

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 an interesting and novel study on estimating the drainable water storage in large river basins based on observed discharge data and/or water storage anomalies from GRACE. The work develops an approach based on the linear storage concept to separate the total drainable storage volume of a river basin into two storage compartments, which are denominated the catchment storage and the river network storage. The manuscript comprehensively presents the methodological and mathematical concept of the approach and nicely illustrates the storage characteristics for the single and the two storage assumption in terms of signal dynamics, amplitudes and phases for

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virtual experiments, including an assessment of uncertainties of the parameter estimation procedure. The concept is then applied to the real world example of the Amazon river basin, leading to interesting lumped results of basin storage and runoff dynamics. Nevertheless, I have some general doubts on the method and the way it is realized in this study:

->Thanks to the referee for the effort. Below you find my respond to his comments in detail

< 1) The storage concept presented here, by looking at linear storages and their storage coefficients or ‘time constants’, takes a purely temporal perspective on catchment storage. It separates two storage compartments of different volume and drainage behaviour in time.

-> For clarification: Generally storage coefficients are defined as storage change versus changes in water head or pressure (P3 L12). Time constants are introduced by the exponential form of a flow from a linear storage if there is no input and are defined as proportionality coefficient between storage and runoff (Eq3).

< While basically a viable approach, this is presumably not as straight forward as the manuscript implies when it comes to linking these quick and slow storages to a spatial (i.e. source area) perspective of storage and flow. For example, a quick runoff response may partly occur from the so-called catchment storage by, e.g., sub- surface storm flow, whereas a slow response may also occur along the river network due to surface water-groundwater interactions or floodplain storage. Thus, I wonder whether the separation into a catchment and a river network storage as implied by the title can really be achieved by the method applied here, instead of a separation of a quick and a slow storage compartment.

-> As already mentioned in the “Introduction” flows from storages draining in parallel superpose, while storages in a sequence lead to a time lag or phase shift (P5 L22-24). Flows draining in parallel can be separated in the runoff curves directly by their

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different response time constant, if there are distinct periods of negligible recharge like in seasonally dry regions (Niger, Tocantins, .etc.) long enough for a sufficient fit. (P4 L8-16). Averaged over the full Amazon catchment there are no dry periods (see below). While in different LSMs (Getirana, (2014) groundwater and surface (overland) flows are summed up as input into the river routing procedure, they are conceptualized here as one flow component and thus one catchment storage (p6 L25-26). Actually, there is no other way to compare calculated streamflows with river discharge measurements, as they cannot be separated into contributions of different dynamic behavior for the full Amazon catchment.

-> The effect of the river network storage with an effective hydraulic time constant over the catchment does not correspond to the superposition of quick and slow flows, but instead leads to a phase shift (Eq27) between catchment storage (groundwater and surface flow storage) and the river network storage as it is in sequence. As it is shown in the "Parameter estimation" section the Cascaded storage approach is not limited to a faster response of the river network ($\tau_{R} < \tau_{C}$) but also permits the description of river systems with a slow response ($\tau_{R} > \tau_{C}$) as it may also occur "along the river network due to surface water-groundwater interactions or floodplain storage" of large river systems. However, as the phase shift (Eq27) is commutative (P16 L1-5) the assignment of the quick or the slow part of the storage to the catchment or river network mass is only possible with additional ground based or remote sensing information on the river network or floodplain extent (P17 L18-20).

-> Compared to inundated areas taken from Global Inundation Extent from Multi-Satellites GIEMS (see Fig.10) the calculated river network mass leads to correlation coefficients of 0.96 for the signal and 0.76 with respect to the mean seasonal cycle. This allows to assign the river network storage calculated here to the observed river network and flooded area volume. The average amplitude ratio MR/MT of the river network to total mass of 50% calculated here fits very well to the estimate of 50% by Papa, F., Frappart, F., Güntner, A., et al., (2013) and the ratio of 41% from Getirana et

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al., (2017a).

-> In the light of the referee's own articles on surface water storage variability in large river basins (Papa, F., Güntner, A., Frappart, F., Prigent, C., et al., (2008)) and especially those for Amazon (Papa, F., Frappart, F., Güntner, A., Prigent, Aires, F., Getirana, A.C.V., (2013)), which come to the same results with different remote sensing methods, it is strange that the referee wonders whether this can be achieved by the proposed method without substantiating his wondering.

