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Interactive comment on

"Quantification of Drainable Water Storage Volumes in Catchments and in River Networks on Global Scales using the GRACE and/or River Runoff" by Johannes Riegger

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This is interesting work showing how GRACE and discharge data can be used to estimate drainable storage in river basins and river networks. Although the ideas are interesting and the data-analysis well developed, there are some major reservations I have with the approach and the paper.

I would like to thank the reviewer for his comments as they triggered some corrections and amendments in the manuscript. Below you find my respond to his comments in detail.

1. I fail to see why knowing the drainable storage of catchments and river networks itself is so interesting. In applications of hydrology one is generally interested in dis-charge anomalies (high flow, low flow), evaporation anomalies (agricultural drought) and flooded areas. So, I feel that the necessity of this work should be re-stated.

   The knowledge of Drainable water storages is essential for the description and prediction of river discharge (high flow, low flow), for water ecology, river management (floods and draughts) and especially for water resources management *(seeP1 L8-10)*. This is what I consider as one of the main concerns in hydrology.

   The knowledge of storage volume changes in the form of seasonal amplitudes and trends, as provided by GRACE, does not help to assess available water resources and especially to quantify possible problems and conflicts with respect to future water supply *(see Introduction P2 L13-P3 L21)*). Time variable storage compartments, not contributing to river discharge like canopy or soil are certainly important for local ecology, but they are normally not relevant for water supply. Water extraction from groundwater storages in low permeable structures or from deep fossil resources means a lot of technical effort and energy input.

Drainable storages comprise all water storages which are accessible with relatively little effort and energy input as for surface water or shallow groundwater systems. Their global scale quantification provides an effective overview on globally available water resources.

The possibility to determine the drainable storage with the approach presented *(see P 23 L26-33, Eq.22a,b,c, Eq 23, Eq35, EQ.36, Eq.38)* allows to observe the storage status of global scale catchment directly by remote sensing from GRACE in a global distribution. This means a major step in environmental remote sensing.

In fact, the main, and very interesting, contribution is that GRACE data alone (together with recharge [precipitation surplus would be a better term] estimates from e.g. moisture convergence) can be used to estimated river discharge in ungauged basins.

The possibility to optimize the approach versus GRACE only using moisture flux divergence as input is a very promising perspective for ungauged catchments. Yet as the accuracy of the drainable water storage and the calculated river discharge depends on the quality of recharge data it is limited by the quality of moisture flux divergence at the moment *(see P24 L3-11).*

2. Similarly, in stressing better the necessity of the approach, it should be made clear why large-scale hydrological models could not be used to do the job.

   The author does not claim that large scale models cannot be used to do the job. Global hydrological models are able to describe a large number of storages like canopy, soil zones, surface water, groundwater, river network etc. and describe their storage volumes and the related flows. This is a real benefit to understand details in the water cycle. However, one of the difficulties in verifying large scale hydrological models consists in the quantification of the individual storage volumes and related flows by ground based measurements. These are mainly point measurements with the necessity of an interpolation and with unknown storage coefficients *(see P3 L8-16)*.

   GRACE anomalies now allow for a direct comparison of the measured total mass changes and the respective sum over all simulated storage compartments with respect to amplitudes and phasings. Comparisons of the simulated total storage versus GRACE show considerable differences for several models as for LAD (Milly and Shmakin, 2002), GLDAS (Rodell et al., 2004) and WGHM (Döll, Kasper and Lehner, 2003), just to mention a few. For the different models an underestimation of the signal amplitudes and phase shifts between measured and simulated total mass is reported (Güntner et al., 2007, Schmidt et al., 2008, Werth et al., 2009, Werth et al., 2010 for WGHM and Sayed et al.,2008, for GLDAS *(see P5 L16-20)*. Schmidt et al., 2008, compare different models (WGHM, GLDAS, LAD) with respect to phase shifts and come to the conclusion that these differences might point to systematic deficiencies in hydrological modelling.

The motivation and the starting point for the development of the Cascaded storage approach was not only to clarify the problem of the phase shift, but to also describe the system behavior in a "Top-Down" approach by macroscopic parameters addressing the coupled / uncoupled storage compartment by their effect on the R-S relationship.
The thoughts and intention leading to its development are the following :

