Observing groundwater depletion in Northern Iraq from space

A comparative study between catchment hydrology and the GRACE satellite mission

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A comparative study between catchment hydrology and the GRACE satellite mission

By

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Foreword

For by grace you have been saved through faith.  
And this is not your own doing; it is the gift of God  
Ephesians 2:8-9

During this study I was many times wondering about the name of the satellite involved, GRACE or the Gravity Recovery and Climate Experiment. Maybe there are a few people around which believe that this abbreviation was just a coincidence, but it’s quite plausible that the developers of this mission choose this name with a reason. And, whether it was an overestimation of the mission or just a pleasant thought, they linked the name of their satellite with the concept of grace. On their website they also state that “These discoveries (from GRACE) could have far-reaching benefits to society and the world’s population”, which is a noble goal for research in general and closely related to the meaning of grace in my opinion.

In this report I will try to show how GRACE measurements are linked with regional hydrology and how they can contribute to our understanding of the regional water flows. Especially, because most satellites have a global coverage, they are a very useful tool to study large scale hydrology. Not just for filling the information gaps, but to explore the general behaviour of complex systems and as a reality check of our current models.

I also hope that this research will have direct or indirect benefit for the population of Northern Iraq, but I am also sure that the impact of GRACE will be negligible when compared to the impact of grace.

I hope you will enjoy reading this report,

Gert Mulder
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Without all the help and support I got during my research it would not have been possible to bring my thesis to a good end. Therefore I would like to thank everyone who helped me during this research in any kind.

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Abstract

Research on hydrology applications of satellite gravimetry has grown in importance during the last decade. Especially regions with large variations or declines in water masses are the focus of this research. Northern Iraq is one of them. Due to strong seasonality and yearly differences of precipitation in the region large variations in water masses are common in this region. And a large decline in water mass during the drought period of 2006 till 2009, was the main reason to start a research on the water management and hydrology of the region. The main question to be answered during the research is: Is it possible to address and explain the water mass variation observed by GRACE using additional data and modeling techniques? This research question is answered using the following main calculation steps:

**GRACE calculations** First the total signal for the area according to GRACE data is calculated using a mascon method. To improve the model accuracy the total research area was expanded to a part of Central Iraq and the Urmia catchment. The variation in equivalent water height over the whole area is about 171 ± 8 mm on a yearly basis and 130 ± 14 mm on the longer trend.

**Lakes and snow** Secondly the GRACE results are corrected for the total mass variation of snow and lake water in the study area. The mass variation of lakes is derived from satellite measurements on lake levels and lake areas and the snow mass is based on results from the GLDAS model. Especially the lakes had a large influence on the total water mass variations and accounts for 74 ± 4 mm decline on the longer trend and 55 ± 5 mm of the yearly variations. The snow mass has only effect on the yearly cycle because it melts away every summer and shows an average maximum of about 20 mm of water mass during the winter season.

**Water fluxes** To get more insight in the hydrology the main water fluxes are quantified and calibrated to be used in a rainfall runoff model. To obtain daily rainfall, both GLDAS and TRMM satellite data where compared and calibrated using rainfall rates of four local gauging stations. This resulted in average yearly rainfall rates of about 500 ± 15 mm with a downward trend of about 10 mm/year and very low rainfall rates in 2008. Daily potential evaporation and the discharge at Dukan dam are also calculated and presented in this chapter.

**Rainfall Runoff model** The final step to address water mass changes in Northern Iraq was a rainfall runoff model of Northern Iraq, which is first calibrated for the Dukan catchment and scaled up for the whole catchment later on. The set-up of the model is mainly based on geology and separates the model in three geohydrological zones: (I) The infiltrative zone, which mainly consists of karstified limestone aquifers, (II) the non-infiltrative zone, which consists of impermeable or almost impermeable rock and (III) the alluvial zone, which mainly consists of alluvial sediments. The resulting water level variations in this model showed that the yearly mass variations can largely be explained by rainfall runoff models. The water
decline on the longer trend shows similar behaviour as the observed water mass and accounts for half to two thirds of the total signal.

From the calculation results it can be concluded that almost all of the yearly variation and a large part of the longer trend of the observed GRACE signal is related to hydrologic processes and lake mass. The remaining signal of about -10 mm/year is likely driven by water extraction in the area, but has a higher uncertainty due to the accumulation of errors from other calculation steps.

