Review of “Synergy between satellite observations of soil moisture and water storage anomalies for global runoff estimation”

We thank the Topical Editor (TE) for their supportive review. In the following, the author replies (AC, blue lines) to the TE comments (red lines) are reported.

TEC: Comments and replies

Dear Dr. Camici and co-authors,

Thank you for your response to the referee comments. I am sending it out for re-review, and am also attaching the following comments of my own, which I would like you to address alongside any new referee comments.

TE1: Please remove all references to future work. We cannot know the future. I think that you can communicate the same and/or similar points about applicability without invoking your specific future plans.

AC: Any references to future works have been removed in the revised manuscript. Specifically, Lines 472-473 of the manuscript:

“A more in-depth investigation about the model calibration procedure and the regionalization of the model parameters will be carried out in future studies.”

have been modified as (see Lines 490-492 of the revised manuscript):

“A more in-depth investigation about the model calibration procedure, with special focus on the regionalization of the model parameters, should be carried out but this topic is beyond the scope of the manuscript.”

Line 569:

“However, this aspect is beyond the paper purpose and it will conveniently be addressed in future works.”

has been modified as (see Lines 587-589 of the revised manuscript):

“As this aspect requires additional investigations and it is beyond the paper purpose, it will not be tackled here.”

Lines 594-599:

“The application of the STREAM v1.3 model on a larger number of basins with different climatic- physiographic characteristics (e.g., including more arid basins, snow-dominated, lots of topography, heavily managed) will be object of future studies and it will allow to investigate the possibility to regionalize the model parameters and overcome the limitations of the automatic calibration procedure highlighted in the discussion section.”

have been modified as (see Lines 614-618 of the revised manuscript):

“The application of the STREAM v1.3 model on a larger number of basins with different climatic- physiographic characteristics (e.g., including more arid basins, snow-dominated, lots of topography, heavily managed) would permit to investigate the possibility to regionalize the model parameters and overcome the limitations of the automatic calibration procedure highlighted in the discussion section.”

TE2: It does not make sense to me why the inclusion of a tributary would actually cause the model to overestimate discharge. Rather, it seems that it would cause a discharge underestimate (but not including some additional inflow).

AC: I think the TE is referring to the overestimation of river discharge over section 7 and to the author reply to comment n.3 of RC2.

In the reply to RC2, the authors would underline that in section 7 there is not an overestimation of river discharge rather than an uncorrected river discharge simulation.

The reason of this uncorrected river discharge simulation over this section is likely due to the fact that the STREAM v1.3 model is calibrated with respect to the river discharge observed in section 6 (see Figure below or Figure 3 in the manuscript). Section 7 is located at the closure section of basin 41, a small portion of the entire basin closed to section 6 (green-colored basin). In this case, the characteristics of the basin 41 could be different from the ones of the entire basin closed to section 6 and this could be the cause of the incorrect river discharge estimation.

We hope that this reply has resolved the TE's doubts.

This aspect has been better specified in the revised manuscript (see Lines 477-482 of the revised manuscript):

“Over section 7, located over the Rock river, a relatively small tributary of Mississippi river (see Table 1), the STREAM v1.3 model overestimation has to be attributed to: 1) the different characteristics of the Rock river basin with respect to the entire basin closed to section 6 where the model has been calibrated (see Figure 3); 2) the small size of the Rock river basin (23’000 km^2, if compared with GRACE resolution, 160’000 km^2) for which the model accuracy is expect to be lower.”

