REGIONAL WATER BALANCE ANALYSIS OF KARSTIC AREAS BY REMOTE SENSING

Ines Vidmar[1], Mihael Brenčič[1,2]

[1] Department of Geology, Faculty of Natural Sciences and Engineering, University of Ljubljana, ines.vidmar@ntf.uni-lj.si

[2] Geological Survey of Slovenia

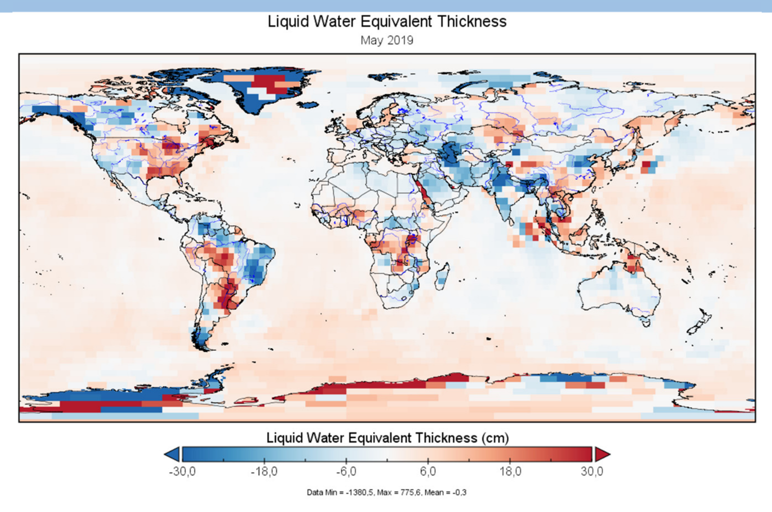

Figure 1 : Global liquid water equivalent (LWE) for May 2019 based on 0.5° mascon data

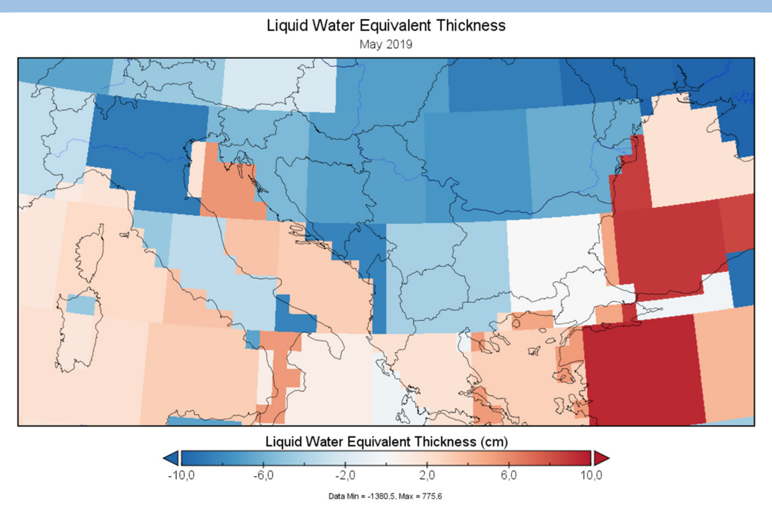

Figure 2 : May 2019 LWE based on 0.5° mascon data for the Balkan Penninsula

INTRODUCTION

Sustainable exploitation of water resources calls for management with a wider perspective. To avoid the overuse or depletion of groundwater, a detailed knowledge of present and projected stresses to aquifers is needed with a consideration of spatial and temporal components of variation.

Knowledge on storage variability can offer researchers and managers insight into the processes and water balance of an aquifer or aquifer systems that can prove to be useful in the long run. In karstic areas, especially where terrain is difficult to reach, ground observation networks are not an appropriate solution to acquire data on storage so remote sensing proves to be a welcome alternative. Current satellite gravimetric observations are an opportunity to monitor the water balance of larger regions but they do limit the research scale to only regional problems.