This means that it is indeed possible to quantify and address the water mass variations in the study area with the given methods. Additionally, the rainfall runoff model has shown a high level of realism, because it was based on the local geology and could represent both discharges and the GRACE signal reasonably well.
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Chapter 1

Introduction

1.1 Water resources in the Middle East and Northern Iraq

Water is a vital and strategic resource in the Middle East, especially in the Tigris-Euphrates catchment, which includes Northern Iraq. Water availability is low and water demand is increasing rapidly, which results in less river flow and deteriorating water qualities. The two main drivers of increasing water demands are expansion of irrigated agriculture and growing populations. A good example is the Southeastern Anatolia Project (GAP) project in Turkey, a large scale development project, which involves the construction of dams and large irrigation schemes.

During the last decade in which the GRACE satellite measures the gravity field of the earth a severe drought occurred in the years 2006 till 2009 (3.4). From GRACE data could be seen that this has a large effect on the total water storage and somehow caused a large decline in water mass Voss et al. (2013). But although it is sure that there is decline of water storage in the area, it is not possible to indicate from GRACE what caused it. Therefore several other datasets are combined in this study to address those losses.

1.2 GRACE and hydrology

To observe the groundwater bodies of Northern Iraq, satellite data from the GRACE satellite mission is used. This satellite mission measures large mass changes of the earths surface and is successfully used to calculate mass changes of the ice caps and large river catchments around the world. In the last years more and more studies are published where GRACE data is applied for land hydrology. In these studies GRACE is mainly used to get insight in the total water mass of a region and especially the change in groundwater levels. To obtain groundwater levels, the GRACE signal has to be reduced according to other mass variations in the area, which are mainly other water storages as snow and surface water. But also erosion or tectonics can have an influence on the GRACE signal. In this study a combination of different satellite datasets and ground data is used, to determine other mass variations, of which the surface water mass is the most important. Then the GRACE signal is corrected for the mass effects to find the changes in groundwater levels in the region. As a last step, this groundwater data is compared with a newly developed rainfall runoff model.
1.3 Research question

The main goal of this study is to specify water losses observed by GRACE, using additional (satellite) data in Northern Iraq. Because groundwater is an important water source in the region, it is also studied how the observed losses in groundwater storage can be explained. Therefore we formulate the following main research question:

- Is it possible to address and explain the water mass variation observed by GRACE using additional data and modeling techniques?

And the sub questions are:

1. What is the most accurate way to derive the water mass variation in Northern Iraq from GRACE?
2. How can the mass variation be separated in groundwater, surface water and snow water mass?
3. Can the observed variation in groundwater mass be explained by rainfall runoff models?
Chapter 2

Study Area

2.1 Hydrology of the region

Almost the whole of Northern Iraq lies inside the Tigris river catchment. The Tigris river originates in Turkey and flows through the eastern parts of Iraq to the Shatt Al-Arab, where it confluences with the Euphrates river. The main tributaries of the Tigris in Northern Iraq are Diyala, Lesser Zab, Greater Zab, Adhaim and Feesh Khabour, which are shown in figure 2.1. With a total flow of about 27 BCM (Billion Cubic Meter) yearly, these tributaries contribute about half of the total flow of the Tigris at Baghdad (UN-ESCWA and BGR, 2013), while the other half originates from Turkey.

These tributaries, except Adhaim, are transboundary rivers, of which the upstream parts lie in Iran and Turkey. In this study these upstream parts, which account for about 30% of the total area, are included. All tributaries have similar flow regimes, with high flows during winter and spring and low flows during summer and autumn (UN-ESCWA and BGR, 2013). This pattern is driven by rainfall and snowfall during winter and snow melt during spring. Differences in flow regime are mainly caused by the amount of snowfall and the degree of regulation through dams and reservoirs in the catchments. The tributaries can be divided in the unregulated and snow rich catchments with later and higher discharge peaks, Greater Zab and Feesh Khabour. And the warmer and regulated catchments with less snow and lower discharge peaks, Diyala, Adhaim and Lesser Zab.

Most of the river water of these tributaries originates from rainfall in the mountainous upstream parts of their catchments, which receive much more rainfall than the rest of Iraq. While the low lying desert area of Iraq has rainfall rates of about 50 to 150 mm/year, these mountainous areas can get more than 1000 mm/year (see figure 2.2). Together with lower evaporation rates this causes that almost all the water of the Tigris river originates from these areas. In addition to these spatial differences in precipitation, there are also large differences between years, which cause strong fluctuations in river flows. For example in the last ten years the amount of rainfall in Sulaymaniyah varied between 350 and 900 mm/year Agro-meteorological department Kurdistan (2013).