- Summarizing all coupled storages contributing to mass and runoff and the uncoupled storages contributing to mass only allows to describe them in their accumulated effect on the runoff-storage relationship of the catchment without the necessity to address storages and flows in detail, while most hydrological models use a "Bottom Up" approach using spatial/temporal distribution of a number of parameters and driving forces.
- A minimum number of input variables and optimization parameters shall be used to describe the system behavior without the necessity to use spatially / temporally distributed data and describe internal processes in detail. Catchment scale parameters shall be used instead to separate coupled and uncoupled storages (like MODIS snow coverage (Riegger and Tourian, 2014))
- Recharge by atmospheric water balance via moisture flux divergence (P-ETa = divQ) or from catchment mass balance (P-ETa = dM/dt+R) on monthly scales is very convenient and quite accurate, however, it is limited to global scales (>200000km2), thus representing the ideal input for Top-Down approaches.
- The linearity in R-S relationship allows for a piecewise analytical solution of the coupled balance equations for two different time constants and thus a mathematical description with no stability and accuracy criteria for the temporal discretization. For numerical solutions big differences in the time constants of the catchment and the river network lead to a high temporal discretization effort *(see P9 L1-6)*.
- The approach allows to determine river runoff from total drainable storage and vice versa directly from respective measurements once the time scales τ_C and τ_R are determined by an optimization *(see P23 L26ff, codes and results implemented in the supplement).* A related description is integrated in the manuscript now in detail. It has to be emphasized here, that this facilitates a purely data driven determination of runoff from drainable storage and vice

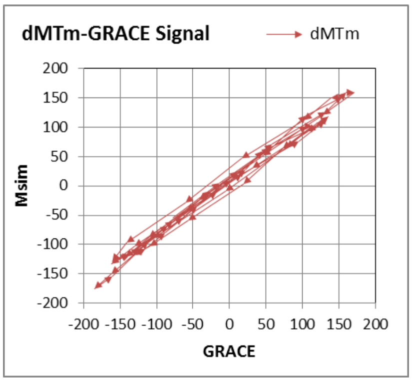
versa with astonishing accuracy and thus permits a closure of data gaps without the necessity of additional model runs.

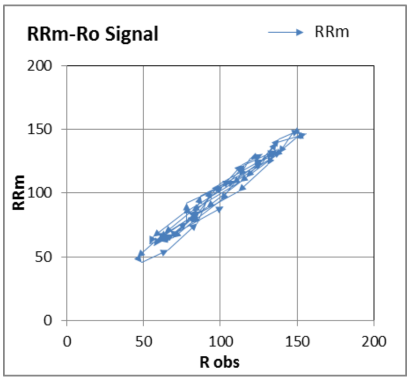
Note that some of these models (such as WaterGap and PCR-GLOBWB) have groundwater parameterizations and are able to reproduce the amplitude and lags observed in GRACE (see e.g. Wada et al., 2012; Water Resour. Res., 48, W00L06).

According to Güntner et al., 2007, Schmidt et al., 2008, Werth et al., 2009, Werth et al., 2010, WGHM, which is related to WaterGap, actually shows a phase shift. However, I am not aware whether there are modifications between WaterGap and WGHM which enable a description of the R-S relationship without a phase shift.

The model based total storage calculated by PCR-GLOBWB (Fig.1, Wada et al., 2012) seems to show some phase differences. As the phase shift is individual for each catchment according to the hydraulic and topographic conditions a direct comparison of the approaches or models for the Amazon catchment upstream Obidos would be necessary. Graphs for the Amazon are not contained in Fig.1 of Wada et al., 2012.

A display of calculated total mass anomalies versus GRACE and of calculated versus measured runoff as shown below (and provided in the supplement) would allow to better recognize phase differences in a comparison.





Thus, it would be quite enlightening for the discussion here if the reviewer would provide analogous graphs for the modeling results of WaterGap and PCR-GLOBWB related to the Amazon catchment. Furthermore a comparison of the optimization performance (according to Table 2) would be helpful.

If the amplitude and phase shift between recharge and runoff are informative about storage and hence discharge, GRACE anomalies could be used to calibrate these models as well, with the added advantage that a) we do not need to assume linearity between storage and discharge; b) these models deal with temporarily unconnected storages as well.

Yes, hydrological models can be calibrated versus GRACE anomalies and runoff without any further assumptions on the R-S relationship, provided that the impact of river routing on river network mass and thus on total mass is described. (Any no zero temporal delay between catchment runoff into the river network and discharge at the catchment outlet leads to mass changes in the river network and thus in total storage (Eq.6).

a.) As investigations on the R-S relationship of global scale catchments (Riegger and Tourian, 2014) have shown for fully humid and for boreal catchments (with temporally uncoupled storages), the relationship between runoff and coupled storage in fact is linear, leading to a Linear Time Invariant (LTI) system behavior. This need not be true for local or regional scale catchments, where thresholds might play a role.

Any non linear R-S-relationship would lead to changes in the functional form of the resulting mass and runoff time series and not just to a pure phase shift. However, as the application to the Amazon catchment here (and to the boreal catchments in Riegger and Tourian, 2018) shows, the signal forms (Fig.10) are reproduced very well by the Cascaded storage approach and show a phase shift only (Fig.11) confirming the linear relationship.

