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European Gravity Service for Improved Emergency Management

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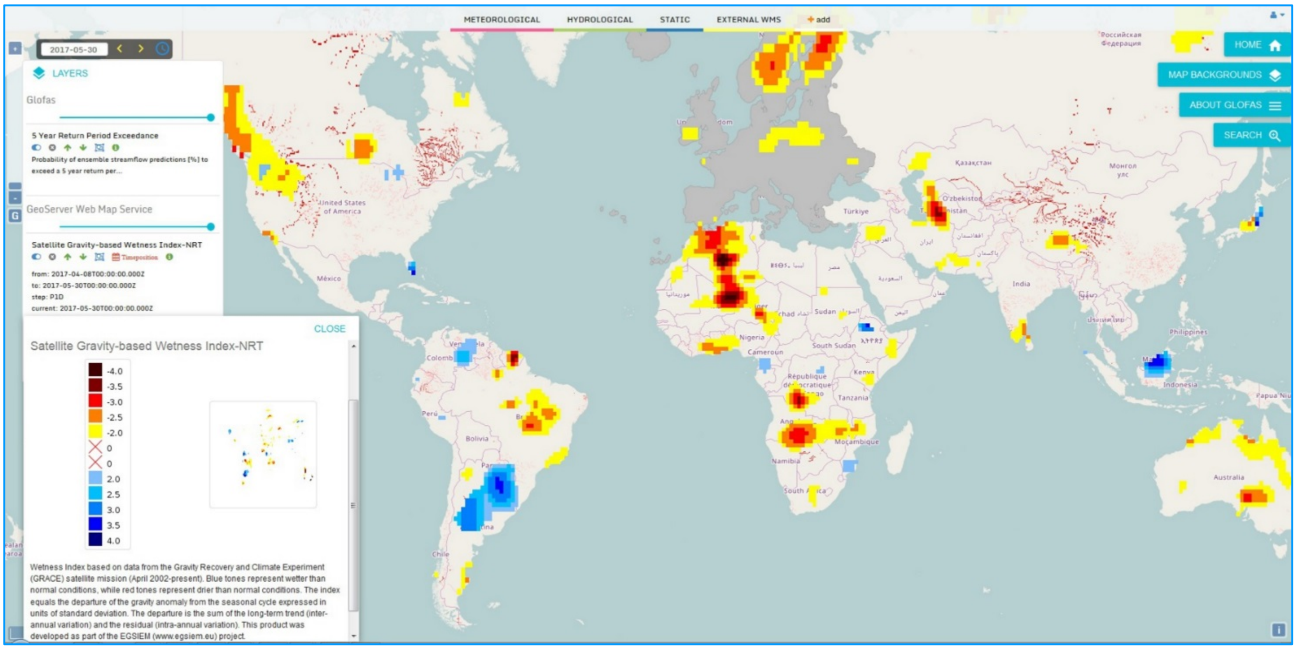

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2. Terms

This document provides the product report of the Hydrological Service of EGSIEM (Work Package 6). It describes the activities in this work package on the validation of new gravity products provided by the NRT Service (Work Package 5) for flood events and on the development of one main product of the Hydrological Service, a flood and drought indicator. This indicator will be incorporated in the near-real time Operational Hydrological Service, reported on in detail in the final deliverable 6.2 (the Operational Hydrological Service Product Report) towards the end of EGSIEM.

3. Overview and Summary

This document outlines the work undertaken during the implementation phase of the Hydrological Service of EGSIEM during the project months M01-M30. The main objectives were (1) the evaluation of new gravity products with daily resolution provided by the Near-Real Time (NRT) and Regional Service as information on water storage anomlies for historical flood events (reported on in Sections 4 and 5 of this report) and (2) the development of gravity-based wetness indices for river basins worldwide as indicators for flood and drought events. The indicators are set up as a main component of an operational Hydrological Service for flood and drought monitoring and forescasting systems (reported on in Sections 6 and 7 of this report). The operational and near-real time implementation of this service will be specified in the Operational Hydrological Service report at the end of the EGSIEM project.

Section 4 provides an evaluation of water storage anomalies derived from the new daily gravity products developed in EGSIEM. Daily gravity field solutions are made available by the German Research Centre for Geosciences (GFZ) and the Graz University of Technology (TUG) in the NRT Service, with each analysis center providing an independent solution. For the example of large floods in the Ganges-Brahmaputra river basin it is shown for the first time, that GRACE is able to reflect temporal variations in river runoff during major flood events at the resolution of few days. These results imply that with the release of the daily gravity field solutions in near real-time, flood monitoring during the event itself can be supported for large events.

Section 5 reports on the development of a method for quantifying flood volumes in inundated areas based on radar satellite data and digital elevation models. It is shown that the automated method can potentially be applied for large-scale flood events worldwide and is ready to be implemented in an already operational Sentinel-1 flood service at DLR's Center for Satellite-based Crisis Information. Flood volumes derived with this method provide an independent means of evaluating the gravity-based water storage variations.

Section 6 presents the method of deriving global wetness indices from the daily gravity-based products of water storage anomalies. Both the GFZ and TUG products are used for a combined Wetness Index. Evaluation for the example of the Danube basin over the entire GRACE operation period demonstrates the capacity of the wetness index to trace the major flood events in the river basin, but even more importantly, to indicate flood-prone above average wetness conditions in the river basin already ahead of the flood event itself.

Section 7 finally illustrates how the Hydrological Service Products are being set up for incorporation into existing mapping and alterting systems. In particular, the EGSIEM gravity-based Wetness Index has been included as a data layer into the European Commission's Copernicus Global Flood Awareness System (GloFAS) platform. At DLR/ZKI, an interactive web viewer has been developed to visualise the wetness index together with other DLR/ZKI data sources such as the operational Sentinel-1 and TerraSAR-X flood services as a basis for improved satellite tasking and acquisition planning for disaster monitoring and management.

4. Evaluation of daily gravity products

Because the satellite data coverage within one day does not allow for a gravity field solution based on GRACE data alone, the computation of daily gravity maps employs a prediction – correction principle. Information obtained from geophysical models on the temporal behavior of the gravity field are used to predict the following day, which is subsequently improved with the available GRACE observations in a Kalman filter approach. Daily gravity field solutions are made available by the German Research Centre for Geosciences (GFZ) and the Graz University of Technology (TUG), with each analysis center providing an independent solution. TUG focuses on improving global gravity field solutions, whereas GFZ implements tailored regional representations of the gravity field. Details are specified in the EGSIEM NRT Service Product Report. Both approaches provide global coverage. Additional processing converts the resulting gravity field solutions, expressed in terms of spherical harmonics coefficients, into global 1^{o} x 1^{o} gridded map of total water storage anomaly (TWSA) in Equivalent Water Height (EWH) in cm.

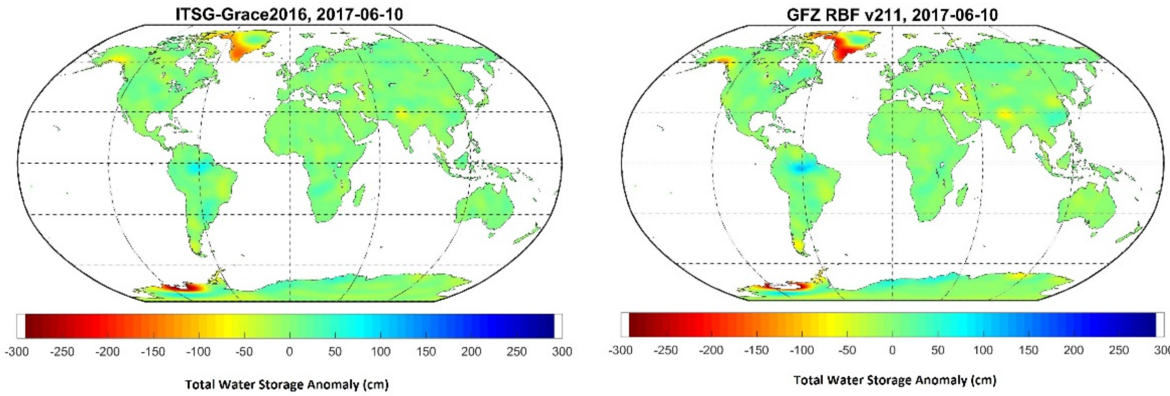


Figure 1: TUG (left) and GFZ (right) daily GRACE gravity solution converted into water storage anomalies for the example of 10 June 2017.

