Satellite-based estimates of groundwater storage variations in large drainage basins with extensive floodplains

Frédéric Frappart, Fabrice Papa, Andreas Güntner, Werth Susanna, Joecila Santos da Silva, Javier Tomasella, Frédérique Seyler, Catherine Prigent, William B. Rossow, Stéphane Calmant, et al.

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Ref.: RSE-D-10-00458
Total water storage decomposition and estimates of groundwater variations in the Negro River Basin

Dear Frédéric,

Two reviews of your paper follow. The third reviewer has evidently moved and left no forwarding address, so we will not have a review from him and will rely on these two. They are quite positive, but Reviewer #1 recommends some refocus and that the evidence that the modeling is accurate needs to be stronger.

Please carefully consider the comments and recommendations below and make appropriate changes to the paper. Publication depends on revision and/or rebuttal of the criticisms made. Further review and revision may be necessary before a final decision can be made.

When you submit your revised paper, please provide a summary of the changes you have made and your responses to the review comments and recommendations.

To submit a revision, go to http://ees.elsevier.com/rse/ and log in as an Author. You will see a menu item called "Submission Needing Revision." You will find your submission record there. Please remove any items that have changed or are no longer needed before uploading your revised manuscript.

Please upload your original files, not PDF files. If you have any problems or questions when uploading your revised manuscript, please contact Betty Schiefelbein at: rse@umn.edu.

I hope that you will undertake the necessary revisions and will look forward to receiving your revised paper.

Sincerely,

Marvin Bauer
Editor-in-Chief
Remote Sensing of Environment

Dear Marvin Bauer,
Editor-in-Chief
Remote Sensing of Environment

Please find enclosed the revised version of our manuscript now entitled "Satellite-based estimates of groundwater storage variations in large drainage basins with extensive floodplains ". We have taken into account their constructive comments to improve the quality of the manuscript.

As suggested by Reviewer 1, we modified the title of the manuscript and added a new figure presenting a) the annual amplitude of the GRACE-based GW seasonal amplitude, b) the hydrologeological of Brazil from the Departamento Nacional da Produção Mineral (1983) to show the reader the similarities between our estimates and the hydrogeological structures in

the Negro River basin. We explained why this comparison is relevant to validate qualitatively our approach. If the seasonal amplitudes of groundwater storage variations will most probably change with the climate forcing of a particular period, *i.e.*, decrease during an El Niño event as in our case, the spatial patterns of variations will persist even for non-average conditions.
We also added in the introduction some sentences on the important role of the floodplains in the hydrological cycle.
We responded Reviewer 3 concerning the type of approach used to filter the GRACE data and added some information about the characteristics of the Negro River basin.
We responded on the scale problem concerning the comparison between the GRACE-derived GW anomalies and the in situ measurements pointed out by the two Reviewers.
We hope these modifications will satisfy the Reviewers comments.
We are looking forward to hearing from you.
Sincerely yours,

Frédéric Frappart, Fabrice Papa, Andreas Güntner, Susanna Werth, Joecila Santos da Silva, Javier Tomasella, Frédérique Seyler, Catherine Prigent, William B. Rossow, Stéphane Calmant, Marie-Paule Bonnet

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Comments from the Reviewers:

Reviewer #1:

This study combines a variety of data and models regarding water levels in various components of the water system in the Negro Basin, South America during 2003-2004. The study starts from GRACE measurements of total water storage (TWS) variations during this time. Then these variations are broken up into variations occurring in the surface water (SW), root zone (RZ), and groundwater (GW) reservoirs (as in equation 1). In particular, SW is constrained by satellite measurements and in situ observations, and RZ from a hydrological model. The authors are then able to solve for GW by removing RZ and SW from the TWS measurements of GRACE. To verify the solution for groundwater, the authors compare to hydrological maps to see if the results seem reasonable.

The authors have thus outlined a method for detecting temporal variations in groundwater storage using GRACE satellite measurements and a variety of additional measurements and models to remove the contributions from SW and RZ. Although similar methods have been used to constrain groundwater variations on a basin-scale (for example, the authors cite Yeh et al., 2006; Rodell et al, 2009; Leblanc et al 2009), this is the first time this method has been performed in a region dominated by wetlands.

The manuscript is reasonably well-written. However, I am concerned about a few issues that relate to verification of the method and to importance with respect to the broader hydrological community. First, it seems to me that this manuscript describes a method for estimating groundwater variations in a wetland environment, but it is presented as an investigation of the hydrology of the Negro basin. In fact, I don't think the manuscript tells us anything new about the Negro basin, and therefore I think the focus of the paper should be altered. I describe my thoughts on this in more detail in points 1

and 2 below. Second, the method that the authors describe should, in principle, be able to constrain variations in groundwater in a wetland basin (otherwise their method is not useful). However, the authors only compare ground water variations obtained using their method to a hydrogeological map of Brazil (and don't show the map), and to groundwater measurements in a single location (the Asu catchment) for which the fit is not that great (see Fig. 3a). Thus, I think the authors need to do a better job in demonstrating that their method is accurately constraining actual variations in groundwater. I describe these concerns below in points 3-5 below.

If the issues I list below can be addressed, then I think that the manuscript could be published. In the meantime, I am recommending "major revision".

We would like to thank Reviewer 1 for carefully reading our manuscript and for providing us with useful/interesting comments, which helped us to improve our paper.

1. This study was performed in the Negro Basin, South America during 2003-2004, because this is a location and time period for which sufficient data exists. I am not aware of an alternative reason for estimating the groundwater variations in this time and location - if there is some other reason for choosing the Negro Basin (e.g., there is persistent aquifer depletion there, or a drought), then the authors should stress this more clearly. If the authors are not addressing any groundwater issues related to the Negro basin, then they should stress that the point of this study is method development and verification, and they are just using the Negro Basin to test their method. Also, in this case, I think that the title the authors chose is slightly misleading because of its mention of the Negro Basin. Instead, the title should be something like "A method for estimating basin-scale groundwater storage variations in a wetland". The authors could add "A case study from the Negro Basin 2003-2004" at the end.

Reviewer 1 is right: we present here a methodology to estimate groundwater variations in a large river basin covered with extensive floodplains, and to our knowledge, this is the first attempt in a such environment. We now mentioned this, both in the introduction and, in the conclusion. The aim of this paper is not to address any groundwater issues specifically related to the Rio Negro, but we chose the Negro River basin as a case study for our method because we already successfully applied our methodology to estimate surface water volume variations combining information on inundation extent from satellite images and water levels from radar altimetry in this basin (Frappart et al., 2005; 2008).
As suggested by Reviewer 1, we modified the title of the paper to “Satellite-based estimates of groundwater storage variations in large basins with extensive floodplains”.

