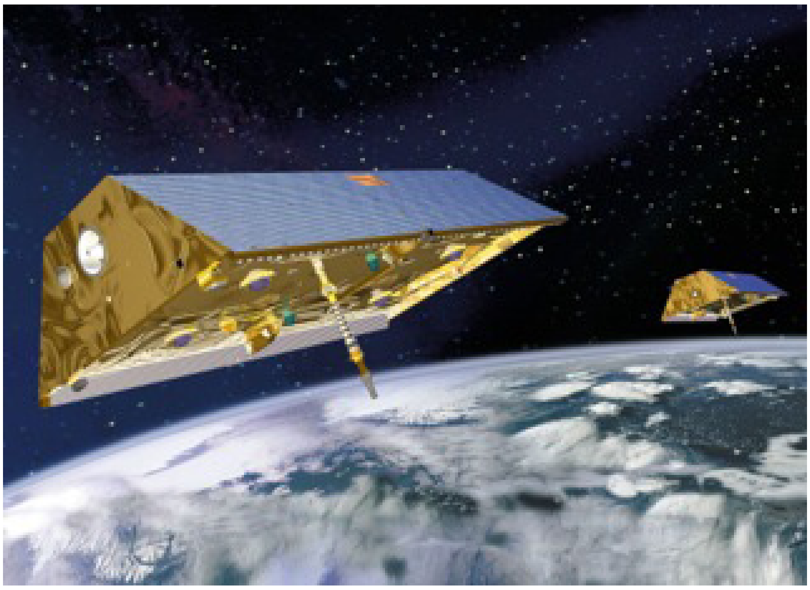
Department of Physical Geography
and Quaternary Geology

Stockholm
University

Estmating groundwater changes in the Rufiji basin by using data from the GRACE satellites



Carl Lindgren

Bachelor's thesis
Hydrology and Hydrogeology, 15 Credits

HG 13
2014

Front cover: Image from NASA Multimedia gallery, http://gracetellus.jpl.nasa.gov/images/Grace/Astrium-grace%207%20copy.jpg

Department of Physical Geography and Quaternary Geology

Stockholm University

Preface

This Bachelor's thesis is Carl Lindgren's degree project in Hydrology and Hydrogeology at the Department of Physical Geography and Quaternary Geology, Stockholm University. The Bachelor's thesis comprises 15 credits (one half term of full-time studies).

Supervisor has been Steve Lyon at the Department of Physical Geography and Quaternary Geology, Stockholm University.

Examiner has been Ian Brown at the Department of Physical Geography and Quaternary Geology, Stockholm University.

The author is responsible for the contents of this thesis.

Stockholm, 11 July 2014

Lars-Ove Westerberg
Director of studies

Abstract

Groundwater is an important water resource and vital for providing water to sustain human life and livelihoods around the world. It is a renewable resource but recharge is often a slow process and there is therefore a significant risk for overuse. It is therefor of importance to monitor how groundwater develops over time, which is a difficult process as changes in groundwater are difficult and expensive to measure. This becomes an even larger issue in developing countries or areas where measurements in the field cannot be performed due to political or economic reasons. The launch of the GRACE satellites in 2002 made it possible to follow groundwater developments through remote sensing and this possibility has been used in numerous studies around the world. This study used the methods developed in previous studies to measure groundwater developments in the Rufiji basin in Tanzania. For the study period 2003 to 2012 no clear trends could be identified in groundwater and the larger variations that occurred during the period coincided with years of more or less precipitation than average precipitation. There is a strong seasonality in groundwater with the lowest levels prior to the rainy season and the highest levels at the end of the rainy season that clearly could be identified from the GRACE data. Although data from the GRACE satellites are a very powerful tool to monitor groundwater developments the low spatial resolution limits its practical applications. For the Rufiji basin, which has large variation in topography and human concentration, groundwater developments are likely to be unevenly distributed which cannot be measured using GRACE due to this spatial limitation.

Table of Content

1. Introduction

The availability of water is critical for life on Earth. Water is therefore a resource that needs to be carefully managed to ensure an availability of good quality at a reasonable cost. To manage this it is necessary to understand the available water resources; specifically, their quantity and quality and how they vary in time.

Although there is ample information available about the water resources on Earth there are significant limits to this knowledge. The quantity and quality of data decreases as we move from the developed to the developing world. This is especially true when discussing data about groundwater.

This is not surprising as groundwater is much more difficult to measure compared to surface water resources. Still, the limited information typically available for groundwater resources is a serious restriction when planning for future water use and management. This becomes even more important in the context of providing food to an increasing world population where irrigation using groundwater is an important part.

The data that historically has been collected about water resources were acquired by observations and measurements in the field. Technological developments and in particular the development of satellites has opened up the possibility of using remote sensing to measure water resources. Remote sensing's ability to cover large areas cost effectively has opened new research possibilities. For the developing world remote sensing is a possibility to partly compensate for the lack of historic data as well as for the difficulty and costs involved in collecting data in the field. Armanios and Fisher (2014) have for example in a study in Tanzania calculated water balances by only using available remote sensing data.

On March 17 2002 the two GRACE-satellites were launched in cooperation between NASA and the German space agency. The two satellites orbit the globe 16 times a day and the satellites sense minute variations in the Earth's surface mass below and corresponding variations in the Earth's gravitational pull (NASA, 2003). The data that the GRACE satellites have recorded has successfully been used to estimate changes in groundwater. This method may be especially relevant in regions with low data availability as it can be used without measurements on the ground. For example, GRACE data has been used to estimate groundwater changes in studies in India (Chinnasamy et al., 2013) and the Middle East (Voss et al., 2013). This method is very useful in areas were political or economic factors makes it difficult to make measurements in the field.

Data recorded by the GRACE satellites are adjusted for atmospheric and oceanic effects to isolate the variations that are mostly due to variations in terrestrial water storage (TWS). There are also other adjustments to increase quality and one useful tool in this process is to use information from land surface models. These models can be used both to adjust the recorded data for noise and measurement errors and also to estimate and eliminate factors that are of less interest in the analysis. One commonly used model is GLDAS (Global Land Data Assimilation System). Finally these models can be used as a check on the reasonability of the observations made.

Data from the GRACE-satellites are available on a spatial scale of about 1 by 1 degrees. According to studies by Forman and Reichle (2013) the smallest areas the TWS data should be considered reliable are 100,000 to 150,000 $km^{2.}$ This is primarily due to noise and measurement errors having to large impact on smaller areas. Forman and Reichle (2013) has also in studies on the Mackenzie River basin investigated if the combination of GRACE data and modeling based on other inputs could be used for investigations of smaller areas (down to 10^3 km) and found that combining data adds value to the models.

Earlier studies using GRACE data focused on establishing reliability methods and process and compared the results from using GRACE data with available field measurements. These studies therefore often focused on areas with good hydrological data. One example of this is the study by Yeh et al. (2006) regarding Illinois. Later studies started using GRACE data without having corresponding ground data. One example of this is the study on the Middle East by Voss et al. (2013). Over time a sizable body of studies has been performed and Tiwari and Wahr (2011) refers to hundreds of studies in an article defending the use of GRACE data against critics. Later studies have focused on using GRACE data for studying specific issues. For example Henry et al. (2011) have done studies in Mali measuring recharge and Armanios and Fisher (2014) have done studies in Tanzania constructing water balances using only remote sensing products. The use of GRACE data has continued to expand and Moore (2012) argues that the most fruitful areas could be monitoring of groundwater extraction, improving models and creating risk maps by combining GRACE data with other data for example poverty indicators.