An evaluation of water storage anomalies derived from the daily gravity products of both processing centres against observed river discharge has been performed in the Ganges-Brahmaputra Delta (GBD) under flood conditions. The GBD is the world's largest river delta, situated at the confluence of the two river systems with a combined discharge surpassed only by the Amazon and the Congo rivers worldwide. The evaluation has been focused on the flood years 2004 and 2007. A summary is given here for the 2007 flood event, similar results have been found for the 2004 event. More details are provided in Gouweleeuw et al. (2017).

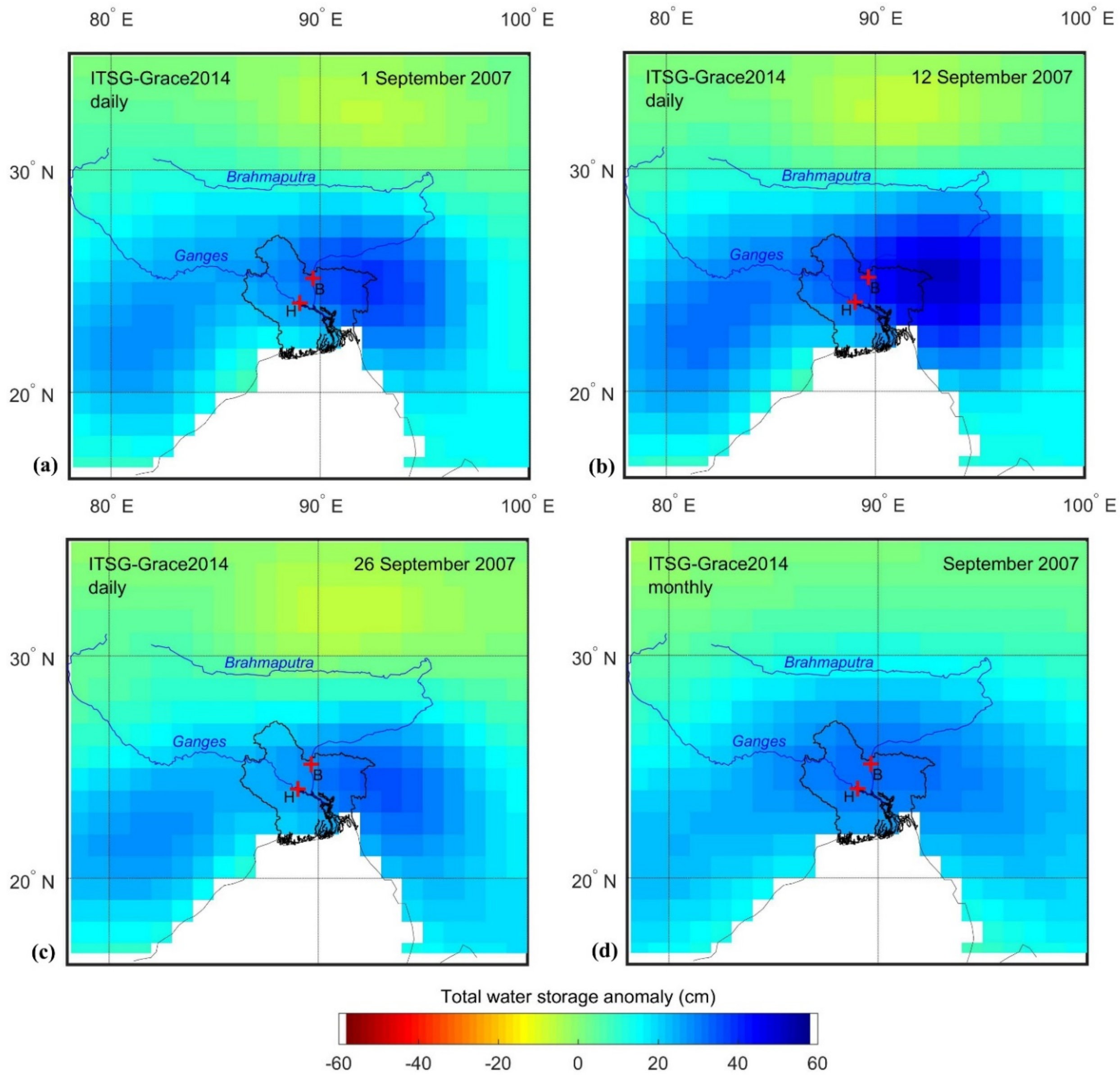


Figure 2. Daily and monthly water storage anomalies of the TUG ITSG-Grace2014 solution for the Ganges-Brahmaputra Delta on (a) 1 September 2007 (b) 12 September 2007 (c) 26 September 2007 and (d) September 2007. Red crosses indicate gaugins statios Bahadurabad (B) in the Brahmaputra and Hardinge Bridge (H) in the Ganges.

Daily snapshots of the gravity-based storage anomlies reflect the progression of flooding in the GBD area (Figure 2) (a) just before, (b) during and (c) after peak flooding, which is additional information on what is available from (d) the monthly solution. This is also cleary expressed in the time series of high-pass filtered daily water storage anomlies when compared to the daily river runoff anomalies, observed at an in-situ gauging station in the area (Figure 3). The daily gravity field solutions clearly reflect the two peaks of the daily river runoff anomalies on 31 July and 13 September, and a smaller peak in-between on 21 August. A stronger correlation of anomalies of water storage with river runoff into the GBD than with precipitation within the

GBD suggests that river runoff is a stronger driver for major flooding than precipitation in the GBD.

