Fundamental methods from satellite gravimetry to the Global Gravity-based Groundwater Product (G3P)

Lecture Notes

June 30, 2021

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1. Groundwater on a global setting

Groundwater is the most abundant freshwater resource on the planet: it provides almost half of all drinking water worldwide, about 40% of water for irrigated agriculture and about one third of water required for industry, with more than two billion people depending on groundwater as primary water resource (Famiglietti 2014). It sustains ecosystem and maintains the baseflow of rivers. Groundwater is a critical storage element for climate-change adaptation, and it prevents land subsidence and seawater intrusion. In many regions of the world, groundwater is the decisive factor for agricultural productivity, as it is heavily used for irrigation.

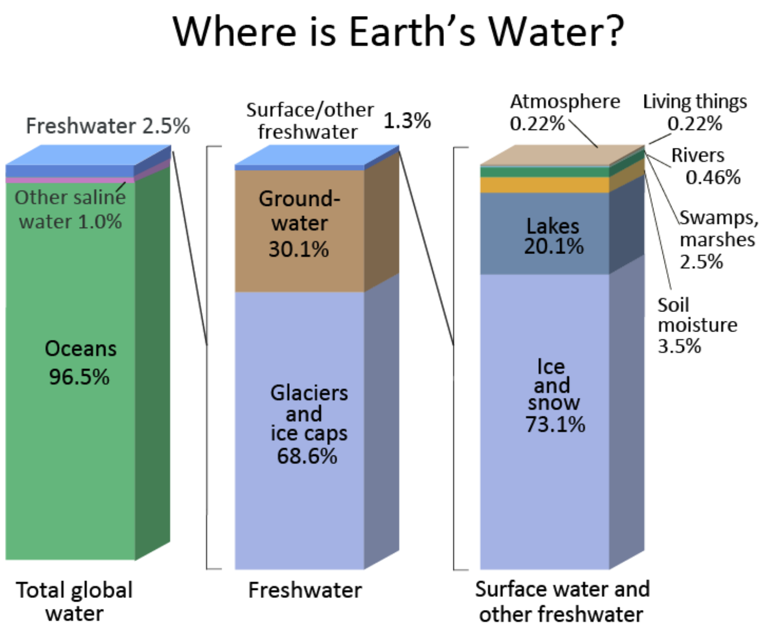


Figure 1 – Distribution of Earth's water. Source: USGS 2021, adapted from Shiklomanov 1993.

Despite its global importance, aquifers are often insufficiently understood and poorly managed. Overexploitation and climate change poses additional stresses on water resources including groundwater. Particularly vulnerable are those areas already affected by water scarcity.

Groundwater management decisions rely on an adequate monitoring at representative places and with a proper frequency. This is difficult to achieve party due to its obscure nature – a resource hidden below the Earth's surface – but also due to the lack of resources (human and economic) to conduct monitoring activities in many areas of the world.

The depletion of groundwater does not only impact freshwater availability but has also numerous serious consequences to all groundwater dependent socio-economic and ecological systems. Typical examples include agricultural productivity, land subsidence, sea level rise, seawater intrusion in estuaries and coastal aquifers, loss of springs and wetlands, ecosystem degradation, regional climate feedbacks following reduced evapotranspiration, and even political unrest.

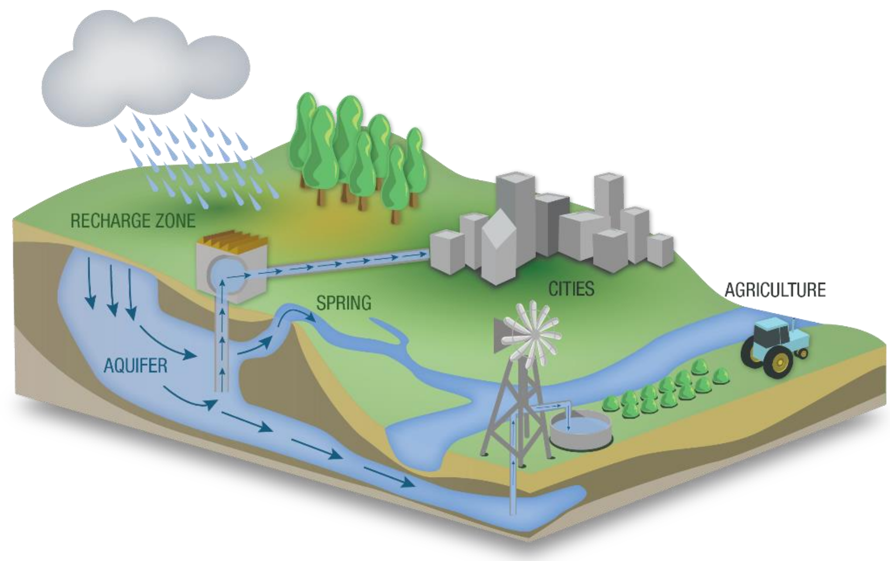


Figure 2 – The water cycle. Source: The hidden resource. Source: Texas Living Waters Project, 2018.
https://texaslivingwaters.org/bestbets/groundwater.html

Due to its fundamental value, groundwater is now considered as an Essential Climate Variable (ECV) by the Global Climate Observing System (GCOS). This evidences the importance of providing a consistent quantification of groundwater changes based on observed data and a global coverage.

2. Groundwater monitoring and its limitations

State of aquifers (both quality and quantity of groundwater) is changing in time due to change of various environmental processes (e.g. change of precipitation pattern) and human impacts (i.e. change of land cover, groundwater abstraction). Groundwater assessment is not complete and no predictions can be made without an analysis of historical measurements (change in time).

Groundwater is monitored around the world by measuring groundwater levels, groundwater abstraction rates, spring discharge and groundwater quality. Globally, there is no sufficient knowledge about the state and trends of groundwater resources, primarily due to insufficient monitoring and limited accessibility to monitoring data/outcomes.

Monitoring of groundwater is more challenging than monitoring of surface water (river and lakes): initial investments (e.g. drilling a borehole) are larger, spatial representativeness of monitoring points (due to hydrogeological heterogeneity) is smaller and assistance of remote sensing (so helpful to surface water observations) is limited. However. The use of satellite gravity-based measurements as means to determine water storage variations represents an opportunity to changes on groundwater storage for large aquifers (Tapley et al. 2004), especially in areas where in-situ groundwater monitoring networks are not available or where data is scarce. It is in this context where the new Global Gravity-based Groundwater Product (G3P) can assist to monitor groundwater storage change on a global scale.

Figure 3 – Screenshot of the groundwater monitoring wells stored in the Global Groundwater Monitoring Network (GGMN). https://ggis.un-igrac.org/view/ggmn

3. A new product : the Global Gravity-based Groundwater Product (G3P)

G3P is introduced in this lecture as a new tool to try to fill the gap in groundwater monitoring in large aquifers around the world based on satellite technology.

The G3P project aims at determining global groundwater storage variations based on satellite gravity data with monthly resolution from 2002 to today, for large aquifers and global coverage (except Antarctica and Greenland). Groundwater storage variations and anomalies will be provided in units of water volume (km^3), with a spatial resolution of 0.5 degree (~55 x 55 km) and as area-average time series for large aquifers and river basins.

Some other of the intended application of G3P are to:

- Enhance and develop datasets of various hydrological components.
- Create awareness about groundwater depletion by improving the understanding of groundwater stresses around the world
- Compare results with existing products (e.g. Groundwater Drought Indicator from NASA[1])
- Estimate historical changes on groundwater storage
- Contribute to improving global hydrological and hydrogeological models: G3P could be integrated into global models to improve the representation of groundwater in those models. For instance,

[1] https://gracefo.jpl.nasa.gov/resources/55/groundwater-drought-indicator/

the global hydrological model PCR-GLOBWB 2 includes a groundwater component based on MODFLOW[2] which could be improved by integrating G3P results in it.