Although remote sensing has opened up new possibilities there are still serious limitations. Armanios and Fisher (2014) in their attempt to create a water balance for the Rufiji basin by using only remote sensing driven data experienced numerous issues. Data for the different components of the water balance equation (precipitation, evapotranspiration and change in storage) was acquired from different satellite programs and in all cases needed significant preprocessing often using models that used sources other then those from remote sensing. Runoff was calculated as a residual from the other components and compared to ground based measures as well as to other models. The predicted runoff from the water balance created by remote sensing was not very accurate and Armanios and Fisher (2014) concluded that the present precision of this method of calculating water balances is to low for this to be of much practical use in water management. They argued that remote sensing at present was more useful in looking at the individual components of the water balance. In their study they also looked at how important the different components of the water balance was for predicting runoff and concluded that changes in storage had a very low impact compared to changes in precipitation and evapotranspiration.

Groundwater extraction has become a serious issue in many developing countries and Voss et al. (2013) has by using GRACE data for example shown that the level of groundwater has decreased with 1.7 cm/year over a period of 7 years in the Middle East region of Tigris-Euphrates-Western Iran. Their study illustrates how useful GRACE data can be in monitoring changes in groundwater in the developing world. They used a method to separate out the different components of changes in water storage. This method included the use of GLDAS (for soil moisture and snow) and local measurements (surface water). They also compared the measured changes to climate changes and changes in human use of water and found these to be in good agreement. Their study illustrated how the use of remote sensing can compensate for the difficulty in obtaining data. The available data for the area is due to conflicts over water between the different countries kept secret.

In a study in India (Chinnasamy et al., 2013) focusing on the state of Gujarat the results of using GRACE in combination with GLDAS to estimate changes in groundwater showed strong correlation with data from measurements in wells. This study only focused on one year (2008), which limits its usefulness, but the correlation for the seasonal patterns between GRACE/GLDAS and data from wells was very strong. In this study the advantages of the GRACE data being monthly with high availability was highlighted and compared favorably with the groundwater monitoring program run by the Government of India that had lower temporal resolution and many gaps and inconsistences in the data series.

The methods developed in previous studies are well suited for use in other developing countries for example Africa were irrigation or other human use of groundwater is likely to be of increasing importance.

Tanzania is a country located in Eastern Africa with a population 2010 of 44 million people (FAO, 2013) on a total area of 885,800 km^2. The population is growing by an average of 3 percent per year and 73.6 percent are classified as rural (FAO, 2013). The climate is subtropical and precipitation (average 1000 mm/year) is relatively high. Tanzania has been growing economically during the last years but is still a relatively poor country with a fast growing population. In the period from 1999 to 2009 GDP per capita increased from $300 to $439 (FAO, 2013). Agriculture is the dominant business activity and most of the population is employed in agriculture. In 2009 agriculture contributed 28 % to the GDP but employed approximately 75 % of the total labor force (FAO, 2013).

According to the FAO (2013) the total area of agricultural land in Tanzania is 355,000 km^2 and the main crops grown in terms of volume are cassava followed by maize and bananas. Coffee and tobacco are the main export crops based on value. Agriculture is mostly small scale and rain-feed and irrigation is used only to a limited extent. There is also commercial farming that has become more modernized and uses irrigation. According to the FAO (2013) the total available renewable water resource is over 96 billion cubic meters of which roughly 5 percent is withdrawn annually. Agriculture is responsible for around 89% of total withdrawals.

There are two different patterns of precipitation in Tanzania with most of the highlands having a unimodal precipitation pattern while some areas for example most of the northern parts as well as the coast has a bimodal precipitation pattern (McSweeney et al., 2014). As the amount of precipitation varies this creates areas were total precipitation is more than sufficient for agricultural needs but its distribution in time creates periodic shortages while in other areas total precipitation is insufficient. Storage of water and development of irrigation from groundwater are potential ways of ensuring that water is available over longer periods and becomes less dependent upon the timing and amount of precipitation.

The amount of groundwater in a location is dependent upon the amount of withdrawals and recharge. Withdrawals include transfers to surface water and human impact through wells.

Studies that try to estimate recharge levels comes to very different results (Conrad et al., 2004) since the estimates depend on a number of factors including precipitation, vegetation and soil conditions. Studies in South Africa (Conrad et al., 2004) indicate that recharge in dry areas can be very small to non-existing even when precipitation occurs. Recharge is a complex process and as discussed by de Vries and Simmers (2002) can vary significantly over short distances.

Studies of water and its development over time often uses river basins as a research area due its spatial delineation also being critical for questions around water and its movement. One of the largest basins in Tanzania is the Rufiji basin. This basin is important for Tanzania as its responsible for a large part of the countries hydroelectric power as well as being the home of more then 3 million people in 2002 (ERB, 2006).

The primary research question this project aims to answer is

- How has the quantity of groundwater changed in the Rufiji basin over the 10 year period 2003 to 2012

The secondary research questions this project will try to answer are

- What are the monthly variations in groundwater in the area and how has this changed over the studied 10 year period
- How suitable are data for the GRACE satellites in estimating groundwater changes in the region

2. Methods and Material

2.1 Site description

This study focuses on the Rufiji basin, which is a significant basin in Tanzania. It is located in the southeast of Tanzania and its outflow is to the Indian Ocean south of Dar es Salaam. It is 177 420 km^2 in size and average yearly precipitation is 988 mm/year (Kashagili, 2010). The climate is mostly tropical with one distinct period of rains. Temperature varies in the basin with temperatures in the coastal areas (annual average in Dar es Salaam 25.9 degrees according to Dar-es-Salaam.climatemps.com accessed on May 29 2014)) and the lower parts of the valley (annual average at Mtera 26.4 degrees according to ERB, 2006) quite high while the temperature in the highlands on average is lower (annual average at Uhafiwa 16.8 degrees according to ERB, 2006). The total population of the Rufiji basin was about 3 million people in 2002 (ERB, 2006) and the main occupation is agriculture.

Figure 1 Map of the Rufiji basin (source gridnairobi.unep.org)

Total precipitation In Tanzania varies between years and has strong seasonally (Figure 2). Total annual precipitation varies between the years and, according to Loisulie (2010), shows a slightly declining trend for the 1979 to 2008 period. Data for the October to May period for the years 2003 to 2008 (Loisulie, 2010) shows very large variations with 2005/2006 being a very dry period (app 1.3 mm of rain per day) while the 2006/2007 period was very wet (app 5 mm of rain per day). The situation in the 2005/2006 season was so bad that many hydroelectric power plants had to limit their activities.

There is limited information available on groundwater withdrawals in the Rufiji basin and according to Kashaigili (2010) there is a need for further research on the available groundwater resources and their potential for use in irrigation development. According to Kongola et al. (1999) there were 440 recorded boreholes in the Rufiji basin of which 268 were high yield (more than 900 l/h).