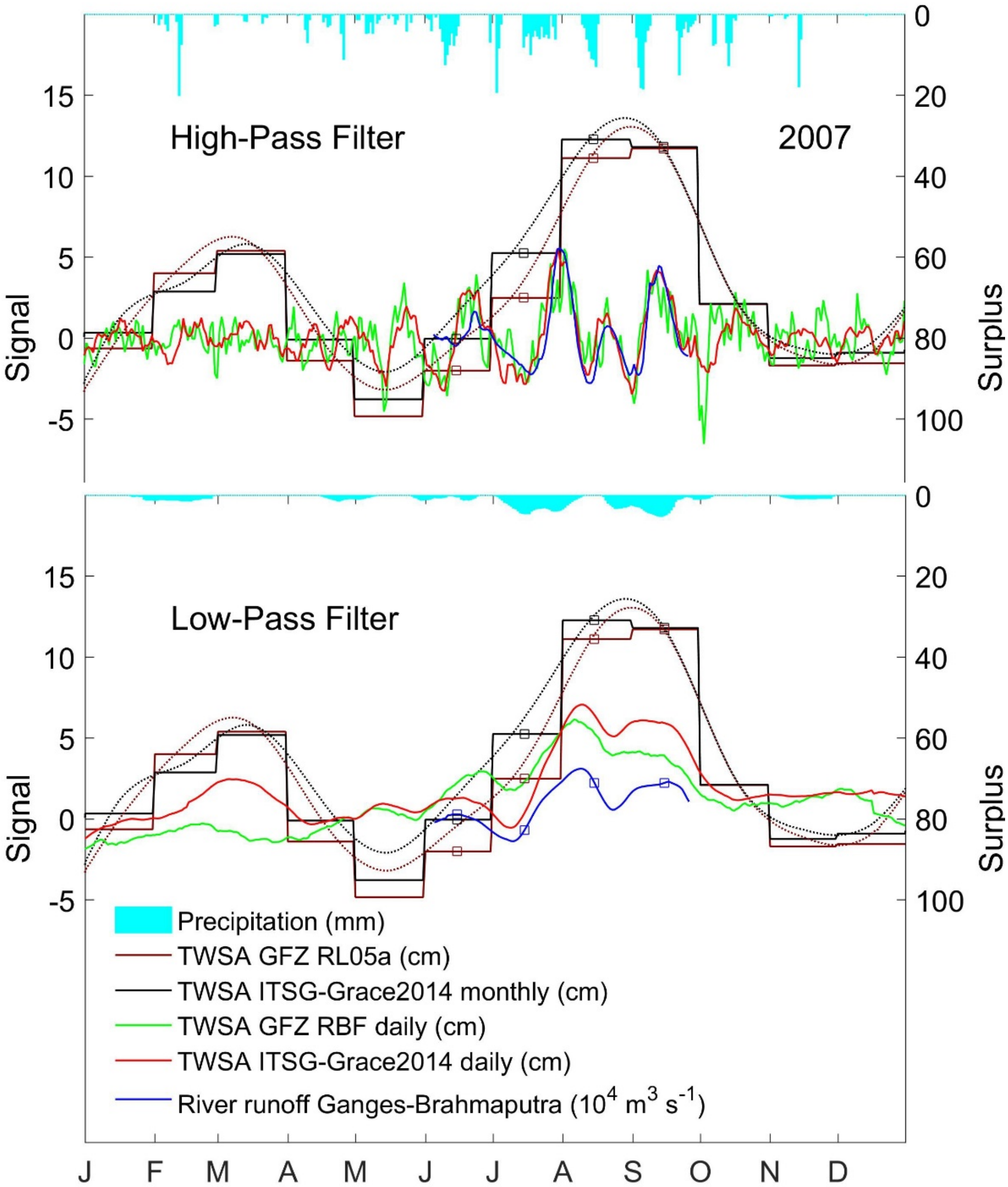


Figure 3. Daily and monthly area mean anomalies of GRACE total water storage anomlies (TUG and GFZ solutions) and of daily river runoff (left axis) from in-situ gauging stations H and B (see Figure 2) together with precipitation surplus (right axis) for the Ganges-Brahmaputra Delta in 2007.

Compared to the monthly gravity field solutions, the variations over periods of a few days in the daily gravity field solutions are able to reflect temporal variations in river runoff during major flood events. The daily temporal resolution is sufficiently high to reflect these area mean variations of water storage anomalies. The hydrological evaluation of the daily GRACE gravity field solutions thus shows their potential for gravity-based large-scale flood monitoring. With the release of the daily gravity field solutions in near real-time by the NRT service, monitoring of extremes events by total water storage variations will be possible at the time the event happens, as opposed to a ‘confirmation after occurrence’, which has been the situation up to only recently.

5. Flood volume estimation based on SAR-satellite imagery and digital elevation models

With the overall goal of the Hydrological Service to evaluate gravity-based water storage anomalies, the aim of this task was to establish an automated method for flood volume estimation for large-scale floods based on Earth Observation data and a Digital Elevation Model (DEM). Compared to existing satellite-based 2-D flood masks, 3-D flood volume estimates for large river basins constitute a higher level product for hydrological and disaster management applications. Since the proposed method only depends on Earth observation data (i.e. Synthetic Aperture Radar (SAR) data), elevation data and in-situ water level measurements it can be compared against hydraulic modelling approaches as well as gravity measurements from space.

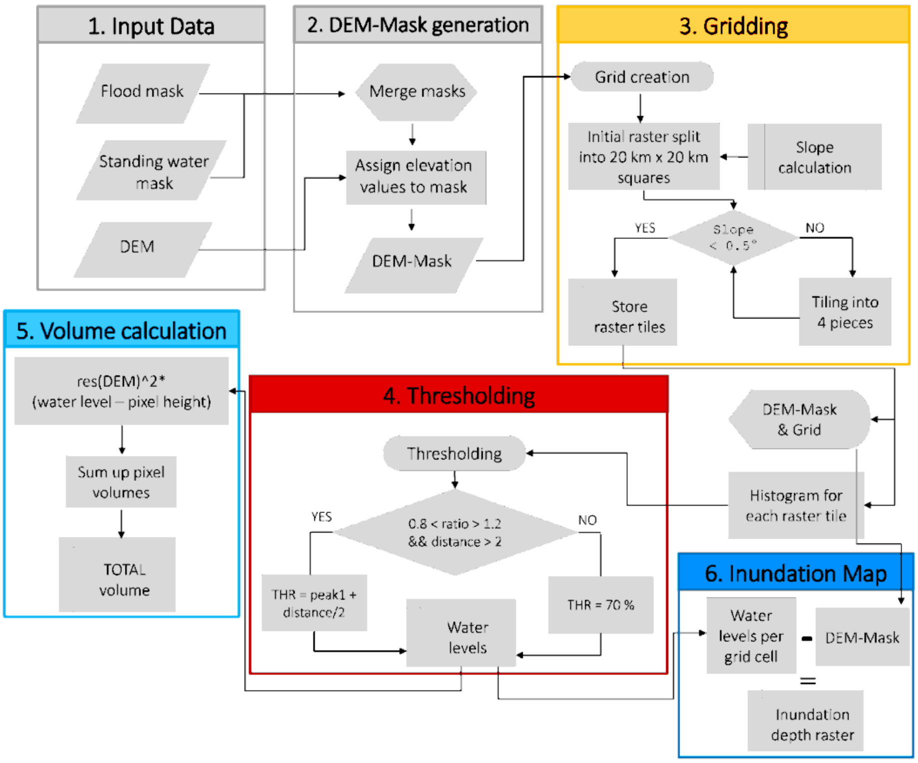


Figure 4: Workflow of the flood volume estimation method

Figure 4 shows the workflow of the method which has been developed for a flood event in the Ganges-Brahmaputra basin (Bangladesh) and was tested for a flood in the lower Mekong river basin.

As a first step, the water masks of the flooded areas must be extracted from Sentinel-1 data (see Figure 5). The flood masks were then merged with the DEM in such way that only flooded pixels with height information remain.

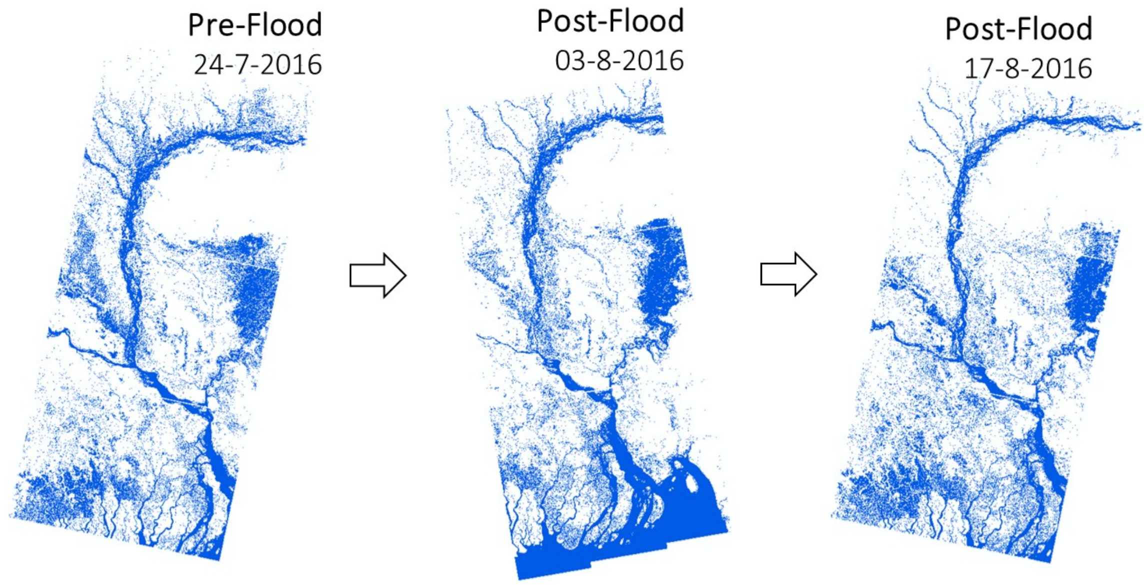


Figure 5: Sentinel-1 derived flood masks from three acquisitions during a flood event in Bangladesh (lower Ganges-Brahmaputra basin)

Next, a fishnet grid is laid over these pixels. Several approaches (see Figure 6) were tested to find the optimal tiling algorithm for defining river sections with a horizontal water surface. Best results were achieved with the dynamic fishnet approach forming grids based on further tiling (5-20 km) according to the slope of the terrain.