2. Furthermore, given that others have estimated groundwater storage variations by combining GRACE and surface water measurements, the angle that is new in this manuscript is the application to a drainage basin dominated by wetlands. Thus, I think that the authors need to stress some of the challenges that are presented by the application to wetlands. Why is performing this type of analysis in a wetland different from performing it in a desert or other environment? I think that this is because much more accurate estimates of surface water fluctuations are necessary in a wetland region. This should be stated clearly. For this study to be useful, the minimum requirements for constraints on surface water variations should also be mentioned - how can a reader

determine if their constraints on surface water variations are sufficient? Finally, I think that a sentence or two about the need for better constraints on groundwater variations in wetland regions is necessary - what are the major applications of such measurements, and why is remote detection better than in situ measurements (wells)?

This paper follows two previous studies on the estimate of surface water storage in the Negro basin, the first one on the methodology (Frappart et al., 2005), the second one on the monitoring of the surface waters on the basin over 1993-2002 (Frappart et al., 2008), as mentioned in part 3.1 Monthly water level maps.

The datasets used in this paper are very similar to the ones from Frappart et al. (2008): the same multisatellite inundation product but which has been extended to the period 2003-2004, a denser network of altimetry stations with more accurate water levels as ENVISAT RA-2 measurements are used instead of Topex/Poseidon.

In this previous study we found a maximum error of 23% of the annual surface water variations. In this new study, taking into account the different sources of error, the maximum error is reduced to ~ 11%. (See the part on surface water error estimates in 3.1 Water volume variations for details on how this error was estimated (lines 188-200)).

We added in the introduction (lines 55-64) a paragraph on the role of floodplains and the interest of using remote sensing information for large river basins instead of in situ as generally for this information is missing for most of the tropical basin, such as the Amazon:

“Although wetlands and floodplains cover only 6% of the Earth surface, they have a substantial impact on flood flow alteration, sediment stabilization, water quality, groundwater recharge and discharge (Maltby, 1991; Bullock and Acreman, 2003). Moreover, floodplain inundation is an important regulator of river hydrology owing to storage effects along channel reaches. Reliable and timely information about the extent, spatial distribution, and temporal variation of wetlands and floods as well as the amount of water stored is crucial to better understand their relationship with river discharges, and also their influence on regional hydrology and climate. Remote sensing techniques are a unique mean for monitoring large drainage basins climate and hydrology where *in situ* information is lacking (as, for instance, over floodplains and wetlands or for groundwater monitoring)”.

Moreover, wells, especially in tropical areas are very sparse and will never provide a complete view of GW variations nor resolve its variations on shorter "weather-like" time scales, which we want to determine in order to investigate processes.

Besides, wells will never provide a complete map of GW for large areas nor, unless continuously monitored, resolve its variations on shorter "weather-like" time scales, which we want to determine in order to investigate processes.

3. I am concerned about the data and method that the authors use to verify their results. The authors estimate the amplitude of groundwater variations (Fig. 1f) by removing SW and RZ from TWS - this seems to be their main result. How can the authors know if these results are correct? They compare their results to a hydrogeological map of the Negro River Basin (see text, near line 197) and find that the GW variation pattern "perfectly matches" the hydrological map. This is a qualitative result at best, especially since the text in the sentences following line 197 is the only comparison that the authors present. Only gross generalizations of the spatial variations in the seasonal cycle of groundwater are presented and compared to the model predictions. I think that at a minimum, some sort of quantitative measure of the groundwater variations should be presented. For example, do the amplitudes of the estimated variations for 2003-2004 match those that are "predicted" by the hydrogeological map? Better, a reproduction of

the hydrogeological map should be included in the paper for direct comparison to Fig. 1f.

The period 2002-2004 was considered as a small El Niño event according to the Multivariate ENSO Index (http://www.esrl.noaa.gov/psd/people/klaus.wolter/MEI/). For the lower and northern parts of the Amazon basin this period was associated with below average precipitation and water storage (*e.g.*, Chen et al. 2010, Xavier et al., 2010). It has to be noted that the hydrogeological map used here for evaluation only shows the spatial distribution of the aquifers, roughly classified by their hydrological importance or yield. The map does not directly give a long-term average representation of groundwater storage variations. Nevertheless, assuming that important aquifers with high yield and important recharge and drainage volumes tend to show larger seasonal storage variations than local and unimportant aquifers with low porosity, we consider the hydrologeological map as a useful albeit qualitative approach to validate the spatial patterns of our estimates. As it can be seen in the Figure 2 of the revised version, the patterns of the annual groundwater storage amplitudes are similar to the spatial distribution of aquifer types of different importance on the hydrogeological map of Brazil. The seasonal amplitudes of groundwater storage variations will most probably change with the climate forcing of a particular period, *i.e.*, decrease during an El Niño event as in our case, but the spatial patterns of variations will persist even for non-average conditions. Thus the evaluation approach remains valid. Given the very low availability of direct groundwater observation data in the area, we consider this approach as another helpful piece of evidence that gives more confidence in our results.

Luciano Xavier, M. Becker, A. Cazenave, L. Longuevergne, W. Llovel, O.C. Rotunno Filho (2010). Interannual variability in water storage over 2003–2008 in the Amazon Basin from GRACE space gravimetry, in situ river level and precipitation data Original Research Article Remote Sensing of Environment, 114(8), 1629-1637.

Chen JL, Wilson CR, Tapley BD (2010). The 2009 exceptional Amazon flood and interannual terrestrial water storage change observed by GRACE, Water Resources Research, 46, W12526..

4. Furthermore, how can we be sure that 2003-2004 was not an unusual year? If, for example, anomalous weather patterns produced unusual spatial variations in groundwater, then a match to the long-term average that is presented in a hydrogeological map would indicate a failure of the model. It seems to me that we should expect to be able to detect unusual ground water variations (e.g., patterns that are not on the hydrogeological map) - otherwise this method is not very useful.

The period 2002-2004 was considered as a small El Niño event according to the Multivariate ENSO Index (http://www.esrl.noaa.gov/psd/people/klaus.wolter/MEI/) and can not be considered such a “unusual year” in the area. This is confirmed by a short analysis on the GPCP data which do not show any large anomalous event as the ones in 2005 (drought) or 2009 (flood).

Moreover, the hydrological map shows where are located the aquifers and their capacity. Regions with no aquifer or with low capacity to store water, will not store water even if large rainfall occur during large La Niña events. The water will flow and will be stored in the large floodplains and then recharge the aquifers. The spatial patterns will not change. Only the water levels in the aquifer will change, not their spatial pattern as it is conditioned by the storage capacity of the soil. As it can be seen in the Figure 2 of the revised version, the patterns of the annual groundwater storage amplitudes are consistent with the spatial distribution of aquifer types on the hydrogeological map of Brazil.

5. The authors do compare their results to in situ measurements of groundwater variations from wells at the Asu micro-catchment. This direct comparison (Fig. 3a) is exactly the type of constraints on the method that are needed. Yet, the authors' method shows a very small variation in groundwater during 2003 (about 100 mm) when in fact there was about 600 mm of variation. Although the method did much better in 2004, the failure to predict 1 out of the 2 groundwater cycles does not give the reader a lot of confidence in the method.