4. How does G3P works?

G3P will be developed by a cross-cutting combination of data from the German-American Gravity Recovery and Climate Experiment (GRACE) and GRACE-Follow On (FO) satellites with water storage data that are based on the existing portfolio of the Copernicus services[3].

GRACE and GRACE-FO are the name of the two satellite missions that map Earth's gravity field monthly with a spatial resolution of a few hundred km. The mission consists of two identical satellites at an orbital altitude of about 450 km and separated by an average of 220 km, but constantly changing due to the varying attraction of masses on the surface and inside the Earth. Figure 4 shows that the distance between spacecrafts remains relatively constant over the ocean, but land's higher gravity pulls the two spacecraft away from each other. The measure of Earth's gravity is based on the ultra-high precision measure of the relative distance between the satellites, which is highly sensitive to the variations of the gravity field. Repeated observations are turned into mass-gravity anomalies mainly caused by water movements, from which total water storage variations (TWS) can be estimated (Figure 5). With more than 15 years of data from the past GRACE (2002-2017) and the current GRACE-FO (since 2018) mission, both the mean seasonal climatology of groundwater variations as well as the long-term change of groundwater storage due to climate change or human exploitation can be assessed.

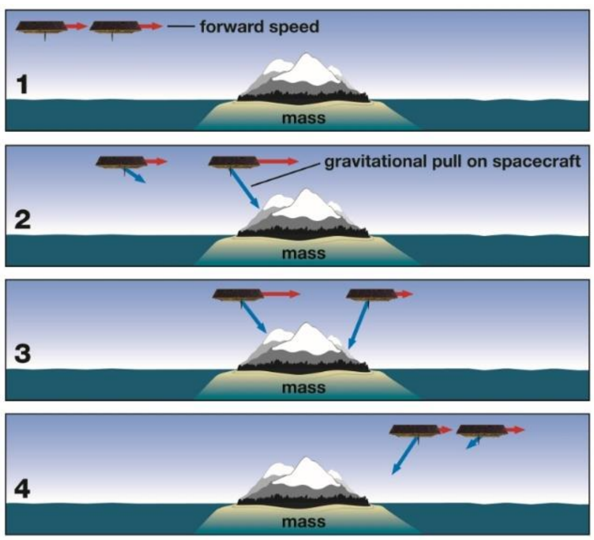


Figure 4 - https://gracefo.jpl.nasa.gov/resources/50/how-grace-fo-measures-gravity/

[2] https://globalhydrology.nl/research/models/pcr-globwb-2-0/

[3] *"Copernicus is the European Union's Earth observation programme looking at our planet and its environment. It offers information services that draw from satellite Earth Observation and in-situ (non-space) data." Source: https://www.copernicus.eu/en*

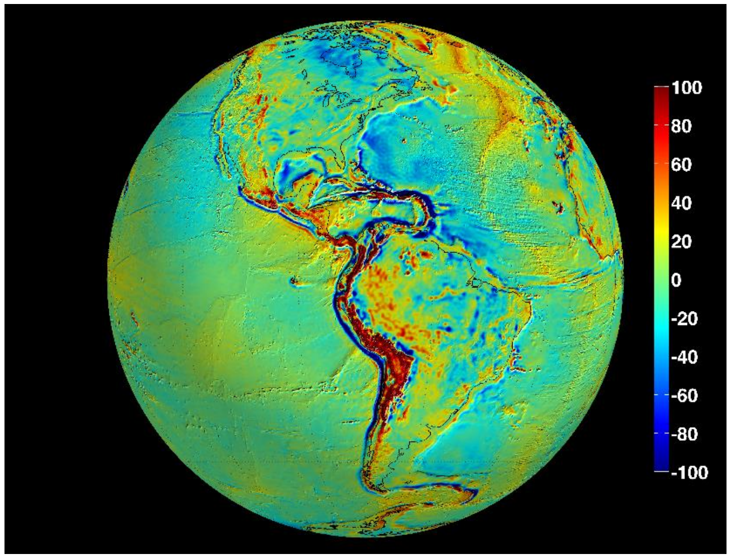


Figure 5 - Static Gravity Field Anomalies. This figures shows the so-called free air gravity deviations from an ideal ellipsoidal Earth model, in units of milli-gal (https://gracefo.jpl.nasa.gov/resources/10/static-gravity-field-anomalies/)

TWS as observed by GRACE/GRACE-FO (without the explicit notion of storage change which applies to each term) is the sum of several storage compartments (Chen et al. 2016): groundwater, soil moisture, snow, ice, and surface water bodies (Figure 6).

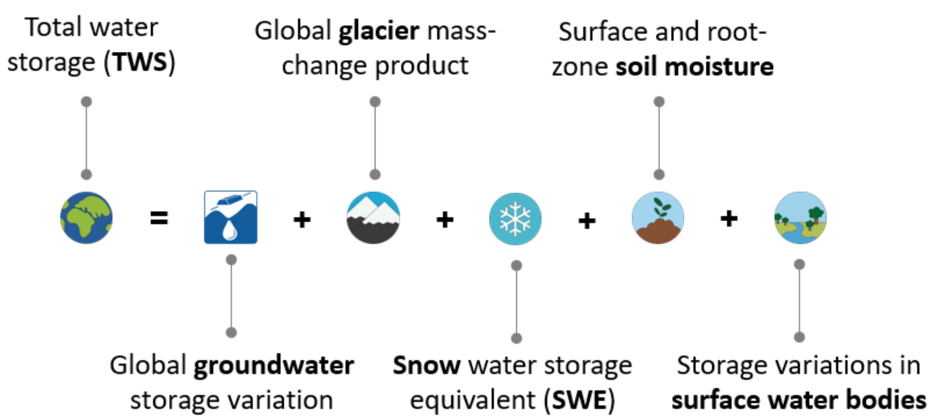


Figure 6 – Total Water Storage as the sum of several water compartments.

To resolve for groundwater storage changes, storage variations in the other storage compartments must be quantified and subtracted from TWS. This approach has been applied to studies in the past, e.g. Güntner et al., 2007.

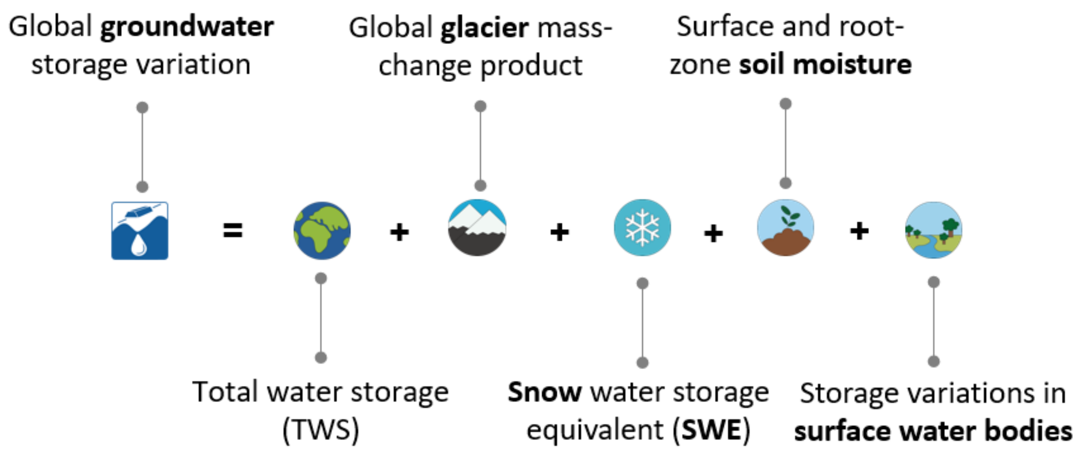


Figure 7 – Global groundwater storage variation as the result of the subtraction of each terrestrial water compartment from TWS

5. How to obtain each water compartment?

Besides ΔTWS data estimated through the processing of GRACE/GRACE-FO satellite gravity data, other storage compartments are quantified based on data collected via the Copernicus service and to a lesser extent on models.