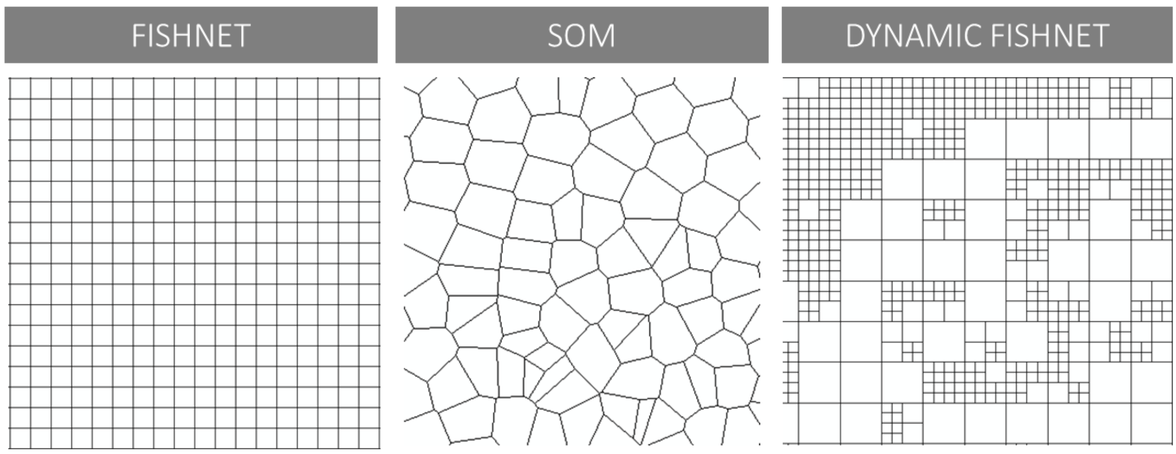
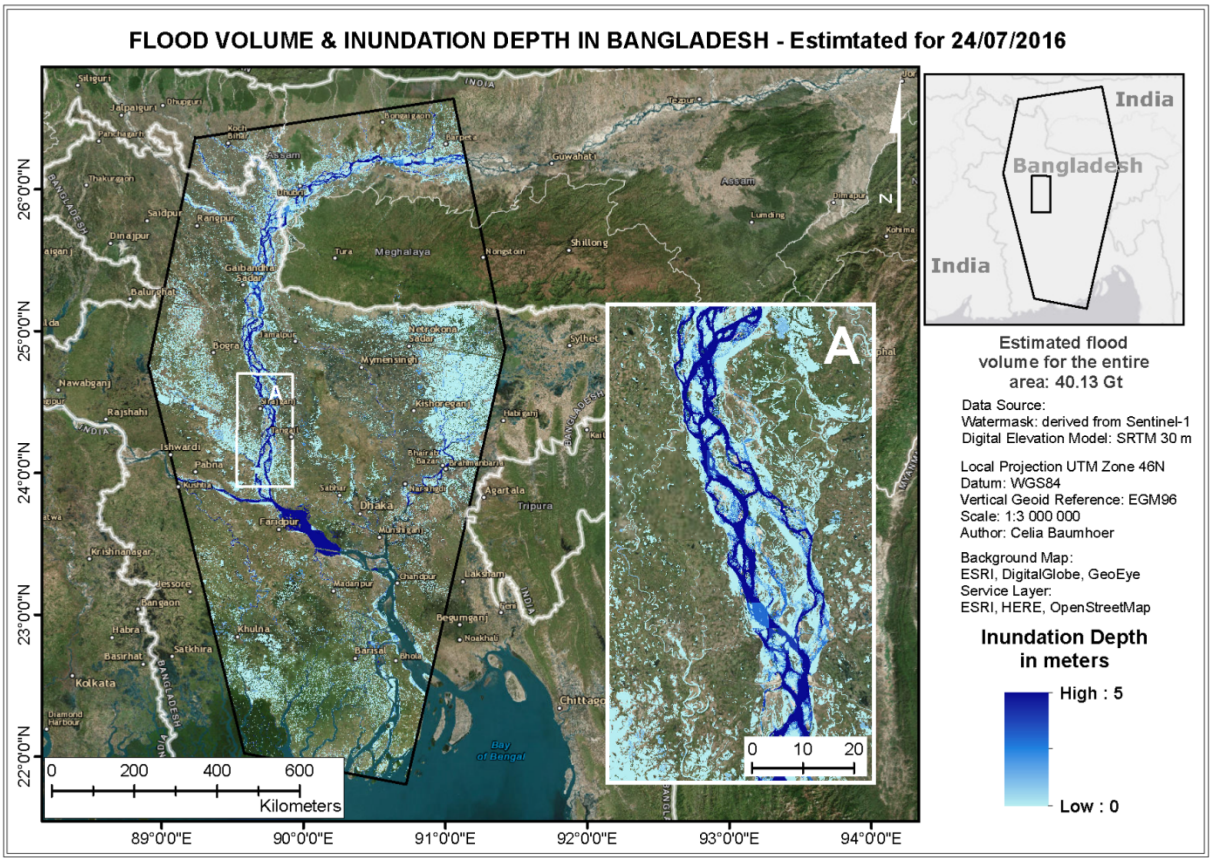


Figure 6: Three different tiling approaches: Static fishnet grid, Self-Organising Map (SOM) and Dynamic fishnet grid

For each raster cell a horizontal water surface was assumed and a histogram of the elevation of all water pixels within this cell was computed. For each of those histograms a threshold is calculated to separate "real" flooded pixels and such with unrealistic height information. Optimal water level calculation can be performed for uni-modal distributions, where an empirical threshold of 70 % of the cumulative pixel sum is applied. A compromise had to be found for bi-modal distributions, which account for less than 1% of the tiles only. After multiple tests with different threshold and tiling approaches, best results could be achieved with a uni-modal threshold and a dynamic fishnet approach when compared to in-situ and satellite altimeter water levels measurements. Results of the applied method are flood inundation maps (shown in Figure 7) and the calculated flood volume for the test area being the cumulative pixel sum of the inundation depth (40.13 Gt for the Bangladesh flood during 2016, and 11.12 Gt for the lower Mekong flood during 2015).