Unfortunately, we found only one small area where groundwater time variations are available. The Asu micro-catchment has a drainage area of ~ 7 km² and is not directly connected to the Negro River. As explained in the manuscript, we can not expect a perfect match between this point-measurement and the GRACE encompassing gridpoint with area of ~10,000 km². The interest of this comparison is to see that the timing is similar between the two datasets and that the range of variations is similar. This is what we observe in Figure 4a.

Other points about the paper:

-- Line 100 - I think the figure callout should be Fig. 1b.

We added Fig. 1b to the callout and changed the legend of the other panels and the figure caption. We modified the text accordingly.

-- Section 2.6. The authors describe how they use a hydrological model to constrain the root zone water storage variations. It is unclear to the reader what inputs go into this model, and what the uncertainty about the outputs - I think additional detail that describes these aspects should be added. This is potentially important because I expect there are tradeoffs between root zone storage and groundwater storage.

In this study, we did not pretend to have run neither WGHM nor LaD models. We are directly using outputs from these two hydrological models. We suggest the readers to refer to the articles describing these two models to obtain the information concerning the resolution of the water balance equation and the allocation in the different water reservoirs (the references are given in the text). No uncertainty is provided with the hydrological model estimates, however, we followed a similar approach to the one proposed in previous studies such as Yeh et al., *Water Resources Research*, 2006; Rodell et al., *Hydrogeology Journal*, 2007; Strassberg et al., *Geophysical Research Letters*, 2007; Leblanc et al., *Water Resources Research*, 2009; Rodell et al., *Nature*, 2009; Sun et al., *Geophysical Research Letters*, 2010 and maybe some others. The only difference is we use the outputs from two hydrological models instead of a single one. The outputs of these two models exhibit very similar spatial and temporal patterns, and also have similar amplitude differences. We used their extrema in equations (1) and (2) to present a mean behaviour and a range of variations.

-- Line 137 - I think that the word "bathymetry" is usually used to mean "seafloor

topography", and not the "unflooded land surface". I think that "land surface" would be a better term here.

We changed bathymetry into land surface as suggested by Reviewer 1.

-- Line 206 (and earlier in the paragraph) - The authors describe the relative "importance" of aquifers. This is a rather unquantitative term - I expect that there are better ways of comparing the groundwater storage variations (see point 3 above)

We also wish we could use more quantitative data to compare our groundwater storage variations. Unfortunately, it is the way the acquifers are mentioned on the one and only hydrogeological map of Brazil which gives the boundaries of the aquifers and their relative importance. We used it to evaluate the spatial patterns of our estimates. See our response to point 3 above.

-- Fig. 3- For parts b and c, it is unclear to me from the caption whether the SW and GW estimates are measured or inferred from the GW=TWS-SW-RZ method described here. Furthermore, the authors state in the text that these two quantities should be the same (since the water table is above the surface), but in that case, shouldn't SW already be subtracted from out, and the GW should be zero?

To make it clearer, we modified Figure 4 (former Figure 3) caption as follows:
"Figure 4: a) Time variations of the GW storage in the Asu catchment (*in situ* - grey) and in the corresponding GRACE gridcell (satellite-based - black). b) and c) Time variations of the surface water levels (altimetry-derived - grey) and the groundwater for the corresponding GRACE gridcell (satellite-based - black) in the swamps of Caapiranga and Morro da Água Preta respectively".
It is not exactly what is written in the text. In these two areas, the water table reach the surface, so the surface water and the groundwater should present similar variations. So GW=TWS-SW-RZ ~ SW. It is what is observed on Figure 4 b) and c).

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Reviewer #3:

This is a very interesting study that combines satellite data and modeling analyses to understand temporal variations in water storage in different components of the system. The strength of the paper comes from the multisatellite data and comparison with model results. I hope the following minor comments improve the manuscript. It seems that GRACE measures changes in water storage, I think it is important to indicate this. Throughout the manuscript it often refers to water storage measurements, rather than specifying changes in water storage. I did not see the area of the basin mentioned in the paper. Maybe I missed it.

We would like to thank both Reviewers for carefully reading our manuscript and for providing us with interesting comments, which helped us to improve our paper.

GRACE measures the total mass variations of the Earth at monthly or submonthly timescales. This measurement is converted into anomalies of TWS by removing the static gravity field obtained as a multi-year average of the monthly gravity field. We added several times in the paper the term anomaly to make it clearer to the reader.
We also added the area of the Negro basin (~ 700,000 km²), which represents 12% of the Amazon basin (line 57).

The authors indicate that the destriped filter with 300 km smoothing provided the best results, but did not indicate relative to what other approaches that were done?

Werth et al. (2009) evaluated six post-processing filter methods for derivation of regionally averaged water mass variations from GRACE's global gravity field solutions against hydrological model outputs, and, for each filter method, a wide range of values for the parameters that define the degree of smoothing were tested. These filters are:

- the isotropic Gaussian filter (Jekeli, 1981),
- two degree-order dependent methods (Swenson & Wahr, 2002)
- a time-dynamic filter (Seo et al., 2006)
- an empirical method know as destriping method (Swen and Whar, 2006)
- an anisotropic method (Kusche, 2007).

For the Negro basin, the best choice according to this methodology was found to be the destriped and smoothed at 300 km post-processing method. We suggest the readers to refer to the Werth et al. (2009) paper already mentioned in the reference list.
We added to the paragraph:
"among six different filtering methods and different parameters (see Werth et al. (2009) for the filters employed and the values of the parameters that define the degree of smoothing used)" (lines 156-157).

Jekeli, C., 1981. Alternative methods to smooth the Earth's gravity field, Tech. Rep. 327, Department of Geodetic Science and Surveying, Ohio State Univ., Columbus, OH.

Kusche, J., 2007. Approximate decorrelation and non-isotropic smoothing of time-variable GRACE-type gravity field models, *J. Geodesy,* **81**(11), 733–749.

Seo, K.W., Wilson, C.R., Famiglietti, J.S., Chen, J.L. & Rodell, M., 2006. Terrestrial water mass load changes from Gravity Recovery and Climate Experiment (GRACE), *Water Resour. Res.,* **42,** W05417,doi:10.1029/2005WR004255.

Swenson, S. & Wahr, J., 2002. Methods for inferring regional surface-mass anomalies from Gravity Recovery and Climate Experiment (GRACE) measurements of time-variable gravity, *J. geophys. Res.,* **107**(B9), doi:10.1029/2001JB000576.

Swenson, S. & Wahr, J., 2006. Post-processing removal of correlated errors in GRACE data, *Geophys. Res. Lett.,* **33,** L08402, doi:10.1029/2005GL025285.