All observation-based data sets of complementary water storage compartments required for the subtraction process from TWS to groundwater storage are generated within the G3P consortium (see Table 1 for an overview). Where necessary because of data gaps, e.g., due to inability of a particular observation-based method to generate the required data for particular conditions, data from simulation results of hydrological models or global land surface models are additionally taken into account and merged with the observation data. This is the case for:

- Snow water equivalent in mountainous areas.
- Soil moisture under dense vegetation in the tropics, and in snow/ice-covered or frozen areas.
- Lake water storage for lakes not observed/observable by the altimetry method. This method is introduced in section 2.4.

Table 1 shows further details on the data used for the quantification of the different storage compartments.

Table 1 – Overview on compartmental water storage data used and processed in G3P

	Source: Earth observation data (EO) or model (M)	Existing Copernicus service product	Development in G3P	Spatial coverage, resolution	Temporal resolution
Snow	EO	Snow water Equivalent in Global Land	Extension to global coverage	Northern hemisphere, 5 km	Daily
Glacier mass changes	EO	C3S glacier extents, elevation changes and mass changes.	Combination of C3S glacier services.	Global, 1 degree.	Annual, seasonal
Soil Moisture	EO + M	Surface soil moisture in C3S	Soil Water Index for the unsaturated zone	Global, 0.25 degree	Daily, 10-daily and monthly aggregates
Lake and reservoir storage	EO	Lake levels in Global land monitoring Service	Combination of lake surface and water level	Global coverage for large lakes	Daily to monthly
River network storage	EO + M	None	Assimilation of altimetry into model	Danube, Niger, Condo	Daily
River network storage	M	GloFAS	None	Global	Daily
Snow soil moisture Lake/reservoir storage	M	GloFAS	None	Mostly 0.5 degree, global	Daily or higher

5.1. Total Water Storage (TWS)

To obtain TWS from raw GRACE/GRACE-FO data, raw Level 1b data will be processed to generate user-adapted Level 3 data of TWS variations (Figure 8).

GRACE data are divided into the following levels: Level-0, Level-1A & Level-1B, Level-2 and Level-3.

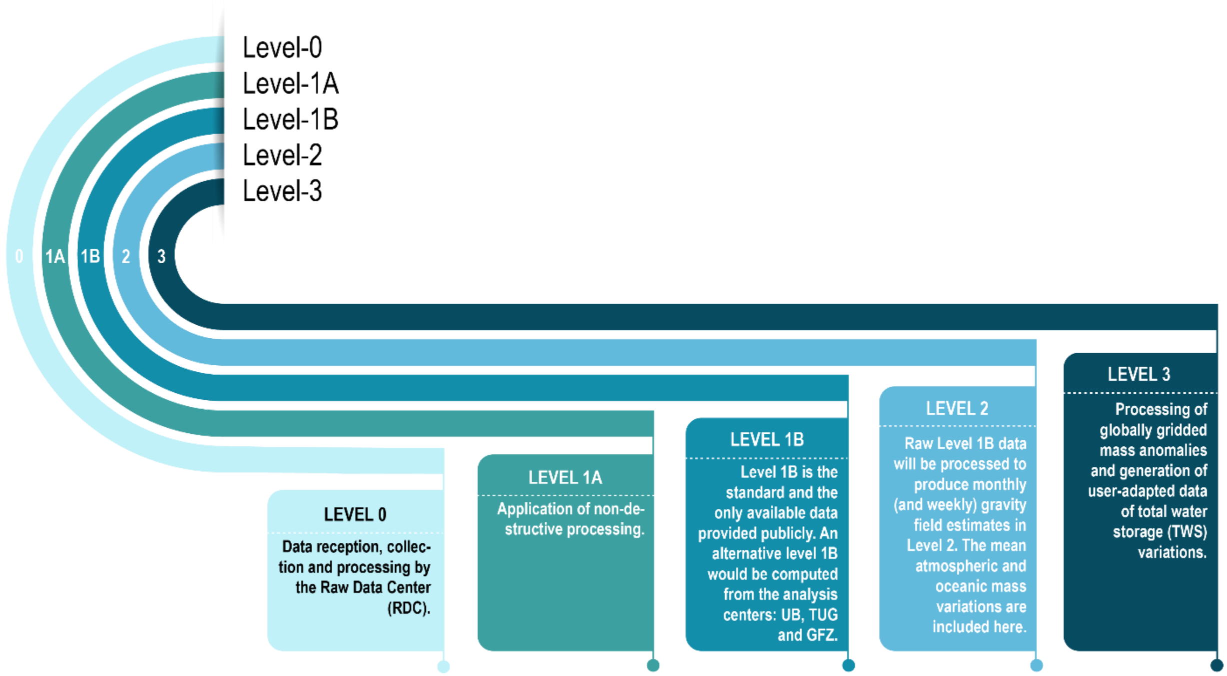


Figure 8 – GRACE/GRACE-FO data levels

Level-0 data is the result of data reception, collection and processing by the Raw Data Center (RDC) located in Neustrelitz/Germany.

Level-1A data products are the result of a non-destructive processing applied to the Level-0 data, i.e. a processing that does not overwrite the original data. The sensor calibration factors are applied to convert the binary encoded measurements to SI base units.

Level-1B data are produced when Level-1A data undergo an extensive processing and are converted to edited and cleaned data products, which is done by the Propulsion Laboratory (JPL). JPL Level-1B are the standard and the only available data provided publicly. However, Level-1A will be also provided by the G3P project to enable the production of alternative Level 1B data.

Level 2 data corresponds to Level-1 data that has been processed, to produce monthly (and weekly) gravity field estimates. This level also includes data sets of mean atmospheric and oceanic mass variations which are necessary to interpret time variability in gravity field solutions.

Level 3 corresponds to the last processing step to convert data in a TWS product.

Three GRACE/GRACE-FO analysis centers (UB, TUG, GFZ) are involved to perform the different processing steps at each data level, but also to capitalize from different processing strategies for GRACE/GRACE-FO data into an optimally combined TWS product and assess the errors in TWS estimates.

5.1.1. Alternative Level-1B Processing: Processing of individual sensor datasets

Input: GRACE/GRACE-FO Level 1A data ➡ Output: Alternative GRACE/GRACE-FO Level-1B data

From an instrumentation point of view, GRACE-FO is an evolution of GRACE with modernizations due to both experience from the GRACE mission and overall technical improvements. The updates on GRACE-FO compared to the predecessor include improved and additional measurements. Therefore, it is essential to implement data handling and processing routines tailored to these new data. As mentioned before, for the first time Level-1A data products will be publicly available to all processing centers, in addition to pre-processed Level-1B data products. The accessibility to Level-1A allows to exploit additional information within the data, but also to enhance treatment of instrument specific error sources. In this way, Level 1A data could be used to produce an alternative Level-1B data that can be compared to the officially available Level-1B. The derived data products will then be cross-validated with the official Level-1B data from JPL.