< 2) As a prerequisite of the applicability of the approach, uncoupled storages (i.e. storage compartments that do not directly drain to the catchment outlet) need to be negligible or time invariant (page 23, lines 4-5). It is assumed that this condition is fulfilled in the study area Amazon basin (page 18). However, I doubt whether this assumption holds true.

->The author is aware of the impact from time dependent uncoupled storages (Riegger and Tourian (2014)). Thus, additional prerequisites are formulated (P23 L 4-9). The prerequisites are extended for a general application of the scheme, such as : b) Separation of coupled and uncoupled storage compartments by conceptual approaches c) Full description of the hysteresis by quantified contributions of the coupled and uncoupled which are not mentioned here. The Amazon basin is chosen for first evaluations of the scheme as it fulfills prerequisite a.).

< Given the strong seasonality of rainfall and evapotranspiration in large parts of the basin, there are substantial temporal variations of water storage in the unsaturated zone (e.g. Tomasella et al., 2008), including moisture states drier than field capacity of the soil, i.e., non-gravity-driven conditions. Such conditions correspond to storage variations in non-coupled storage compartments as defined for this study and were assumed to be negligible. This calls the approach into question.

-> As data - provided in the supplement - indicate monthly recharge $N = P-ET$ is positive for the full Amazon catchment upstream Obidos. This is also confirmed by the

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study of Getirana et al. (2014) (Fig.5), where the monthly climatology of full Amazon is compared for 14 different global Land Surface Models.

-> In addition, any non negligible impact of time dependent uncoupled storages could be recognized in the R-S diagram and would also effect the scatter plots of simulated versus observed runoff or mass anomaly if the description of the uncoupled storage behavior were not sufficient.

-> For the full Amazon catchment this means that averaged over the full catchment area soil water content remains constant with permanent input, i.e. the uncoupled storage is time independent. This might not be the case for all sub catchments. In fact, dry out effects, i.e. mass changes without changes in runoff can be recognized in the R-S diagram of seasonally dry or monsoonal catchments with distinct wet and dry seasons like Niger etc (see P24 L17-20). According to above conditions b.) and c.) additional conceptual approaches or information from remote sensing are needed for the temporal description of the uncoupled storage. In Riegger and Tourian (2014) it has been shown for boreal regions that the uncoupled storage (in this case snow and ice) can be described satisfyingly by MODIS snow coverage. As emphasized in the outlook (P24 L17-20) for monsoonal regions the respective methods for the quantification of uncoupled storages by remote sensing (soil moisture and open water body altimetry from satellites) need to be developed.

-> It is one thing that the referee unfoundedly insinuates a time dependent uncoupled storage for the full Amazon catchment. It is however unintelligible that this could call the approach into question without explaining and supporting this judgement adequately in the light of the given prerequisites (P23 L 4-9).

< 3) The separation approach (i.e. Cascaded storage approach ??) presented requires an estimate of recharge for the river basin of interest. Three options are suggested (page 18). Following these suggestions, the input that should rather be called precipitation surplus, as commented by another referee, is not necessarily what it is claimed

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to be, i.e., it is not groundwater recharge or a similar flux term that contributes directly to a connected storage, but may at last partly go into an intermediate storage or it may experience travel times to the saturated zone given large groundwater depths in some parts of the Amazon basin. Thus, I wonder what the effect of this discrepancy between precipitation surplus and the required contribution to the connected storage is on the validity of the results and the values obtained here (e.g. of time constants).

-> The expression recharge (Eq32-34) is used here to generally describe the lumped fluid input into a catchment received from either aggregated hydrometeorological data, the catchment's atmospheric water balance or the catchment's water balance using runoff and GRACE. It is not discriminating input leading to surface (overland) flow or groundwater flow (P6 L25-27), as for the Amazon catchment baseflow and surface (overland) flow components cannot be distinguished by observations. Thus, instead of using separate linear reservoirs for surface (overland) flow and groundwater flow as it is done in HyBam (Getirana et al. (2012), Eq.1) or in many LSMs (Getirana et al. (2014) only one linear reservoir is used here for simplicity for both flow contributions.

-> In WGHM (Döll et al., (2003) Eq.5) for example only one linear reservoir is used for groundwater flow yet none for surface flow with the consequence that the respective overland flow is routed to the river network without a delay. Generally, linear reservoirs for the different flow components are used in many hydrological models and LSMs in order to describe the dynamic system response including the time delay and the related storage volumes. The above mentioned models as well as WGHM do not describe flow in the unsaturated zone or other intermediate storage. The related transition times in this case are assumed to be negligible compared to the hydraulic time constant.