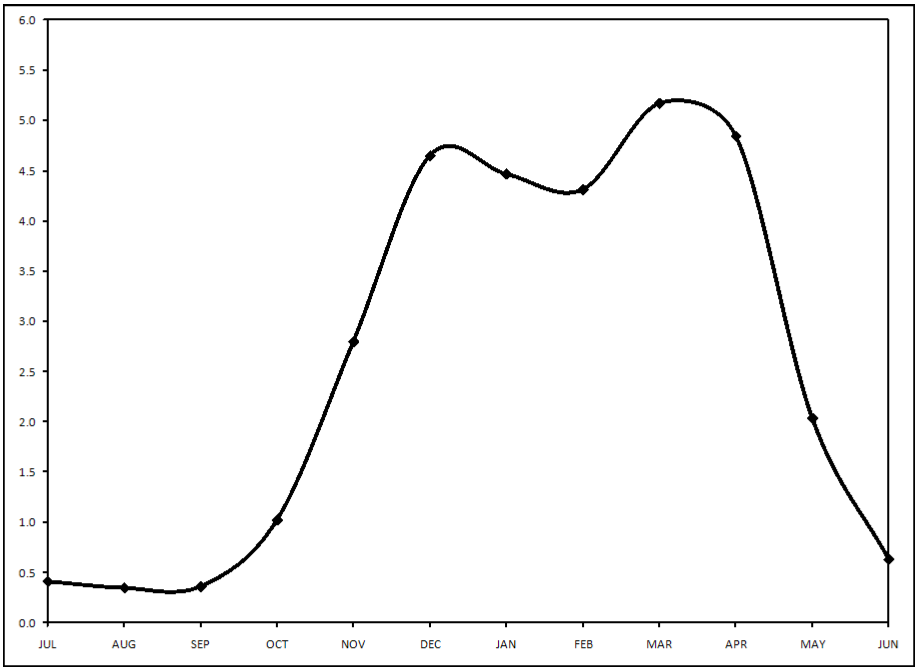


Figure 2 Seasonality of precipitation in Southern Tanzania (source Loisulie, 2010)

2.2 GRACE and datasets

On March 17 2002 the two GRACE-satellites were launched in cooperation between NASA and the German space agency. According to the press kit issued by NASA (2002) at the launch their mission and function was described as

"As they race around the globe 16 times a day, the satellites will sense minute variations in the Earth's surface mass below and corresponding variations in the Earth's gravitational pull. Regions of slightly stronger gravity will affect the lead satellite first, pulling it slightly away from the trailing satellite. By measuring the constantly changing distance between the two satellites and combining that data with precise positioning measurements from Global Positioning System (GPS) instruments, scientists will be able to construct a precise Earth gravity map."

Data recorded by the GRACE satellites are adjusted for atmospheric and oceanic effects to isolate the variations that are mostly due to variations in terrestrial water storage (TWS). To achieve this the long term average (2003 to 2007) is subtracted from the data so that only deviations remain. NASA to eliminate noise and measurement errors from the original data also preprocesses the original GRACE- data for TWS. This is done by truncating and applying a Gaussian filter (Landerer and Swenson, 2012). The effects of this are much smoother data however this also weakens the underlying signal.

From a map of the Rufiji-basin, from the United Nations Environment Programme GRID Africa geoportal, all satellite observation points with coordinates located within the basin was identified. This process yielded 12 different geographic locations with the following coordinates:

7.5 degrees South and 34.5, 35.5 and 36.5 degrees East

8.5 degrees South and 34.5, 35.5, 36.5, 37.5 and 38.5 degrees East

9.5 degrees South and 35.5, 36.5 and 37,5 degrees East

10.5 degrees South and 36.5 degrees East

GRACE monthly data of deviations in TWS for the period April 2002 to January 2014 were downloaded from The Jet Propulsion Laboratory, California Institute of Technology, NASA. Each downloaded dataset consisted of all observations (covering most of Planet Earth) for a given month so a total of approximately 125 different datasets were downloaded. From each dataset the data for each of the coordinates identified was extracted manually and included in separate Excel-models for each month.

GLDAS (Global Land Data Assimilation System) is a global, high-resolution, offline (uncoupled to the atmosphere) terrestrial modeling system that incorporates satellite- and ground-based observations in order to produce optimal fields of land surface states and fluxes in near–real time (Rodell et al., 2004). It has been developed by the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) and the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP)

Based on GLDAS data from GSFC, datasets of deviations in TWS that are directly comparable both spatially and temporally to the GRACE data for deviations in TWS, has been produced by NASA. It is important to note that TWS as defined in GLDAS data includes only snow, soil moisture and canopy water storage while TWS as defined for GRACE includes all water storage. GLDAS data files showing deviations in TWS for each month in the April 2002 to December 2013 period was downloaded from NASA. Each downloaded datasets consisted of all calculated values (covering most of Planet Earth) for a given month so a total of approximately 125 different datasets were downloaded. For each of the coordinates identified the relevant data were extracted manually and included in the same monthly Excel-models as the GRACE-data.

2.3 Preparation of data

The datasets downloaded for GRACE had been preprocessed which results in a weakening of the signal in the data. Using scaling factors can mitigate this. NASA publishes a set with grid-by-grid scaling factors that can be used to help restore the original signal. These scaling factors were used to scale up the downloaded data. This was achieved by applying the scaling factor for each geographic location to every GRACE observation (app 125 observations for each geographic point) from that geographic location individually. There are a number of different ways to use scaling factors as discussed by Landerer and Swenson (2012) with different advantages and disadvantages. In some studies specific scaling factors has been estimated for a basin, while another possibility is to use regional scaling factors. For the purpose of this study grid-by-grid scaling factors were most useful as they made designing a certain basin easy.

All data extracted from GRACE and GLDAS was extracted manually. To ensure quality and minimize the number of errors in this extraction process a number of steps were taken. First all numbers for a specific month was viewed for reasonability before being included in the Excel models. The data showed distinct patterns so the general size could be judged. Secondly the average value from the GRACE and GLDAS data was compared and if they showed different trends the underlying data was double-checked. Finally all data included in the Excel-models were read through a second time after the extraction was completed and odd values double-checked against the data files. In no case was any data from GRACE or GLDAS adjusted from the datasets downloaded. The purpose of the steps taken was only to minimize errors in the compilation process.

2.4 Analytical Analysis

The data that was acquired from The Jet Propulsion Laboratory , California Institute of Technology, NASA and extracted to fit the Rufiji basin as discussed in 2.2 has been compiled into monthly averages for the Rufiji basin. Each monthly average was defined by simply taking the arithmetic average of the observations from the 12 different geographic locations for that month. So for example the average for March 2006 was calculated by adding the values from the 12 different geographic sites for March 2006 and dividing by 12. These averages have then been compiled into time series covering the 2003 to 2012 time period for. These calculations and compilations were performed for both the GRACE and GLDAS data and were done using Excel.

The data acquired for GRACE covered the period from April 2002 to January 2014 and the GLDAS data covered April 2002 to November 2013. There are some months for which data are missing in the GRACE-series and at two occasions the GLDAS data for two consecutive months are identical. There are more data missing in the GRACE-series in 2002 and 2013 and as a consequence it was decided to limit the overall analysis to the full years 2003 to 2012.

For 5 months in the 2003 to 2012 period GRACE data are missing and for one-month two data series are available (January 2012). The missing data have been filled using the monthly average for the same month estimated from the rest of the time series. In three cases (January 2011, May 2012 and October 2012) only one specific month was missing so the data were based on 9 monthly averages and in one case two month are missing (June 2003 and June 2011) so the substituted data were based on 8 monthly averages. For the month where there were two observations at different dates (2 January and 17 January 2012) these were added together and the average of the two observations was used.