5.1.2. Level 2: Processing of global monthly gravity fields

Input: Alternative GRACE/GRACE-FO Level 1B data and standard JPL Level 1B data ➡ Output: Three different series (one of each Analysis Centers (AC)) of monthly gravity field solutions (Level-2 data)

Through rigorous and independent processing approaches based on the latest processing standards and background models of the latest operational release, the analysis centers will compute gravity field solutions (Level 2 products) using both the standard Level 1B and the alternative Level 1B data. The long-term stability of the time-series will be also validated by comparing the GRACE/GRACE-FO gravity measurements with gravity measurements obtained from other sources, namely Satellite Laser Ranging data and/or satellite altimetry over glaciated regions.

5.1.3. Combination of Level-2 Products from different ACs

Input: Monthly gravity field solutions, GRACE solutions from already existing releases ➡ Output: Combined monthly gravity field solutions

Combining the Level-2 products from different ACs, where each of which performs independent analysis methods but employs consistent processing standards, will significantly increase the quality, robustness, and reliability of the monthly gravity field solutions. This process will be carried out using Combination Service of Time-variable Gravity field models (COST-G).

COST-G operationally delivers combined monthly gravity field solutions derived from GPS positioning with cm-precision and inter-satellite K-Band ranging with micrometer-precision. The K-band ranging (KBR) system is the radio frequency front-end of the satellites. It is the key science instrument of GRACE/GRACE-FO which measures the dual one-way range change between both satellites with a precision of about 1 µm per second.

5.1.4. Level-3 Data: Processing of globally gridded mass anomalies

Input: Combined monthly gravity field solutions ➡ Output: Globally gridded monthly estimates of TWS based on GRACE and GRACE-FO gravity field information including its spatially correlated and time-variable uncertainties (Level-3 data).

The calculation of Level-3 TWS products consists in using the global gravity field models obtained from GRACE/GRACE-FO sensor data and subsequently transform them into gridded TWS anomalies, also called globally gridded mass anomalies.

Mass signatures not related to the continental hydrosphere will be removed by means of background models and/or empirical estimates obtained from time-series of gravity fields available so far. The related uncertainties will be provided at 1° global grids. Data of individual and combined products will be validated with independent observational data.

5.2. Quantification of storage compartments

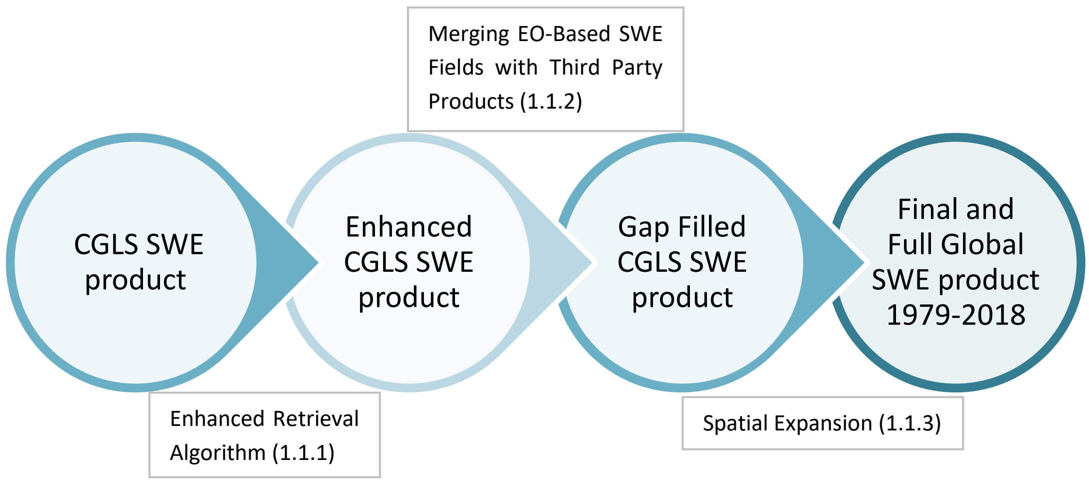
The quantification of glaciers, snow, soil, and surface water bodies storages will be generated using operational Copernicus service products that will be further developed and adapted for the subtraction process from TWS. This refers in particular to the full spatio-temporal coverage of all data sets and to error estimates.

5.2.1. Snow Water Equivalent (SWE) Product Development

The snow water equivalent (SWE) describes the amount of liquid water in the snowpack that would be formed if it were completely melted. SWE is an important measure of availability of water resources since it relates to the runoff of rivers and variations in groundwater levels. The snowpack that accumulates during the winter has a significant role in groundwater recharge during spring. In turn, water stored in the snowpack is one component that needs to be removed from TWS in order to resolve for groundwater storage in higher latitudes and mountainous regions across the world. However, a global-scale observation-based harmonized product on Snow Water Equivalent (SWE) does not yet exist. To address this issue, currently existing data products will be extended, methods and lessons learnt from earlier projects will be utilized, and a harmonized data product with global coverage will be produced. The final product will be generated by developing the Copernicus Global Land service (CGLS) SWE[4] retrieval approach for satellite based SWE retrieval (Takala et al. 2011). Three key steps will be carried out:

- The development of an enhanced SWE retrieval algorithm,
- the merging Earth Observation (EO)-Based SWE Fields with Third Party Products, and
- the spatial expansion of the SWE Product.

[4] https://land.copernicus.eu/global/products/swe



Development of an Enhanced SWE Retrieval Algorithm

Input: CGLS SWE product ➡ Output: Enhanced CGLS SWE product

- The retrieval methodology will combine satellite passive microwave measurements[5] with ground-based weather station observations.
- The retrieval algorithm enhancements include improved emission modelling through the utilization of an advanced model (i.e. taking into account the presence of sub-grid lake ice and an improved forest transmissivity model).
- Out of this process, a temporally and spatially variable snow density field will be developed.
- A sensitivity analysis to assess the influence of land cover variability on snow depth and effective grain size used within the retrieval process will also be carried-out to increase the preciseness of the product.

Merging EO-Based SWE Fields with Third Party Products

Input: Enhanced CGLS SWE product ➡ Output: Gap Filled CGLS SWE product

The next step consists in filling the gaps of the Enhanced Copernicus Global Land Service SWE just developed. To do so, it is proposed to use Snow Extent (SE) measurements and EO-based SWE estimates to reach full coverage.

According to the Copernicus Global Land Service, SE is highly sensitive to changes in temperature (freezing/thaw) and precipitation (snowfall, rain, hail). Snow stores a significant mass of water and has a strong effect on regional and global energy and water cycles. Up-to-date knowledge about the snow cover extent is an important information for hydrological runoff modelling, together with the Snow Water

[5] *"All objects emit microwave energy of some magnitude, but the amounts are generally very small. A passive microwave sensor detects the naturally emitted microwave energy within its field of view" Source:* https://www.nrcan.gc.ca/maps-tools-publications/satellite-imagery-air-photos/remote-sensing-tutorials/microwave-remote-sensing/9371

Equivalent (SWE) product from passive microwave sensors, that provides information on the water content in the snow on plain areas, with limitations in mountainous areas.

More specifically, the passive microwave's technique used within CGLS SWE for the snow detection scheme has a proneness to uncertainty during the snow melt season and will thus be replaced by a SE product. Further data gaps that need addressing occur in mountain areas, and this will be covered by using Earth Observation- based SWE estimates with Land Surface Model (LSM) SWE fields.

Spatial Expansion of the Snow Water Equivalent (SWE) Product

Input: Gap Filled CGLS SWE product ➡ Output: Full Global SWE product 1979-2018

The final step will be to reach full global spatial coverage, meaning to extend to full Northern Hemisphere and full Southern Hemispheric coverage. This will be done by expanding to full global spatial coverage the current CGLS SWE by using data series from 1979 to 2018.