Line 227: the paper indicates that groundwater levels were assumed to be below 2 m depth; however, the following paragraph (line 236) indicates that the groundwater table permanently reached the land surface?

The groundwater levels are assumed to be below 2 m in the Asu catchment, and to reach the surface in the swamps of Caapiranga and Morro do Agua Preta. We added "in the Asu catchment" in the text to make this point clearer to the reader.

I think comparing GRACE output with groundwater storage in such a small area is a little problematic.

We totally agree with Reviewer 3 comment. The scales are completely different. Nevertheless, it was the only groundwater measurements we have in the Negro basin. The interest of this comparison is to see if the timing is similar between the two datasets and the range of variations is similar. It is what we observe on Figure 4a.

I did not see where the widths of TW, RZ, etc are explained.

We added the following paragraph explaining how were obtained the widths of the different terrestrial water reservoirs (lines 241-245):
"The deviations correspond to the extrema values for the different water reservoirs and obtained as the monthly range of variations of the GRACE-derived TWS from CSR, GFZ and JPL, of RZ from LaD and WGHM outputs, the mean surface water volume variations more or less the error computed using (4), the GW extrema by difference of the formers".

Figure 3. The lines could be labeled directly.

As suggested, we added labels on Figure 4.

See attached file for additional comments and suggestions.

All the comments and corrections suggested by Reviewer 3 have been taken into account. The major ones are responded below:

1) The title has been changed to "Satellite-based estimates of groundwater storage variations in large basins with extensive floodplains" according to Reviewer 1 suggest.

2) We indicated in the abstract that WGHM and Lad hydrological models were used (lines 27-28).

3) GRACE measures anomalies of TWS. We added anomalies in the second paragraph of the introduction (lines 50 and 60).

4) Frappart et al. (2006a) and Santos da Silva et al. (2010) showed that the accuracy of Envisat RA-2 derived surface water levels is most of the time from12 to 40 cm, knowing that the distance between the altimetry and the *in situ* stations can reach several tenths of kilometres (lines 93-95).

5) In Prigent et al., 2007, uncertainties on the multisatellite inundation product was found to be of ~10% (comparison with high resolution SAR data) with some limitations to detect small wetlands fractions (lines 82-83). As mentioned in Frappartet al. ,2008 in the Negro basin, the

multisatellite product is not adequately detecting the small floodplains upstream of the Negro and its two major tributaries (see Frappart et al., 2008 for more details). However, all these informations about the uncertainty are used to compute the error bars on the surface water estimates (see above).

Satellite-based estimates of groundwater storage variations in large drainage basins with extensive floodplains

Frédéric Frappart (1), Fabrice Papa (2,3), Andreas Güntner (4), Susanna Werth (4), Joecila Santos da Silva (5), Javier Tomasella (6), Frédérique Seyler (7), Catherine Prigent (8), William B. Rossow (2), Stéphane Calmant (3), Marie-Paule Bonnet (1)

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Revised version submitted to Remote Sensing of Environment the 17 January 2011

Abstract:

This study presents monthly estimates of groundwater anomalies in a large river basin dominated by extensive floodplains, the Negro River basin, based on the synergistic analysis using multisatellite observations and hydrological models. For the period 2003-2004, changes in water stored in the aquifer is isolated from the total water storage measured by GRACE by removing contributions of both the surface reservoir, derived from satellite imagery and radar altimetry, and the root zone reservoir simulated by WGHM and LaD hydrological models. The groundwater anomalies show a realistic spatial pattern compared with the hydrogeological map of the basin, and similar temporal variations to local *in situ* groundwater observations and altimetry-derived level height measurements. Results highlight the potential of combining multiple satellite techniques with hydrological modelling to estimate the evolution of groundwater storage.

Keywords: groundwater, remote sensing, hydrological modelling

1. Introduction

The water cycle of large tropical river basins is strongly influenced by seasonal and interannual variability of rainfall and streamflow, affecting all the components of the water balance (Ronchail et al., 2002; Marengo et al., 2009). The Terrestrial Water Storage (TWS), which represents an integrated measurement of the water stored in the different hydrological reservoirs and is the sum of the surface water, root zone soil water, snowpack and groundwater, is a good indicator of the changes that occur in hydrological conditions globally and at basin scales. Nevertheless, TWS is difficult to measure due to the lack of *in situ* observations of the terrestrial hydrological compartments.

The Gravity Recovery And Climate Experiment (GRACE) mission, launched in 2002, detects tiny changes in the Earth’s gravity field which can be related to spatio-temporal variations of TWS at monthly or sub-monthly time-scales (Tapley et al., 2004). Previous studies provide important information on changes in TWS over the Amazon (Crowley et al., 2008; Chen et al., 2009). Variations in groundwater storage can be separated from the TWS anomalies measured by GRACE using external information on the other hydrological reservoirs such as *in situ* observations (Yeh et al., 2006), model outputs (Rodell et al., 2009), or both (Leblanc et al., 2009). No similar studies have been undertaken yet for large river basins characterized by extensive wetlands or floodplains.

Although wetlands and floodplains cover only 6% of the Earth surface, they have a substantial impact on flood flow alteration, sediment stabilization, water quality, groundwater recharge and discharge (Maltby, 1991; Bullock and Acreman, 2003). Moreover, floodplain inundation is an important regulator of river hydrology owing to storage effects along channel reaches. Reliable and timely information about the extent, spatial distribution, and temporal variation of wetlands and floods as well as the amount of water stored is crucial to better understand their relationship with river discharges, and also their influence on regional hydrology and climate. Remote sensing techniques are a unique mean for monitoring large drainage basins climate and hydrology where *in situ* information is lacking (as, for instance, over floodplains and wetlands or for groundwater monitoring).

In this study, a new technique is proposed to derive the spatio-temporal variations of water volume anomalies in the aquifer of the Negro River basin, a large tropical basin dominated by extensive floodplains (see Figure 1a and b for its location). The Negro River basin, with a drainage area of 700,000 km², is indeed the second largest tributary to the Amazon River, covering 12% of the Amazon basin, with a mean annual discharge of 28.400 $m^3.s^{-1}$ (Richey et al., 1989; Molinier et al., 1992). The method is based on the combination of multisatellite-derived hydrological products and outputs from global hydrology models. Water storage anomalies in the different hydrological reservoirs are removed from the TWS anomalies measured by GRACE to isolate the groundwater anomaly storage over 2003-2004. Results are both evaluated and validated using a hydrogeological map of Brazil, *in situ* measurements of groundwater level variations in a micro-catchment, and altimetry-derived water stages for zones where the aquifers reach the land surface.