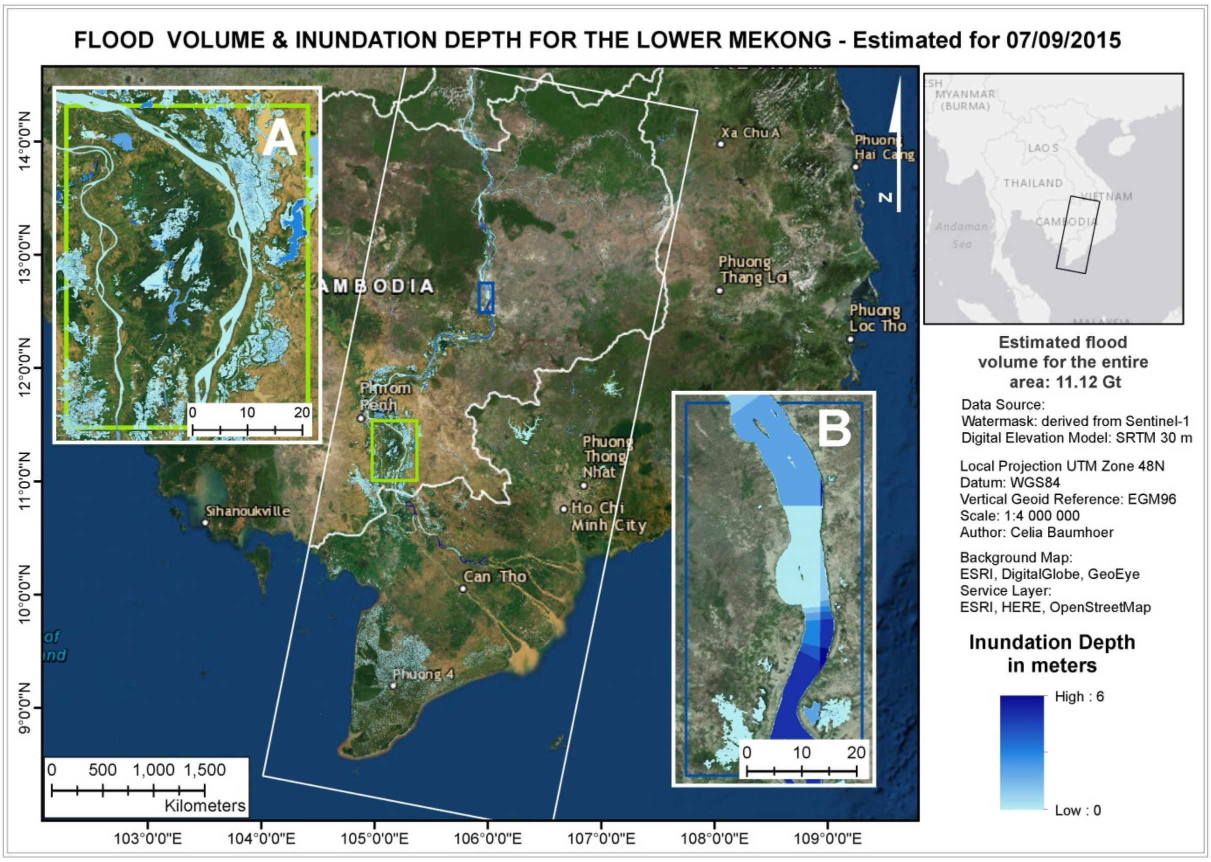


Figure 7: Flood inundation maps for Bangladesh based on Sentinel-1 acquisition 24/07/2017 as well as for the lower Mekong based on Seninel-1 acquisition 07/09/2015.

Accuracy of the method is mainly dependent on the quality (i.e. vertical accuracy) of the DEM. For the results presented here, the SRTM DEM was filtered to reduce the influence of 1-meter steps in the initial SRTM. Higher accuracy yields much better results. Hence, the acquisition date of the DEM as well as the editing for water surfaces has a high influence on the results. Tests with a more accurate TanDEM-X DEM promised much better accurate results, whereas lower resolution flood masks (e.g., ENVISAT-ASAR) gave less accurate results. It could be shown that the automated method can potentially be applied for large-scale flood events worldwide and it is ready to be implemented on top of the already operational Sentinel-1 flood service (2-D flood masks) at DLR's Center for Satellite-based Crisis Information.

6. Global satellite gravity-based wetness index: Method and Evaluation

Contrary to other Earth observation data, gravity represents total water storage variations (i.e., variations of all surface and subsurface water storage compartments). As such, it provides unique information on the wetness state of a river basin with regard to its actual flood generation potential or its susceptibility to a drought. For the development and testing of indicators of such hydrological extreme events, we take advantage of the integrative nature of the gravity data and evaluate how large-scale water storage anomalies derived by NRT, daily and regional GRACE products can be used as early warning indicators in flood and drought monitoring and alerting services.

A Wetness Index (WI) was developed as a dimensionless entity, as suggested by user feedback from the European Commissions' Joint Research Center to ease interpretation for end-users. The WI expresses the deviation of the GRACE-derived total water storage anomaly (*Xtot*) from the mean seasonal cycle (*Xseas*) in dimensionless units of standard deviation (*S*). The departure is the sum of the inter-annual variation (*Xinter*) and the intra-annual variation or residual (*Xres*):

$$Xinter + Xres = Xtot - Xlin - Xseas, \quad (1)$$

where:

$$Xlong = Xinter + Xlin \quad (2)$$

The time series decomposition separates the total signal (*Xtot*) in a long-term component (*Xlong*), a seasonal component (*Xseas*) and an irregular component or residual (*Xres*). The long-term component (*Xlong*) then consists of the linear trend (*Xlin*) and the inter-annual variation (*Xinter*).

Figure 8 shows an example of the Wetness Index derived from the TUG (left) and GFZ (right) daily gravity solutions for 10 June 2017. Blue tones represent wetter than normal conditions, while red tones represent drier than normal conditions. Similarities between the two patterns exist for instance for unusual wet conditions in the La Plata basin in South America, and for marked below average water storage conditions e.g. in Central Brazil. Differences between the two Wetness Indices based on the two daily gravity solutions may be regarded as an indication of the uncertainty of the methods, both in the daily gravity field solutions as well as in the index calculation.

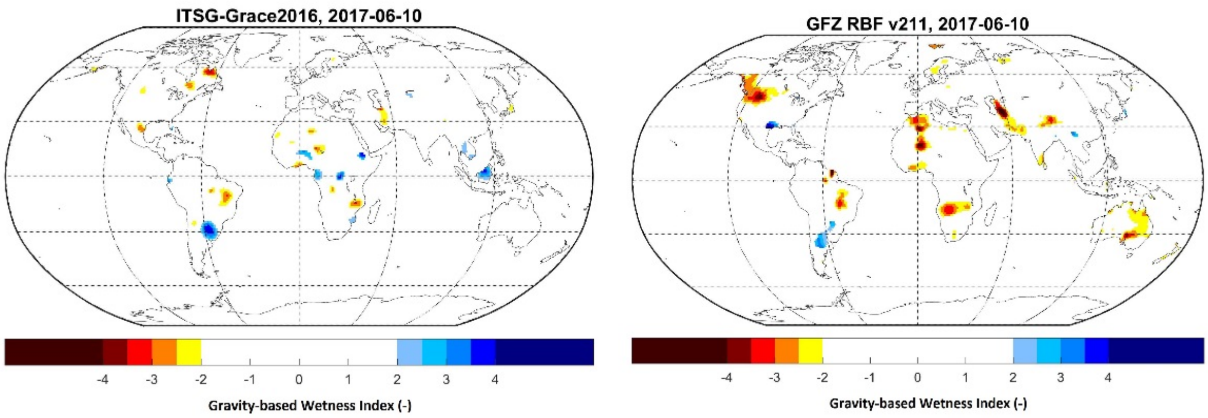


Figure 8: TUG (left) and GFZ (right) daily satellite gravity-derived Wetness Index for 10 June 2017.

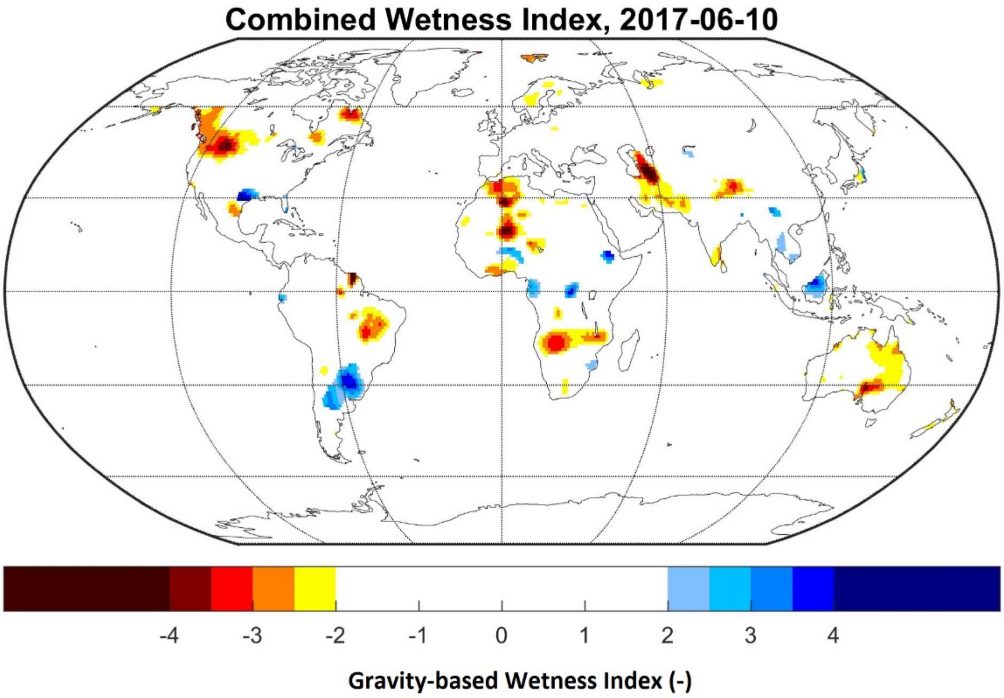


Figure 9: Combined daily satellite gravity-derived Wetness Index for 10 June 2017.