Recent global karstic potable water analyses have shown that despite their unstable hydrological regimes and higher vulnerability to pollution, karstic aquifers still represent a significant share of water supply where they are widely present (Stevanović, 2019). One such case is the Dinaric karst region covering the northwestern part of the Balkan Penninsula from Italy to Albania (Figure 3).

Analysis of groundwater variability in a karstic-fractured aquifer of Dinaric karst is presented for a continuous 19-year period using the GRACE and GRACE-FO satellite observations. They are available freely and publicly online in the form of total water storage (TWS) time series for global coverage as the liquid water equivalent (LWE) product. This data has been analysed in terms of their temporal and spatial coverage with the goal of a detailed analysis of water storage variaton of the Dinaric Karst aquifer in the last 2 decades. This could prove to be a useful and novel water balance method for use in regional karstic hydrogeological analyses.

Figure 3 : Digital elevation model of the wider area of Dinaric Karst

SATELLITE-BASED GRAVIMETRIC WATER BALANCE METHOD

Since 2002, GRACE (Gravity Recovery and Climate Experiment) satellite has been acquiring precise data on the Earth's gravity through an innovative system measuring the distance between two instruments during their path around the Earth which changes due to the Earth's gravity (Figure 4). These measurements are the basis for the most precise geoid model yet, however they also enable research of the processes that affect the gravity field in smaller time scales, which include the water mass movements of the planet.

The measurements of distance between the two satellites as they orbit the Earth are performed with microwave K-band ranging system with 2 frequencies (24 GHz K-band and 32 GHz Ka-band) and from the newer GRACE-FO mission that replaced the older in 2018 with an additional laser ranging system with an increased accuracy (Cooley et al., 2019).

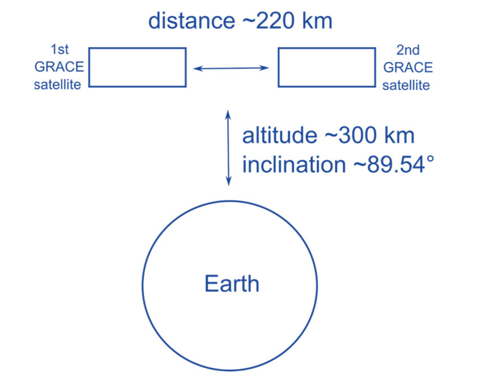

Figure 4: GRACE mission satellites' position and measurements

Before the data is available for water balance analyses, the measurements are preprocessed by data research centres in the USA and Europe correcting and isolating the observations by using other types of measurements and models.

During this preprocessing phase, ionospheric correction is performed and non-gravitational accelerations are removed, such as the impact of air drag and solar radiation pressure. To isolate the water gravity signal, solid Earth and oceanic tides, selected secular variations, pole-tide effects, and a combination of atmospheric pressure variations as well as the response of a barotropic ocean model driven by ECMWF (European Center for Medium-Range Weather Forecasts) models of atmospheric pressure and winds (Tapley et al., 2004) are used.

Apart from improving the geoid model, GRACE gravity data has also been used in other scientific fields (hydrology, oceanography, cryology) to monitor and analyse flood potential, drought, ice mass, sea level, earthquakes, weather, and groundwater variability and depletion. This is possible after removing signals from GRACE gravity data coming from other sources so only the selected dominant signal remains evident in the monthly gravity estimates (Tapley et al, 2004).

Terrestrial water variations that can be used for groundwater variation analysis are publicly and freely available as Liquid Water Equivalent (LWE) product with a monthly temporal resolution. Groundwater variability and depletion based on GRACE data has already been studied globally (Döll et al., 2014; Richey et al., 2015) or in specific regions (Rodell et al., 2009; Longuevergne et al., 2010).

There is no vertical resolution of GRACE's data, so in order to separately observe the variation of a particular hydrologic cycle component (for example groundwater), the vertically integrated water storage signal needs to be disaggregated either by assumptions (neglecting other components) or modelling based on other observations (Longuevergne et al., 2010). One such model is GLDAS NOAH (Figure 9).