2. Datasets

2.1. GRACE-derived land water mass solutions

The Gravity Recovery And Climate Experiment (GRACE) mission, launched in March 2002, provides measurements of the spatio-temporal changes in Earth's gravity field. Several recent studies have shown that GRACE data over the continents can be used to derive the monthly changes of the total land water storage (Ramillien et al., 2005; 2008; Schmitt et al., 2008) with an accuracy of ~1.5 cm of equivalent water thickness when averaged over surfaces of a few hundred square-kilometres. We used the Level-2 land water solutions (RL04) produced by GFZ, JPL (for these two first products, January 2003, June 2003 and January 2004 are missing), and CSR (June 2003 and January 2004 are missing) with a spatial resolution of

~333 km, destriped and smoothed by Chambers (2006) with an accuracy of 15-20 mm of water thickness. They are available at ftp://podaac.jpl.nasa.gov/tellus/grace/monthly.

2.2. The multisatellite inundation extent

This dataset quantifies at global scale the monthly distribution of surface water extent and its variations at ~25 km of resolution. The methodology which captures the extent (with an accuracy of ~10%) of episodic and seasonal inundations, wetlands, rivers, lakes, and irrigated agriculture over more than a decade, 1993–2004, is based on a clustering analysis of a suite of complementary satellites observations, including passive (SSM/I) and active (ERS) microwaves, and visible and near-IR (AVHRR) observations (Prigent et al., 2007; Papa et al., 2006; 2008; 2010).

2.3. Envisat RA-2 radar altimeter-derived water level heights over rivers and wetlands

Silva dos Santos et al. (2010) build 140 time series of water levels derived from RA-2 ranges processed using the Ice-1 retracker over the Negro River drainage basin (see Figure 1c for their locations), for the period 2002-2008, as suggested by Frappart et al. (2006a). The uncertainty associated with the water level height ranges between 5–25 cm for high water season to 12–40 cm during low water season (Frappart et al., 2006a; Santos da Silva et al., 2010).

2.4. In situ surface water levels

We used daily measurements of water stage from eight leveled *in situ* gauge stations from the Brazilian Water Agency (Agência Nacional de Águas or ANA - http://www.ana.gov.br), see Figure 1c for their location.

2.5. *In situ groundwater levels*

The Asu micro-catchment, with a drainage area of 6.58 km², ~90 km north-northwest of Manaus, was instrumented with dipwells in 2001 (see (Tomasella et al., 2008) for a complete description of the catchment instrumentation). We used the well measurements to evaluate our estimates of the groundwater storage variations at that location.

2.6. *Root zone water storage outputs from hydrological models*

Hydrological model outputs are widely used to analyze spatio-temporal variations of water storage content at basin and global scales. We used water storage in the root zone from the Land Dynamics (LaD) model (Milly and Shmakin, 2002) outputs and from the latest version (Hunger and Döll, 2007) of the WaterGAP Global Hydrology Model (WGHM) (Döll et al., 2003).

2.7. *Precipitation estimates from the Global Precipitation Climatology Project (GPCP)*

These data quantify the distribution of precipitation over the global land surface (Adler et al., 2003). We used the monthly Satellite-Gauge Combined Precipitation Data product Version 2 data, available from January 1997 to present with a spatial resolution of 1° of latitude and longitude. Over land surfaces, uncertainty in rate estimates from GPCP is generally less than over the oceans due to the *in situ* gauge input (in addition to satellite) from the GPCC (Global Precipitation Climatology Center). Over land, validation experiments have been conducted in a variety of locations worldwide and suggest that while there are known problems in regions of persistent convective precipitation, non precipitating cirrus or regions of complex terrain, the uncertainty estimates range from 10 to 30% (Adler et al., 2003).

2.8. *Hydrogeological map of Brazil*

We used a hydrogeological map from the Brazilian Department of Mineral Production (DNPM, 1983) which provides the boundaries and the hydrogeological importance of the aquifers of the whole Brazil. This map, holdings of ISRIC, is made available by the European Commission - Joint Research Centre through the European Digital Archive of Soil Maps (EuDASM) (Selvaradjou et al., 2005):

http://eusoils.jrc.ec.europa.eu/esdb_archive/EuDASM/EUDASM.htm

3. Methods

3.1. Monthly water level maps

Monthly maps of water level over the floodplains of the Negro River Basin have been determined by combining the observations from a multi-satellite inundation dataset, RA-2 derived water levels, and the *in situ* hydrographic stations for the water levels over rivers and floodplains (see Figure 1c for the location of altimetry-based and *in situ* stations). For a given month during the flood season, water levels were linearly interpolated over the flooded zones of the Negro River Basin. A pixel of 25 km x 25 km is considered inundated when its percentage of inundated area is greater than 0. The elevation of each pixel of the water level maps is given with reference to its minimum computed over the 2003-2004 period. This minimum elevation represents either the land surface or very low water stage of the floodplain. More details about the methodology used here can be found in Frappart et al. (2005, 2006b, 2008).

3.2. GRACE leveling and time-shift

An optimum filter method was developed by analyzing the correspondence of GRACE basin-average water storage to the ensemble mean of hydrological models (WGHM, LaD) and by analyzing the error budgets (satellite/leakage errors) and amplitude and phase biases for the different filter types. For the Negro River Basin, the destriped filter with 300 km smoothing radius provides the best results among six different filtering methods and different parameters (see Werth et al. (2009) for the filters employed and the values of the parameters that define the degree of smoothing used). Only a very small bias in the seasonal phase of storage changes resulted due to filtering. The GRACE products have been rescaled with a factor of 1.061 to account for amplitude smoothing due to filtering determined from smoothed and unsmoothed basin-average model ensemble time series of water storage.

3.3. Groundwater storage estimates

The time variations of the TWS expressed as anomalies are the sum of the contributions of the different reservoirs present in a drainage basin:

$$\Delta TWS = \Delta SW + \Delta RZ + \Delta GW \qquad (1)$$

where SW represents the total surface water storage including lakes, reservoirs, in-channel and floodplains water; RZ is the water contained in the root zone of the soil (representing a depth of 1 or 2 m), GW is the total groundwater storage in the aquifers. These terms are generally expressed in volume (km^3) or mm of equivalent water height.

The GW anomaly over 2003-2004 is obtained in (1) by calculating the difference between the TWS anomaly estimated by GRACE and the SW level anomaly maps previously derived from remote sensing and the RZ anomaly derived from hydrological models outputs. The TWS and RZ monthly anomalies are the average anomalies of respectively the Level-2 GRACE CSR, GFZ and JPL destriped and smoothed solutions at 300 km of averaging radius, and the outputs from LaD and WGHM, resepctively.

3.4. Water volume variations

For a given month *t*, the regional water volume of *TWS*, *SW*, *RZ* or *GW* storage $\delta V(t)$ in a basin with surface area *S*, is simply computed from the water heights δh_j, with j = 1, 2, . . .