With extreme hydrological events in focus, a combined Wetness Index is derived by selecting the most extreme absolute values of either index in the combination product. For the example of 10 June 2017, the combined index is shown in Figure 9. The different Wetness Indices are calculated for the most recent daily gravity products provided by the Near-Real Time Service, but also in a retrospective analysis for the historical period of GRACE operation.

In a regional context, Figure 10 shows a retrospective analysis of daily gravity solutions and the Wetness Index for the years 2002-2015 for the Danube basin. Both the gravity solutions of TUG and GFZ (ITSG-Grace2016 and GFZ RBF v211) and the gravity-based indices derived from these solutions indicate increased values during widespread flooding in the Danube basin in 2002, 2006, 2010 and smaller floods in 2013 and 2014, respectively. Particularly relevant with respect to early flood warning is the build up of basin-wide water storage of several months duration prior to the larger flood events of 2006 and 2010, which were triggered by a combination of early season snowmelt and excessive rainfall. The similarity of the two Wetness Indices, despite differences in dynamics of the individual daily gravity solutions they are derived from, is striking for this study area (Figure 10c).

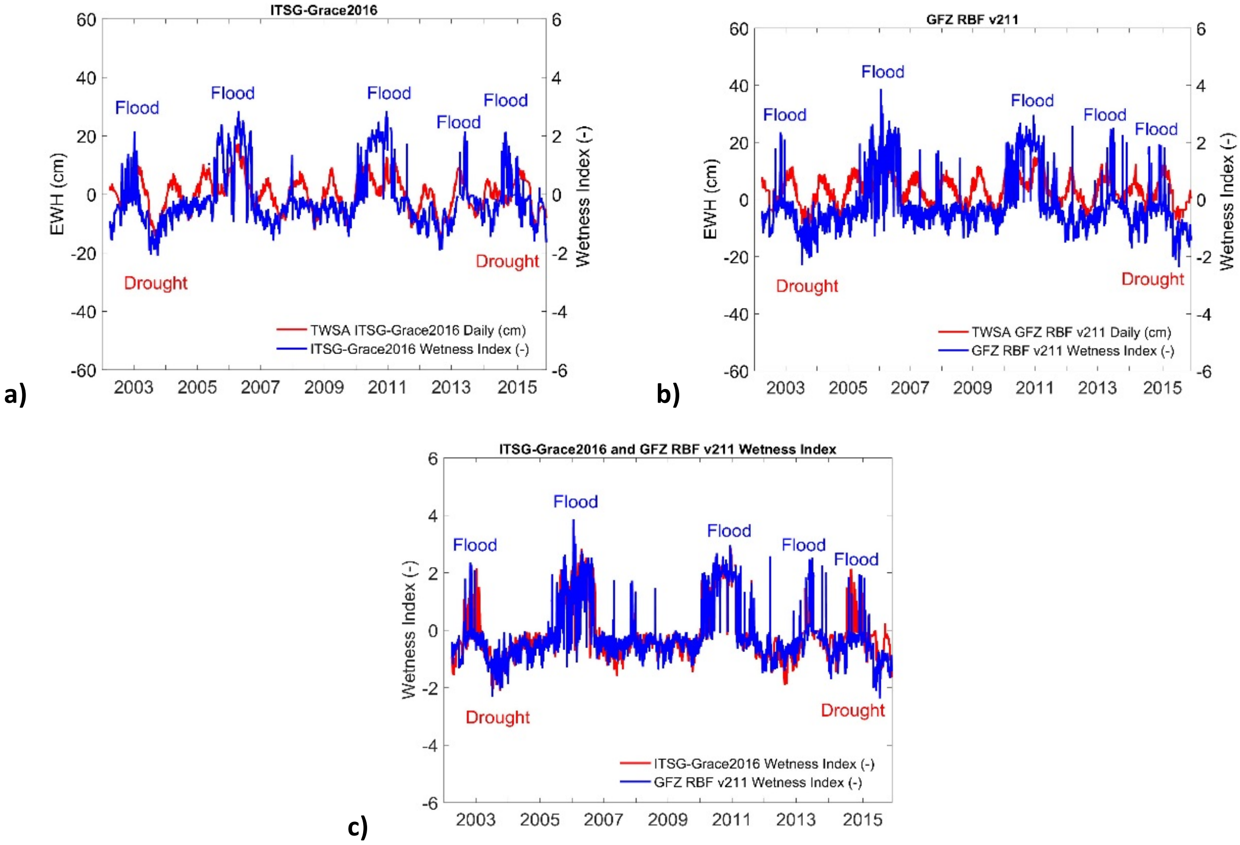


Figure 10: Daily gravity solutions and gravity-derived Wetness Indices for the Danube basin (2002-2015) for a) TUG ITSG-Grace2016 and b) GFZ RBF v211 as well as c) for both Wetness Indices.

The flood events in 2013 and 2014 that were smaller and of shorter duration are also detected by the Wetness Indices, were however characterized with shorter lead times. This possibly indicates a different flood generation mechanism with less water storage built up before. Lead time for the 2002 basin-wide flood event is also relatively short, probably due to technical initialization issues of the GRACE twin-satellite mission at the time. Minima of the wetness index reflects dry conditions during the 2003 and 2015 Central European heatwaves.

Figure 11 illustrates the spatial patterns of the daily gravity solutions and the gravity-derived Wetness Indices for the Danube basin on 26 April 2006, close to the day of the flood peak at the gauging station Isaccea in Romania, at the basin outlet to the Black Sea. Increased gravity TWSA values (dark blue) in both gravity solutions are reflected in elevated Wetness Index values (blue tones). For this particular date the combined Wetness Index resembles the Wetness Index based on the GFZ RBF v211 gravity solution quite strongly, representing the more extreme index values.