5.2.2. Combination of Copernicus Climate Change Services (C3S) into global glacier mass-change product with annual updates

Input: C3S glacier extent, C3S glacier elevation changes, C3S glacier mass changes ➡ Output: global glacier mass-changes, 19 RGI[6] regions, annual from 1961-2016, and then 2017-2021

Glaciers distinct from the Greenland and Antarctic Ice Sheets cover an area of approximately 706 000 km² globally (RGI 2017) with an estimated total volume of 170 000 km³, or 0.4 m of potential sea-level rise equivalent (Huss and Farinotti 2012). Retreating and thinning glaciers are icons of climate change and impact regional runoff as well as global sea level (Bojinski et al. 2014). The World Glacier Monitoring Service (WGMS), hosted at the Department of Geography of UZH, oversees compiling standardized data on glacier changes in length, area, volume, and mass (WGMS 2017). Starting in 2017, the WGMS was integrating a global glacier inventory (RGI 2017) as well as glaciological and geodetic mass change series with annual updates (WGMS 2017), and earlier reports, into the C3S Climate Data Store. Based on these datasets, Zemp et al. (2019) developed a new method to combine the temporal variability from the glaciological sample with the glacier-specific values of the geodetic sample. The new approach allowed assessing annual glacier mass changes from 1961 to 2016 for all glacierized regions as well as the corresponding contribution to global sea-level rise, including corresponding uncertainties.

For our purpose the Zemp et al. (2019) approach will be further developed to

1. <u>Provide annual updates for glacier mass-change estimates:</u> The regional mass changes from Zemp et al. (2019) as reference dataset for the period 1961 to 2016 and the annual updates from the glaciological observation network of the WGMS will be used. Related uncertainties will be included based on new glaciological measurements after 2016: for each year after 2016 the observational bias of the glaciological sample over the reference period will be assessed and

[6] *The Randolph Glacier Inventory is a global inventory of glacier outlines. Source: https://www.glims.org/RGI/*

provide an estimate of the regional and global glacier mass changes until a new global re-assessment becomes available.

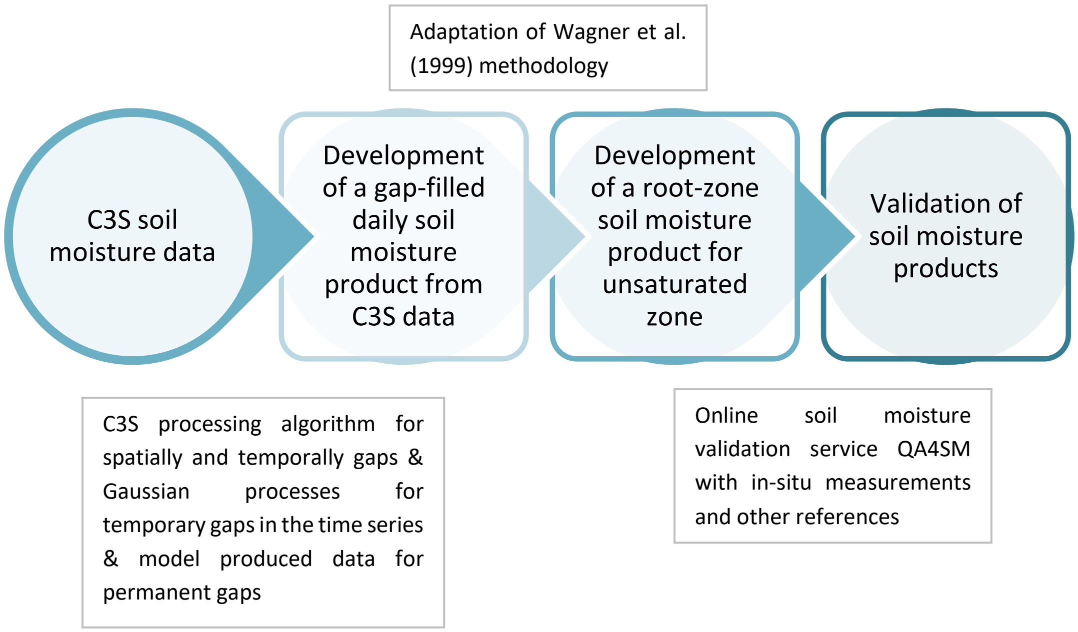
2. Improve the spatial resolution: Building on the approach by Zemp et al. (2019) that provides averaged values of mass change for the 19 key regions of the RGI, in this project a method to provide regional glacier mass changes as a gridded dataset as required for the global groundwater product will be developed.
3. Improve the temporal resolution: The glaciological method typically provides glacier mass changes at annual time resolution. An elaboration and comparison of methods to increase the temporal resolution of this product by using seasonal observations from the glaciological sample (Zemp et al. 2015; Huss et al. 2008) will be carried out. The results will be compared to mass-balance results from numerical modelling with meteorological observations and reanalysis data from the C3S Climate Data Store.

5.2.3. Enhanced global C3S-based surface and root-zone soil moisture datasets

Soil moisture represents only 0.3% of the water stored on land but shows strong spatial and temporal variations in response to precipitation and evapotranspiration (Seneviratne et al. 2010). Thus, sampling soil moisture with high spatial and temporal resolutions is prerequisite for monitoring long-term, inter-annual, seasonal, and daily fluctuations. With rising global temperatures and changing precipitation patterns, soil moisture is expected to decline in many areas, leading to more frequent droughts and yield losses (Dai 2013, Sheffield & Wood 2011, IPCC, 2014).

Since 2011, long-term variability of soil moisture is systematically mapped within the European Space Agency (ESA)'s Climate Change Initiative (CCI) (Dorigo et al. 2017). ESA CCI Soil Moisture combines multiple soil moisture products from passive and active microwave satellites into harmonized Climate Data Records spanning the period 1978-near present at a 0.25° spatial and daily temporal resolution. In 2017, the operational production of ESA CCI Soil Moisture was transferred to the Copernicus Climate Change Service C3S, where the data are now routinely distributed through the Climate Data Store. Every year, the C3S production algorithm is updated with the latest scientific and methodological insights. C3S soil moisture is offered as daily, 10-daily, and monthly aggregates and is updated within 10 days after satellite overpass with the latest available microwave satellite observations.

To develop an enhanced global C3S-based surface and root-zone soil moisture datasets, a daily gap-filled process will be carried out to the soil moisture product from C3S data, which will then be used to develop a root-zone soil moisture product to cover the unsaturated zone. Data will then be validated with in situ measurements and other references.



Development of a gap-filled daily soil moisture product from C3S data

Input: C3S soil moisture product; processing algorithm for C3S / CCI soil moisture product; land surface models; additional data ➡ Output: Gap-filled daily soil moisture product

The daily C3S Soil Moisture data will be used as basis to determine the soil moisture storage variations presenting spatial and temporal gaps. Gaps are due to seasonal snow cover, frozen conditions, and vegetation growth; or to permanent ice cover and dense vegetation (tropics) which persist throughout the year.

The occurrence of seasonal and permanent data gaps obstructs a proper estimation of groundwater variability, and limits the use of C3S in global climate assessments (Dorigo et al. 2018). To overcome this issue, the C3S processing algorithm will be used to produce a spatially and temporally gap-filled soil moisture product. Temporary gaps in the time series will be filled using methods based on Gaussian processes (Piles et al. 2018). These processes will use the high degree of temporal autocorrelation present in soil moisture data and the ability to incorporate prior error knowledge. Regarding permanent gaps, they will be filled using multi-model (e.g., ERA5, ERA5/Land, GLDAS) soil moisture data from other sources.