(expressed in mm of equivalent water height) inside S, and the elementary surface $R_e^2 \sin\theta_j \delta\lambda\delta\theta$ (and the percentage of inundation P_j for SW):

$$\delta V(t) = R_e^{2} \sum_{j \in S} P_j \delta h_j(\theta_j, \lambda_j, t) \sin\theta_j \delta\lambda\delta\theta \qquad (2)$$

where λ_j and θ_j are co-latitude and longitude, $\delta\lambda$ and $\delta\theta$ are the grid steps in longitude and latitude (generally $\delta\lambda = \delta\theta$), and R_e the mean radius of the Earth (6378 km). The surface and total water volume variations are expressed in km^3.

Error on anomalies of surface water volumes were computed in the Negro basin using (3) :

$$dV = \sum_{i=1}^{n} \left(S_i d\delta h_i + dS_i \delta h_i \right) \qquad (3)$$

where dV is the error on the monthly water volume anomaly (V), S_i the ith elementary surface, δh_i the ith elementary water level variation between two consecutive months, dS_i the error on the ith elementary surface, and $d\delta h_i$ the error on the ith elementary water level variation between two consecutive months.

The error sources include misclassifications, altimetry measurements and the linear interpolation method. The maximum error on the volume variation are monthly estimated as:

$$\Delta V_{\max} \leq \Delta S_{\max} \delta h_{\max} + S_{\max} \Delta(\delta h_{\max}) \qquad (4)$$

where: ΔV_{max} is the maximum error on the water monthly volume anomaly, S_{max} is the maximum monthly flooded surface, δh_{max} is the maximum water level variation between two consecutive months, ΔS_{max} is the maximum error for the flooded surface, and $\Delta(\delta h_{max})$ is the maximum error for the water level between two consecutive months.

4. Results & Discussion

Monthly estimates of water storage in the different hydrological reservoirs are computed for two years (2003-2004) for which the different datasets overlap in time. Maps of annual amplitudes of TWS, SW, RZ and GW are respectively presented in Figure 1 d to g. They were obtained by fitting simultaneously the temporal trend, the amplitudes of the annual and semi-annual cycles by least-square adjustment at each grid point. The amplitude of the annual cycle for TWS is maximum along the Negro River, and the downstream part of the Branco River, and also over the non flooded areas in the northwest of the Branco River (see Frappart et al. (2005) for a classification of the vegetation and flood extent in the Negro River Basin), reaching 300 mm in the downstream part (Figure 1d). This area corresponds also to the maximum of amplitude of the SW (Figure 1e), clearly related to substantial backwater effects produced at the Negro-Solimões confluence (Filizola et al., 2009). The amplitude of the annual cycle for RZ (Figure 1f) is small except in the upstream part of the Branco River sub-basin, where large precipitation occurred without significant flood events. The largest amplitudes of the annual cycle for the GW (Figure 1g) were observed along the Negro River stream, peaking at 250 mm, *i.e.*, ~72% of the TWS, in the downstream part of the basin. In contrast, small amplitudes were obtained in the Branco and Uaupes Basins. The pattern of GW storage variations observed in Figure 2a tends to be similar to the hydrogeological structures of the Negro River Basin (Figure 2b). For important aquifers, higher yield, recharge and drainage volumes and thus larger seasonal storage variations can be expected than for local and unimportant aquifers with low porosity. According to the hydrogeological map of Brazil (DNPM, 1983), the lower part of the basin (longitude ≥ -67° and latitude ≤0°), where the amplitude of the GRACE-based GW seasonal cycle is the largest, is characterized by continuous aquifers of medium hydrogeological importance. The Uaupes Basin, which only contains local aquifers of relatively small importance, and the Branco Basin, which presents a mixture of local aquifers and small continuous aquifers of relatively small importance, and zones with almost no aquifers, correspond to the smallest amplitudes of the GW seasonal cycle. Note that a secondary maximum of the amplitude of the GW seasonal cycle (66°W, 2°N) can be observed in the upper part of the Negro River which is in good agreement with the presence of two small aquifers of medium importance (DNPM, 1983).

Figure 3a shows the time variations (and deviation at each time step) of the water storage anomalies in the TWS, SW, RZ and GW reservoirs for 2003 and 2004. The deviations correspond to the extrema values for the different water reservoirs and obtained as the monthly range of variations of the GRACE-derived TWS from CSR, GFZ and JPL, of RZ from LaD and WGHM outputs, the mean surface water volume variations more or less the error computed using (4), the GW extrema by difference of the formers. The TWS signal is dominated during high waters (May to July) by SW variations. The RZ varies in phase with both TWS and SW and the amplitude of its variations represents a third of the amplitude of TWS variations, which is similar to what was obtained by Kim et al. [2009] for the whole Amazon basin. The resulting GW variations exhibit a more complex profile with two peaks. Its time variations follow the bimodal distribution of the precipitation resulting from the geographical location of the basin in both hemispheres (Figure 3b). A large variability, reaching several months, is observed in the timing the extrema across the basin: GW storage is maximum (minimum) in July-August (December-March) in the western part (Uaupes and west of the Negro), in June-July (February to April) in the centre of the basin and the downstream of the Branco, in August-September in the upper part of the Branco, and in May-June (October to December) for the downstream part of the Negro basin. These results are consistent with *in situ* measurements from sites located in the downstream part of the Negro basin (Do Nascimento et al., 2008; Tomasella et al., 2008) and closely related to the timing of GW recharge and soil thickness. In Manaus, the time-lag between the maxima of rainfall and GW is 3 months, which is similar to what is observed with *in situ* measurements.

Figure 4 compares *in situ* measurements of GW levels from the Asu catchment and water levels from the Caapiranga and Morro da água preta swamps with the estimated anomalies of GW.

The GW levels in the Asu micro-catchment (below 2m) were converted into GW storage using a specific yield of 0.17 as in Tomasella et al. (2008). Figure 4a shows the 2003-2004 time variations of the GW storage of the Asu catchment and the encompassing GRACE gridcell. They show similar temporal variations. Very good agreement is found between mid 2003 and 2004. Nevertheless, the increase in GW starts later in 2003 for the *in situ* measurements and the maximum value is three times lower. A less pronounced decrease can also be observed for 2004. Two main factors can account for these differences: the respective sizes (7 km² against 10,000 km²), and the fact that the Asu catchment is not directly connected to the Negro River, so the recharge processes may be different.

The groundwater table permanently reaches the surface in several parts of the Negro River Basin. Two of these regions, the Caapiranga and Morro da água preta swamps (Figure 1c), are flooded and can be monitored using radar altimetry. In these cases, we expect GW to have similar time variations as surface water levels. Time series of SW and corresponding GW anomalies over 2003-2004 are presented in Figures 4b and c for Caapiranga and Morro da água preta respectively. Except for February 2004, where the SW derived from radar altimetry present an abnormally low level (larger errors on altimetry-derived stages during the low water season, due to the presence of dry land or vegetation in the satellite field of view have also been reported by other studies, see for instance Frappart et al., (2006a) or Santos da Silva et al., (in press), both time series agree well (R=0.76 for Caapiranga and 0.73 for Água do Morro Preta) and exhibit similar temporal patterns and amplitudes. The comparisons in Figure 4 give confidence in the groundwater variations derived by the approach presented here.