The downloaded GLDAS data shows changes in soil moisture (down to 2 m according to Rui, 2011), canopy water storage and snow. According to Syed et al. (2008) this value shows good correlation with the GRACE data and is often labeled TWS but it can also be used to isolate the groundwater change component by subtracting the GLDAS value from the GRACE value. This was done in this current study to explore potential variations in groundwater.

There are two other components of TWS that were ignored in the calculation. These are changes in water in the biomass and in surface water. Previous studies as described by Henry et al. (2011) shows that the changes of water in biomass are below the detection limit of GRACE while changes in surface water in most locations are at least a magnitude lower then changes in groundwater.

The equation for calculating groundwater change can be written as follows:

Change Groundwater= Change GRACE TWS- Change GLDAS TWS
as this is a reasonable approximation of:

Change Groundwater = Change total storage- Change in soil moisture, snow, surface water, water in biomass and canopy

The resulting data set of 120 monthly averages (GRACE TWS, GLDAS TWS and the net value labeled Groundwater) has been used to compile a time series showing seasonal fluctuations. Annual averages have been used to plot a trend line for the area and trend lines for the highest and lowest levels from each year have also been constructed. As the highest and lowest values from each year have been used these values are not taken from the same month each year due to seasonal variations.

3 Results

The resulting data set of 120 monthly averages of deviations in TWS as recorded by GRACE for the Rufiji basin (Figure 3) showed a clear seasonal pattern with the highest positive deviations in April following the rainy period and the highest negative deviations in October/November prior to the rainy season. The month with the highest deviations in TWS (Figure 4) as recorded by GRACE varied between the years with April having the highest value in 8 years and March having the highest value in 2 years. The same is true for the highest negative deviation in TWS with October having the highest negative deviation in 5 years and November having the highest negative deviation in 5 years.

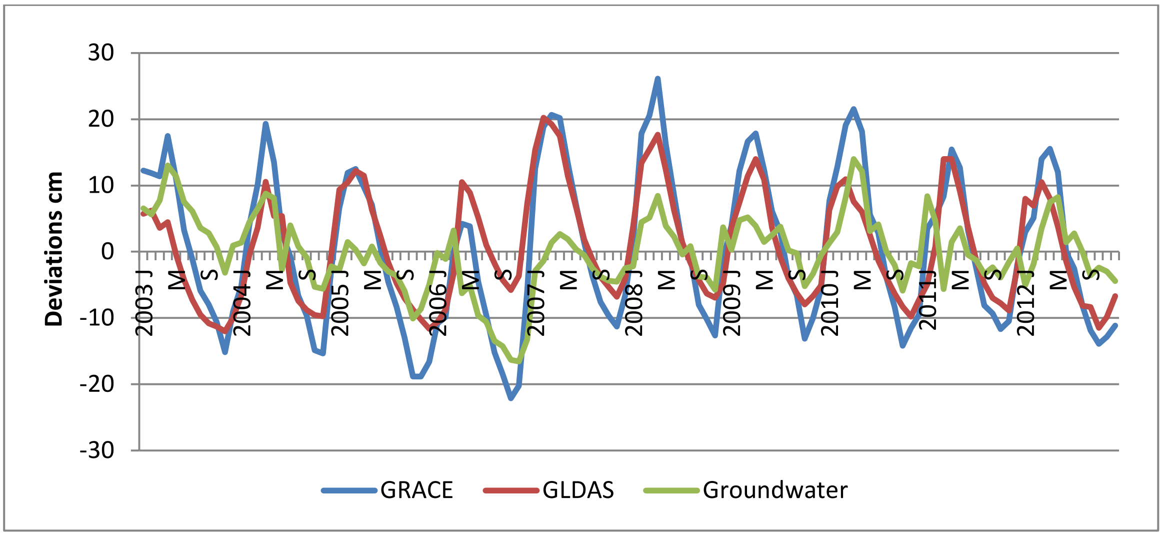


Figure 3 Monthly deviations for 2003-2012.GRACE data are the average deviation in TWS for the 12 different geographic points for each month. GLDAS data are the average deviations for TWS (which excludes groundwater and surface water) for the 12 different geographic points for each month. Groundwater is the residual for each month when deducting GLDAS TWS from GRACE TWS.

Year	Highest positiv deviation	Average deviation	Highest negative deviation
2003	17,50	1,45	-15,16
2004	19,31	-0,43	-15,34
2005	12,50	-2,63	-18,85
2006	4,23	-9,06	-22,10
2007	20,64	4,60	-11,29
2008	26,11	4,91	-12,65
2009	17,87	2,76	-13,13
2010	21,54	3,36	-14,18
2011	15,45	0,38	-11,67
2012	15,52	-0,92	-13,92

Figure 4 Summary of values for deviations in TWS recorded by the GRACE satellites. Deviations are defined as the difference from the average for the 2003-2007 period. The highest positive monthly deviations in each year occurred in March or April (5 years for each) and the highest negative deviations in November (8 years) and October (2 years). The average deviations are calculated as the arithmetic average of the 12 month.

In Figure 5 the highest positive and negative deviations in TWS as recorded by GRACE for each year is shown as well as the average from each year. There was no clear trends visible in the yearly averages and when doing a regression analysis of these yearly averages the best fitted equations showed a slight increase (+0.3 per year) over the 10 year period however this regression did not have a good fit to the observations (R^2 0.05). This poor fit however could to some extent be explained by the 2006 and 2007 period which showed large variations compared to the other years in the period.

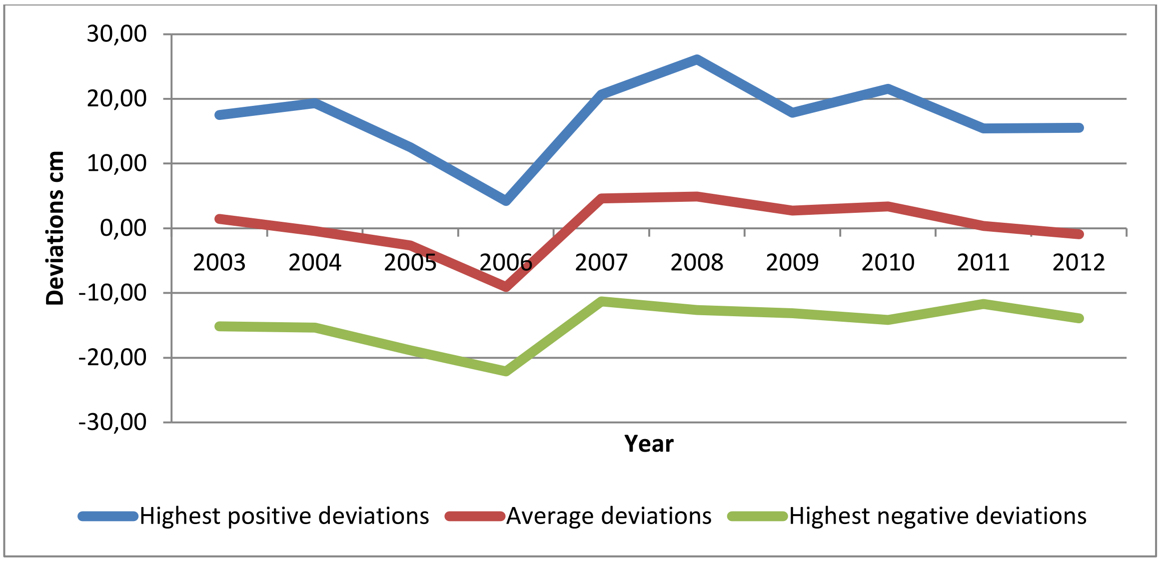


Figure 5 Diagram showing the deviations in TWS recorded by the GRACE satellites. Deviations are defined as the difference from the average for the 2003-2007 period. The highest positive monthly deviations in each year occurred in March or April (5 years for each) and the highest negative deviations in November (8 years) and October (2 years). The average deviations are calculated as the arithmetic average of the 12 month.

