 2 µGal)? It looks like 23.8 was used to convert between µGal and mm in Table 1. Unless I misunderstand, this is a major error that needs corrected, and impacts all of the conclusions of the paper (I'll assume I'm mistaken w.r.t the rest of my comments).

The reviewer is right: there is a typo in the conversion between uGal and mm of water from the Bouguer slab approximation. From Bouguer slab, 1 uGal ~ 23,86 mm of water. With S2D twice the Bouguer is measured: 1 uGal = 11,93 mm of water (1 m = 83,8 uGal). The table 1 and the annex 1 are not clear. In the annex, the raw S2D gravity differences have been reported (twice the Bouguer slab). In the table 1, half of the S2D gravity differences between two measurements periods (equivalent to the Bouguer slab) have been reported! But the Equivalent Water Height was calculated with the right value and do not change. The results remains unchanged. It will be clarify in the revised version with coherent S2D gravity values. Error of copy/paste in the error in the table 1 for the BEAU site has also be corrected thanks to reviewer 1.

L. 410: optimum = minimum and maximum?

Corrected

L. 411: "without": here, and elsewhere, I think the authors overstate the accuracy of the results. It may be appropriate to state the yearly cycle is measured with minimal ambiguity, but probably not without any ambiguity (uncertainty would be a better word).

Corrected. The discussion about the uncertainty of the measurement has been done in more detailed and rigorous way (see answer to reviewer 1) without overstate the accuracy of the results.

L. 411-412: Is it necessary to add all depths for the BESS site? Why not just difference the surface station and the deepest station?

It was in reality the difference between the surface and the deepest station. As stated by the reviewer 1, the gravity variations below 12 m are not significant and therefore only the variations between 0 and 12 m are display in the table 1.

L. 415: It would be helpful to indicate, here in the text (e.g., "spring to summer") and/or in the table, which are the discharge periods.

It has been added in text. The table 1 has also be reformatted to clearly distinguish recharge and discharge periods.

Table 1: The reference to recharge and discharge periods doesn't seem consistent with the dates of the surveys: Feb-Aug is a discharge period at SEOU, but Nov-Sep is a discharge period at BEAU? I would like to see some discussion as to how this inconsistency affects the results, particularly the statement "Contrary to the two first sties, cumulative precipitation have a similar values..."

Feb-Aug (or Sept depending of the first rainfall event) is the typical discharge period in a Mediterranean climate but the start and the end of the recharge period can be highly variable. All the gravity measurements have been done in Feb and Aug (or Sept) with the same CG5 (#127) to reduce instrumental bias except one: in Feb 07 in the site BEAU, the CG5 #323 is used as the CG5 #167 was not available. As the #323 has a high drift, the results are more noisy and can not be used. Fortunately, almost no rainfall are recorded during Nov 06 and Feb 07 (see Jacob et al., 2009; Figure 7). Sept-Nov 06 can be used as the recharge period. More detail table caption have been added.

L. 442: NWI should be described before Table 1 is introduced. It looks like NWI uncertainty was calculated as the root mean square of the P and AET uncertainty? Please state that's the case. Please double check, the value for BEAU Sep07-Feb08 (and maybe others) is off: sqr(17^2 + 17^2) = 24.
The NWI is calculated as the root mean square of the P and AET uncertainty. There was a typo for BEAU in the table 1 and table 1 was double check.

L. 473: The gravity depth-profiles have opposite shapes, not nearly the same shapes.
Corrected

L. 478: Is 2.5-3.5 μGal from the error budget, or is it from the network adjustment? I think it's the latter.
It is from the network adjustment. Corrected.

Figure 6: Suggest showing this in units of mm of water, rather than μGal.
Units are now in mm in the figure 6.

L. 481: Shouldn't it be -1 and 2, instead of 1 and 2?
Corrected

L. 495: "Gravity measurements must be very useful..." The English is incorrect. You could say "...measurements may be useful...", or could be useful. Rarely is the word "very" useful in scientific writing.
Corrected

L. 497: The Deville paper appears to be quite relevant to the present work, yet isn't mentioned at all in the introduction/literature review.
Some references (see reviewer 1 comments) have be added in the introduction including Deville et al., 2012.

L. 498: Figure 6 suggests the error budget is 50 percent or larger than the gravity variation amplitude. L. 499: As mentioned earlier, I think you overstate the value of your data here. If the gravity differences are only due to hydrology, why are the error bars in fig. 6 so large, relative to the signal?
The error bars in fig.6 are due to instrumental errors mainly (second order non linear drift and potential instrumental biases). The sentence has been removed to not overstate the gravity data. Some corrections and more detailed and rigorous analyses of the instrumental errors have been done (see answer to the reviewer 1).

L. 501: You probably mean minimized, not optimized.
Corrected

L. 504: If you only do one loop, how could you know if the drift is linear?
The base station is measured at least at three times during the survey.

L. 507: I don't understand the phrase "the coherence of the gravity measurements with respect to depth..."
It was the coherence of the gravity measurements at all depths between the dry and the wet season. It has been changed. And a MRS profile has been added for comparison and discussion.

L. 522+: This discussion is hard to follow because it's in units of mm of water, whereas the results are presented in microGal.

The equivalent value in uGal has been added.

L. 533: What are ‘spoiled structures’?
It has replaced by ‘Weathered’ for clarity

L. 538: This paragraph is important, because you start to show how the gravimetric method can be useful for investigating pollution infiltration. But it’s vague. Can you better describe how exactly the present data, for a different dataset, can be used in the context of pollution? I’m not a karst hydrogeologist but I’m guessing the conclusion that storage changes are greatest near the surface isn’t a major breakthrough.
In karst hydrogeology, the saturated zone was often assume to be one of the major reservoir of groundwater. Nowadays, different studies (geophysical and hydro-chemical) have shown the importance of the subsurface or the epikarst reservoir. Beyond the karst issue, the water saturation has a large impact on the permeability in unsaturated medium and therefore in the pollution infiltration. It has been more detailed in the revised version of the paper.

L. 562+: This paragraph makes an important point, and demonstrates the major advantage of gravity, with its large region of sensitivity, vs. other methods.
Thanks for the comment. We agree with the reviewer that the large area of sensitivity in a karst hydro-system is one major advantage of the gravity (with the high accuracy of the gravity measurements) compare to most of other methods. One sentence has been added in the introduction to clearly introduce the now-days interest of gravity for heterogeneous hydro-sytems studies.

L. 587: I don’t understand the reference to mudstone, a fine-grained, non-limestone sedimentary rock. Apparently packstone is a limestone with a high clay content, but I don’t think the term is widely used. Are there any references, or laboratory analyses, that can support the conclusion that the BESS/SEOU sites are characterized by fine-grained limestone?
Packstone and mudstone are used in the classification of carbonate rocks of Dunham (1962). For clarity only fine-grained limestone are now used in the revised paper. The identification of the type of limestone comes from field observations and core samples porosity measurements. It has been added in the description of the sites.

L. 577+: This paragraph is interesting, but largely conjecture (lots of “coulds”). I would be interested in reading about whether additional data (including microgravity – perhaps with more stations at shallower depth?) could help resolve some of the ambiguity.
Removing some of the ambiguity needs surely additional sites in the same hydro-meteorological context and complementary measurements such as core samples and MRS (geological setting has the main impact on the MRS measurements in Mazzilli et al., 2016). It has be added to the discussion. More information from core samples porosity estimation have added also in the site description.

L. 607: “Water transfer properties” isn’t clearly defined. You mean properties of the aquifer, e.g., hydraulic conductivity and specific yield? Or magnitude of storage changes?
We mean properties of the aquifer or some part of the aquifer. It has been rewritten for clarity.

L. 628: I don’t understand the basis for the 3.5 and 13 months figures. 3.5 refers to BESS/SEOU, and 13 to BEAU? Where do these numbers come from?

The 3,5 months refer to limestone sites (BESS/SEOU) and the 13 months to dolimite sites (BEAU). The numbers come from a simple reservoir modeling to estimate a characteristic transfer time (with a classical Maillet law). The sentences have rewritten for clarity.

L. 638: heterogeneities: *it depends on the scale. Small scales heterogeneities are averaged as stated by the reviewer and gravity reveals larger scale heterogeneities. The sentence has been reworded for clarity*.

L. 648: *The phrase has been removed from the text in the revised version.*

L. 659: Some additional description of gravity-differences vs. absolute-gravity measurements in the introduction or methods would be useful.
In the introduction, the description in the surface to depth gravity and its potential has been added. The added value of absolute gravity measurements are detailed in the part 3) data interpretation

L 666: The “total water stock” *has been changed in the discussion. The idea is to use MRS to estimate the groundwater stock (with depth) and gravity to monitor transient storage (with depth when done in caves) thank to the accuracy of the gravity measurements.*

L. 712: A paper with a 2012 date probably isn’t “in press”. (it looks like the paper has been published).
Corrected

Estimating epikarst water storage by time-lapse surface to depth gravity measurements

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Accepted *date*. Received *date*; in original form *date*

Abstract:

~~In this study we evaluate t~~The magnitude of epikarstic water storage variation is evaluated in various karst settings using a relative spring gravimeter. Gravity measurements are performed ~~twice~~during one ~~a~~ year and half at the surface and inside caves at different depths on three karst hydro-systems in southern France: two limestone karst systems and one dolomite karst system. We find that significant water storage variations occur ~~mainly~~ in the first ten meters of karst unsaturated zone. The subsurface water storage is also evidenced by complementary magnetic resonance sounding. Afterward, surface to depth gravity measurements are compared between the sites with respect of net water inflow. A difference of seasonal water storage is evidenced probably associated with the lithology. The transmissive function of the epikarst has been partially deduced from the water storage change estimation. Long (> 6 months) and short (< 6 months) transfer time are revealed in the dolomite and in the limestone respectively.