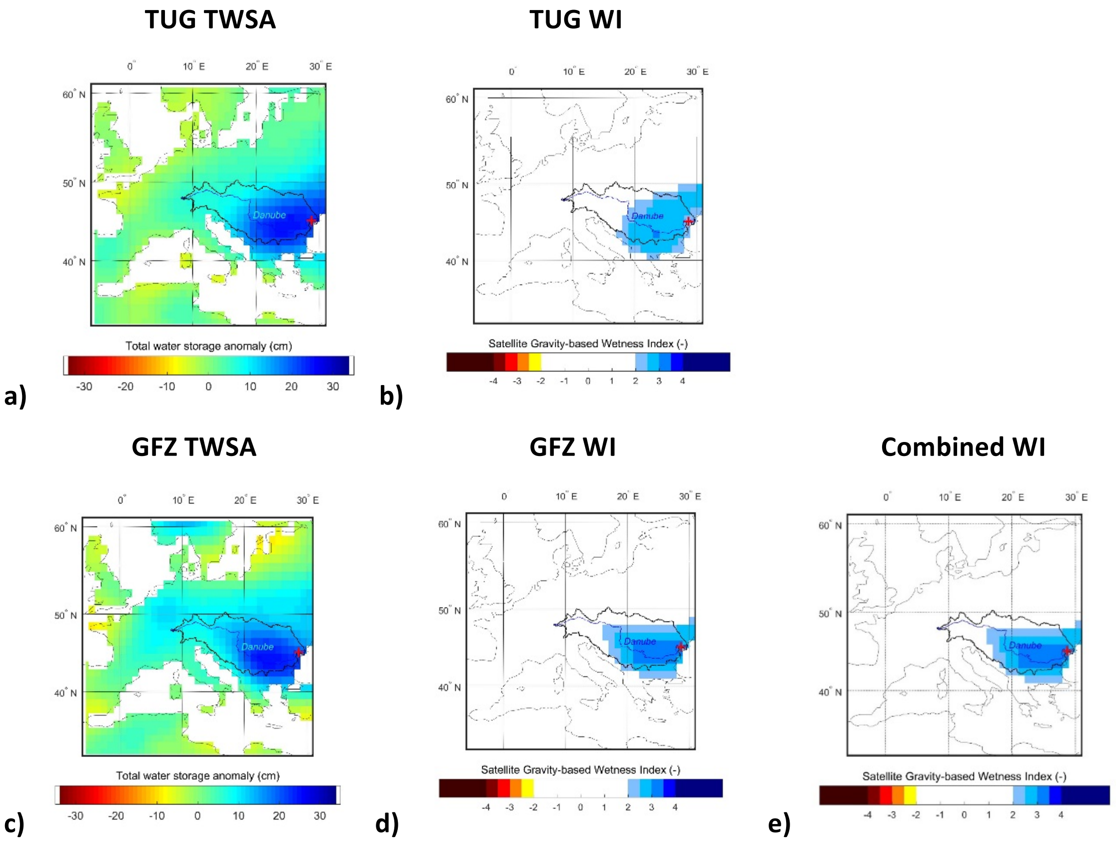


Figure 11: Daily gravity-based water storage anomlies (TWSA) and the gravity-based Wetness Indices (WI) for the Danube basin for 26 April 2006 based on the TUG ITSG-Grace2016 data (a, b) and the GFZ RBF v211 data (c,d,) as well as the combined index (e). Red cross indicates the location of the gauging station Isaccea.

7. Integration into Mapping and Emergency Management Services

Towards the integration of Hydrological Service Produts into Operational Flood and Drought Mapping and Forecasting Services, as a first step, the integration of the EGSIEM gravity-based Wetness Index into the European Commission's Copernicus Global Flood Awareness System (GloFAS) platform (http://globalfloods.jrc.ec.europa.eu/) has been realized. Figure 12 shows the combined Wetness Index, for the example of 31 May 2017, visualized as a data layer in a WMS (Web Mapping Service) format in GloFAS. Wetter than normal conditions (2.5-3 times the standard deviation) are indicated for parts in Latin America, signaling 'El Niño` conditions and causing flooding in southern Columbia and Uruguay, as reported in the International Charter of natural and man-made disasters (https://disasterscharter.org). Hotspots of considerably drier than normal conditions indicate ongoing drought-related humanitarian crises in Africa (Zambia, Angola, North-Eastern Africa). The Wetness Index can currently be compared in the GloFAS platform with other global data layers that characterize the preconditions and the event characteristics of flood events worldwide.

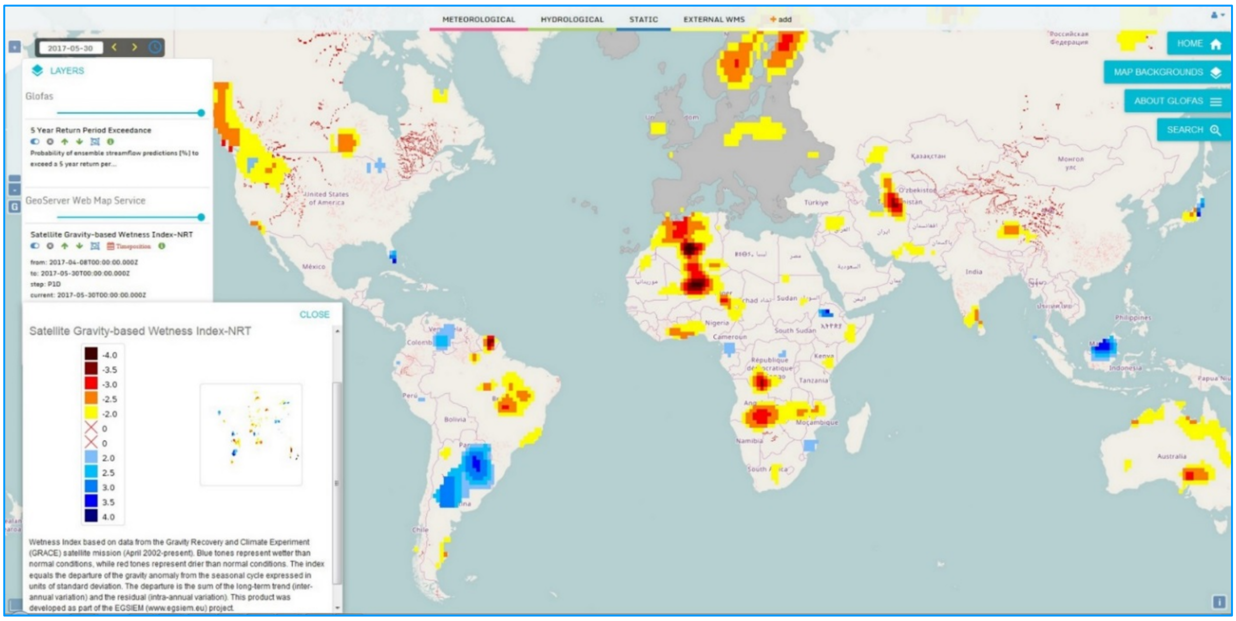


Figure 12: EGSIEM combined daily satellite gravity-derived Wetness Index of 31 May 2017, visualized within the GloFAS platform.

Another target for integration of the gravity-based Wetness Index is the operational DLR/ZKI rapid mapping service. Its rapid mapping concept (Figure 13) has been developed and refined over the years based on experiences made in rapid mapping activities for national, European as well as international users in the domain of disaster relief and civil protection.