When doing a similar exercise on the highest positive and negative deviations for each year one could see a similar pattern with no clear trends. The highest positive deviations showed a very small increase (+0.3 cm per year) over the years with the equation having a low fit while the highest negative deviations showed a small decrease (-0.5 cm per year) over time however again this trend has a poor fit.

Variations of the highest positive deviations were larger then variations in the highest negative deviations for all years in the period studied except one. Average change in deviation from one year to the next was 6.3 cm for the highest positive deviations and 2.8 cm for the highest negative deviations.

The total amplitude for each year between the highest positive and negative deviations can be seen from Figure 6. This amplitude showed a small decline over the period and a regression analysis indicated a reduction in amplitude of 0.2 cm per year but again this had a very low R^2 value. Total amplitude has high variations with the highest value being 38.76 cm (2008) and the lowest 26.33 cm (2006).

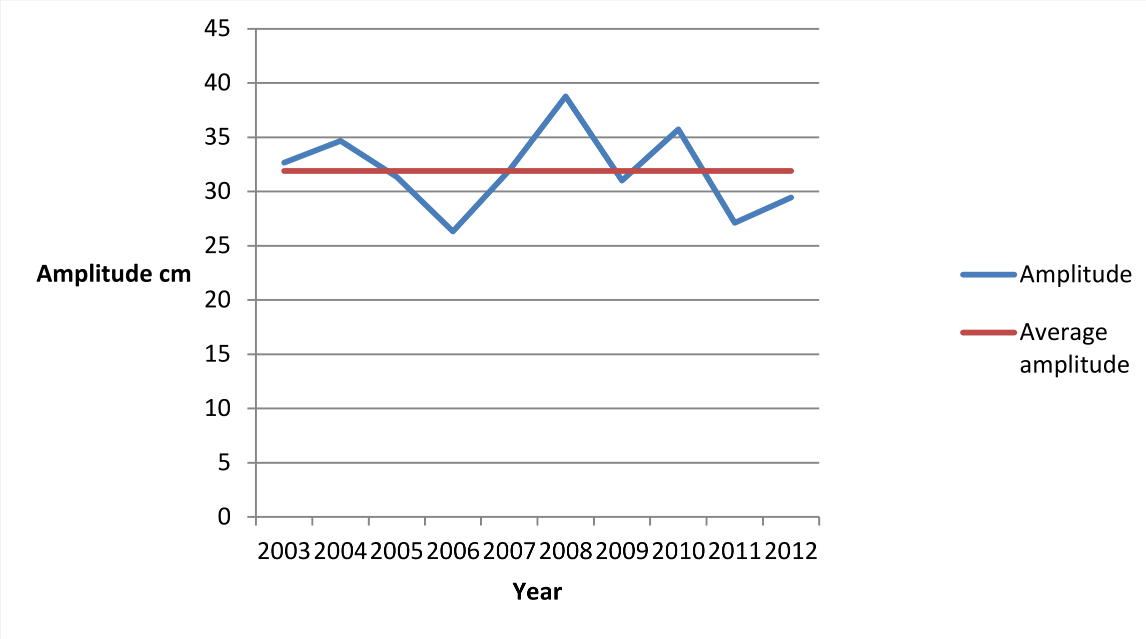


Figure 6 Amplitude of GRACE observations. This is defined as the difference between the highest positive and negative deviations in each year. As this is based on calendar years this becomes a measure of how much TWS declines from the peak at the end of the rainy season (March/April) to the driest point just prior to the next rainy season (October/November).

The average deviations in TWS from GRACE data are compared with values from GLDAS from the same period in Figure 7. The GLDAS data showed a similar pattern as the GRACE data with clear seasonality (Figure 3) and no clear trend regarding the highest, lowest and average values per year. The amplitude in the GLDAS data (Figure 8) was however lower but does not show the same decreasing trend as the GRACE data does.

A regression analysis shows small increases over time in the average, highest and lowest value (0.3, 0.4 and 0.1 cm per year) however these again have a very poor fit (R^2 less than 0.1). The slight increase in amplitude over time shown in the regression analysis is also statistically very week (R^2 of 0.11)

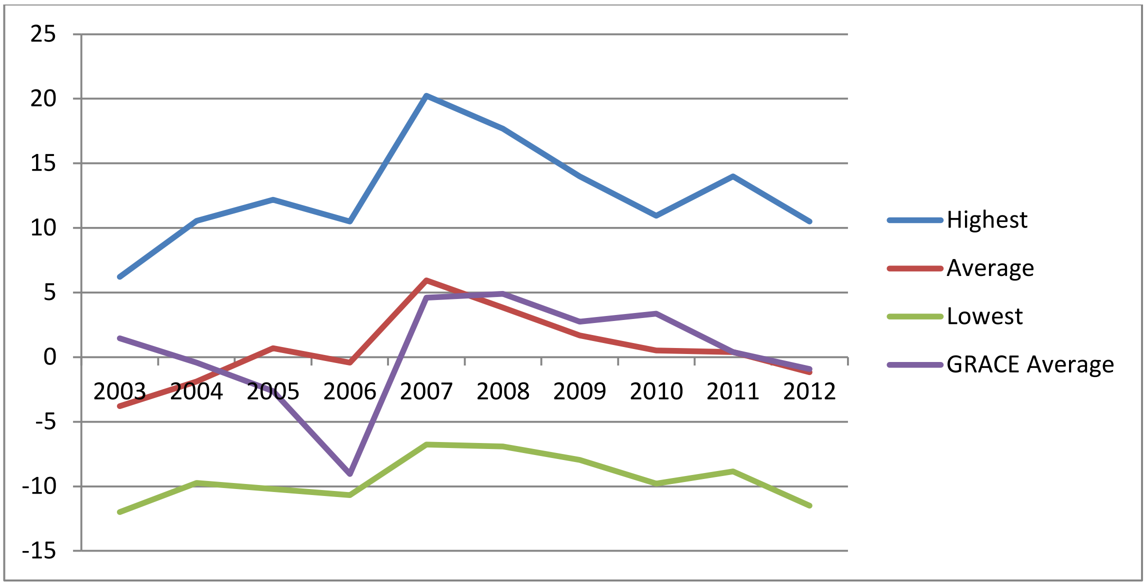


Figure 7 Summary of GLDAS data for TWS. All values are calculated as the arithmetic average of the 12 geographic measurement points for each month. The values shown are the highest positive and negative deviations for each calendar year as well as the arithmetic average for each year. The comparable average for data from the GRACE satellites is also shown.