-> I wonder why the referee rises the complex question of travelling times in unsaturated zones and their impact on storage volume here as he - as a prominent user of WGHM - is certainly familiar with simplifications in LSMs and in the WGHMs calculation scheme.

< 4) The approach assumes a linear storage concept for representing the river network

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dynamics. As commented by another reviewer, this may not be adequate for several river basins. In particular, it does not apply to the Amazon basin given the particular dynamics of floodplains and inundation areas, and different gradients of large-scale water levels at the seasonal scales between the rising and falling limb of the annual flood wave.

-> As already mentioned in my response to Mark Bierkens any non negligible, non linear contribution to the R-S-relationship would lead to changes in the functional form of the resulting mass and runoff time series and not to a phase shift only. Mathematically, only a linear R-S relationship in Eq7 can lead to a pure phase shift in the solution of Eq11 without any impact on the functional form. Data from the full Amazon catchment impose a behavior as a Linear Time Invariant (LTI) System (see Fig.1 for phase adapted mass and Riegger and Tourian, (2014)).

-> Complex river routing schemes such as HyBam used in the LSM comparison study of Getirana et al. (2014) come to similar results. With a Nash-Sutcliffe (NS) coefficient of 0.74 and a correlation (c) of 0.90 (with respect to the mean seasonal cycle) compared to an NS of 0.58 and a c of 0.84 for the best LSM (Getirana et al. (2014)) the Cascaded Storage approach outperforms the LSMs in combination with HyBam.

-> A possible explanation of this linear behavior between streamflow and storage for CATCHMENTS is that the river network system consists of many river branches, which interfere, and not of one branch or channel only. Hydraulically this might be understood, as flow in a river network with many contributing channels and branches behaves similarly to groundwater flow in a fractured system. The flow in a volume large enough to contain many contributing channels behaves like a porous continuum and can be described by Darcy's law -which is linear - instead of a discrete channel flow.

-> If the referee might have a closer look at the model he uses himself he will find out that in WGHM "the river itself is treated as a linear storage element similar to groundwater" (Döll et al., (2003), Eq.5)).

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< 5) It should be clarified to which extent the drainable storage values obtained for a particular river basin depend on the actual time period used in the analysis and on their particular observed storage amplitudes (which probably are smaller than what is physical reasonable and possible at the long-term), or whether they represent some fundamental catchment property.

-> The time constants adjusted within the optimization periods might slightly change with the length of the period, yet generally are considered as a kind of fundamental catchment property as long as there are no significant changes in land surface properties or river hydraulics and as long as no anthropogenic impacts occur.

-> Runoff statistics for Amazon upstream Obidos deliver for GRDC measurements :

- R = 42.3 – 170.5 , average R = 99.5 stdev 28.8 [mm/mo] for 1980-2008

- R = 45.5 – 140.5 , average R = 96.2 stdev 26.2 f[mm/mo] or 2003-2008

and for Hybam measurements :

- R = 45.5 – 155.5 , average R = 96.2 stdev 26.2 [mm/mo] for 2003-2008 used in the study here

-> This means that – apart from some high discharge events before 2003 - the range covered by the modelling period corresponds to the long term statistics.

-> As the observed runoff does not cover a range from zero to the observed minimum, a superposition of a storage with a much longer time constant and thus leading to a very small contribution to runoff might not be visible at present. An additional storage release could come from a deep confined aquifer underneath the unconfined aquifer close to the surface. Most of the hydrological and LS models (like WGHM (Döll et al., (2003) amongst others) do not consider more than one groundwater storage.

-> However, in this study no deviation from the linear behavior caused by a contribution of such an aquifer can be observed at the present runoff range. -> Generally, the

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possible impact of such a storage means that the drainable storage determined from the mass and runoff range in this study is a lower limit of possible drainable storages.

-> An extrapolation to a runoff range beyond the maximum will have to face the same challenge as other hydrological or LS models such as WGHM (Döll et al., (2003), which use a linear storage for the river network.

-> I am wondering why the referee creates the impression that the problem of an extrapolation beyond the parameter range used for optimization is a specific problem of the Cascaded storage approach but letting unmentioned that all hydrological or LS models using a linear storage for the river system – including WGHM - have to face the same problem.