The mathematical framework for the Cascaded storage approach and the resulting consequences for the optimization properties are based on a linear storage. Thus the investigation of the optimization properties (based on a sinusoidal input for the synthetic case) with respect to the uniqueness and accuracy of the results cannot be transferred to non linear cases without further investigations.

For catchments with non negligible river network storage the Cascaded storage approach is needed to describe the amplitude and phase shift between recharge and runoff with enhanced accuracy (see Column C in Table.2).

b.) The temporarily unconnected storages calculated in spatially / temporally distributed hydrological models on global scales can hardly be verified by ground based measurements. The Top-Down approach presented here does not describe unconnected storages in detail, but attempts to describe them by their impact on the R-S relationship (runoff independent contributions) based on a macroscopic, basin scale parameter, which is derived from additional information like remote sensing. This additional information is used for a separation of total storage into coupled and uncoupled storages *(see P5L20-24)* . For boreal catchments MODIS snow coverage serves as a separation parameter (Riegger and Tourian, 2018). For seasonally dry catchments the separation is still a major task as the uncoupled storages are dominated by open water bodies and soil moisture *(see Outlook P24 L14-22).*

3. Modelling the effect of the drainage networks as a linear storage-outflow relationship may be valid for the Amazon where during peaks the whole basin turns into a huge flooded area resembling a lake. But in many rivers of the world, e.g. the Danube, the Rhine, the Nile, water during high stages is confined in the channel or in narrow valleys and the lag between catchment discharge and discharge at the basin's outlet is more of a travel-time phenomenon then a storage attenuation phenomenon. In this case, a routing routine such as used in many global hydrological models would be more suitable, with the unknown parameters the channel and floodplain resistance parameters (e.g. Manning coefficient).

The Cascaded storage approach intends to describe global scale catchments considerably above the resolution limit ~200000km^2 (like Amazon, Yenissei, Lena, Ob, Mackenzie, Yukon, Niger, Kongo, Mekong etc) in order to achieve reasonable accuracy for both, GRACE measurements and moisture flux divergence. The catchments mentioned (Danube, Rhine, Nile) are either too small or managed by hydraulic structures i.e. not draining without anthropogenic impacts. The approach here is a conceptual approach not claiming to describe internal processes like river routing. The hydraulic properties of the river network (topography, channel cross section and roughness, channel length and river gradient), which are not known very well on global scales, are summarized in this approach as one efficient hydraulic time constant τ_R describing the overall river network dynamics and not the superposition of sub branches.

Of course it would be interesting to compare the hydraulic time constants of river routing schemes with the one obtained by this approach. It will also be interesting *(see Outlook P38 L23-26)* to compare the river network mass (determined here in an independent way) versus the flood areas (GIEMS) or river / flood volumes from GIEMS and altimetry for other global scale catchments. This would provide insights into global scale river and flood hydraulics.

4. More generally: the approach seems to be valid in large humid basins, without cold-region processes, where all active stores are permanently connected to the discharge mechanism, while routing is such that the drainage network can be represented by a storage-outflow relationship. This makes the applicability of the approach somewhat limited.

As mentioned in the "Introduction" *(see P5 L20-24)* in the "Conclusions and Discussion" *(see P5 L20-24)* a prerequisite for the approach is that the coupled and uncoupled storages can be separated by other means like remote sensing. For boreal regions with relatively homogeneous snow depth (opposite to mountainous regions) this can be done with the help of MODIS snow coverage (Riegger and Tourian, 2014). It has been shown that the snow covered parts represent the uncoupled, solid storage, while the open area represents the coupled, liquid part. This separation leads to a linear R-S relationship for the liquid part.

Modelling of snow accumulation and melt over the snow covered parts and integrating the phase shift between runoff and total mass in the calculation scheme (Riegger and Tourian, 2014) leads to very reasonable results, thus confirming the benefits of a Top Down approach. The integration of the Cascaded storage approach into the calculation scheme for boreal catchments was beyond the scope of this publication and is the subject of present investigations.

For seasonally dry catchments like Niger, Tocantins etc. the separation of the time dependent uncoupled storage compartments like soil or isolated surface water bodies remain a major task for remote sensing, i.e., for satellite soil moisture measurements and open water body altimetry *(see Outlook (P24 L14-22)*.

5. The writing should definitely be improved. For instance, the abstract reads like an extended summary with an introduction and is too long and too specific. Also, the use of the English language should be checked by a native speaker. Suggestions for improvements and some other small remarks are given in the annotated manuscript attached.

According to the HESS guidelines for authors the abstract should comprise the motivation, an introduction into the method, a summary of the key points and directions of prospective research. This is actually the case. Nevertheless, the attempt was made to shorten the text.

The whole manuscript text has been checked by a native speaker and is revised accordingly.

Changes are marked and integrated into the new version number 3.