Development of a root-zone soil moisture product

Input: Gap-filled daily soil moisture product and assessment of input data; C3S soil moisture product ➡

Output: Gap-filled daily unsaturated zone soil moisture product (data); Unsaturated zone daily soil moisture product (based on C3S) (data)

The water balance approach used in this project requires the moisture contained in the surface layer and the moisture contained in the deeper soil layers. Notably, there is a strong connection between surface soil moisture and soil moisture deeper in the unsaturated zone, typically with a lag of days to several months, depending on depth, soil type, and climate (Albergel et al. 2008, Paulik et al. 2014). Apart from being an essential variable to estimate the recharge of groundwater, estimates of soil moisture in the root zone and deeper layers are indispensable for assessing the impacts of drought on plant growth and hence food-security. Using the gap filled dataset and the original C3S data, a soil moisture product representative for the unsaturated zone will be generated based on the methodology initially proposed by Wagner et al. (1999).

Validation of soil moisture products

The gap-filled daily soil moisture product and root-zone soil moisture product will be validated using in-situ measurements from the International Soil Moisture Network (ISMN) (Dorigo et al. 2011, 2013) and other reference data. This will be achieved using the online soil moisture validation service QA4SM (http://qa4sm.eodc.eu/) and with an inter-comparison to the original C3S soil moisture data.

5.2.4. Storage variations in surface water bodies

The assessment of surface water storage variations is complex and requires a multi-sensor approach together with the use of hydrological and hydraulic models.

The space sensors of interest are already on-board of satellites of the Copernicus program:

- Altimeters providing historical to near-real-time water surface height measurements worldwide,
- Optical and/or SAR (Synthetic Aperture Radar) images providing historical to near-real-time water bodies extent worldwide.

Altimetry is already used on inland water surfaces in the CGLS and the C3S to provide respectively Short-Time Critical (3-day timeliness) and Delayed-Time (6-month timeliness) Inland Water Level Level-3. Building upon these reliable, validated and operational products, an operational Surface Water Storage Variations service will be provided. The approach considers a different methodology for quantifying surface water storage for large lakes and for large rivers.

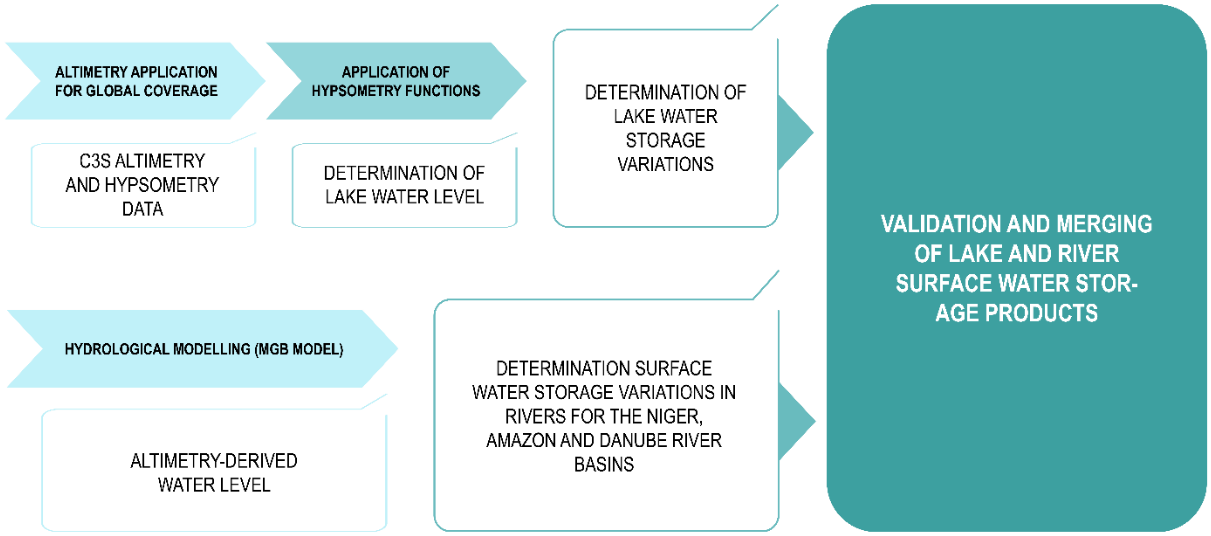


Figure 9 – Steps to estimate storage variations in surface water bodies

The development of an operational product of water storage variations for large lakes will be based on altimetry and hypsometry. Altimetry (technique for measuring height) will be used to extend the number of lakes monitored and acquire global coverage as required. A Level-3 Lake Water Level product will be generated and used to determine a Level-3 Lake Water Storage Variations product through hypsometry (measurement of land elevation (relative to mean sea level)) functions (Crétaux et al., 2011).

The second methodology consists in using hydrological modelling (MGB model (Modelo de Grandes Bacias or Large Basins model)) (Collischonn et al. 2007, Pontes et al. 2017) and data assimilation of altimetry-derived water level to determine surface water storage variations in rivers. This process will be applied to three river basins: the Niger, Amazon and Danube river basins. River discharge and storage variations will be then produced.

The last step will aim at validating and merging lake and river surface water storage products. The lake water storage variation product will be evaluated by comparison of lake water levels to in-situ data, and the hypsometry relationships by comparison with theoretical models. When possible, lake water extent or storage outputs will be confirmed with datasets from other methodologies.

The river water storage variation product will be evaluated through comparison of discharge and water level with in-situ data and other hydrological models such as GloFAS[7]. The consistency of the lake and the river water storage products will be assessed thanks to the comparison of storage for lakes within specific river basins: Lake Kainji in Niger basin, Lake Tanganyika and Mweru in Congo basins.

[7] http://www.globalfloods.eu/

6. Subtraction process and groundwater development product

To subtract glacier, snow, soil moisture and surface water storage from TWS, first the different data sets have to be made compatible in terms of spatial and temporal coverage and resolution. The target resolution of all components for the subtraction process is 0.5 degree globally in space and monthly in time.

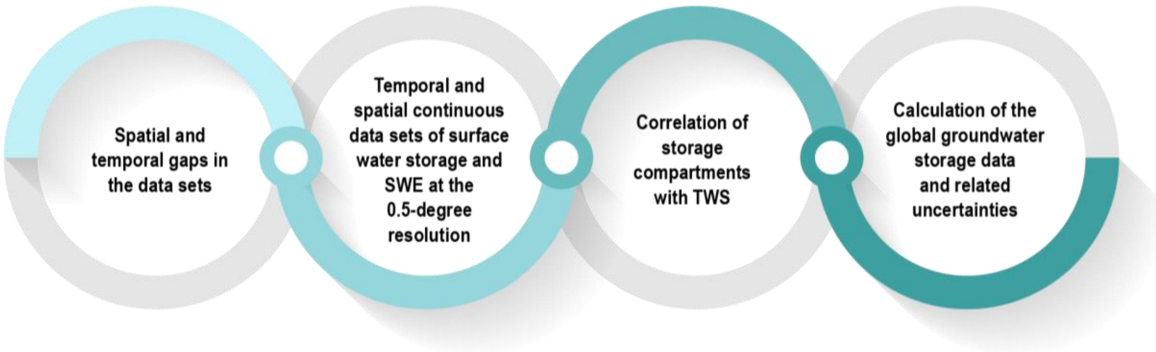


Figure 10 – Steps to make each water compartment compatible before the subtraction process

6.1. Merging of observation and model-based storage data sets

Spatial and temporal gaps in the data sets of single storage compartments (surface water storage, soil moisture, SWE) will be filled with the help of simulation results of hydrological / land surface models. Ensembles of model outputs will be used to assess the uncertainty of the model data in the merging process.