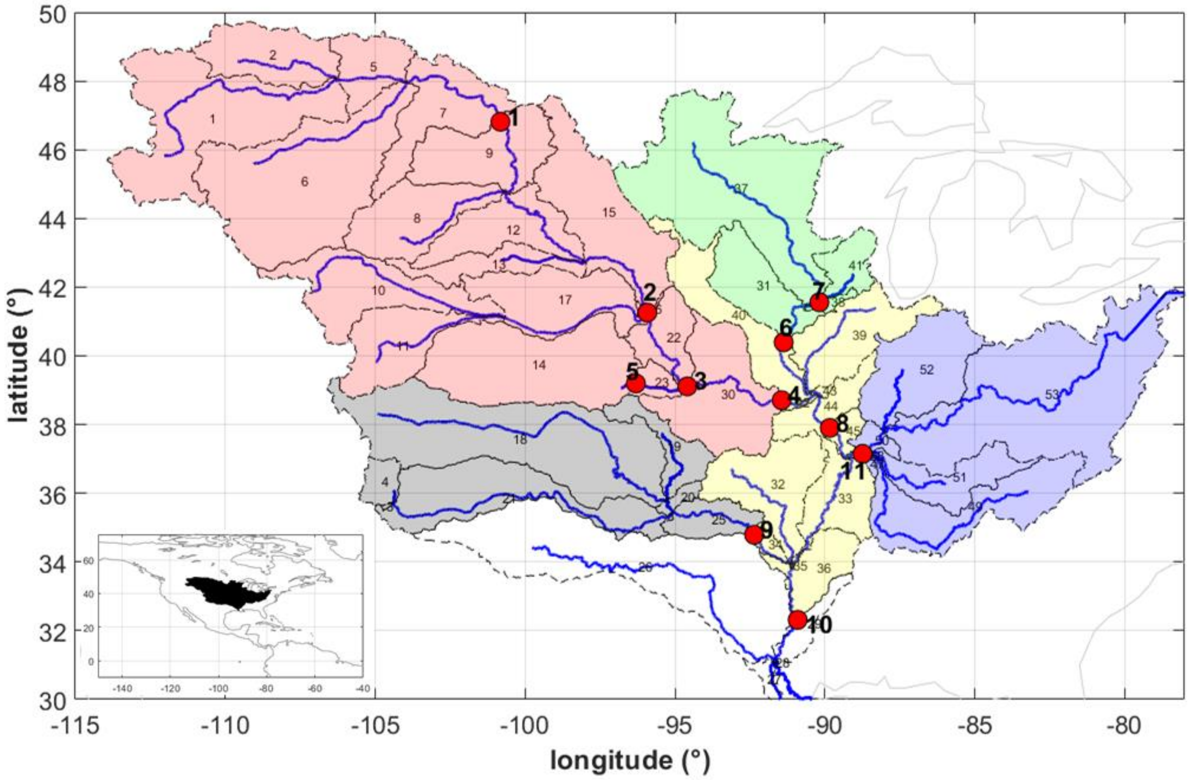


Figure: Mississippi sub-basin delineation. Red dots indicate the location of the discharge gauging stations; different colours identify different inner sections (and the related contributing sub-basins) used for the model calibration

TE3: The dams on the Mississippi are run-of-the-river dams. They do not have significant storage, nor do they substantially affect the discharge. I suggest that you take this into account when discussing the errors.

AC: We are aware that most of the dams along the Mississippi are run-of-the-river and they do not substantially affect the discharge. However, the dams which we are referring to in section 1 and 2 are the Garrison and Gavins dams (see Table 1), with a maximum storage of 29’383×10^9 and 0.607×10^9 m^3, respectively. As an example, the figure below by Skalak et al. (2013) represents the river discharge time series recorded at Bismark (section 1 in the manuscript) from 1930 to 2010. After the Garrison dam construction, a strong impact on river discharge is evident.