1) **Introduction**

Despite carbonate karst systems are largely spread in the Mediterranean area, their associated water resources and vulnerability remain poorly known. In a context of climate change and population increase, the karstic areas are becoming key water resources. A better knowledge of the properties of the karst reservoir is therefore needed to manage and protect the resources (Bakalowicz, 2005). Increasing the knowledge of karst hydrogeological properties and functioning is not a simple task. Indeed, a karstified area is complex and spatially heterogeneous with a non-linear response to rainfall. Numerous in-situ field observations lead to the identification of three karst horizons: epikarst, infiltration zone and saturated zone. The epikarst has been first defined by Mangin (1975) as the part of the underground in interaction with the soil and the atmosphere. It is often described as highly altered zone with a large porosity. In many cases, the epikarst is thought to be a significant water reservoir (Lastennet & Mudry, 1997; Perrin et al., 2003; Klimchouk, 2004; Williams, 2008). Chemically based modeling studies suggest that the epikarst or the infiltration zone could contribute to the total flow discharge at the spring from 30% to 50% (Batiot et al., 2003; Emblanch et al., 2003). This view drastically differs from other studies that attribute most of the discharge to a deeper storage (Mangin, 1975; Fleury et al., 2007). As the epikarst is also vulnerable to potential surface pollution, a better understanding of its hydrological behavior is welcome for an optimal management and protection of water resource and biological activity.

The studies about the karst water transfer and storage use tools generally based on chemical analysis, borehole measurements and spring hydrograph often associated with modeling approach (Pinault et al., 2001; Hu et al., 2008; Zhang et al., 2011). Spring chemistry or flow approaches provide useful information at basin scale however bringing limited clues about the spatial distribution of hydrogeological properties. On the opposite, borehole measurements provide useful quantitative information but relevant only for the near field scale because of the strong medium heterogeneity. At the intermediate scale (~100 m), the determination of the hydrogeological karst properties can be reached by geophysical experiments. Therefore, a collection of geophysical observations at intermediate scale can be valuable for constraining distributed modeling studies and more understanding of epikarst processes. Various geophysical tools are used to monitor, at an intermediate scale, transfer and storage properties such as Magnetic Resonance Sounding (MRS) (Legchenko et al. 2002), 4D seismic (Wu et al., 2006; Valois, 2011), Electrical Resistivity Tomography (ERT) (Valois, 2011) and gravity measurements (Van Camp et al., 2006a; Jacob et al., 2010) among others. Both distributed geophysical measurements (ERT, 4D seismic) and integrative methods (MRS, gravity) revealed spatial variations associated to medium heterogeneities.

Gravity methods are nowadays pertinent tools for hydrogeological studies in various contexts (Van Camp et al., 2006a; Davis et al., 2008). The value of the gravity at Earth surface is indeed directly influenced by underground rock density. A variation of density due to water saturation at depth can be directly measured from the surface through the temporal variation of the gravity (Harnisch & Harnisch, 2006; Van Camp et al., 2006b). Modern and accurate ground-based gravimeters provide a direct measurement of the temporal water storage changes in the underground without the need of any complementary petrophysic relationship (Davis et al., 2008; Jacob et al., 2008; Jacob et al., 2010; Deville et al., 2012; Fores et al., 2017). Time-lapse gravity measurements stand as an efficient hydrological tool for the estimation of water storage variations in both saturated and unsaturated zone. Moreover, the sampling volume of the gravity is increasing with depth: at 10 meters depth, the gravity integrates over ~~a~~a surface of a circular area with a radius of about ~~100*~~100 m. S~~ averaging~~ ~~s~~mall scale ~~variability~~heterogeneities are averaged in gravity observations. In highly heterogeneous hydro-sytems, non-locale observations are uncommun and of great potential for both processes identification and modeling. As surface gravity measurement integrates all density changes above the gravimeter, observed temporal variations can be related to both saturated and unsaturated zones. Time-lapse surface gravity measurements alone provide poor information about the vertical distribution of water. To get around the absence of vertical resolution, gravity measurement can be done at different depths in caves or tunnels (Jacob et al., 2009, Tanaka et al., 2011). Such time-lapse Surface to Depth (S2D) gravity measurement allows estimating water storage variations in the unsaturated zone of the karst. S2D gravity experiments allow also more accurate measurements by common mode rejection. Previous studies of gravity S2D measurements made in natural cave suggest that water storage variations in the epikarst can be a major part of total water storage changes across the aquifer (Jacob et al., 2009, Fores et al., 2017). In the present study, we use gravity data to quantify the influence of the epikarst in term of seasonal water storage in two karst systems in the south of France. We first present the hydrogeological situation of the sites and the experimental setup are introduced. Then the gravity data processing is detailed and results are presented. Results from another site in neighboring area (Jacob et al., 2009) are recalled and discussed in comparison with the results from the additional sites survey. Subsequently, time-lapse S2D gravity variations are analyzed in the light of these depth distributions and of a complementary MRS sounding. Finally, the seasonal water storage for all sites is discussed in terms of processes during the recharge~~ and discharge~~ of the ~~epi~~karst and its link with lithology and geomorphology.

1) Hydrogeological setting of studied karst systems

a) Lamalou karst system (SEOU site)

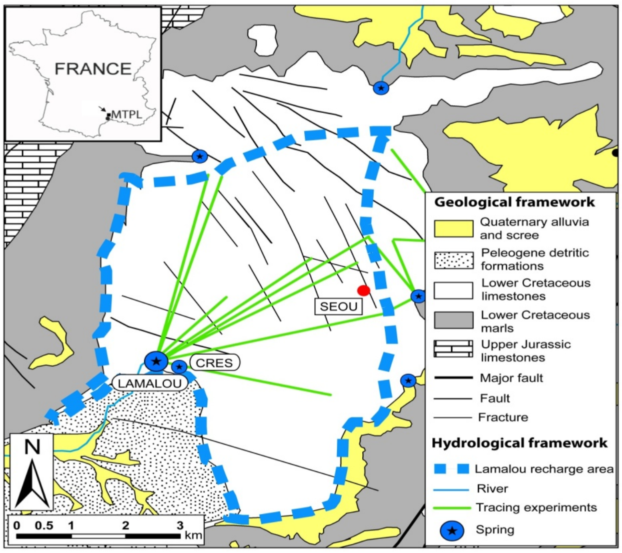

Figure 1 : ~~a)~~ Hydrogeological setting of Lamalou karst system on the Hortus plateau. Seoubio cave (SEOU) is indicated by a red dot;

The Lamalou karst system is located on the Hortus plateau (South of France). The aquifer is set in 100 m thick formation of lower Cretaceous compact limestone (Figure 1) deposited on Berriasian marls formation. These marls act as an impermeable barrier and define the lower limits of the saturated zone. Tertiary deposits overhang Cretaceous formations at the south-west and limit the aquifer. The karstified limestone formation is weakly folded as a NE-SW synclinal structure linked to Pyrenean compression. The main recharge of the Lamalou karst system comes from rainfall which annually reaches 900 mm. Snow occurs less than once a year and is negligible in the seasonal water cycle. Surface runoff is extremely rare except during high precipitation events when most of the system is saturated (Boinet, 1999). Discharge of Lamalou karst system only occurs at perennial Lamalou-Crès springs system composed of two perennial springs connected during high flow period (Durand, 1992). Daily discharge is 5 l/s and 1.5 l/s respectively for Lamalou spring and Crès spring (Chevalier, 1988). From combination of geomorphological observations, tracing experiments and mass balance modeling, the Lamalou recharge area is estimated of ~30 km² (Bonnet et al., 1980; Chevalier, 1988). The vadose zone has a maximum thickness of ~45 m. The epikarst thickness is estimated to 10 – 12 m depth at spring vicinity (Al-fares et al., 2002) and corresponds to an altered limestone with a strong secondary porosity such as opened fractures. Small matrix porosity have been estimated from core samples ranging between 0.5 and 1.3%.
The Lamalou experimental site is a cave called Seoubio (SEOU) located to the North-East part of the system in Valanginian limestone (Figure 1). The surface topography is nearly flat around the cave entrance, which corresponds to a vertical pothole of 5 m diameter and 30 m depth allowing a straight descent through the epikarst (Figure 3a). The depth of saturated zone

is around ~~39~~40 m below surface as attested by two siphons. The neighboring landscape is made of a ‘lapiaz’ structure with opened fractures and a ~~very~~ thin soil. The land use around the site is a natural typical Mediterranean scrubland.

b) Gourneyras karst system (BESS site)

The Gourneyras karst system is located in the southern part of Grands Causses area (south of France). The aquifer is set in Middle to Upper Jurassic limestone and dolomite topping Liassic marls formation. The latter formation defines the lower limit of the saturated zone of the karst system. The main recharge of the system comes from rainfall which reaches ~1100 mm annually. The rare snowfalls are included in the precipitation measurements. Discharge occurs only at the Gourneyras Vauclusian-type perennial spring. Discharge is not continuously monitored but punctual measurements suggest a discharge of ~20 m^3/s during flood events. Recharge area of Gourneyras spring is estimated to ~41 km² (SIE Rhône-Méditerranée, 2011). The vadose zone has a maximum thickness of 450 m. Fractures plugged with calcite are seen in the cave.