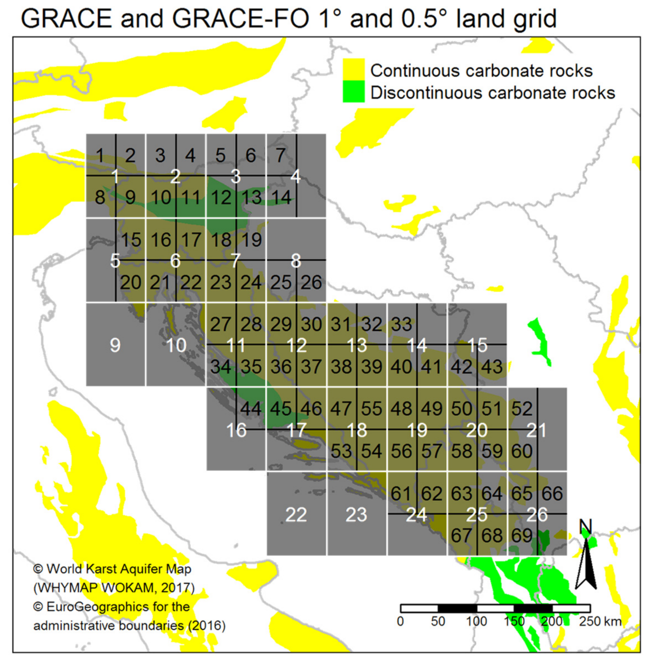

Figure 5 : GRACE and GRACE-FO grid coverage of the wider area

SPATIAL VARIATION

Spatial variation of LWE was analysed by plotting the values of LWE in the selected grid cells covering the wider area of Dinaric Karst. Figure 6 shows 6 examples of the 1 ° CSR solution from the available time period of LWE data where the left figures show the maps of LWE with a common color scheme for the whole time period, and the right figures adapt the color schemes for each individual month so they show variation even if it is quite small according to all of the data range.

Based on the 177 monthly CSR 1 ° averages, the maximal difference between the grid cells for the same monthly value is 12.49 cm, the minimal is 1.09 cm while the mean difference is 3.92 cm. For the GFZ 1° solutions, the differences are similar with a slightly smaller minimal difference; the maximum difference is 12.28 cm, the minimal 0.77 cm and the mean difference is 4.07 cm. For the JPL solutions of the same resolution, the maximum difference is smaller (9.45 cm) while the minimal difference is between the CSR and GFZ solutions (0.97 cm). The mean difference of same monthly values for JPL 1°solution is similar to GFZ and CSR (4.01 cm).