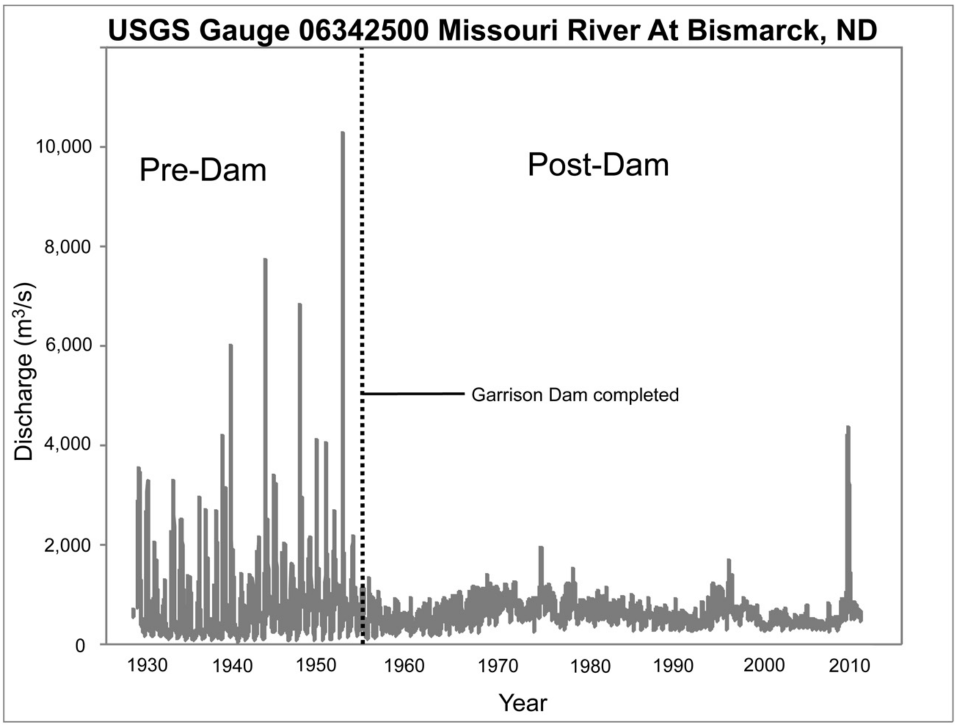


Figure: Hydrograph for the stream gage at Bismarck (USGS 06342500). The year the Garrison Dam was completed is indicated separating pre- and post-dam flows. There is an increase in baseflows and decrease in peakflows as a result of the dam (by Skalak, K. J., Benthem, A. J., Schenk, E. R., Hupp, C. R., Galloway, J. M., Nustad, R. A., & Wiche, G. J. 2013. Large dams and alluvial rivers in the Anthropocene: The impacts of the Garrison and Oahe Dams on the Upper Missouri River. Anthropocene, 2, 51-64.).

This aspect has been specified in the manuscript, Lines 169-170 have been modified as follows (see Lines 170-176 of the revised manuscript):

The basin is also heavily regulated by the presence of large dams (Global Reservoir and Dam Database GRanD, Lehner et al., 2011) most of them located on the Missouri river. In particular, the river reach between Garrison and Gavins Point dams is the portion of the Missouri river where the large main-channel dams have the greatest impact on river discharge providing a substantial reduction in the annual peak floods, an increase on low flows and a reduction on the overall variability of intra-annual discharges (Alexander et al., 2012)."

Lines 194-196 have been modified as follows (see Lines 199-204 of the revised manuscript):

"As it can be noted, mean annual river discharge ranges from 141 to 17'500 m^3/s, and 3 out 11 sections are located downstream big dams (Lehner et al., 2011). In particular, Garrison (the fifth-largest earthen dam in the world), Gavins Point and Kanopolis dams located downstream section 1, 2 and 5 respectively (see Figure 3 and Table 1), are three large dams with a maximum storage of 29'383×10^9 m^3, 0.607×10^9 m^3, and 1.058×10^9 m^3 respectively.

An additional remark has been added to Lines 467-475 of the revised manuscript:

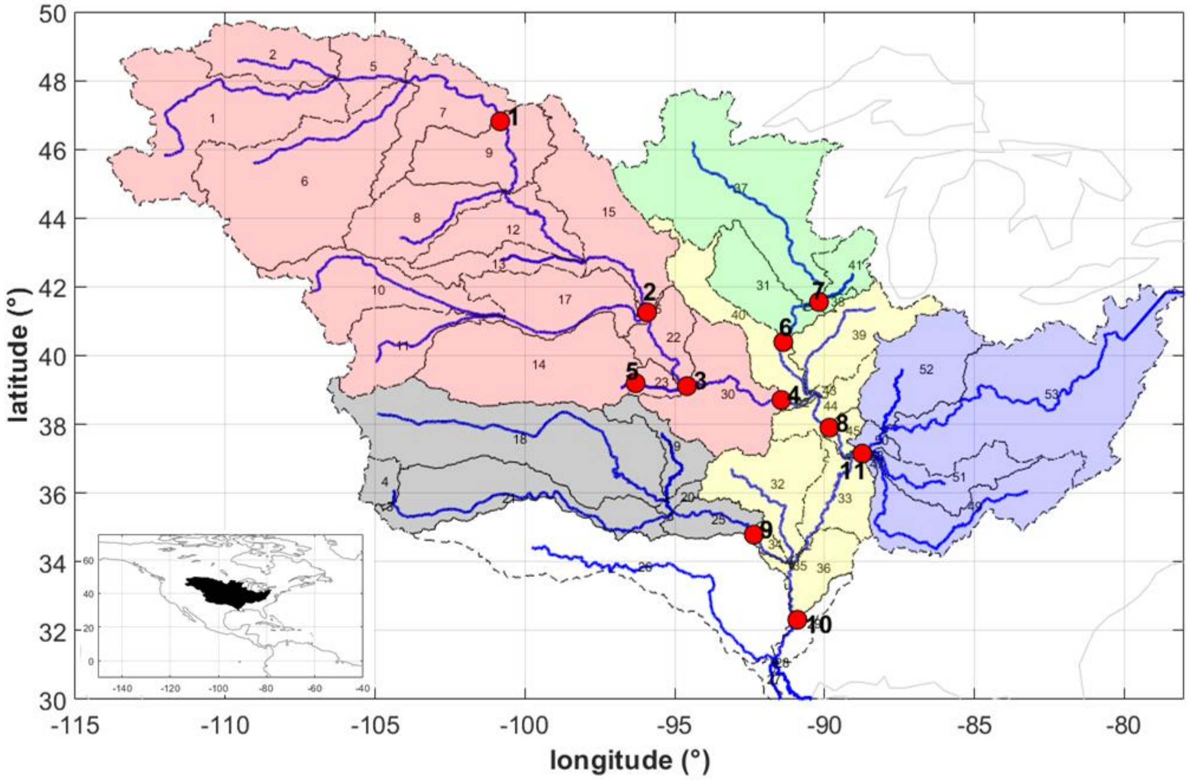
"In particular, for river sections 1 and 2 even if KGE reaches values equal to 0.35 and 0.40 (for the whole period), respectively, there is not a good agreement between observed and simulated river discharge and the R score is lower than 0.55 for both river sections. The worst performance is obtained over section 5, with negative KGE and low R (high RRSME). These results are certainly influenced by the presence of large dams located upstream to these river sections (i.e., Garrison, Gavins Point and Kanopolis dams, see Table 1) which have a strong impact on discharge: the model, not having a specific module for modelling reservoirs, is not able to accurately reproduce the dynamics of river discharge over regulated river sections.”

REFERENCE:

Alexander, J. S., Wilson, R. C., and Green, W. R.: A brief history and summary of the effects of river engineering and dams on the Mississippi River system and delta (p. 53), US Department of the Interior, US Geological Survey, https://doi.org/10.3133/cir1375, 2012.

TE4: Point 7 on Fig. 3 appears to be behind the semi-transparent basin polygon. It is also substantially north of Keokuk, IA. Some numbers on this figure are obscured. Please clean it up and fact-check it.

AC: Figure 3 has been improved according the TE suggestion.



TE5: This is a point that I raised initially: Your notes about snowfall indicate mountainous regions, and yet a significant fraction of the snowmelt comes from the northern lowland regions in the Mississippi River watershed. Could you look through your article and double check that you are including a proper description of the hydrology, rather than applying some a priori assumptions that may come out of experiences in Europe?

AC:According the TE suggestion, we modified the description of the Mississippi river basin hydrology as follows:

The river flow has a clear natural seasonality mainly controlled by spring snowmelt (coming from the Missouri and the Upper Mississippi, the eastern and the upper part of the basin, respectively, Dyer 2008) and by heavy precipitation exceeding the soil moisture storage capacity (mostly occurring in the eastern and southern part of the basin, Berghuijs et al., 2016). The basin is also heavily regulated by the presence of large dams (Global Reservoir and Dam Database GRanD, Lehner et al., 2011) most of them located on the Missouri river. In particular, the river reach between Garrison and Gavins Point dams is the portion of the Missouri river where the large main-channel dams have the greatest impact on river discharge providing a substantial reduction in the annual peak floods, an increase on low flows and a reduction on the overall variability of intra-annual discharges (Alexander et al., 2012).

Anyway, we would like to outline that the basin description does not impact the model results (driven by observation of precipitation, temperature, soil moisture and terrestrial water storage anomalies)

REFERENCES:

Dyer, J.: Snow depth and streamflow relationships in large North American watersheds, J. Geophys. Res., 113, D18113, https://doi.org/10.1029/2008JD010031, 2008.

Alexander, J. S., Wilson, R. C., & Green, W. R. (2012). A brief history and summary of the effects of river engineering and dams on the Mississippi River system and delta (p. 53). US Department of the Interior, US Geological Survey.