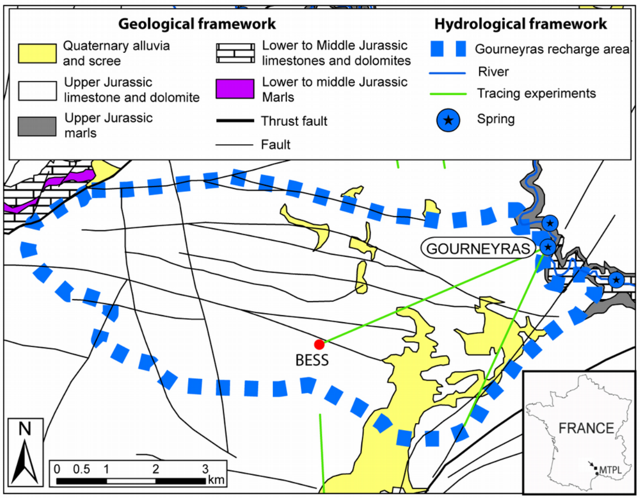

Figure 2:~~ :~~ Hydrogeological location map of Gourneyras karst system. Besses cave is indicated by a red dot (BESS)

The Gourneyras experimental site is a cave called “Les Besses” (BESS) (Figure 2). The surface topography around the cave entrance is a gentle slope to the south-east. The cave is located in Kimmeridgian limestone formations. At the cave location, limestone is overhead by a thin dolomite formation. Typical porosity of the matrix from core samples ranges between 1.6 and 7% depending on the depth. Shallow alteration deposits such as clay are present at the surface. Above the cave, the land use is a natural typical Mediterranean scrubland. The cave morphology allows an easy afoot descent except between 670 m and 690 m elevation where abseiling rope is necessary. The cave topography allowed ~~us~~ taking gravity measurements at 5 different depths (Figure 3b). Saturated zone is probably at 450 m depth below the surface a few tenths of meters above spring elevation.

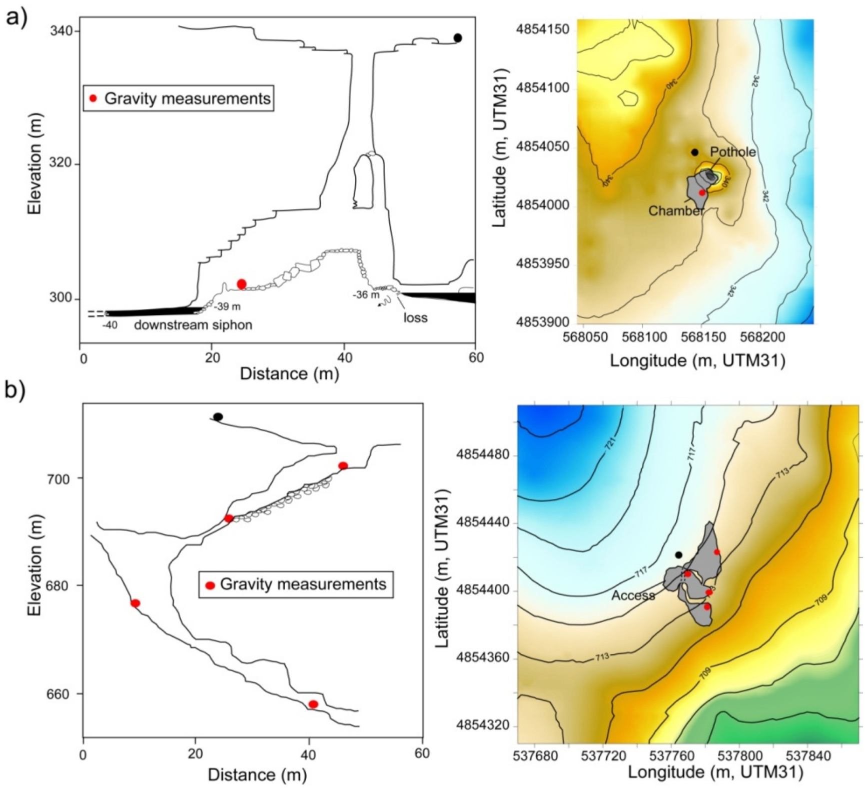

Figure 3: Developed cross-section and topography surrounding a) Seoubio caves, after Boinet (2002); and b) Besses caves. Black and red circles indicate the location of gravity measurements. Elevations are in meters. The projections of the cave in surface are represented in gray on topography.

The two karst systems of SEOU and BESS sites have been presented above but the results from a previous study (Jacob et al., 2009) are extensively used in the discussion (BEAU site). A detailed description of the site BEAU is available in Jacob et al. (2009). BEAU and BESS sites are located 25 km away at the same elevation with a similar geological and climatic setting. However, the BEAU site is embedded in a highly altered dolomite (typical porosity from core sample between 5 and 11%) capped with a shallow soil of the Durzon karst hydro-system.

2) Data acquisition and processing

a) Cave topography

Positions of cave gravity stations at each site were measured using standard speleologists tools. Azimuth, inclination and distance measurements were performed along 2 topographic surveys between surface and depth stations. The closing misfit between these surveys indicates an elevation accuracy of about 0.2 m.

b) Meteorological data

Precipitation and potential evapotranspiration are provided by the French national meteorological agency (Météo-France). The nearest meteorological station of each site was selected. Precipitations are daily monitored respectively at 4 km to the South-East of SEOU site and 5 km to the South of BESS site. Rain gauges are automatic tipping-bucket with a resolution of 0.2 mm. Accuracy of rain gauges is equal to 4% during weak precipitation, but the errors increase when precipitation exceeds 150 mm/h (10% accuracy) (Civiate & Mandel, 2008) which is rare in the area. The rainfall have shown to be spatially homogeneous at the seasonal scale but not at the event scale (Fores et al., 2017). Both sites (BESS and SEOU) are mainly influenced by Mediterranean climate even if in BESS a clear influence of the oceanic climate can be observed. Daily potential evapotranspiration (PET_d) is calculated using Pennman-Monteith's formula by Météo-France. PET_d is given at respectively 7 km to the south-west of SEOU site and 5 km to the south of BESS site. The actual evapotranspiration *(AET)* has been calculated from the potential evapotranspiration (PET_d) and a crop coefficient (k). The crop coefficient is time-variable (i.e. during a season) (Allen et al., 1998) and includes effects of water availability and physiological properties of plants. The seasonal variation of the crop coefficient ~~cannot~~have been evaluated ~~without~~from 2 years of direct monitoring of actual evapotranspiration~~ but a mean yearly value of the crop coefficient can be estimated using yearly actual evapotranspiration (AET_y)~~ by a flux tower (Fores et al., 2017) and daily potential evapotranspiration (PET_d).~~ Turc's formula gives the AET_y as function of yearly rainfall and yearly mean air temperature (Turc, 1961; Réméniéras, 1986). Yearly average of the crop coefficient (k) is the ratio between AET_y and yearly total PET_d.~~ The crop coefficient varies seasonally between 0,55 in summer (as low soil moisture is available) and 1,20 in winter. The same crop coefficient has been used on the three sites as the climate and the land use are similar. On an annual baseline, the average crop coefficient ranges between 0,5 and 0,7 in the same area (Jacob et al., 2009).

~~Based on 12 and 5 years depending on site, the crop coefficient was found equal to 0.51 and 0.49 respectively for SEOU and BESS site. The crop coefficient on the BEAU site in the Durzon karst hydro-system (climate and land use similar to the BESS and SEOU site) has~~

~~been calculated using different methods and ranges between 0.5 and 0.7 (Jacob, 2009). A value of 0.6 for BEAU site has been selected. D~~Due to the lack of realistic error estimation, accuracy of AET is fixed to 15% based on recent estimation of AET from flux tower measurements (Fores et al., 2017). As the ratio AET versus precipitation amount is much smaller during winter than during summer, the impact of the AET uncertainty is higher during the discharge period (summer) ~~but~~and allows more confident interpretation during the recharge period (winter).

c) MRS survey

At the site BESS, two MRS survey has been conducted in May 2011 and Aug. 2011. A NUMIS-LITE equipment from IRIS Instruments has been used with a 40×40 m square loop. A notch filter is used for cutting the harmonics of 50 Hz. The data were processed and inverted with SAMOVAR-11.3 software (Legchenko et al., 2004). The same procedure as in Mazzilli et al. (2016) where more details can be founded.

~~c~~d) Surface to depth gravity experiment

Experimental setup

The surface to depth (S2D) gravity experiment consists in measuring the time-lapse gravity difference between surface and depth at a given site. ~~S2D was used in previous study in cave about 25 km NW from BESS (Jacob et al., 2009).~~ The morphology of the caves allows taking measurements in the interior of karst and at different depths in the unsaturated zone. For each karst system we choose one cave where the surface and the underground access can be managed with a relative gravimeter. S2D gravity measurements are done at the surface and ~-35m depth at the SEOU cave. For BESS cave, gravity stations are located throughout the cave at different depths: the surface, -12 m, -23 m, -41m and -5~~3~~3 m. ~~gravity sensor are fixed for all stations using a brass ring positioned on carved holes in the basement rock. CG-5To limit temporal bias linked to gravimeter position, the height and orientation of the~~

Gravity measurements have been done during ~~at least~~ two years (2010-2011) in late summer and early spring in order to catch the seasonal water cycle. When more than two measurements per year have been done, all the results are averaged at a bi-annual frequency.

A relative gravimeter (Scintrex CG5) is used to measure the relative difference in gravity between two locations or stations. As measurements are only relative (not absolute), the gravity readings have a large and unknown offset to the absolute gravity value.

Scintrex relative gravimeter CG5 has been used ~~as in previous studies~~ for precise micro-gravity survey (Bonvalot et al., 2008; Merlet et al., 2008; Jacob et al., 2010; Pfeffer et al., 2013). The gravity sensor is based on a capacitive transducer electrostatic feedback system to counteract displacements of a proof mass attached to a fused quartz spring. The ~~CG-5~~CG5 instrument has a reading resolution of 1 µGal and a repeatability smaller than 10 µGal

(Scintrex limited, 2006). The compactness and the accuracy of the gravimeter match the requirements of micro-gravity in natural caves. As gravity signals of hydrological processes display relatively small variations of 10-30 μgal, a careful survey strategy and processing must be applied to gravity data. To limit temporal bias linked to gravimeter position, the height and orientation of the CG5 gravity sensor are fixed for all stations using a brass ring positioned on carved holes in the basement rock. ~~Relative gravity measurements also need to be corrected for calibration and instrumental drift.~~ We used only the ~~CG-5~~CG5#167 for the measurements because of its known low drift and to limit instrumental bias.