6.2. Spatial correlation lengths and smoothing of storage data sets

The next step will consist in correlating the spatial extent of storage compartments with the TWS and producing coherent data sets of all individual storage compartments compatible with GRACE / GRACE-FO-based TWS.

GRACE based datasets have already a spatially smoothed nature due to the observation process itself and due to filtering for noise elimination. Storage data sets of individual storage compartments will be made compatible by Gaussian filtering on the sphere performed either in the spatial or in the spherical harmonics domain.

6.3. Calculation of the global groundwater data set and of related uncertainties

The global gravity-based groundwater storage will finally be calculated by the subtraction process of gravity-based TWS variations and all compatible data sets of storage variations in individual storage compartments, as explained before The groundwater product and its uncertainties will be computed on the global 0.5-degree grid and as area-average time series for the selected large aquifers worldwide.

7. G3P validation using in-situ monitoring data

As an additional step, results will be compared with estimations of ΔGWS calculated using in-situ groundwater monitoring data and local hydrogeological data in selected aquifers (Figure 11). It has to be noted, however, that the groundwater information derived in G3P from time-variable satellite gravity data is unique in the sense that there is no other technique available that allows for a direct observation of the mass changes associated with groundwater storage changes, nor there is any other technique that provides storage changes as an integral value of large areas instead of point (groundwater well) observations. A thorough validation of G3P results thus is limited by this particular. Nevertheless, an evaluation of G3P results will be performed in selected aquifers for a time period starting with the GRACE operation phase in 2002.

The evaluation will be made after transformation of in-situ groundwater levels to area-average groundwater storage time series or by other statistical approaches. In-situ data will be collected from different sources within this task, for example, water directorates of geological surveys from selected countries. The methodology will be based on Shamsudduha et al (2012), which has been also applied in other studies. In their study, the ability of the GRACE satellite to track intra-annual (seasonal) and inter-annual changes in groundwater storage (ΔGWS) was tested using in-situ observations of groundwater levels and specific yield data from pumping test records distributed across the study area, estimating ΔGWS as:

$$\Delta GWS_{in-situ} = \Delta h \cdot \mathrm{S} \cdot A$$

Where:

S: Storativity
Δh: Groundwater level change
A: Area of the aquifer

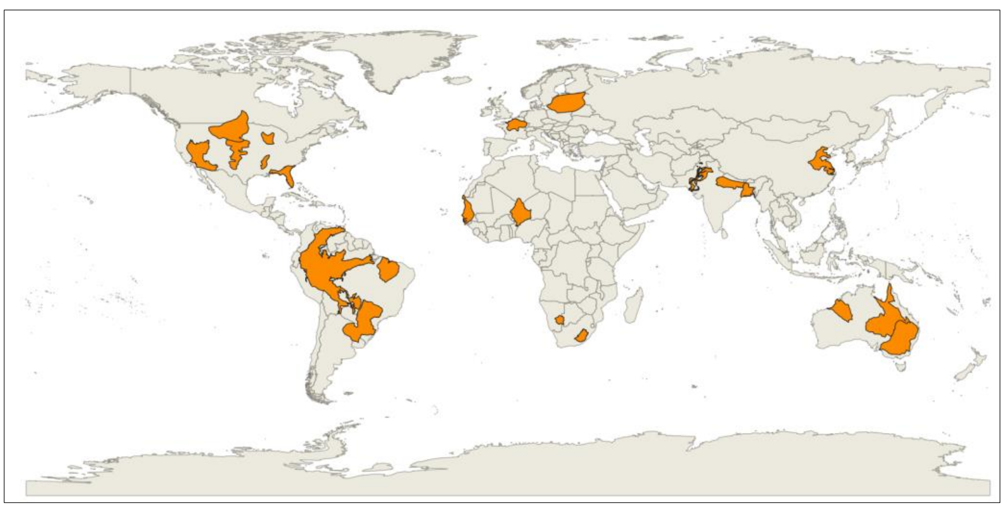


Figure 11 – Aquifers selected preliminarily to evaluate G3P against ΔGWS calculated using in-situ observations

8. G3P Limitations

Water resources planning is carried out at several scales and by different users. Data thus needs to be adapted to these requirements to enable an effective use of groundwater storage change datasets. This methodology will be an improvement towards the use of satellite -based groundwater storage change but the following limitations are identified:

- Accumulated uncertainties contained in the modelled hydrological components.
- Uncertainties associated with the interpretation of water storage data from satellite gravimetry and its accuracy in relation to the spatial resolution.
- Limited studies available on the use of observational data from satellites or in-situ measurements for the subtraction process.
- There are no products based on in-situ measurements to compare results

In addition, the interpretation of water storage data from satellite gravimetry data does not provide one distinct spatial resolution but it exhibits an exponential relation between spatial resolution and accuracy. This means that at low spatial resolution (300-400 km or about 3 degree) monthly water storage variations can be observed at a millimeter (water equivalent) level accuracy. At a 0.5-degree resolution, however, the accuracy is lower and data filtering must be applied to get a coherent pattern of storage variations.

Considering these characteristics of gravity data and the accumulation of errors in the processing chain towards the final groundwater product, providing uncertainty estimates, product documentation and user guidelines to adequately exploit gravity-based groundwater storage data will be essential.

9. G3P application: DEWS Infosequia

Increasingly, Drought Early Warning Systems (DEWS) that incorporate satellite-based drought indices are becoming useful tools to support drought management and planning and to reduce the impacts of droughts and water scarcity events. Traditionally, most of the indices used in drought monitoring systems have been focused on the characterization of the meteorological, agricultural or hydrological droughts. Groundwater drought has received less attention most likely due to large discontinuities, spatial under-sampling or complete lack of near-real-time ground-based groundwater level data. Estimates of groundwater storage variations derived from GRACE/GRACE-FO observations are contributing to bridge this gap and could be integrated into the monitoring component of InfoSequia, a FutureWater's in-house DEWS. This process is tested for inherent reliability and flexibility at the basin level in Southern Spain, where unsustainable groundwater development threats the water security in the region, but also the ecological status and preservation of unique and highly protected ecosystems in Europe (e.g., Doñana National Park, Daimiel National Park, Mar Menor coastal lagoon). The output will enhance a more accurate picture of the dynamics and persistence of droughts, and thus to more useful decision support tools.