TE6: As such, I would also like you to re-address RC3, Line 262: The grid size of your model IS appropriate to simulate much of the snow in the northern reaches of the Mississippi basin, and the upper Mississippi above Keokuk (IA) contains significant snow. (I wonder if this might relate to some of the observed discrepancy between model and data noted in RC2, Comment 3.)

AC: Thanks for this comment. In our reply to RC2, comment 3 we meant that the scale of the model is not suitable for comparison against in situ point-scale snow observations (unless they would cover the 25 km pixel with hundreds of them which is not the case here)

However, in the manuscript we could evaluate the impact of snow on runoff. To do so and to in depth analyze the observed discrepancy between model and data noted in RC2 comment 3, we should select a snow-dominated basin and run the model with and without the snow module. Accordingly, we selected the basin closed to section 7 (basin 41 in Figure 3) and we calibrated the STREAM v1.3 model with and without the snow module. We obtained a good agreement against observed data (KGE=0.71) both by including or not the snow module as shown in the Figure below.

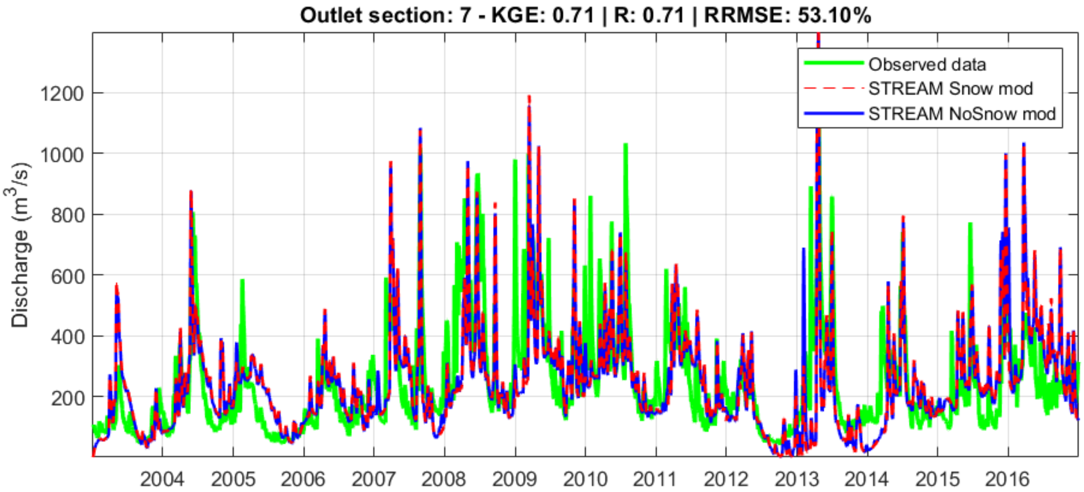


Figure: Comparison between observed (green line) and simulated river discharge data at the outlet section 7, by including (red dashed line) or not (blue line) the snow module in the STREAM v1.3 model.

This result indicates that:

1) the snow impact on runoff cannot be easily distinguished in the sections selected in the paper;

2) the uncorrected river discharge simulation over section 7, shown in the paper, is due to the "uncorrected" model parameters associated to basin 41. Likely, the characteristics of this basin are different from the ones of the entire basin closed to section 6 where the model has been calibrated (see reply to TE2).

This last point has been stressed in Lines 477-482 of the revised manuscript:

"Over section 7, located over the Rock river, a relatively small tributary of Mississippi river (see Table 1), the STREAM v1.3 model overestimation has to be attributed to: 1) the different characteristics of the Rock river basin with respect to the entire basin closed to section 6 where the model has been calibrated (see Figure 3); 2) the small size of the Rock river basin (23'000 km2 , if compared with GRACE resolution, 160'000 km2) for which the model accuracy is expect to be lower."

TE7: "Although the mascon size is smaller than the inherent spatial resolution of GRACE, the model exhibits a relatively high spatial resolution." It is highly resolved, yes, but I wonder if you are discussing accuracy more than resolution? Could you explain this a bit more?