Gravity data processing and error estimation

As demonstrated by Budetta ~~&~~and Carbonne (1997), Scintrex relative gravimeters need to be regularly calibrated when used to detect small gravity variations over extended periods of time. The calibration factor was measured before each gravity period at the Montpellier-Aigoual calibration line (Jacob, 2009). The accuracy of the calibration is 10^{-4}. Calibration factor of ~~CG-5~~CG5#167 is almost stable during the studied period (annex 1). ~~The error of the calibration factor change is therefore negligible.~~

The gravity data are corrected for Earth tides using ETGTAB software (Wenzel, 1996) with the Tamura tidal potential development (Tamura, 1987). Considering the distance of Atlantic Ocean, the ocean loading effects are weak (6 μGal) and have been removed using Schwiderski tide model (Schwiderski, 1980). Atmospheric pressure loading is corrected using a classical empirical admittance value of -0.3 μGal/hPa (pressure measurements have an accuracy of about 1 hPa with a ~~small~~ field barometer). Polar motion effects are not corrected because they are nearly constant over the time span of one ~~S2D~~gravity ~~measurement~~survey (~ 8 hours).

The drift of the ~~CG-5~~CG5 sensor is linked to a creep of the quartz spring and must be accurately corrected for obtaining reliable values of gravity variation. To estimate the drift, gravity survey are setup in loops: starting and ending at the same reference station. The reference station is occupied several times during a survey. The instrumental drift is assumed to be linear during the short time span of the loops (less than one day). ~~The linear drift can be evaluated with repeating measurements at the same station during a day.~~ The drift of the CG5#167 gravimeter is known to be particularly small (~~Jacob et al., 2009;~~ Jacob et al., 2010). The gravity differences relative to the reference station and the drift value are obtained using a least-square adjustment scheme. ~~We consider that the effects of temperature change on gravity variations are uncorrelated with the drift.~~ Software MCGRAVI (Belin, 2006) based on the inversion scheme of GRAVNET (Hwang et al., 2002) is used to adjust gravity measurements and drift. Unknowns to be adjusted are gravity value at each station (surface and depths) and the linear drift of the gravimeter. Measurements of one station (m_d) relative to the reference station (m_s) can be expressed as:

$$C_f\left(m_s^{t_j}-m_d^{t_i}\right)+v_{S_i}^{S_j}=g_s-g_d+D_k\left(t_j-t_i\right) \qquad (1)$$

Where C_f is the calibration correction factor, m_s^{tj} and m_d^{ti} respectively the reference and station gravity reading at time t_j and t_i, v_{Si}^{Sj} the residuals of (m_s^{tj} - m_d^{ti}), D_k the linear drift of the loop k, g_s and g_d the gravity values at the reference and the station. The variance of one gravity reading is given by the standard deviation of 90 s measurements series and additional errors of 2 µGal for inaccurate gravity corrections and possible setup errors. The a-posteriori variance of unit weight is computed as:

$$\sigma_0^2=\frac{V^T PV}{n-(m+s)} \qquad (2)$$

Where n is the number of gravity reading averaged for each station occupation~~is the number of gravity station~~, s the number of loops, m the number of gravity station~~the number of gravity reading~~, V is an n vector of residuals and P is a weight matrix. The table 1 summarizes the results of the gravity experiments at each site. One can note that gravity errors budget is ~~always~~ smaller than the measured gravity variations validating the survey setup and processing.

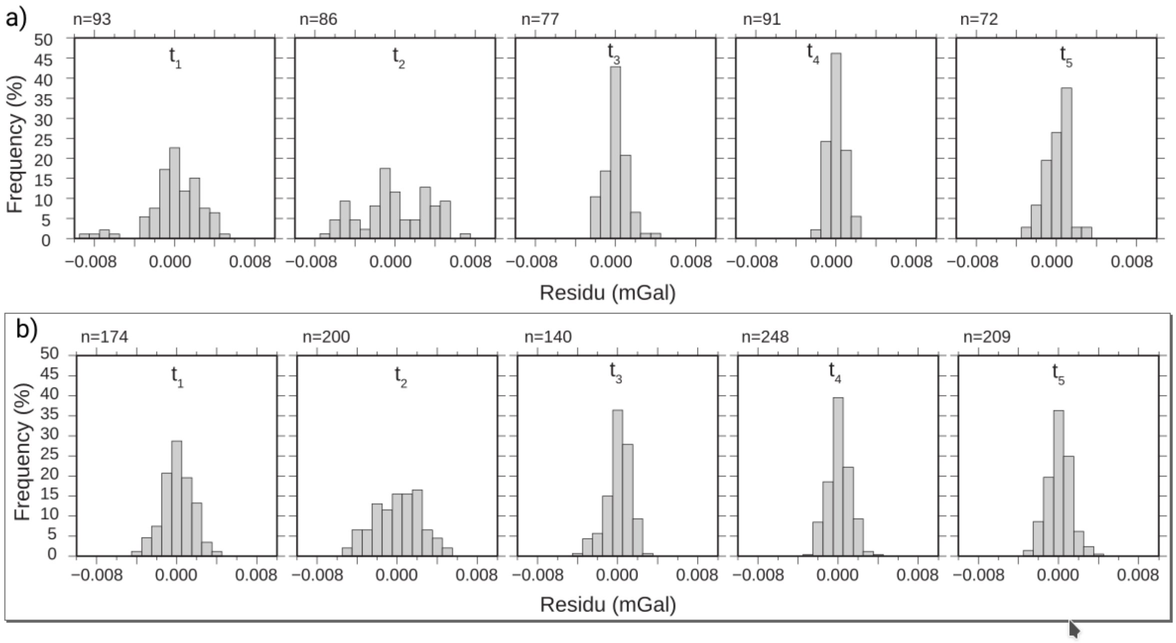

Figure 4 : Histogram of residuals of the observed gravity differences versus the adjusted gravity differences ~~of the fit~~ at a) SEOU site, and b) BESS site for each measurements

periods. During t1 and t2, short term strategy was used and long-term strategy during t3, t4, t5.

Measurement relaxation and measurement strategy

In addition to the daily drift, the transport of the gravimeter causes a relaxation of the quartz spring that leads to a rapid variation of the gravity value during the first ~40 minutes of measurements (in our case for the ~~CG-5~~CG5 #167). Such a relaxation has been already related in previous studies such as Flury et al. (2007). The relaxation may sometimes be greater than the ~~daily~~ drift of the gravimeter and displays variable amplitude depending probably on the time and the type of transport and meteorological variations. Contrary to the drift, reasons of the relaxation are not clearly understood and cannot be modeled. Without the correction of the relaxation, the relative gravity measurements must be accounted for in the~~lack a clear~~ error budget. To resolve this problem, we setup a new measurement strategy which allowed removing relaxation and we compare it with a usual gravity measurements strategy.

Two measurement strategies are used in this study. The usual one, called "short time strategy" consists to ~~measure~~multiply the occupations at the ~~reference~~all the stations~~ and the other stations many times~~ (4 and 5 loops in our case). For each single occupation, 10 measurements of 90 s at 6 Hz sampling are performed. Only the last 5 or 6 nearly constant measurements are selected. Frequent reference station measurements during a loop allow for constraining the instrumental drift and the number of occupations leads to a statistical decrease of the error. With the short time strategy, one assumes that the relaxation due to the transport always results to the same bias from site to site. The time of transportation between two stations is ke~~e~~pt as constant as possible to obtain similar relaxation bias. This strategy was used for the two first ~~measurements campaigns~~gravity surveys (winter 2010 and summer 2010).
The new strategy, called "long time strategy" aims to overcome the relaxation phenomena and is used for the three last ~~measurements campaigns~~gravity surveys. Only two or three occupations at the reference station and only one at the other stations are done. For each occupation, a minimum of 40 measurements of 90 seconds at 6 Hz sampling are performed (~ 1 hour). The duration is carefully chosen: the relaxation of the gravimeter must be achieved. The gravity reading then follows the daily linear drift. A minimum of 20 gravity reading during the linear, stable measurement period are kept. Such a strategy can be applied only if the drift of the gravimeter is small and linear, which is the case of ~~CG-5~~CG5#167.
The evaluation of the measurement accuracy can be partially done with the help of the residuals. The residuals are the differences between the measured gravity value and the estimated gravity value. The residuals depend on the accuracy of the processed data and on the robustness of measurements strategy. For example, if a histogram of residual is centered on 0 then it let think that correction process have not introduced a bias in gravity value. The

dispersion of the residuals can indicate noisy measurements or non-linear drift. The shape of the histogram shows the global accuracy of dataset. The residuals were estimated for each dataset (Figure 4) and can be used to compare the two measurement strategies.