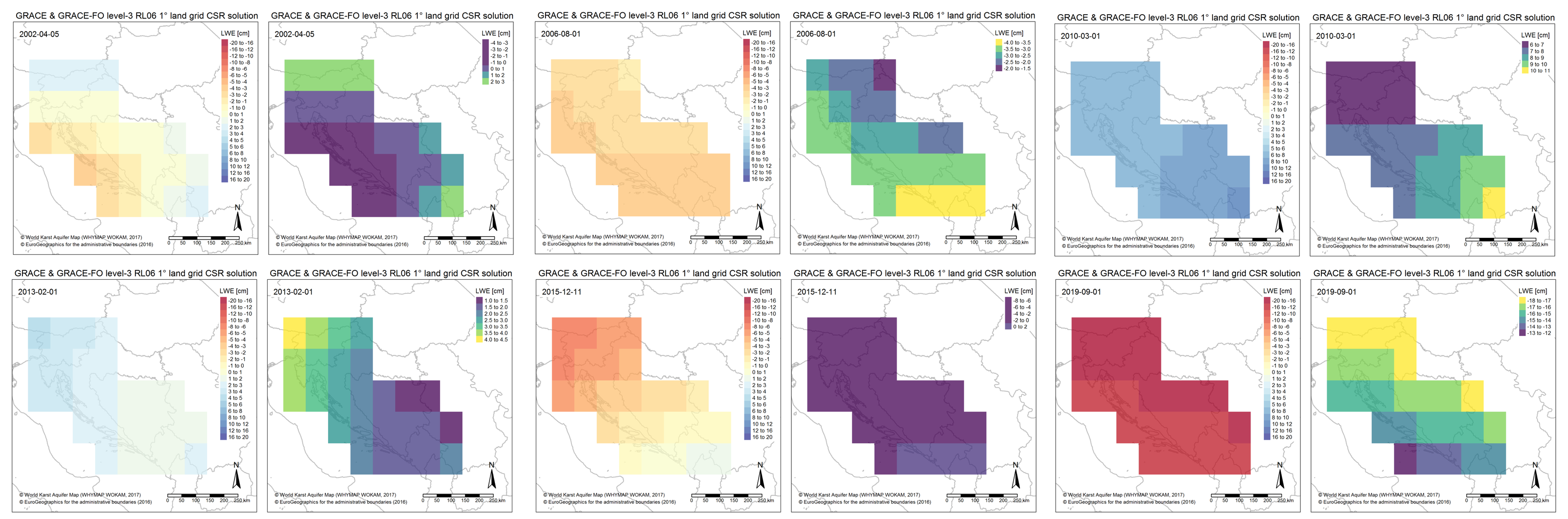

Figure 6 : GRACE and GRACE-FO grid coverage of Dinaric Karst and the wider area

RESULTS

Time series of 1° resolution grid cells were plotted for the three data centres solutions: JPL, CSR and GFZ (Figure 7). They differ because of the slightly different values of parameters used during the preprocessing phases by the three different data processing centres. The differences between the three data centers' LWE solutions for 1° grid cell with the center at 14.5 latitude and 45.5 longitude are small and visible when comparing the statistical measures of the time series data. The total range of variation reaches 29.554 cm in the JPL solution, 29.968 cm in the CSR and 28.285 cm in the GFZ solution. The minimum value is the lowest in the case of the GFZ solution and reaches -14.849 cm, while it is -15.788 cm in the JPL and -16.669 cm in the CSR solution. The mean and maximum values are the most similar between different solutions; the mean values range from -1.154 to -1.012 cm and the maximum from 13.298 cm to 13.765 cm.

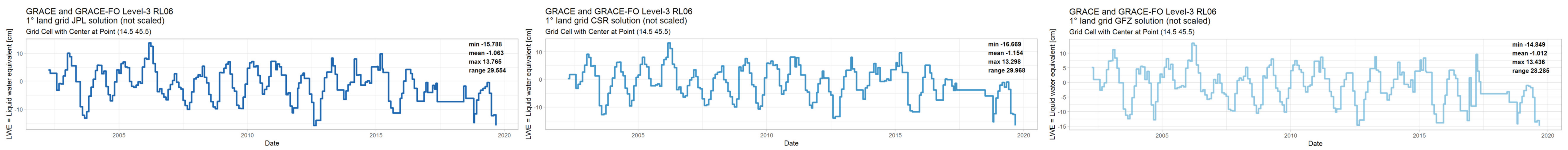

Figure 7 : Time series of 1-degree JPL, CSR, GFZ solutions

LIQUID WATER EQUIVALENT VARIATION

An example of a selected grid cell covering the south of Slovenia and northwest of Croatia (cell number 6 in Figure 5) is representative for all 26 of the analysed 1° grid cells. The differences in values between the three different solutions show that GFZ solution yields the highest mean values that are 1-2 mm higher than CSR mean values for each grid cell time series and either 1 mm higher or the same as JPL solution. Mean values from CSR solution are mostly 1 mm lower than in JPL solution.

Looking at the cell-by-cell grid time series, CSR has higher ranges of data than GFZ in the northwest while the situation is reversed in the southeast. The same relationship is present between GFZ and JPL solutions. Differences in range between GFZ and CSR and between GFZ and JPL do not exceed 1,8 cm. The range of data is more similar between CSR and JPL, on average, JPL has a 3 mm higher range, although CSR can be higher than JPL in some cases, but the difference is maximally 1 cm.