2.2 Geology of the region

Especially in Northern Iraq, geology plays a key role in the regional water distribution. This is mainly caused by the geological diversity of the area, in which the subsurface varies from solid impermeable rocks to strongly karstified areas and from bare and steep rocks to gently sloped sedimentary valleys. In this paragraph a concise insight is given in the geology of the area and its link to hydrological behavior of the areas.
Figure 2.1: Tributaries of Tigris river in Northern Iraq. The light blue area indicates the catchment of the Tigris from Baghdad and the dark blue line is the border of the tributaries inside the study area.

Figure 2.2: Yearly rainfall in Iraq and surrounding areas from 2002 till 2012 based on data from TRMM mission Huffman et al. (2007)
General geology of Northern Iraq

The main part of Iraq is part of the Arabian plate. The borders in the South and West at the Gulf of Aden and Red Sea, are spreading ridges. These ridges are mainly passive boundaries where the plates move calmly apart. But the Eastern and Northern sides lie along the Zagros-Taurus Suture and are compressional and active, which caused several large earthquakes during the last decade. A Suture Zone is a place where different plates collide. In this case the Arabian and the Iranian plates in the East and the Arabian and Turkish plates in the North. This collision zone is the thriving process behind the development of the Zagros-Taurus mountain range. Through collision or strong compression at the suture, the geologic formations are folded and uplifted, which causes the large Zagros anticlines Jassim and Tibor (2006).

The whole of Iraq is generally divided in the stable shelf and the unstable shelf. The stable shelf covers the main part of Iraq, is less influenced by the collision of the different plates and has no anticlines. Contrary to the stable shelf, the unstable shelf is highly influenced by the collision and surface folds are a main characteristic. The unstable shelf experienced also the highest subsidence of the whole Arabian Plate, which was one of the thriving factors behind the deposition of thick Neogene formations in the area in the Western part of the unstable shelf and the far Eastern part of the stable shelf Jassim and Tibor (2006). In figure 2.4 a cross section of the eastern part of the stable and the unstable shelf is given.

Northern Iraq is mainly part of the unstable shelf as shown in figure 2.3 and can be divided in four main zones. The Foothill Zone, High Folded Zone, Imbricated zones and the Zagros Suture. Although the largest areas of the unstable shelf lie within the Foothill Zone, the other zones are hydrologically of the same or even higher importance, due to higher rainfall rates. Therefore, the geology of all four zones is described separately in the following section. Because the Imbricated zone and the Zagros-Taurus Suture are only small, they will be treated as a part of the High Folded Zone in the rest of the report.

Geology of the Foothill Zone

The south west boundary of the Foothill Zone follows a large anticline on the line Makhul - Hamrin. Figure 2.4 shows that beside this first anticline, there are several other anticlines in the Foothill Zone parallel to the Zagros-Taurus Suture, which are the main geological features in this region. According to the location of the anticlines, the anticlines have lengths of 10 to 200 km in the Foothill Zone. In the North, closer to Mosul the size varies mainly between 10 and 30 km, while closer to Kirkuk the size can be 100 to 200 km (Jassim and Tibor, 2006). Hydrologically these anticlines play an important role, mainly in the areas closer to the High Folded Zone. In these areas the Pila Spi, Awanah and Sinjar formations are exposed to the surface at the cores of those anticlines, which creates a large potential for groundwater infiltration. This formation consists of highly fractured limestone, which has transmissivities of 3.5 to 42000 $m^2/day$ and an infiltration rate between 30 and 40 % (Stevanovic and Markovic, 2004; Krásný et al., 2006). The aquifers mainly drain through springs in deep incised valleys, where the fractured formations are exposed to the surface, but also through fractures and sinkholes in the area.

One of the areas, called Awa Spi, or White Water, was visited in October 2013 as part of this research. The reason why those sinkholes and fractures can develop, is the thin impermeable top layer. Because there are large holes dissolved by water flows in the underlying layers, the upper layers collapse, which results in large cracks and sinkholes (Stevanovic et al., 2009). In figure 2.6 one of those cracks is shown. The main spring is shown in figure 2.5. A gypsum bed on top of the aquifer colors the springwater white. When the alkaline water from the limestone aquifer flows through the gypsum bed hydrogen sulphide $[H_2S]$ is formed and dissolved in the water,
Figure 2.3: Division of Northern Iraq in four zones of the unstable shelf. Jassim and Tibor (2006)

Figure 2.4: Cross section of the eastern part of the stable and the unstable shelf of the Arabian Plate in Northern Iraq?
causes the white color and a high sulphide content of the river water.