Most of the histograms display a Gaussian shape centered on zero with a small dispersion showing the good quality of the gravity readings and hence the robustness of the surface to depth gravity differences (Δg_{S2D}). However, the residuals of -8 µGal (Figure 4a) for the period t_1 at SEOU site are due to an unexpected gravity jump during the survey. As no explanation was found for the gravity jump, they are kept for data adjustment even if the dispersion of the gravity residuals increases accordingly. For the two first datasets, ~~Gaussian shapes are observed and~~ 90 % of residuals are comprised in 8 µGal interval. For the three last datasets, 90 % of residuals are between -2 µGal and +2 µGal. R~~The "long time strategy" reduces the errors of the corrected gravity value. Indeed, r~~esiduals histograms of the "long time strategy" are narrower than those of the "short time strategy" which confirms the improvement of the field experiment strategy (Figure 4). The relaxation due to transportation or non-linear drift would have induced non Gaussian shape of the histograms and not centered on zero as seen during the survey 2 at SEOU site (Figure 4a). We have tested in a cave the "long time strategy" using repeated measurement on a single station interrupted by hand transportation. As for the data shown here, these unpublished results, show a smaller dispersion of the residuals~~-~~ than the one provided by the "short time" method and an unbiased ~~than the one provided by the "short time" method.~~mean.

~~All raw~~ G~~g~~ravity data after correction and drift adjustment are presented in the Annex 1. For SEOU site, the Δg_{S2D} values show significant temporal variations ranging from -3.897 mGal to -3.914 mGal~~ (annex 1)~~. At BESS site, between surface to 12 m depth, Δg_{S2D} values is ranging from -1.523 mGal to -1.537 mGal~~; ~~. Below 12 m, gravity variations are not significant~~from 12m to 23m depth, Δg_{S2D} show a weak variation and the values ranged between -1.317mGal and -1.322 mGal; for the two latest depths, Δg_{S2D} have no significant variations of -1.724 mGal to -1.728 mGal and -1.272 mGal to -1.277 mGal respectively for 23 to 41m and for 41 to 58m depth intervals.~~. ~~See annex 1 for more details.~~

3) Data interpretation

Surface to Depth formulation

The $\boldsymbol{\Delta g_{S2D}}$ gravity values contain the variations associated to elevation and to the differential attraction of rocks masses. These time independent effects must be removed for accessing to water storage variations. In the following we assume that the sedimentary formations between the two measurement sites have no lateral variations of density. ~~Let g_s and g_d be the gravity value respectively at the surface and at depth at heights z_s and z_d.~~

~~The surface and depth gravity measurements g_s and g_d can be expressed as (Jacob et al., 2009):~~

 ~~(3)~~

 ~~(4)~~

~~Where (all parameters in SI units) G is the universal gravitational constant, h is the height difference between two stations, ρ_{app} the apparent density of the rock mass below depth station, T_S and T_d the terrain effects at the surface and depth, $grad(g_\theta)$ the vertical normal gravity gradient known as free-air gradient, Δg_b the Bouguer anomaly, g_θ the normal gravity for surface and depth station at latitude φ_S and φ_D. Additional terms $g^S{}_{LW}$ and $g^d{}_{LW}$ are the long wavelength effects of global hydrology which are dominated by surface deformation induced by hydrological continental loading. At the spatial scale of a few tenths of meters that we consider, the vertical deformation induced by regional hydrological loading is supposed constant. The surface to depth gravity difference can therefore be expressed as:~~

 ~~(5)~~

~~Where $\Delta_z T$ is the difference of terrain effects between surface and depth station, $\Delta_z g_B$ the difference of Bouguer anomaly between surface and depth station, $\Delta_z g_\theta(\varphi)$ the change in gravity due to latitude difference between surface and depth station.~~

~~*Seasonal water storage variations from time-lapse S2D*~~

Once surface to depth gravity differences are calculated, looking at temporal variations allows for retrieving the water storage variations. Time-lapse S2D gravity can be interpreted in term of equivalent water height changes, assuming that the water storage variations are laterally homogeneous~~homogenous~~ at investigated temporal (seasonal) and spatial (~100 m) scales. Such hypothesis is likely to be untrue in a karstic area because voids and heterogeneities are potentially present at all scales. Looking at a temporal snapshot of the total water storage (porosity time~~'~~s saturation) in the first meters of the karst should probably show a high heterogeneity as seen in boreholes. Nevertheless, we justify our working hypothesis as follows:

- ✓ S2D gravity measures at an *intermediate (100 m) scale*. The laterally integrative property of the gravity leads to ignore small scale (up to a few meters) heterogeneities which is one of the main advantage of the gravity method. T~~Moreover, t~~he large scale heterogeneities (> 100 m) are negligible ~~because of the differences between surface and depth.~~as they have an equivalent impact on the gravity measurements in surface and in depth (common mode rejection in the S2D method).

- ✓ Time-lapse S2D gravity measures underground water variations associated to a *seasonal water cycle*. At the seasonal time-scale, the ~~capacitive~~storage function of the karst is probably largely dominant and the transfer function as the fast transfer (at the flood scale) is not measured.
- ✓ Time-lapse S2D gravity measures the average water storage *variations* (i.e. porosity time~~'~~s saturation variations). As in our case the epikarst is never completely saturated during the measurements, the heterogeneity of the water storage variations is likely to be associated to saturation variation (due to climate) and not to porosity (due to heterogeneities).

~~Taking into account previous hypothesis, the time variations of each term of equation 5 can be evaluated. The free-air gradient, normal gravity and depth are constant with time because of the absence of tectonic activity.~~ For the duration of investigation, the effects of erosion on topography, caves and potential tectonic activity can be considered as negligible for all sites. ~~Therefore, we can consider topography variations around sites and caves volumes constant with time.~~ Additionally, temporal variations of the terrain correction are not significant ~~apparent density variations due to water storage variations yield a negligible influence on terrain effects~~ (Jacob et al., 2009~~<1μGal~~). Hence, the evolution of surface to depth gravity with time can be reduced to:

$$\Delta_z^t g = 4\pi G\,\Delta_z^{\delta t}\rho_{app} h \qquad (\cancel{6}3)$$

Where $\Delta^t\rho_{app}$ is the apparent density change over time t. Surface to depth gravity variations during time period $\Delta_z^t g$ correspond to twice the Bouguer attraction of a plate with $\Delta^t\rho_{app}$ density of height h and ~~therefore~~ increases by two the signal to noise ratio. Finally, the apparent density variations depend only on water saturation variations. Time-lapse water saturation variation can be approximated to an equivalent water height (EqW) variation (eq. ~~7~~4). Let $\Delta^t{}_z l$ be the equivalent water layer height variations over time t within height h. Eq ~~7~~4 induces the density change $\Delta^t\rho_{app}$. Finally, the time-evolution of $\Delta^t{}_z g$ can be expressed in the following manner:

$$\Delta_z^t g = 4\pi G \rho_w \Delta_z^t l \qquad (\cancel{7}4)$$

where ρ_w is density of water. Therefore, a S2D gravity ~~variation~~difference of 2 μgal is associated to an effective water slab of 23.~~3~~86 mm.

Site	Time period	*Gravity difference (µGal)*	*Equiv. Water height ~~(EqW)~~ (mm)*	*Cumulative precipitation (mm)*	*Cumulative AET (mm)*	*Net water inflow ~~(NWI)~~ (mm)*	*EqW / NWI ratio (%)*
SEOU	Feb10-Aug10	-17 ± 3.9	-203 ± 48	281 ± 11	~~239~~377 ± ~~48~~56	~~41~~-96 ± ~~49~~58	212
	Aug10-May11	8 ± 3.9	95 ± 48	628 ± 25	~~254~~328 ± ~~51~~49	~~373~~300 ± ~~56~~55	31
	May11-Sep11	-3 ± 2.0	-35 ± 25	256 ± 10	~~344~~309 ± ~~69~~46	~~-88~~-53 ± ~~69~~47	67
~~12m~~)BESS (0-12m~~0-~~	Feb10-Aug10	-1~~2~~4 ± 3.1	-~~143~~167 ± 37	315 ± 13	~~381~~473 ± 7~~6~~1	-~~66.6~~158 ± 7~~7~~2	105
	Aug10-May11	~~10~~9 ± 3.~~5~~5	~~119~~107 ± 42	854 ± 34	~~266~~471 ± ~~53~~71	~~587~~383 ± ~~63~~78	28
	May11-Sep11	-~~11~~9 ± 2.6	-~~131~~107 ± 31	162 ± 6	~~320~~441 ± 6~~4~~6	-~~158~~ 278± 6~~4~~6	38
BEAU	Sep06-Nov06	26 ± 2.5	310 ± 30	445 ± 18	~~69~~70 ± 1~~4~~0	375 ± 2~~2~~1	83
	Nov06-Sep07	-20 ± 3.2	-238 ± 38	482 ± 19	~~753~~502 ± ~~150~~75	-~~271~~20 ± ~~151~~78	*
	Sep07-Feb08	25.~~7~~8 ± 3.0	307 ± 32	424 ± 17	20~~8~~1 ± ~~17~~30	2~~17~~23 ± ~~4~~34	137

Table 1: Time-lapse S2D gravity difference, Equivalent water height, cumulative precipitation, cumulative ~~evapotranspiration~~evapo-transpiration and total water inflow with the associated errors at SEOU, BESS and BEAU site for different recharge and discharge periods. Recharge periods are indicated by the gray color.~~Recharge periods are indicated by the gray color.~~ For BEAU site, only measurements with the CG5 #167 are kept.

~~Results to be checked in the text~~

~~Results of the time-lapse gravity difference and associated equivalent water height are presented for each site between two consecutive periods (Table 1). Results of BESS and SEOU site are compared to the ones obtained at the BEAU site. As t~~The measurements ~~are~~must be done approximately~~ every 6 months ~~during the ~~optimum~~minimum and maximum of the seasonal water cycle~~, ~~: the ~~yearly~~seasonal cycle is measured with a minimum uncertainty~~out ambiguity~~ and the potential aliasing is reduced. In the Mediterranean climate, high precipitation events (HPE) have a large impact in the yearly accumulated precipitations. HPE occurs mainly in autumn (September mainly): a gravity survey (t3) has been done in October 2011 but due to climate variability, in 2011 an exceptional HPE occurs in March. ~~Gravity differences from all depths have been added for BESS site to obtain a total EqW. Error budget of EqW is retrieved from S2D gravity standard deviation.~~ An additional gravity survey (t4) has been done in early May 2011 to have the complete recharge. The low temporal sampling of the gravity survey could produce aliasing. To limit the impact of the aliasing, gravity surveys (except the first one) have not been planned just after significant rainfall events. The gravity models and monitoring in the Larzac (Deville et al., 2012) was used to plan the S2D gravity surveys.