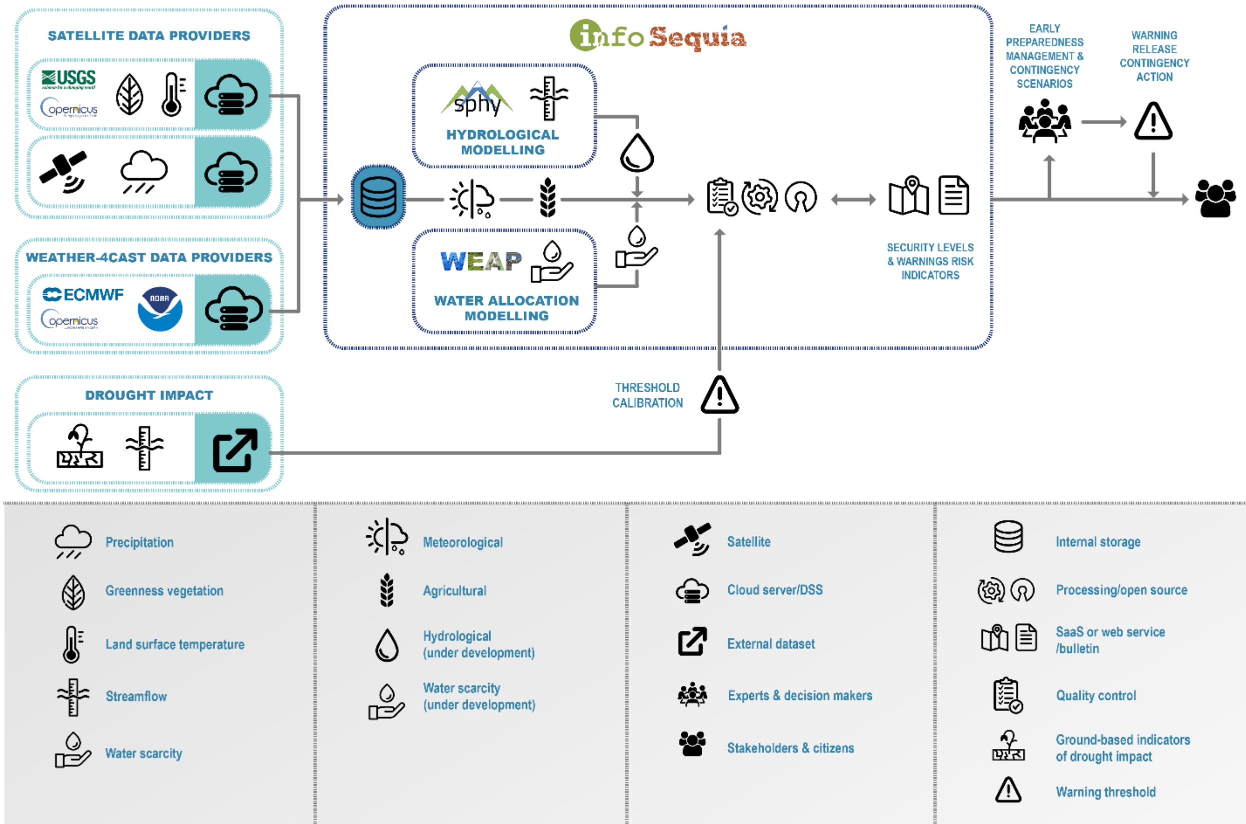


Figure 12 – Structure of the InfoSequia Drought Early Warning Systems and integration of the new groundwater G3P-based drought monitoring component

10. Dissemination of the data.

The global gravity-based groundwater storage data will be open access (https://www.g3p.eu/), offering the possibility for any interested party to use it. This data would also be added at:

- The Gravity Information Service of the German Research Centre for Geosciences (GFZ) (GravIS)
- The Global Groundwater Monitoring Network GGMN portal (https://www.un-igrac.org/ggis/ggmn-portal).

The derived information from each compartment in the subtraction process will also be used for integrated resources management where possible, to improve service and global hydrological models.

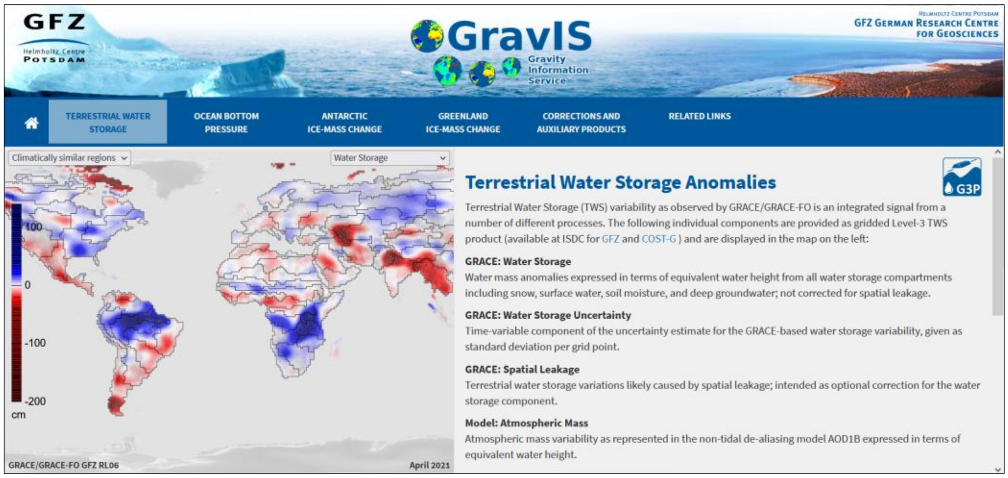


Figure 13 – The Gravity Information Service of the German Research Centre for Geosciences (GFZ) (GravIS). Source: http://gravis.gfz-potsdam.de/home

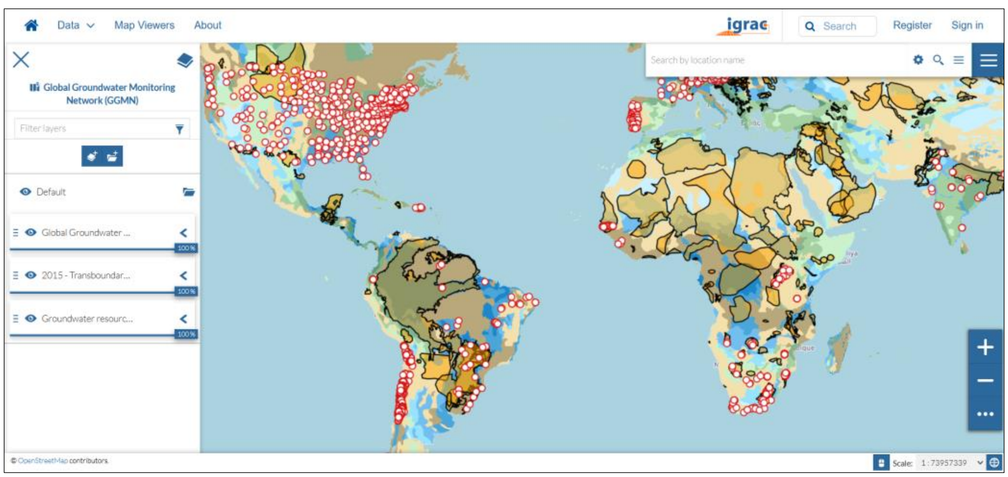


Figure 14 – The Global Groundwater Monitoring Network (GGMN) portal. Source: https://www.un-igrac.org/ggis/ggmn-portal.

11. Concluding remarks

- Globally, despite its importance, groundwater is often not included in sustainable water management actions and plans due to limited data availability on groundwater. Satellite based gravity groundwater storage enables to bridge this gap and improve water resources decision-making;
- TWS, as observed by GRACE/GRACE-FO, is the sum of several storage compartments: groundwater, soil moisture, snow, ice, and surface water bodies. G3P provides a product of groundwater storage change by subtracting variations in each individual water compartments from TWS (Figure 7).

- For the subtraction process, a consistent approach is necessary to limit the error margin generated through modelling processes. Such approach is global in extent and utmost based on observation data. Most of the storage data needed for the subtraction process already are at least partly available from existing Copernicus service products. They are mainly available in the form of products based on satellite observations, in-situ monitoring, and as results of hydrological models. In some cases, observation-based data is merged with simulation-based data where necessary to achieve full spatial and temporal coverage;

- Three key steps are followed to estimate G3P:
    - satellite gravity data processing,
    - quantification of storage compartments, and
    - subtraction of satellite gravity data and storage compartments to determine groundwater storage variations

- The global gravity-based groundwater storage data will be finally provided as global grids with 0.5-degree (~55 x 55 km) resolution, and as area-average time series for large aquifers and river basins.

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