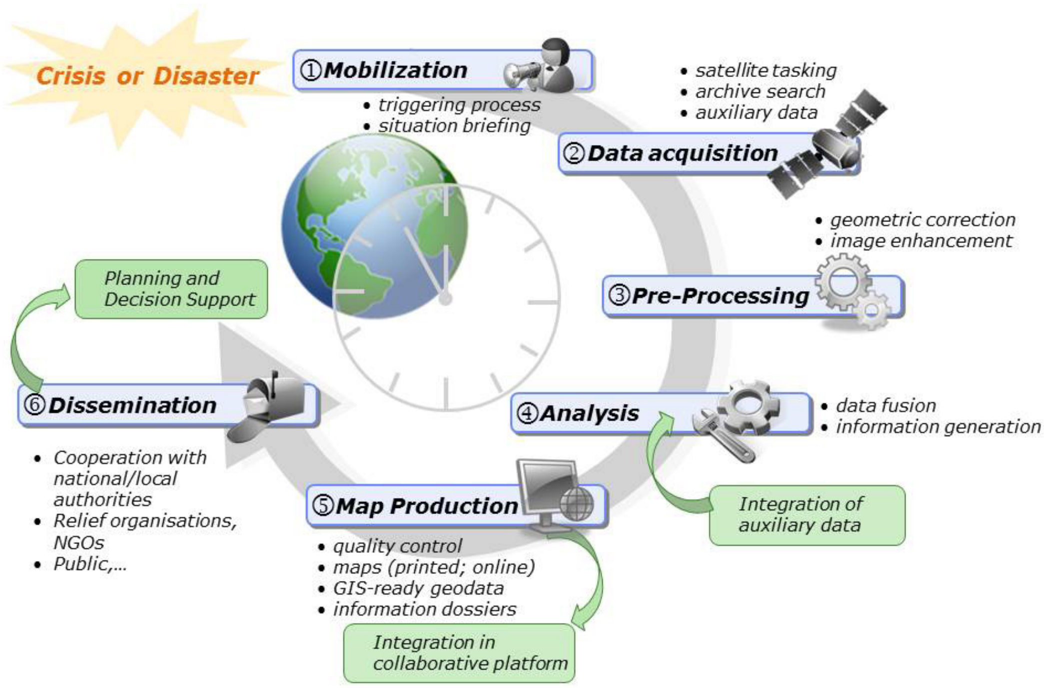


Figure 13: Rapid Mapping workflow of the DLR/ZKI rapid mapping service

The EGSIEM wetness index, being an indicator for flood forecasting and drought monitoring, can facilitate an early warning component and thus improve the first two steps of the rapid mapping workflow: the mobilization and data acquisition. Requirements expressed by DLR/ZKI users focus on timely and high frequency flood monitoring from the onset of a flood event with a special focus on mapping the flood extent at peak level until water levels have receded to near normal stages. For this task, a number of SAR and optical satellites have to be tasked, as it is done within mechanisms such as the International Charter or the European Copernicus Emergency Management Service (EMS). Both mechanisms are activated upon user request, which means that satellite tasking does not start before a user request has been received. In some cases, i.e., when a large flood evolves quickly or has not been considered as evolving into a major flood event, user requests came in relatively late and satellite tasking could not be put into effect until the flood peak had already passed the area of interest. For such cases, a proactive satellite tasking based on external information such as the gravity based wetness indicators are of key importance. In order to enhance the rapid mapping service with such indicators an interactive web viewer has been developed (see Figure 14) to visualise the daily gravity based wetness indicator provided by GFZ together with other DLR/ZKI data sources such as the operational Sentinel-1 and TerraSAR-X flood services during the EGSIEM operational NRT test phase since April 2017.

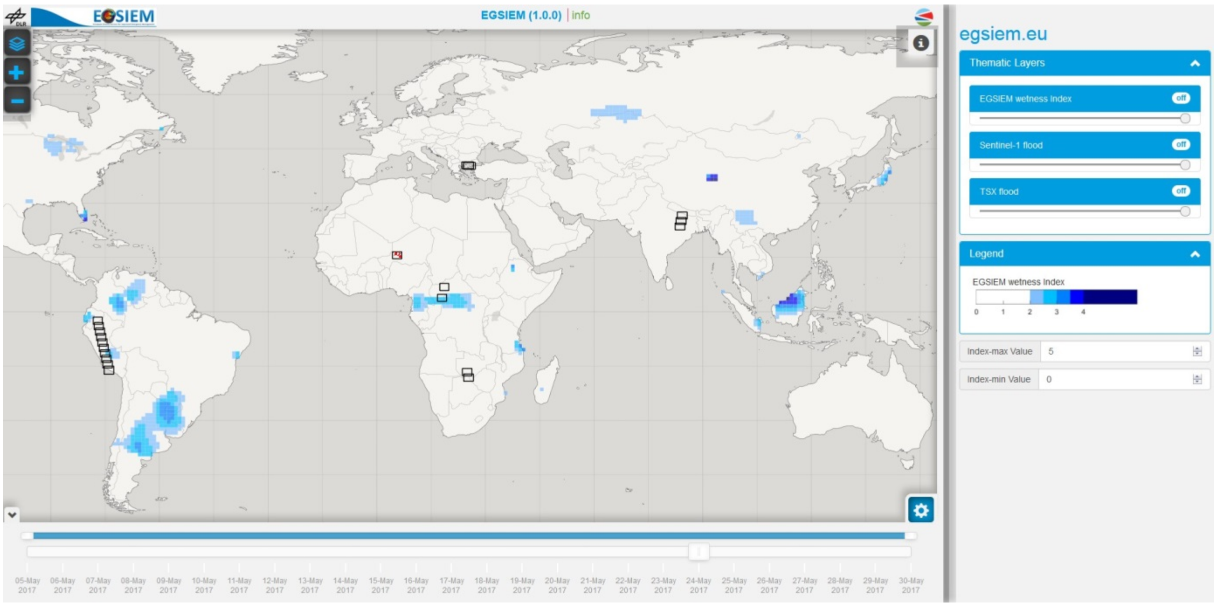


Figure 14: DLR EGSIEM Viewer showing daily gravity based wetness indicator and the operational Sentinel-1 and TerraSAR-X flood service

With the help of this tool (Figure 14), operational workflows for improved on demand programming of high and medium resolution satellite data are being developed and evaluated. This includes raising the awareness of the users for potential large scale floods in their countries, promote early activation (mobilization) of the International Charter or the Copernicus EMS and facilitate proactive tasking (data acquisition) of satellites such as TerraSAR-X in such cases. A detailed acquisition plan for all relevant earth observation satellites (e.g. from the Charter) can then be conducted by selecting the optimal orbits and satellite overpasses with the help of the software tool “Savoir Acquisition planner” (Figure 15). Overall, this is expected to allow for more detailed disaster monitoring, and thus offering the possibility of a much more effective disaster management.

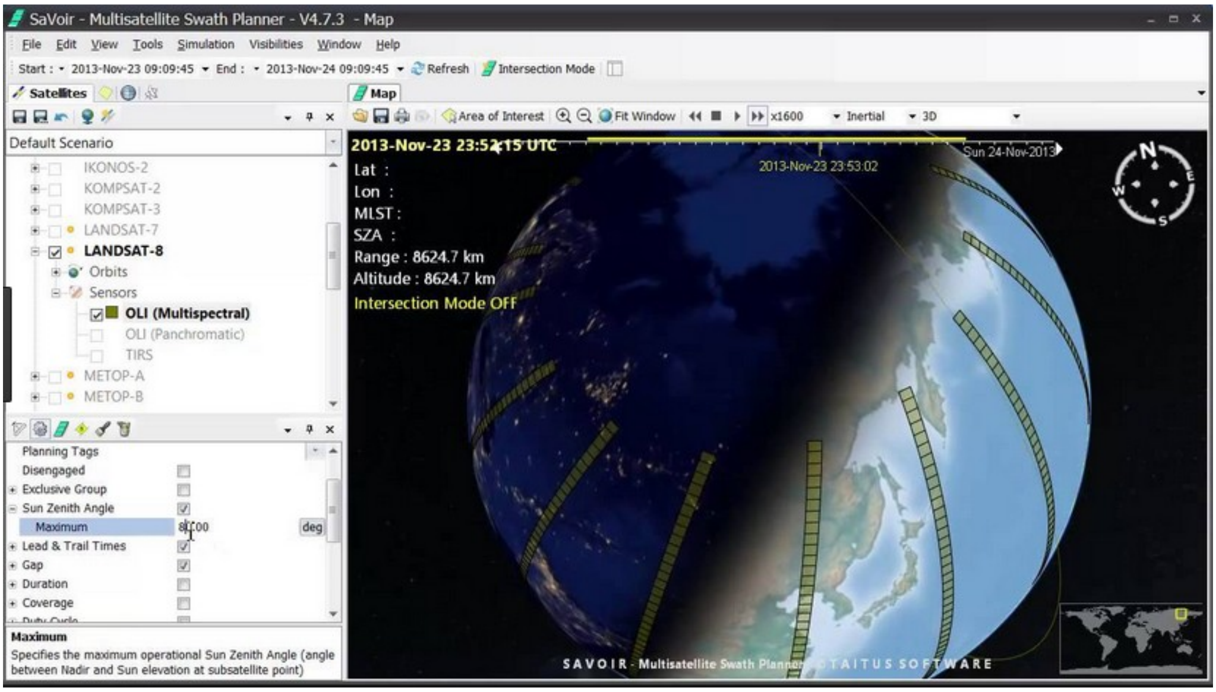


Figure 15: User interface of the Savoir Multi-satellite Swath Acquisition Planner at DLR/ZKI (software from TAITUS)

8.Bibliography

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9. Glossary

DEM	Digital Elevation Model
DLR	German Aerospace Center
EMS	Copernicus Emergency Management Service
GFZ	German Research Centre for Geosciences Potsdam
GloFAS	Global Flood Awareness System
NRT	Near Real Time
RBF	Radial Basis Function
SAR	Synthetic Aperture Radar
SRTM	Shuttle Radar Topography Mission
TUG	Technical University of Graz
TWSA	Total Water Storage Anomaly
WI	Wetness Index
ZKI	Center for Satellite Based Crisis Information at DLR