During all discharge periods, gravity differences are negative in the three sites indicating a decrease of EqW. For all recharge periods, gravity differences are always positive indicating an increase of EqW. At SEOU site, the two dry seasons lead to a loss of about 203 mm and 3~~6~~5 mm EqW respectively for first and second discharge period. During recharge period, increase of EqW is equal to 95 mm, in accordance with high precipitation value during this period. At BESS site between 0 and 12 m, the two discharge periods show a similar loss around ~~131~~167 mm ~~in spite of large precipitation variations~~and 107 mm. Recharge period has a positive EqW equal to 1~~19~~07 mm with the respect of high precipitation value. At BEAU site, only one discharge period was monitored and the loss is equal to 2~~62~~38 mm. For the two recharge periods EqW have the same value ~~of~~around 3~~25~~00 mm~~ with similar cumulative precipitation~~, larger than SEOU and BESS sites.~~ Contrary to the two first sites, cumulative precipitation have a similar values whatever recharge or discharge period, but cumulative AET shows a significant variation with time period.~~ Except for the first recharge period at the SEOU site, the EqW during recharge and during discharge are equivalent.

~~Epikarst~~Seasonal water storage

As the precipitation and the evapotranspiration can vary geographically from site to site, EqW cannot be directly compared. Looking to the ratio between the time-lapse S2D gravity variations (or EqW) and the net water inflow~~-~~ (NWI) allows the inter-comparison between different sites and the interpretation in terms of water storage capacities. The normalization of EqW by the net water inflow allows also comparing EqW measured at other period such as at BEAU site in 2007-2008. ~~N~~As no surface runoff has been observed at the three sites~~ even after heavy rainfall. W~~, we ~~then~~ consider that all rainfall directly infiltrate into soil. As AET contribute to take out water to the soil, it was taking into account in mass balance. The effective precipitation or the net water inflow~~ (NWI)~~ during a time period is the difference between the cumulative precipitation (P_c) and the cumulative actual evapotranspiration (AET_c) for the given site:

$$NWI = P_c - AET_c \qquad (\cancel{8}5)$$

The net water inflow exhibits as expected a seasonal cycle. High values (up to ~~600~~383 mm) during the recharge and small or negative value during the discharge (up to -2~~63~~78 mm) have been ~~recorded~~estimated (Table 1).

During the discharge period, EqW and NWI are all negative~~ except for 2010 in SEOU where NWI is equal to 41 mm (a possible explanation is presented later in the section 4. interpretation)~~. The EqW is larger than NWI for the February 2010 to August 2010 discharge period at SEOU and BESS site. On the opposite, for May 2011 to September 2011 discharge period, EqW is lower than NWI (Table 1).~~ At BEAU site, EqW are sometimes larger and sometimes lower than NWI during the discharge.~~ Such unrelated relationship between EqW variations and NWI seems to be typical of the discharge and prevent simple interpretati**on. The discharge is also characterized by a high error budget of NWI value as the evaluation of AET is dependent of the relative low accuracy of** ~~k~~the crop **coefficient. As** during the discharge **the AET is important**~~ during the discharge~~ compare to the precipitations**, the uncertainty of AET prevents further interpretation. The discharge period is therefore not included in the following discussion.**

During the recharge, the two sites BESS and SEOU exhibit a similar pattern as the EqW is ~~always~~ smaller (about ~~three times~~30%) than the net water inflow (Figure 5). For example, at BESS site EqW is equal to ~~119~~107 mm when the net water inflow reaches ~~587~~383 mm. During the similar season, BEAU exhibits a~~ different pattern~~n opposite pattern with an EqW equivalent to the NWI (83 and 137 %).~~ We obtain 325mm of EqW with 376mm for NWI. Looking to the year 2011 for SEOU site, EqW corresponds to 30% of net water inflow. For BESS site, the EqW/NWI ratio is equivalent to SEOU site (~30%). On the opposite, EqW/NWI ratio is of about 80% at BEAU site.~~ As the EqW/NWI ratio is an attempt of~~a~~ climatic normalization~~ of the seasonal water storage~~, the heterogeneity in the seasonal water storage is therefore clearly shown as expected in a karstic environment. The EqW/NWI ratio confirms the direct S2D measurements reading with larger S2D gravity variations in BEAU than in SEOU and BESS (Figure 5).

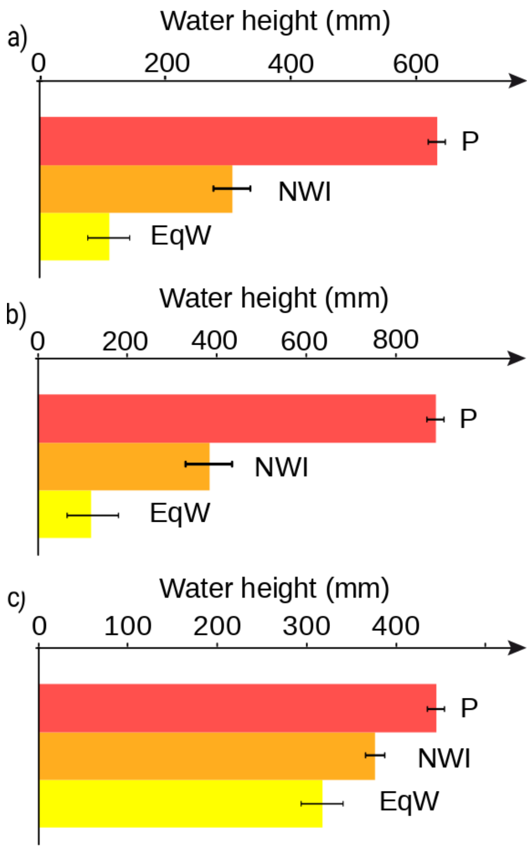

Figure 5: Precipitation, net water inflow and EqW during recharge period for a) SEOU site; b) BESS site and c) BEAU site.

Depth distribution of seasonal EqW

Results summarized in Table 1 for BESS site are the~~ total~~ EqW ~~from the surface until the deepest station at -58m~~between the surface and the 12 m depth station. In the BESS site, EqW deduced from gravity measurements are available at 5 different depths. Gravity depth profiles have nearly the ~~same~~opposite shape during recharge and discharge periods (Figure 6 :). During recharge period, gravity variation is equal to 107 mm (9 µGal) between surface and 12 m depth with a small error budget (3 µGal).~~ EqW variation is then significant at this depth with a value of 110 mm.~~ Below 12 m depth, gravity variations are not significant (~~2µGal, 2µGal and 0µGal respectively ~~< 3 µGal for the second, the third and the fourth depth stations).~~ Error budget is ranging for 2.5 and 3.5µGal for the three depths respectively.~~ For discharge period, time-lapse S2D gravity variation has also a value of 107 mm (-9 µGal) for the first depth with 2.5 µGal of error budget with not significant gravity variations below. ~~Between 12m to 23m depth, gravity variation is equal to -4µGal. Below 23m depth, gravity variation are small, 1µGal and 2µGal respectively for 23-41m and for 41-58m depth intervals.~~

~~For these two periods, EqW variations are significant only between the surface and 12m depth (~100mm). Below 12m depth most of gravity variations are not significant. Only during the discharge period, a possibly significant EqW decrease of 40 mm is measured between 12m and 23m depth.~~ The vertical gravity profile can be compared to the MRS vertical profiles at the same place (Figure 6). The MRS profile clearly indicate a significant water content near the surface with a maximum around 10 m depth. The correlation between the both independent geophysical methods confirm the importance of a superficial reservoir in the first 10 m depth. No significant variations between the two MRS survey can be evidenced from the inversions. It allow to quantify a maximum MRS water content variations around 1 % (130 mm in EqW) in the first 10 m depth. The 1 % maximum MRS water content variations is coherent with the gravity estimation around 100 mm (not significant for the MRS).

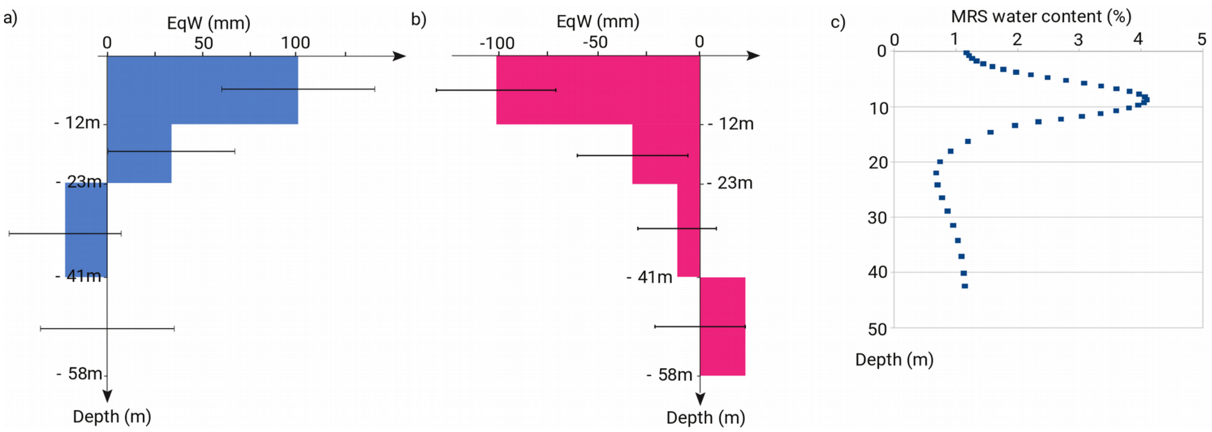

Figure 6~~:~~: S2D gravity difference function of depth at the BESS site for a) recharge period (t2-t4) in 2010; b) and discharge period (t4-t5) in 2011; c) MRS ~~-~~profile of May 2011 at the BESS site~~-~~.