5. Conclusion

This study presents the first attempt to estimate time variations of GW anomalies using GRACE-based TWS in combination with other remote sensing measurements and model outputs for a large river basin characterized by extensive inundation. Both spatial and temporal patterns of ground water storage anomalies exhibit realistic behaviour. Comparisons with scarce *in situ* and satellite information show good agreement, in spite of the difference in spatial scales. This promising study will be soon extended to the entire Amazon basin and for more years as all datasets will soon be available over a longer period of time (2002 to present). Extending this method to characterize the evolution of water storage in other large river basins, especially in semi-arid regions, is also important as it will provide regional estimates of groundwater variations, a key variable for water resource management.

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Figure 1: a) Overview map of South America with the location of the Negro River Basin (b)). c) Map of the Negro River sub-basin extracted from SRTM DEM. Each thin line of black dots represents a ENVISAT track. Yellow dots represent *in situ* gauge stations, and red dots represent altimetry stations. d), e), f) and g) Maps of amplitude of the annual cycle for TWS, SW, RZ and GW respectively.

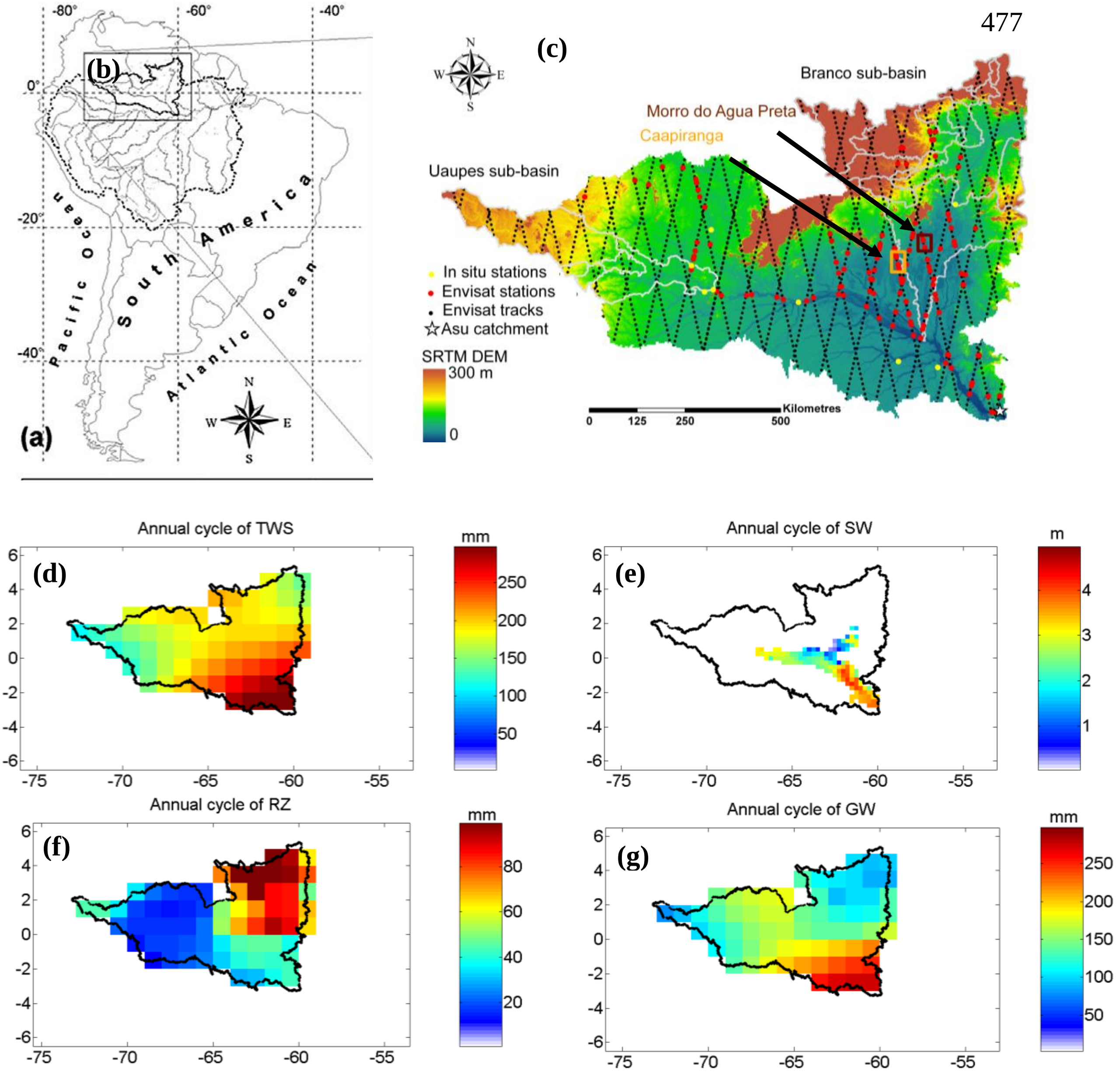
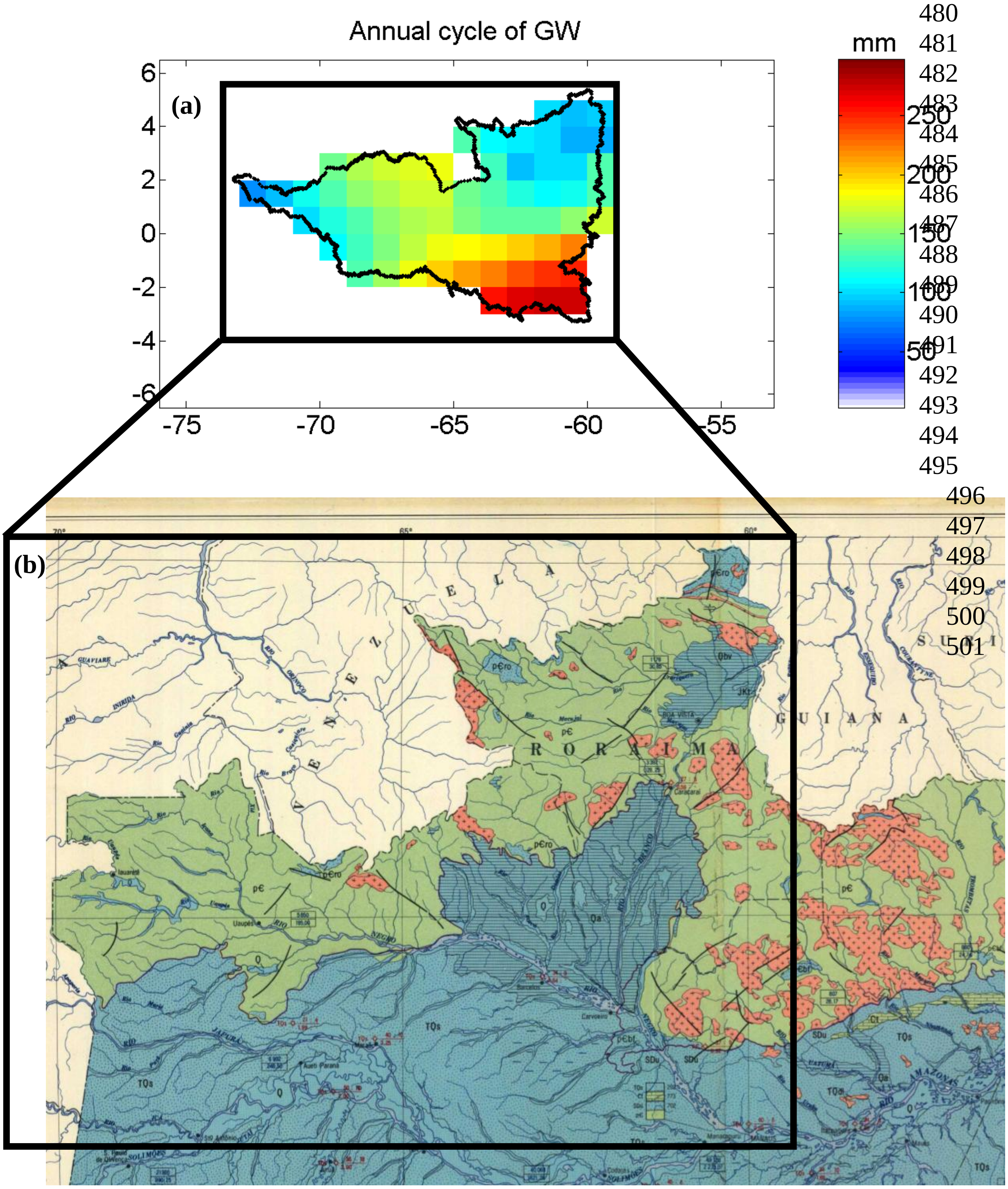