GFZ has higher maxima than CSR when analyzing the grid cells one-by-one in almost all cases, except for the 3 most western cells which have either the same or 1 mm lower maximum. All other cells show higher GFZ maximum values with an increase toward the east up to the difference of 1,9 cm. JPL solution grid series maxima are also higher than CSR, this time in all grid cells. Unlike the CSR and GFZ, the JPL solution maxima reach differences with CSR that are slightly lower (to 1,2 cm) but are higher than differences between the first two solutions in the west. GFZ maxima are higher than JPL maxima in the west while the situation is reversed in the east. In both cases, the differences reach only 7 mm.

GFZ solution minimal cell grid series values are mostly lower (up to 1,9 cm) than in CSR except in 3 cases when they are the same or higher for 1 mm, but they are mostly higher (up to 1,2 cm) than in JPL solution, especially in the western part of the selected area where they are up to 7 mm lower. CSR minima are mostly lower than JPL without an apparent spatial pattern.

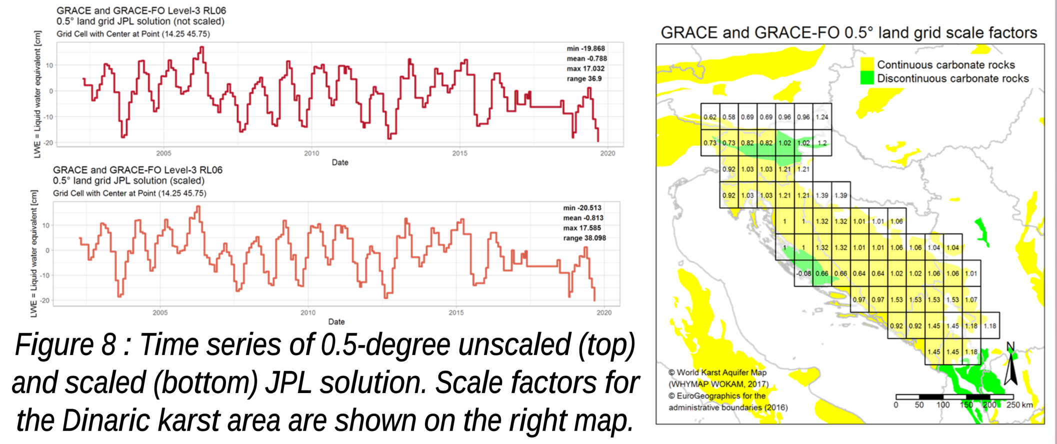

Figure 8 : Time series of 0.5-degree unscaled (top) and scaled (bottom) JPL solution. Scale factors for the Dinaric karst area are shown on the right map.

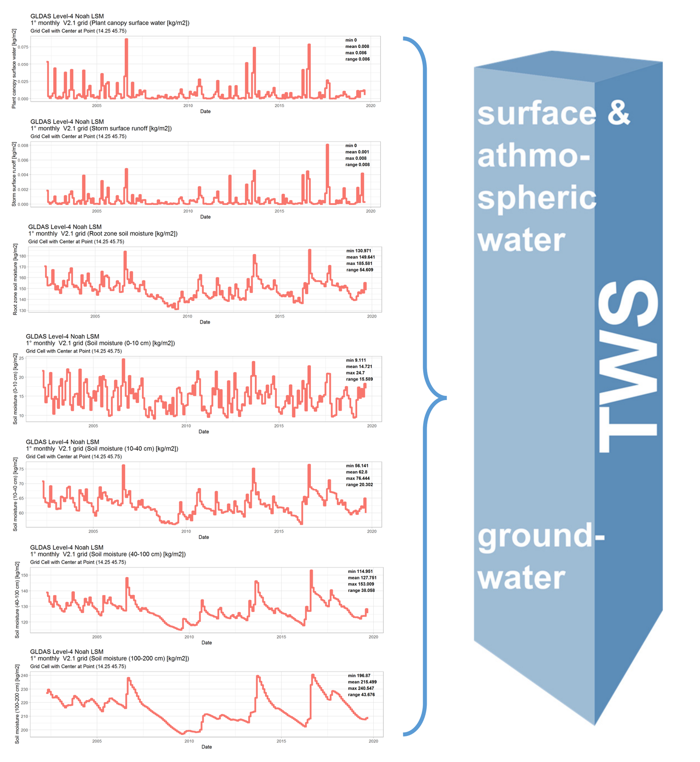

Figure 9 : Disaggregation of total terrestrial water storage (TWS) variation into surface water, atmospheric water and groundwater variation components by using GLDAS NOAH land surface model data