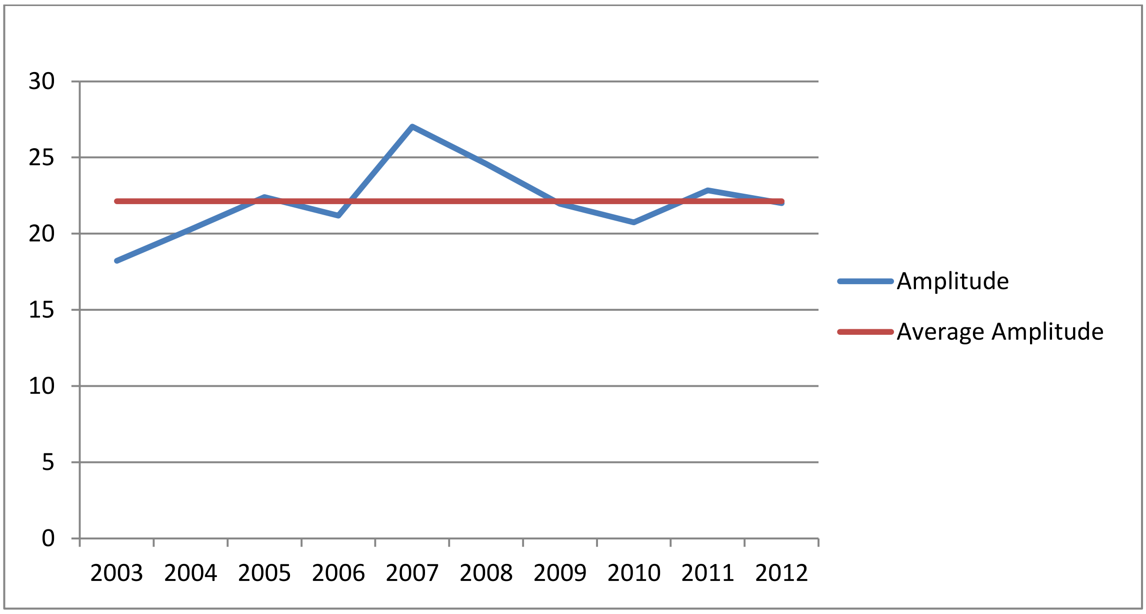


Figure 8 Amplitude of GLDAS data. This is defined as the difference between the highest positive and negative deviations in each year. As this is based on calendar years this becomes a measure of how much TWS (defined by GLDAS as being soil moisture (down to 2.0 meters), canopy water storage and snow) declines *from the peak at the end of the rainy season (March/April) to the driest point just prior to the next rainy season (October/November).*

The downloaded GLDAS data that has been used uses changes in soil moisture (down to 2.0 meters), canopy water storage and snow as a proxy for changes in TWS. This proxy does not include groundwater or surface water changes. When estimating changes in groundwater as the difference between the GRACE TWS (average deviation for each year) and the GLDAS TWS (average deviation for each year) the result, which primarily is deviations in groundwater, can be seen from the Figure 9 below.

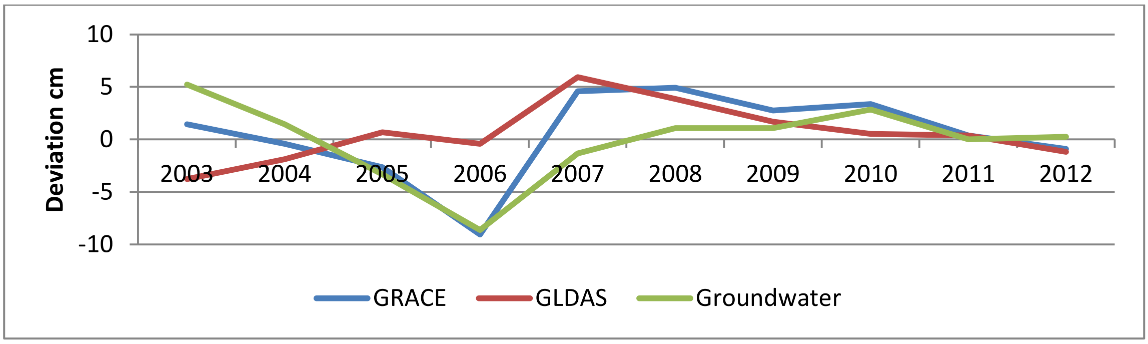


Figure 9 Summary of groundwater developments. The GRACE and GLDAS values are average deviations in TWS for each calendar year. The residual when calculating the difference between these two values are a measure of groundwater deviations (primarily).

A regression analysis on the groundwater change estimated shows a weak positive trend with very low fit (R^2 less than 0.1). The pattern of stable groundwater levels except for the very negative developments 2006 are the same as for TWS however the recovery after 2006 takes a longer time. Groundwater shows the same seasonal developments as does TWS (Figure 3) due to the seasonal pattern being similar for GRACE TWS and GLDAS TWS and the amplitude being smaller for the GLDAS values.

All the results presented above are based on the whole Rufiji basin and are averages of the 12 different geographic locations. The data used both from GRACE and from GLDAS varies between these 12 locations. Due to the different methods used to source these data and the preprocessing done on the data from the GRACE satellites there are significant differences in the range of values between GRACE and GLDAS. As seen in Figure 10 the range defined as the difference between the largest and the smallest deviation for each month is significantly higher for GLDAS then for the data from the GRACE satellites.

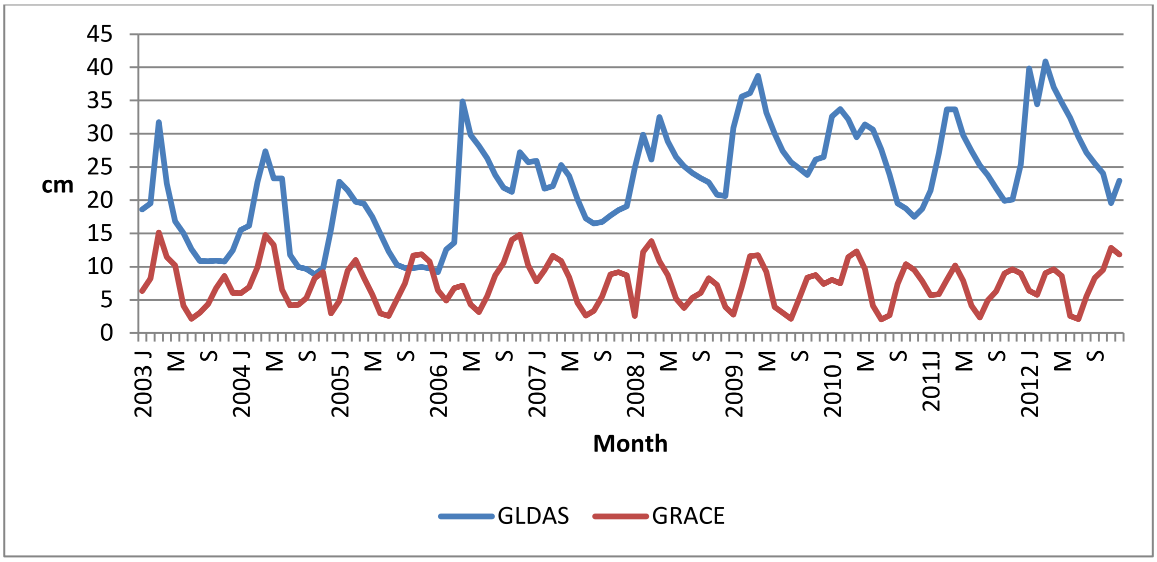


Figure 10 Range of geographic variations. The monthly values shown are the range from the location with the highest positive deviation (or smallest negative) to the location with the smallest positive deviation (or largest negative deviation). This can be seen as a measure of how much local conditions effect measurements. The GLDAS values are taken directly from NASA. The GRACE values are also taken directly from NASA but adjusted for scaling. If the scaling element is excluded the range of GRACE values decrease as compared to the values shown in the figure.