Figure 2 : a) Map of annual amplitude of GW in the Negro River Basin. b) Hydrogeological map of Brazil from DNPM (1983).



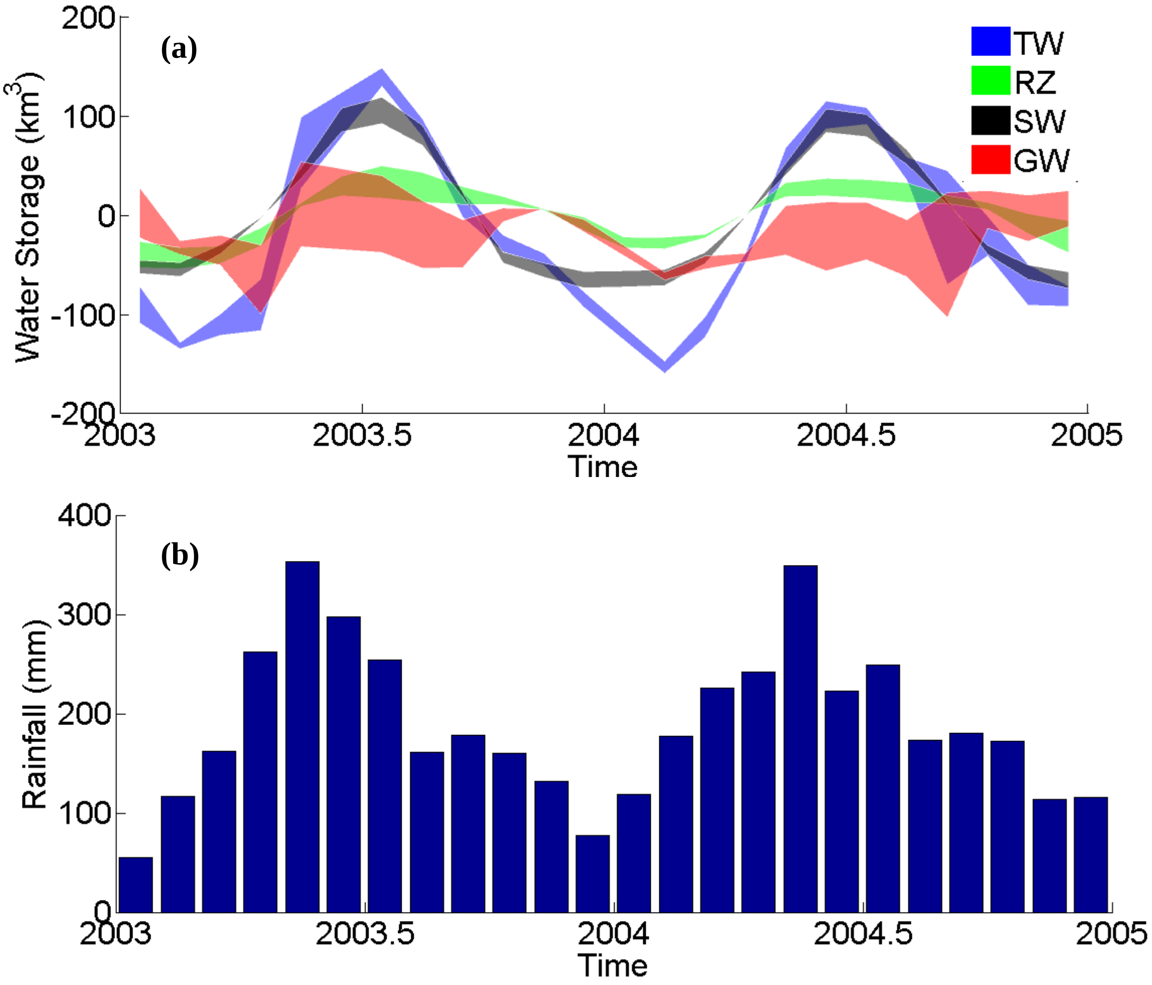
🟦 Continuous aquifers of regional extension, free or confined. Medium hydrogeological reservoir.

▤ Local aquifers or continuous aquifers of limited extension. Two levels of water: free and/or confined. Small hydrogeological reservoir.

🟩 Local aquifers restricted to fractured zones. Small hydrogeological reservoir.

🟥 Almost no aquifer. Very small hydrogeological reservoir.

Figure 3: a) Time variations of the water storage contained in the different hydrological reservoirs: TWS (blue), RZ (green), SW (black), GW (red). b) Monthly distribution of the rainfall (GPCP).



<u>Figure 4:</u> a) Time variations of the GW storage in the Asu catchment (*in situ* - grey) and in the corresponding GRACE gridcell (satellite-based - black). b) and c) Time variations of the surface water levels (altimetry-derived - grey) and the groundwater for the corresponding GRACE gridcell (satellite-based - black) in the swamps of Caapiranga and Morro da Água Preta respectively.