4) Discussion

Accuracy of S2D measurements

~~Gravity measurements must be very useful to determine water storage variation in unsaturated zone. In some Mediterranean areas, water storage variations lead to a maximum of 30μGal on gravity amplitude between dry and wet season (Deville et al., 2012). In our case, error budget is one order of magnitude lower than seasonal gravity amplitude. Because of an improved measurement method, we are confident that gravity differences are only due to hydrological processes.~~

We show using two measurement strategies that the error budget can be ~~optimized~~minimized. A long time measurements strategy (45 min per site) displays a better error budget than a short time strategy (10 min per site). However, we perform the long time strategy with a unique measurement on each station (except the base station). T~~Therefore, t~~his strategy can be performed only if the gravimeter has a quasi-linear and small drift~~ over one day~~. ~~Because we are looking to a differential precision of 1 µgal, this means that the gravimeter drift curve should follow a linear trend at µgal level.~~ In the BESS site, the ~~coherence~~similarity of the gravity measurements with the MRS profile (fig. 6)~~respect to depth~~ is an indirect information of the quality of the gravity measurement. The coherence of the gravity between the wet and the dry season is another indirect confirmation of a significant signal to noise ratio. Indirectly, an accuracy of the gravity measurements can be deduced from the MRS profile. From the MRS, the water content variations should not vary significantly below 15 m. The S2D gravity below 15 m depth ranges between -3 and 3 µGal, leading to an indirect estimation of the S2 gravity accuracy around 3 µGal. The~~We are therefore confident that our~~ measurements are suitable for a quantitative interpretation of differential gravity in term of water storage.

~~AET data has been estimated using a constant crop coefficient (k). The crop coefficient is known to be variable with time. Hence a time-constant crop coefficient leads an error on AET value. However during recharge period (i.e. autumn and winter season) evapotranspiration is low and its associated error is therefore weak. During the discharge period, the evapotranspiration plays a major role in the net water inflow error budget. The large uncertainty in the evaluation of the evapotranspiration leads a large uncertainty on the value of NWI that does not allow a reliable interpretation of the discharge period. Moreover, ambiguity remains between evapotranspiration error and water transfer below the depth of investigation.~~

Quantification of the epikarst water storage

The ~~measurements~~gravity survey done at BESS site allow ~~for~~ evaluating the depth distribution of the seasonal water storage variations. Both recharge and discharge periods show water storage variations in unsaturated zone ~~mostly~~ located within the first 12 meters (Figure 6 :). The seasonal water stored in BESS reaches ~~110~~107 mm (9 µGal) over th~~is~~e thickness. ~~-~~The ~~W~~water ~~storage~~ content between 12 m and 5~~5~~8 m depth is too small to be measured by both the gravity and the MRS.~~is limited to a maximum value of 30mm which is the resolution of the gravity method. Therefore, water storage on this site is likely to occur in a shallow zone corresponding to the epikarst~~At BESS site, the subsurface reservoir can identify as the surface thin dolomite formation and/or as an epikarst both characterized by an enhanced porosity. ~~This storage location may be enhanced by a larger porosity occurring at those depths (Williams, 2008). The unsaturated zone below (i.e., infiltration zone) may have mainly a transfer function and a small water storage capacity.~~ Various ~~estimations of water storage in the high porosity zone~~studies support the hypothesis of a key role of the epikarst in the seasonal water storage (Mangin, 1975; Perrin et al., 2003; Klimchouk, 2004; Williams, 2008). ~~Spoiled~~Weathered structures (and especially in dolomite rocks) allow water reservoir in the first meter of unsaturated zone of karst system. Following Williams (2008), epikarst thickness may vary from ~~10m~~zero to 30 m and epikarst water storage occurs because of a strong porosity in the epikarst associated to a reduced permeability at its base. Surface to depth gravity and MRS allows at BESS site a precise quantification of both ~~storage~~ thickness and amplitude ~~in the unsaturated zone~~ of subsurface water storage.

~~This result is important for the evaluation of the karst vulnerability. The pollution vulnerability of a karst system is complex and specify to each karst system (Marin et al., 2012; van Beynen et al., 2012).~~ The knowledge of the amount and depth of water storage in epikarst provide new and quantitative information for the modeling of groundwater transfer. ~~pollution~~The epikarst is one major reservoir in pollution vulnerability ~~infiltration~~ mapping in karst hydrosystem as in the PaPRIKa (Protection of the aquifers from the assessment of four criteria: Protection, Rock type, Infiltration and Karstification degree) method for example~~For example, the~~ (Dorfliger et al., 2010). When pollution occurs, a part is immediately carried away to the spring, but another part of the pollution is stored seasonally in the first meter of unsaturated zone. ~~Most of the gravity studies in the karst (REF) demonstrate the importance of subsurface groundwater storage.~~ In particular, high water content in subsurface may facilitate the piston flow effect and accelerate the flood dynamics but not necessary the transport. The coupling between gravimetric hydrological and MRS measurements may provide significant knowledge on unsaturated aquifer pollution: Mazzilli and co-authors (2016) in the same area highlight the role of water saturation in the infiltration zone from MRS measurements.

~~PaPRIKa (Protection of the aquifers from the assessment of four criteria: Protection, Rock~~

~~Role of lithology on epikarst~~Variability of epikarst water storage ~~properties~~

Comparison of the ratio EqW versus NWI allows a quantification of the transient water storage ~~properties~~ ~~of~~in the epikarst. Significant seasonal water storage is measured at the three sites but ~~with~~different ~~the~~ associated ratio ~~are significantly different~~. Overall, ~~such~~the results confirm the role of the epikarst as an active reservoir at seasonal time scale but also highlight the heterogeneity of the karst. ~~Recharge periods of autumn and winter are weakly influenced by evapotranspiration due to low atmospheric temperature. Hence large uncertainty in the evaluation of the evapotranspiration does not critically affect the estimation of net water inflow.~~ During recharge period, EqW increase correspond to 30 % of net water inflow at SEOU and BESS sites whereas at BEAU site EqW increase is as large as 80 % of NWI.

The ~~spatial~~ variability of the ratio EqW versus NWI can be associated to a variety of factors: lithology, thickness of the unsaturated zone or depth of the measurements, thickness of the epikarst, intensity of the fracture and alteration, among ot**hers.** ~~We discuss here the variability of seasonal epikarst water storage due to thickness of the unsaturated zone, depth of the measurements and lithology can be investigated.~~**The thickness o**f unsaturated zone could be correlated with its storage capacity if~~s~~ the sto~~Therefore, one could think that a~~rage occurs on the ~~is~~whole thickness.~~ Also, one may think that a deep saturated zone could favor a fast infiltration and reduce water storage in unsaturated zone.~~ **Regarding the three sites, BESS and SEOU site have a similar EqW to NWI ratio in spite of a large difference of** unsaturated thickness, which are respectively of 40 m and 300 m. Also, BEAU and BESS site have a si~~seems~~mil~~therefore ~~ar u~~to be~~nsaturated thickness (200-300 m) but have a great difference in Eq~~ of the epikarst~~W to NWI ratio. Therefore, th~~This finding can be understood if~~ickness of unsaturated zone is not a critical factor influencing seasonal water storage c~~ as we found for BESS site~~apacity of ~~epi~~the karst.

The EqW to NWI ratio from the gravity measurements is now interpreted in the terms of karst morphology or lithology. Water storage capacity ~~seems~~in the three site is~~ to be~~ largely dependent on the kind of host rock~~ (~~: limestone for BESS (except in near surface: dolomite) and SEOU sites and dolomite for BEAU site~~)~~.

A~~lmost all~~ high ratio of the~~ seasonal~~ NWI is stored in subsurface~~the epikarst~~ in ~~of ~~the dolomite site BE~~.~~AU as expected from others studies in the same area (Fores et al., 2017). The amount of gravity variations is typical of the area and significantly larger than BESS and SEOU sites. ~~On the opposite, i~~In the compact limestone sites (BESS and SEOU), only one third of the NWI is stored. ~~A possible explanation is that dolomite could favor seasonal water storage thanks to a developed porosity. Indeed, a~~Alteration of the dolomite~~ favours~~ develops new ~~the development of ~~micro-porosity which in turn increases the reservoir properties~~ of the epikarst~~ (Quinif, 1999). E~~Also, e~~nlarged fractures associated to secondary porosity are also filled by the residuals of dolomite alteration (sand).~~ Structure only constituted by porosity is less permeable than a structure with clear fracture or opened fracture.~~ By contrast, in BESS and SEOU sites the limestone is rather characterized by a small to medium micro-porosity (characterized by core samples porosity measurements~~mudstone or packstone)~~ from 0.5 to 5 %) drained by open fractures. Only a small part on the net water inflow can be stored in the primary and secondary porosity. As a consequence, seasonal water storage capabilities of dolomite~~'s epikarst~~ is~~could be~~ more important than those of limestone~~'s epikarst~~. Unsaturated zone of dolomite karst (BEAU site) has~~could have~~ a ~~great~~large capacitive function (up to 80% of NWI) and a relatively limited transfer function. On the opposite, unsaturated zone of limestone karst system (SEOU and BESS sites) has~~could have~~ a ~~smaller~~reduce capacitive function (around 30% of NWI).