4 Discussion

In this study no clear trends for changes in groundwater were identified for the 2003 to 2012 study period. As most other studies, using GRACE data, for other parts of the world has been good at identifying trends this would indicate that the groundwater in the Rufiji basin has not changed significantly during the period. It is possible that there are changes in groundwater that the GRACE data does not reflect however no such indications have been identified.

Previous studies focusing on the Middle East and India identified clear trends of changes in groundwater. These studies involved larger areas 750 thousand km^2 and 200 thousand km^2 respectively and it is possible that there could be trends in the smaller area of the Rufiji basin that was not picked up due to the size of the basin being near the lower limit of when it's possible to use GRACE data reliably. Conditions in the Rufiji basin also varies significantly with different levels of precipitation and very different topographic conditions with mountains, wetlands and other flat areas. The population is concentrated in the low laying areas. It is likely that groundwater extraction therefor is unevenly distributed throughout the basin and any depletion of groundwater levels are therefor also likely to be unevenly distributed. The low level of spatial resolution of the GRACE data is not able to observe local trends unless they are so strong that they impact the average for the entire area. It is therefore possible that there is a trend of groundwater depletion in parts of the Rufiji basin, which is not large enough to be observed in the data for the whole basin.

When analyzing groundwater developments the method used are based on using GLDAS to eliminate components of TWS so that only variations in groundwater remains. The differences in the datasets therefor limits the possibility of calculating groundwater developments reliably to areas large enough so that the smoothing effects in the GRACE data has less impact. This has in previous studies been shown to be approximately 150,000 km^2. For areas like the Rufiji basin with an area close to this level the effect of surrounding areas on the smoothing is still significant. Dependent upon how much conditions in the surrounding areas vary from the target area this could have an important influence on the results. In this study no attempt has been made to estimate these effects. This should be considered when evaluating the results.

Precipitation varies significantly between the years and it is likely that the very dry 2005/2006 rainy season is an important part of explaining the low levels of groundwater for 2006 while the very wet 2006/2007 rain period is likely to explain the rebound in groundwater levels in 2007. According to the GRACE data average TWS levels declined every year in the 2003 to 2006 period and three years out of four in the 2009 to 2012 period. It is possible that there is a negative TWS trend that cannot be identified for the 2003 to 2012 period due to the effects of the very wet 2006/2007 rainy period however the time series is not long enough to conclude.

Variations in precipitation between the years are also likely to be the explanation for the larger variations in the highest positive deviations in TWS then in the highest negative deviations. Changes in precipitation have an immediate impact on TWS so a year with high precipitation during the rainy season will see increased TWS momentarily while the reverse is true if precipitation is lower during the rainy season. As the highest positive deviations in TWS were recorded at the end of the rainy season precipitation changes will be seen as variations in these data. The highest negative deviations are also impacted by changes in precipitation but as these occur prior to the rainy season they are also impacted by a number of other factors for example runoff and evapotranspiration. As these factors also will be larger in a year of higher precipitation they will mitigate the effects. This could also be explained by looking at the components of TWS. Groundwater is likely to be a higher proportion of TWS in the dry periods then in wet periods and lower variations in groundwater will therefore be seen as lower variation in the highest negative deviation then in the highest positive deviations.

The variations seen in the amplitude within a calendar year becomes a measure of the decline in TWS from the end of the rainy season to the driest period, which is just prior to the next rainy season. This measure shows a large variation and is probably also explained primarily by changes in precipitation. The lowest decline (i.e., smallest amplitude) was recorded in 2006 after a very weak rainy season. With less water available both evapotranspiration and runoff is likely to decline. It is interesting to note that even though the decline increased in 2007 after the very wet rainy season the highest decline (i.e. largest amplitude) was in 2008 after a year of more normal precipitation. This indicates that there is a time lag, as storage has to recover after a dry period before water becomes fully available for evapotranspiration and runoff.

The GLDAS data that are model based with different input data shows a similar development as the GRACE data. No clear trends could be identified in the GLDAS data either and the seasonality that is clear from the GRACE data as well as the anomalies that the 2006/2007 years show can be clearly identified. That both datasets gives a similar result strengthens the likelihood that the level of groundwater has remained relatively stable for the 2003-2012 periods.

Although GRACE and GLDAS show similar developments for the entire basin there are large differences in the underlying datasets. The smoothing that is done for the GRACE data in preprocessing results in a dataset for an individual month that varies little for the 12 different locations. GRACE data is therefore of low value for any given location which is one reason that GRACE data should not be used for smaller areas. GLDAS datasets shows much higher variations, as they dependent upon data for the individual locations. As such they are more relevant for each location but has the limitation that they are model based and not the result of "direct" measures as GRACE is. There is a strong seasonality for how the range develops over time for the GLDAS data. The highest range are during the rainy season which is reasonable as precipitation varies in the Rufiji basin which should impact the GLDAS data for the same reason as discussed previously regarding the higher variations in the highest positive deviations. Although less distinct there is a similar pattern in the range developments for GRACE data. This indicates that even after smoothing local variations affect the GRACE measures.

Even though the results of this study look reasonable and explanations have been found for trends and anomalies there are a number of uncertainties and sources of error. The most important uncertainties are related to the methods used. The data from the GRACE satellites calculated TWS from changes in gravity. Could there be other causes of deviations in gravity and how good are the measurements in themselves? The measurements are subjected to significant adjustments during preprocessing. Are these adjustments reasonable and relevant for the Rufiji basin? For other studies comparisons has been made with ground data that has not been possible in this study. Although previous studies indicate that the data from he GRACE satellites after preprocessing are a good measure of TWS this may not be the case for the study area. To arrive at groundwater changes TWS is adjusted by using GLDAS data. For this to be relevant the quality of the GLDAS models estimates of soil moisture and canopy water has to be of good quality. This is probably the largest source of uncertainty as this is based on models not on measurements and could if not accurate have a large impact on the estimated trends in groundwater. Finally the models assume that changes in surface water and water in biomass are so small that they can ignored. This may not be a relevant assumption in an area like the Rufiji basin with wetlands and abundant vegetation. There are also sources of error in data handling as this study involves extracting large amounts of data manually. Care has been taken to limit errors but this is no guarantee.

There is now a body of studies that shows the value of GRACE-satellite data in monitoring long-term changes in groundwater for larger areas. As such this is a powerful tool as it can easily be used on a global scale. This should become an important part in the global and regional discussions on groundwater use. The relatively low spatial resolution of the data however limits the usefulness for local planning purposes and it also limits the usefulness for groundwater research. The primary reason is that the low spatial resolution makes it difficult to connect changes observed by GRACE to activities on the ground and local changes.

5 Conclusion

It is not possible from this study to draw any clear conclusions on the long-term developments of TWS or groundwater for the studied period. There are some weak indications that there may be a negative trend in groundwater developments that future studies could investigate. The results can be interpreted as showing a strong connection between precipitation and developments in TWS and groundwater. Years of very high or low precipitation have an impact both on the amount of water available for storage but also on the amount of water available for evapotranspiration and runoff. This agrees well with the results in this study. One area of future interest would be to look at the connection between precipitation and groundwater developments as well as the connection between precipitation and evapotranspiration/runoff for the entire period up to present on a more detailed level than has been possible in this study.