AC: Sure. We would be happy to expand on this. Here, we are indeed discussing the spatial resolution of the model. A high spatial resolution of the model is attributed to an application of a Wiener filter. This filter makes use of full covariance matrices of noise and signal in GRACE data. The filter ensures that a minimal smoothing is applied to GRACE data. To that end, it exploits noise and signal covariance matrices in the spatial domain. The filtering is performed in the spatial domain, too. It is done in line with these noise and signal covariance matrices. This means that the higher signal-to-noise ratio in a particular area, the less smoothing is applied and the vice versa. This way, the filter avoids an aggressive smoothing when it is not necessary. This leads to a higher spatial resolution of the model. This is discussed in details in (Klees et. al 2008), where evidences of a higher spatial resolution as a result of an application of such a filter are provided, too. We have now briefly incorporated these remarks in the updated manuscript and lines 222-226 in the manuscript:

"This is attributed to a statistically optimal Wiener filtering, which uses signal and noise covariance matrices. The coloured (frequency-dependent) noise characteristic of KBR data was taken in to account when compiling the model, which has allowed for a reliable computation of these noise and signal covariance matrices."

have been reformulated into the following (see Lines 227-235 of the revised manuscript):

"This is attributed to a statistically optimal Wiener filtering, which uses signal and noise full covariance matrices. This allows the filter to fine tune the smoothing in line with the signal-to-noise ratio in different areas. That is, the less smoothing, the higher signal-to-noise ratio in a particular area and vice versa. This ensures that the filtering is minimal and aggressive smoothing is avoided when unnecessary. Further details of such a filter can be found in (Klees et. al 2008). Importantly, the coloured (frequency-dependent) noise characteristic of KBR data was taken in to account when compiling the GRACE model, which has allowed for a reliable computation of the aforementioned noise full covariance matrices."

REFERENCE:

Klees, R., Revtova, E.A. , Gunter, B.C. , Ditmar, P., Oudman, E., Winsemius H.C., and Savenije H.H.G.: The design of an optimal filter for monthly GRACE gravity models, Geoph. J. Intern., 175 (2): 417–432, https://doi.org/10.1111/j.1365-246X.2008.03922.x, 2008.

TE8: Regarding RC3, Line 520: Could you please dig a bit deeper to address this question about human activities and GRACE, including looking into published works on reservoirs and GRACE? I realize that there is a large scale gap (so the spatial resolution will be poor) but these reservoirs can be quite significant -- as can human activities that affect soil moisture and groundwater storage.

AC: We checked the literature and we found support to our to RC3, Line 520 reply. Indeed, Longuevergne et al. (2013) or Deggim et al. (2021) clearly explain that GRACE can "see" mass changes due to large human controlled reservoirs or natural lakes with strong (seasonal) variations and/or trends. Specifically, Longuevergne et al. (2013) wrote:

"Virtually all reservoirs are point masses at the spatial resolution of GRACE. For example, a large reservoir with a typical surface area of ~ 1000 km^2 (Garrison reservoir in the Mississippi is 1500 km^2) is about two orders of magnitude less than that of the smallest basin (~ 200 000 km^2) that can be typically resolved by GRACE observations. The precision of GRACE observations allows detection of 1 cm TWS change within a 200'000 km^2 basin (= 2 km^3 TWS change). This is comparable in mass (hence detectability) to a 2 m water level change within a 1000 km^2 reservoir".

However, they specify that "it has not been clear how small scale and/or discontinuous distributions of water sources affect basin-scale average water storage changes typically estimated from GRACE data". The main problem is that the mass changes do not necessarily appear exactly at the location of their origin and with the correct magnitude. Thus, they can distort the water storage estimate for neighbouring areas or the average over a river basin (Deggim et al., 2021).

For that, the use of GRACE data to take into account the human activity or the water extraction practices over a basin is not straightforward. A possible solution to address this problem is try to disentangle the reservoir/lakes impact on GRACE or use the RECOG RL01 product ad hoc developed by Deggim et al. (2021). However, this aspect is beyond the paper purpose.

REFERENCES:

Longuevergne, L., Wilson, C. R., Scanlon, B. R., & Crétaux, J. F. (2012). GRACE water storage estimates for the Middle East and other regions with significant reservoir and lake storage. Hydrol. Earth Syst. Sci. Discuss, 9(10), 11-131.

Deggim, S., Eicker, A., Schawohl, L., Gerdener, H., Schulze, K., Engels, O., ... & Longuevergne, L. (2021). RECOG RL01: Correcting GRACE total water storage estimates for global lakes/reservoirs and earthquakes. Earth Syst. Sci. Data, 13, 2227–2244. https://doi.org/10.5194/essd-13-2227-2021.