Some studies indicate that epikarst seems to have a large capacitive function and corresponds to a main seasonal stock of water (Klimchouk, 2004; Williams, 2008). ~~In line with the previous study of Jacob et al. (2009), t~~The predominant role of epikarst for water storage is confirmed by th~~is~~e S2D gravity survey and the MRS. ~~For dolomite rock, the capacitive~~

~~function of the epikarst could retain up to 80 % of water inflow. Limestone sites reveal to be less efficient for epikarst water storage. Indeed, 60% of NWI is transferred in the infiltration and/or in the saturated zone where storage could occur.~~ However, porosity is highly dependent of the type of limestone and our two sites have compact limestone. The impact of the lithology should be further studied by adding different sites in the same hydro-climatic context with complementary measurements such MRS and core samples (Mazzilli et al., 2016). ~~We also acknowledge also that the deep saturated water storage cannot be measured from S2D gravity measurements except if the survey includes surface absolute gravimeter measurements.~~From MRS mapping survey conducted by Mazzilli and co-authors (2016) in the same area, one important result is the high water content not only in the subsurface or epikarst but also in the infiltration zone, independently of the lithology. The BESS site water content profile is not typical but an exception. The main geological particularity of the BESS site is the thin top formation of dolomite above the limestone which could enhance the capacitive function of the epikarst.

Capacitive and transmissive reservoir properties

~~Surface time-lapse gravity survey highlights only storage properties of karst system (Deville et al., 2012). Surface time gravity measurements do not allow an interpretation of water transfer properties.~~ W~~However, w~~**hen** surface only **gravity time-series are associated to a** simple **hydrological model to correct surface effects (topography and building umbrella effect),**~~ one can determine~~ ~~water~~reservoir **transfer properties** (hydraulic conductivity or specific yield) can be determined (Deville et al., 2012).~~ But~~ S~~s~~**uch a** ~~study~~model **requires** continuous or frequent **gravity measurements** ~~with time-spacing lower than two months~~ **which is**~~ clearly~~ **not the case in the present study. However, due to time-lapse S2D measurements, it is possible to deduce partially** ~~water~~reservoir **transfer properties.** As gravity measurements are repeated ~~every 6 months~~seasonally, the ratios EqW versus NWI indicate if the water time transfer is larger than 6 months (or not). During the recharge period, the epikarst reservoir is filled by water fluxes from surface. As large seasonal water storage are observed such in BEAU, the transfer time of the epikarst reservoir should excess 6 months. As almost no inter-annual cycle has been observed (Deville et al., 2012) on Durzon karst system from surface absolute gravity measurements, the transfer time should be less than one year. The range of transfer time is also in accordance with the model result obtained on Durzon karst system~~ (Deville et al., 2012)~~. A long transfer time of the epikarst reservoir to the infiltration zone of about 6-12 months can be proposed for altered dolomite karst with a lack of high transmissive fractures. The characteristic transfer time is in accordance with the models fitted using continuous superconducting gravity data (Fores et al., 2017).

On the opposite, only a small part of the NWI is stored in the limestone epikarst (BESS, SEOU) after the recharge period. A short transfer time (< 6 months) in the limestone karst is therefore necessary and can be due to open fracture as observed in surface. The poorly capacitive epikarst at SEOU site is highlighted by nearby MRS measurements (near the spring 5 km away) measuring water content between 0 and 1,7 % (Vouillamoz et al., 2003). ~~*At SEOU site,*~~ Chevalier (1988) shown also with the analysis of spring during flood events that water transfer is fast between surface to spring (few days) and the major part of net water inflow is retrieved some days after rain at the spring.

Using a reservoir modeling with a classical Maillet (1905) law, ~~With an exponential decrease model of the epikarst water,~~ transfer times of 3.5 months for limestone sites (SEOU/BESS) and 13 months for dolomite site (BEAU) can be estimated~~a mean life-time of 3.5 and 13 months for the short (limestone) and long (dolomite) transfer time can be estimated~~. One can finally look at the SEOU recharge 2010 survey which has an abnormal high EqW increase (table 2). The measure was done only a few days (one day) after a heavy rainfall and a ~~major~~significant part of water from ~~fast transfer~~ rainfall is probably still present in the unsaturated zone.

5) Conclusion and perspectives

~~Our~~The time-lapse S2D methodology uses in-situ measurements in karst~~ic~~ caves during ~~the extrema of the~~a seasonal climatic cycle. ~~The~~As large volumes are investigated by gravity, small scale heterogeneities (~ 10 m) are averaged.~~ measurements scales to the depth of investigation which is here 10-50 m. This leads~~ ~~to~~Gravimetry allows investigating~~e medium~~ heterogeneities~~y~~ at intermediate or meso-scale (~100 m)~~over this spatial scale~~ well suited to further assimilation in numerical models. The three~~ studied~~ ~~areas~~sites display different morphology~~,~~ and lithology~~ and climate~~. However, a significant seasonal water storage is always ~~present~~measured. ~~Physical reservoir properties and their difference from site to site have been estimated.~~No relation between seasonal water storage amplitude and morphology of karst system (i.e. unsaturated zone thickness) has been observed. By contrast, the seasonal water storage (EqW) versus net water inflow (NWI) ratio seems to be dependent from the lithology. Especially, the alteration of the dolomite seems to enhance storage properties of the epikarst. Dolomite's epikarst seems to a greater capacitive function than limestone's epikarst. We highlight a different capacitive function between the two sites located in limestone with respect to the one embedded in a dolomite environment.~~ One explanation of these specific behaviors could be a petro-physical difference between limestone and dolomite.~~

The thickness of the epikarst has been estimated in the BESS site thanks to gravity stations regularly spaced in depth. The seasonal water storage mostly occurs in the 12 first upper meters in accordance with MRS profile. The 12 m sub-surface reservoir~~, possibly matching~~ can be identified as the high porosity zone of the epikarst and/or dolomite versus limestone changes. The limestone infiltration zone below 12 m seems to have only a transfer function. ~~Therefore, even in a relatively shallow epikarst, seasonal water storage is never negligible (about 30% of net water inflow).~~

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The transmissive function of the epikarst can be partially estimated from the gravity water storage estimations. Long transfer time in the dolomite (> 6 months) and short in the limestone (< 6 months) are observed. The study of the karst transfer function cannot be done directly from surface gravity measurements and is a clear advantage of S2D setup. The addition of an absolute gravity monitoring at the surface allow to estimate the water storage both between the surface and depth but also below the depth measurement and could give constrain on the infiltration / saturated zone.

Since the paper focus only on three sites, the results should be compared with other measurements in various karst systems to analyze more rigorously the impact of the fracture, the alteration and the lithology. Moreover, gravity observations should be combined with in-situ flux such as seepage or geophysical such as Magnetic Resonance Sounding (MRS) measurements (Mazzilli et al., 2016) in order to study the relation between groundwater storage (from MRS) and transient seasonal variations of the groundwater storage (from gravity) ~~groundwater storage (from MRS) and transient seasonal variations of the groundwater storage (from gravity)~~. These collocated measurements should lead to a better knowledge of unsaturated zone properties and processes as demonstrated for the BESS site. ~~Transfer and storage modeling could then be constrained at an intermediate scale (~100m). In order to investigate epikarst time-dependent properties, continuous gravity observatory coupled with local evapotranspiration measurements are mandatory (Fores et al., 2017).~~

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Annex 1 : *Results of the least square inversion for each site and each time periods. Results at BESS site is represented for each thickness. Strategy stands for the number of gravity measurements at the reference gravity points depending on the strategy (long or short). Recharge periods are indicated by the gray color.*

Site	Date	Strategy.	Calibration correction factor	ΔgS2D (mGal)	σ STD (mGal)
SEOU	t_1 : 24/02/2010	short	0.999377	-3.897	0.0014
	t_2 : 26/08/2010	short	0.999337	-3.914	0.0036
	t_3 : 07/10/2010	long	0.999337	-3.910	0.0014
	t_4 : 03/05/2011	long	0.999569	-3.906	0.0014
	t_5 : 13/09/2011	long	0.999569	-3.909	0.0014
BESS (0,12m)	t_1 : 01/03/2010	short	0.999377	-1.523	0.0014
	t_2 : 24/08/2010	short	0.999337	-1.537	0.0028
	t_3 : 01/10/2010	long	0.999337	-1.531	0.0014
	t_4 : 05/05/2011	long	0.999569	-1.528	0.0022
	t_5 : 06/09/2011	long	0.999569	-1.537	0.0014
BESS 12, 23m)	t_1 : 01/03/2010	short	0.999377	-1.320	0.0014
	t_2 : 24/08/2010	short	0.999337	-1.320	0.0022
	t_3 : 01/10/2010	long	0.999337	-1.322	0.0014
	t_4 : 05/05/2011	long	0.999569	-1.317	0.0020
	t_5 : 06/09/2011	long	0.999569	-1.320	0.0014
BESS (23, 41m)	t_1 : 01/03/2010	short	0.999377	-1.724	0.0022
	t_2 : 24/08/2010	short	0.999337	-1.724	0.0022
	t_3 : 01/10/2010	long	0.999337	-1.728	0.0014
	t_4 : 05/05/2011	long	0.999569	-1.726	0.0010
	t_5 : 06/09/2011	long	0.999569	-1.727	0.0014
BESS (41, 58m)	t_1 : 01/03/2010	short	0.999377	-1.277	0.0028
	t_2 : 24/08/2010	short	0.999337	-1.275	0.0028
	t_3 : 01/10/2010	long	0.999337	-1.272	0.0014
	t_4 : 05/05/2011	long	0.999569	-1.275	0.0014
	t_5 : 06/09/2011	long	0.999569	-1.273	0.0014