The results from this study using GRACE data to evaluate TWS looks reasonable and shows both the expected normal seasonal variations as well as the impacts of years with higher or lower precipitation then normal. The results for groundwater developments also look reasonable although these data are more uncertain. This is due to the cumulative impact of uncertainties in the GRACE data as well as the added uncertainty that results from GRACE data being combined with model data. Using data from the GRACE satellites to monitor groundwater developments has proved to work well in a number of previous studies. Nothing in the present study indicates that the methods used (in previous studies as well as in this study) do not give a relevant view of groundwater developments. It would be of significant global interest to use this possibility to develop programs to follow groundwater developments on a continental scale with Africa and Asia being of specific interest. This should both help local countries in their development but also provide a solid base for global discussions on water issues and water security.

One disadvantage of using the GRACE data in isolation is its low spatial resolution. There is research ongoing into whether models with higher spatial resolution could be developed by combining them with GRACE data. It would be of great interest to investigate that possibility for the Rufiji basin by using the quality of the GRACE data to develop more practical tools. The GLDAS data has higher effective spatial resolution then GRACE data and as shown in this study is more impacted by local conditions. It would be of interest to evaluate the GLDAS data for smaller areas by using field measurements to determined if GLDAS data although not directly based on measurements could be used for planning purpose.

6 References

Armanios, D. E., and Fisher, J.B.,2014, Measuring water availability with limited ground data: assessing the feasibility of an entirely remote-sensing-based hydrologic budget of the Rufiji Basin, Tanzania, using TRMM, GRACE, MODIS, SRB, and AIRS, Hydrological Processes. 28, 853–867.

Chinnasamy, P., Hubbart, J.A., and Agoramoorthy, G., 2013, Using Remote Sensing Data to Improve Groundwater Supply Estimations in Gujarat, India, Earth Interactions Vol. 17, Paper 1, 1-17.

Conrad, J., Nel, J.,and Wentzel, J., 2004, The challenges and implications of assessing groundwater recharge: A case study – northern Sandveld, Western Cape, South Africa, Presented at the 2004 Water Institute of South Africa (WISA) Biennial Conference, South Africa.

ERB (Economic Research Bureau), 2006. A Study to Establishing Mechanism for Payments for Water Environmental Services for the Rufiji River Basin in Tanzania, Revised Report, s.l.: Ministry of Natural Resources and Tourism, Forest and Beekeeping Division.

FAO, Bioenergy and Food security Projects,2013, Tanzania BEFS Country Brief,www.fao.org/bioenergy/foodsecurity/befs.

Forman, B., and Reichle, R.H., 2013, The spatial scale of model errors and assimilated retrievals in a terrestrial water storage assimilation system, Water Resources Research, Vol. 49, 7457-7468, doi:10.1002/2012WR012885.

Henry, C.M.,Allen, D.M., and Huang J., 2011, Groundwater storage variability and annual recharge using well-hydrograph and GRACE satellite data, Hydrogeology Journal ,19, 741-755.

Kashaigili, J., 2010, Assessment of groundwater availability and its current and potential use and impact in Tanzania, Report prepared for the International Water Management Institute (IWMI).

Kongola, L.R.E., Nsanya, G., and Sadiki, H., 1999, Groundwater resources: development and management, an input to the Water Resources Management Policy Review (Draft), Dar es Salaam.

Landerer, F.W., and Swenson, S.C., 2012, Accuracy of scaled GRACE terrestrial water storage estimates, Water Research, Vol. ???. XXXX,DOI:10.1029/,

Loisulie, S.,2010, Vulnerability of Tanzanian Hydropower Production to Extreme Weather Events, Sokoine University of Agriculture, Morogoro,Tanzania.

McSweeney, C., New, M., and Lizcano, G., Tanzania, UNDP Climate Change Country Profiles, http://country-profiles.georg.ox.ac.uk, accessed May 20 2014.

Moore, S., 2012, The role of GRACE (Gravity Recovery and Climate Experiment):Derived data in groundwater resource management, GWF Discussion Paper 1231, Global Water Forum, Canberra, Australia.

NASA, 2002, GRACE Launch, Press Kit, http://www.gsfc.nasa.gov.

NASA, 2003, Studying the Earth's Gravity from Space: The Gravity Recovery and Climate Experiment (GRACE), NASA Facts, http://www.gsfc.nasa.gov.

Rodell, M., Houser, P.R., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C.-J., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entin, J.K., Walker, J.P., Lohmann, D., and Toll, D., 2004, The Global Land Data Assimilation System, American Meterological Society.

Rui, H., 2011, README Document for Global Land Data Assimilation System Version 1 (GLDAS-1) Products, NASA.

Syed, T. H., Famiglietti, J.S., Rodell, M., Chen, J., and Wilson, C.R., 2008, Analysis of terrestrial water storage changes from GRACE and GLDAS, Water Resources Research, Vol. 44, W02433, doi:10.1029/2006WR005779.

Tiwari, V.M., and Wahr, J., 2011, Correspondence: GRACE Estimates of Water Mass Loss from Northern Indian Region, Journal of the Geological Society of India, Vol.78.

Voss K.A., Famiglietti J.S., Lo M., de Linage C., Rodell M., and Swenson C., 2013, Groundwater depletion in the Middle East from GRACE with implications for transboundary water management in the Tigris-Euphrates-Western Iran region, Water Resources Reasearch, Vol. 49. 904-914, doi:10.1002/wrcr.20078.

de Vries, J.J., and Simmers, I., 2002, Groundwater recharge: an overview of processes and challenges, Hydrogeology Journal, 10, 5-17.

Yeh, P. J.-F., Swenson, S.C., Famiglietti, J.S., and Rodell, M., 2006, Remote sensing of groundwater storage changes in Illinois using the Gravity Recovery and Climate Experiment (GRACE), Water Resources Research, Vol. 42, W12203, doi:10.1029/2006WR005374.

7 Data and Images

Datasets used in this study was made available by NASA and for these datasets the following apply:

GRACE land data (available at http://grace.jpl.nasa.gov) processing algorithms were provided by Sean Swenson, and supported by the NASA MEaSUREs Program.
References:
Landerer F.W. and S. C. Swenson, Accuracy of scaled GRACE terrestrial water storage estimates. Water Resources Research, Vol 48, W04531, 11 PP, doi:10.1029/2011WR011453 2012.
Swenson, S. C. and J. Wahr, Post-processing removal of correlated errors in GRACE data, Geophys. Res. Lett., 33, L08402,
doi:10.1029/2005GL025285, 2006.

GLDAS data was received from "http://grace.jpl.nasa.gov" which used the "Goddard Earth Sciences Data and Information Services Center".
References:
Rodell M, P. R. Houser, U. Jambor, J. Gottschalck, K. Mitchell, C.-J. Meng, K. Arsenault, B. Cosgrove, J. Radakovich, M. Bosilovich, J. K. Entin, J. P. Walker, D. Lohmann, and D. Toll (2004) : The Global Land Data Assimilation System. Bulletin of the American Meteorological Society, vol 85 (3), pp 381-394.

The image used on the front cover was downloaded from NASA Multimedia gallery, http://gracetellus.jpl.nasa.gov/images/Grace/Astrium-grace%207%20copy.jpg "