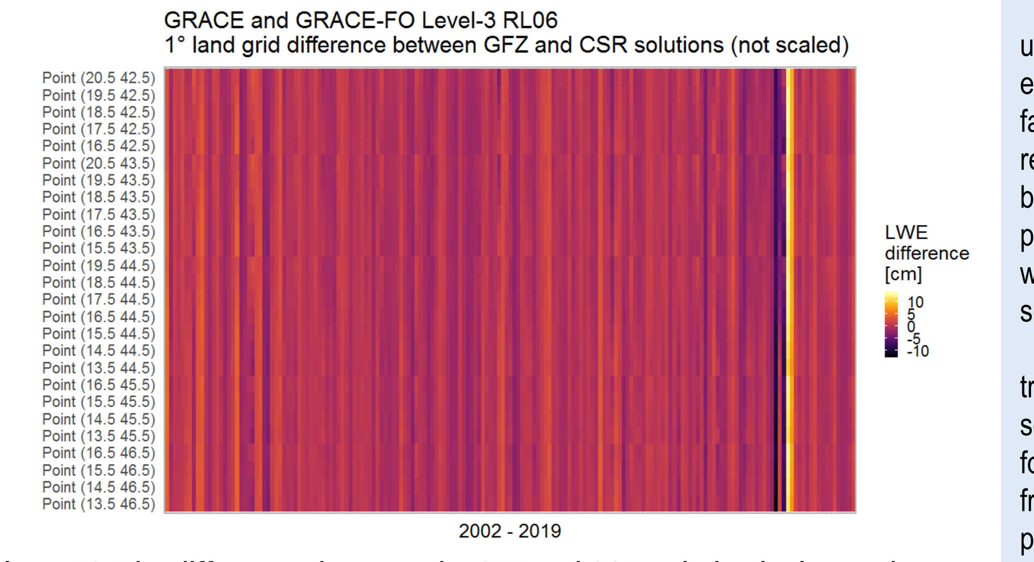

Figure 10: The differences between the GFZ and CSR solution in time and space

SCALE FACTORS AND TRENDS

Simulations of terrestrial water storage variations from land-hydrology models were used to produce gain factors (Landerer & Swenson, 2012), included in the data to remove errors leading to uncertainty because of measurement and signal leakage errors. Gridded-gain factors estimated as a function of temporal frequency restore signal amplitudes which were removed in the filtering process which is most useful for seasonal variation analysis of specific basins. In the Dinaric karst region, the scale factors range from -0.08 to 1.53. They are mostly positive and around 1, the only negative value is for the land grid cell at Šibenik (Croatia) where almost half of the cell is covered by the Adriatic Sea (Figure 8). The differences in scaled and unscaled time series for a grid cell with a scale factor 1.03 are shown on Figure 8.

Preliminary trend analysis using the linear model fit found no pronounced long-term trends in any of the analysed grid cell time series using either scaled or unscaled data. The seasonal variation component is, however, visible in the data and warants an in-depth analysis for the available time period of the last 19 years. The time series data may also show a larger frequency variability than only seasonal and will also be analysed during the following research phases by using additional model fits, such as loess or polynomial (Figure 11).