< 6) While phase shifts between simulation results of hydrological models and GRACE storage variations exist as noted by the author, it is generally accepted that they can be attributed to model deficiencies in representing river flow routing or inundation dynamics, and the discrepancies may eventually be used to improve the model.

-> In his paper (Schmidt, R., Petrovic, S., Güntner, A., (2008)) the referee states that the phase shift “points to systematic deficiencies in hydrological modeling. For example, water storage in surface water bodies will cause a delay of freshwater runoff from continental areas. However, processes of runoff routing in the river network and lake/wetland water retention are not taken into account by hydrological model versions used in this study, except for WGHM”. However, he does not mention how model deficiencies are removed in WGHM. In Werth S., Güntner, A. (2010) he reports that “WGHM still tended to underestimate seasonal TWS variations and phase shifts appeared”.

-> Thus, it would be quite illuminating if he would provide recent simulation results from WGHM for runoff as well as total and river network mass for the Amazon basin upstream Obidos and sort their performance into the comparison study of the LSMs by Getirana et al., (2014).

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< In my view, parts of the manuscript that indicate that this study provides a new explanation for these phase shifts (e.g. page 5 last paragraph, page 23 line 11) may need to be re-written as I do not see this potential new contribution.

-> According to science theory there are many ways to Rome. Therefore, a hypothesis or approach is accepted if it gives reasonable physical and mathematical explanations for an observed effect, if it describes it sufficiently and if it does not lead to contradictions. This includes approaches on different temporal and spatial scales.

-> In their spatially distributed approach combining 14 different LSMs and the river routing scheme of HyMap Getirana et al., (2014) show that implementing an appropriate routing schemes permits an appropriate description of the TWS amplitude. In their study of Rivers and Flood plains storage Variability Getirana et al. (2017a) they state that “Adding SWS (corresponding to river network storage) and LWS (corresponding to catchment storage) improves the phase agreement with GRACE based observations”. They emphasize that “SWS is a major component of TWS variability in the tropics. . . , where that storage component has been neglected in a series of previous hydrological studies”.

-> In the study here a different approach is chosen for a different purpose. Based on the reported LTI behaviour of coupled storage and runoff for the entire catchment the absolute drainable storage volume shall be determined. This goes beyond the description of storage variations. Thus, for a lumped description of catchments by their mass balance an appropriate concept must be found in order to describe the effect of the phase shift by a physical concept. (In previous studies (Riegger and Tourian, (2014) the phase shift had been integrated into the numerical calculation scheme without the necessity of a detailed understanding (P5 L 21), yet leading to a description of the system behavior with high accuracy (NS=0.6 and correlation=0.85 for full Amazon w.r.t. mean seasonal cycle)).

-> In order to account for the phase shift the river network is conceptualized as one

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(lumped) storage with an effective (lumped) time constant in sequence to the catchment storage comprising surface (for overland flow) and groundwater storage. This permits a piecewise analytical description of the coupled system without the disadvantages of numerical calculations. This concept and its realization is a new contribution to global scale modeling.

-> The Cascaded storage approach, in which the system behavior of the land surface AND the river network is described by the two time constants t_c , t_R exclusively, leads to the same conclusions and to analogous results as Getirana et al., (2014), yet from a different perspective.

< In particular, given the lumped temporal nature of the approach presented here, the study does not contribute to a better understanding of reasons for phase shifts from a process-based perspective (page 5, line 21).

-> As the title indicates the main purpose of this paper is to determine the absolute drainable storage volume of catchments based directly on observations from GRACE and runoff. It was never intended to describe the system from a process based perspective.

-> In this paper the physical effects of a storage cascade on the phasing and signal amplitude are investigated extensively in order to clarify, if an optimization versus GRACE anomalies or measured runoff leads to unique results in absolute storage volume. Its application to the full Amazon basin provides a very accurate description of phase and amplitude for runoff and mass and in addition an independent, quite accurate description of the river network volume.

====> Looking at the structure of his comments it is obvious that the referee puts approaches and concepts into question without substantiating his wondering. The referee expresses his doubts, however, neither explains and supports his judgements adequately nor reveals possible contradictions or inconsistencies. He doubts and wonders about approaches which are generally accepted in other modeling concepts and which

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are even used by himself applying WGHM. So I think, it is up to the referee to prove how a wrong approach with wrong assumptions can lead to a model performance as presented here. All data and calculations are provided in the supplement.

Minor Comments

The referees minor comments will be considered in the revision of the paper.

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