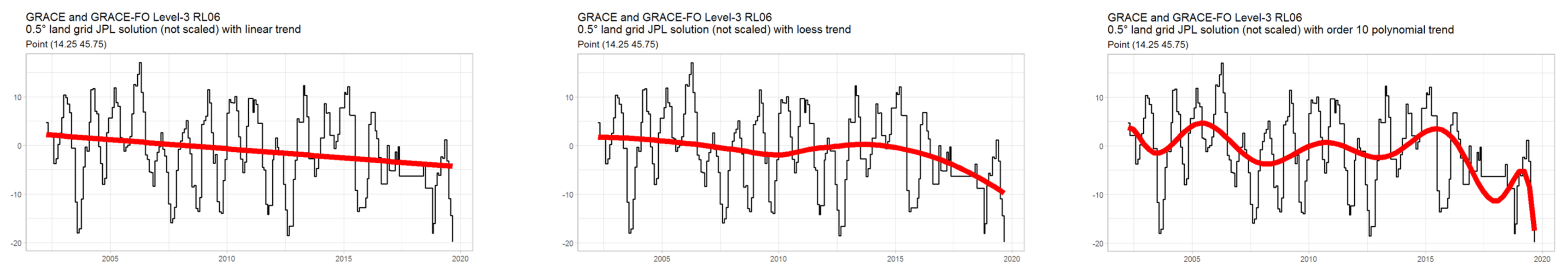

Figure 11: Three trend fits to the GRACE time series data: linear (left), loess (midle) and polynomial (right)

CONCLUSIONS

- Preliminary data analysis for Dinaric Karst shows the storage variability between approximately ±30 cm relative to the average of the 2004-2009 period without a prominent long-term trend.
- There are only minor differences between the different 1° grid cell solutions. Certain leakage errors are corrected with the use of scale factors for 0.5°grid cells in certain parts of the aquifer, although the majority of the multiplicative factors for use in seasonal variation hydrological studies are around 1.
- Vertical disaggregation of total water storage will need to be verified with the use of ground observations and other model storage determinations. Here, the NOAH land surface model data could provide data for several of the surface water and atmospheric water components with the goal of isolating the groundwater variability signal, which is assumed to be the strongest in karstic areas.
- The data offers the possibility of identifying areas of Dinaric karst with different patterns of groundwater variability. These results could present a basis for improving the water balance monitoring of an important international water source while offering a new method for water balance analysis for other regional karstic aquifers as well.

SOURCES

COOLEY, S. S., LANDERER, F. W. 2019 GRACE D-103133 Gravity Recovery and Climate Experiment Follow-on (GRACE-FO) Level-3 Data Product User Handbook. NASA Jet Propulsion Laboratory, California Institute of Technology, March 27, 2019.

DÖLL, P., MÜLLER SCHMIED, H., SCHUH, C., PORTMANN, F. T. & EICKER, A. 2014. Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modeling with information from well observations and GRACE satellites. Water Resources Research, 50, 5698-5720, doi: 10.1002/2014WR015595.

LANDERER, F. W. & SWENSON, S. C. 2012. Accuracy of scaled GRACE terrestrial water storage estimates. Water Resources Research, 48, W04531, doi:10.1029/2011WR011453.

LONGUEVERGNE, L., SCANLON, B. R. & WILSON, C. R. 2010. GRACE Hydrological estimates for small basins: Evaluating processing approaches on the High Plains Aquifer, USA. Water Resources Research, 46, W11517, doi:10.1029/2009WR008564.

RICHEY, A. S., THOMAS, B. F., LO, M. H., REAGER, J. T., FAMIGLIETTI, J. S., VOSS, K., SWENSON, S. & RODELL, M. 2015. Quantifying renewable groundwater stress with GRACE. Water Resources Research, 51, 5217-5238, doi: 10.1002/2015WR017349.

RODELL, M., VELICOGNA, I. & FAMIGLIETTI, J. S. 2009. Satellite-based estimates of groundwater depletion in India. Nature, 460, 999-1002, doi:10.1038/nature08238.

STEVANOVIĆ, Z. 2019. Karst waters in potable water supply: a global scale overview. Environmental Earth Sciences (2019) 78:662 doi: 10.1007/s12665-019-8670-9.

TAPLEY, B. D., BETTADPUR, S., RIES, J. C., THOMPSON, P. F. & WATKINS, M. M. 2004. GRACE measurements of mass variability in the Earth system. Science, 305, 503-505, doi: 10.1126/science.1099192.