In addition to the karstified formations in the Foothill Zone, the Bai Hassan formation has significant recharge rates and transmissivities Al-Manmi (2013a). This formation consists mainly of conglomerates. The Bai Hassan formation is the youngest Tertiary formation and is exposed to the surface at places where no Quaternary deposits exist, or where all these deposits are eroded.

The areas which are not a part of the Pila Spi, Avanah, Sinjar or Bai Hassan formations consist of quaternary deposits, siltstone or claystone layers Geosurv (1997). Generally the infiltration rates of these areas are low because the quaternary deposits consist of clay and silt layers and the siltstone and claystone layers are almost impermeable.

**Geology of the High Folded Zone**

The High Folded Zone lies mainly parallel to the Foothill Zone in south east to north west direction. The borders are in the south west marked by the first high anticlines, which coincide with a large fault. The north east side is also marked by a fault, which separates this area from the Imbricated zone. The zone has a width of about 25 to 50 km and covers a large part of Iraqi Kurdistan. Contrary to the Foothill Zone this area is uplifted and mainly consists of a mountainous area. The area is strongly deformed and comprises a sequence of anticlines and narrow deep synclines (Jassim and Tibor, 2006). Most anticlines are steep at south western side, figure 2.7, while they are more gently sloping at the north eastern side. In this area also reverse faulting occurs, see figure 2.8, where the geologic formations are faulted and pressed upwards over the formations to the south west. Because the anticlines are eroded at the top, older geological formations are exposed to the surface and younger formations at the flanks or in the valleys.

The most important aquifer in this zone is the Bekhme aquifer, which covers a large area of the
High Folded Zone and includes also parts of the Qamchuqa, Dokan, and Kometan formations. The Bekhme aquifer is very heterogeneous and highly fractured and karstified, with numerous channels and caves (Stevanovic et al., 2009). The aquifer mainly discharges by springs, which are a common source of water of many towns and cities in the Kurdistan region. Although a part of those springs has fallen dry in the past years, most springs are a reliable source of water, with almost constant water flows during the dry season. The average recharge rates from this aquifer are estimated more than 50% and transmissivities range from 9 to 8000 $m^2/day$ (Krásný et al., 2006; Stevanovic and Markovic, 2004).

Geology of the Imbricated and Suture Zone

The major part of the Imbricated Zone consists of the Balambo-Tanjero formation, which extends from the south east to the north west with a width of maximum 25 km. This zone mainly consists of Cretaceous formations which are imbricating, or overlapping each other. In general, the geological processes in this zone are comparable with the High Folded Zone, because they are both determined by anticlines and faults. The only difference is that the folding and faulting is more intense in the Imbricated zone. The consequence of the intense folding is that the reverse faults overtop the anticlines and are the most dominant process in the area.

The Imbricated zone is divided in the Balambo and Tanjero geological formations, which have different geohydrological characteristics (Jassim and Tibor, 2006). While the Balambo formation is a fractured limestone aquifer with medium to high infiltration rates, the Tanjero formation mainly consists of sandstone and claystone, which have therefore lower infiltration rates and transmissivities.

The Suture zone is of a totally different origin than the High Folded or Imbricated zones are. This zone consists of formations from adjacent plates that were thrust or pushed over the Arabian plate. This area has a complex geology with many different formations, which can not easily be described by just some main characteristics. Also the hydrological behavior of the region can vary...
Figure 2.7: High inclination angles at south west side of an anticline

Figure 2.8: Cross section of High Folded, Imbricated and Thrust zone Geosurv (1997)
widely (Krásný et al., 2006). On the one hand there are many impermeable formations, which cannot hold water by themselves, but on the other hand there are some formations that could act as an aquifer. The fractured nature of this formations could also allow groundwater flow in these areas.

2.3 Geohydrologic division of the region

In the previous section the geology of Northern Iraq and its implications for the (geo)hydrology of the region are introduced. In this section a division of the region in three main parts is proposed. These are the infiltrative, non-infiltrative and the alluvial zone. A division between the alluvial and the higher infiltrative and non-infiltrative zones is given in figure 2.9 (Geosurv, 1997).

infiltrative zone

This zone consists of those parts of the study area, where the geological formations with high infiltration rates are exposed to the surface. This zone includes the main aquifers of the region. Although these aquifers extend underneath other formations, these areas are not included because the main purpose of this zoning is to calculate total infiltration into the aquifers. And as the infiltration occurs at the surface, zonation is based on formations exposed to the surface.

The infiltrative zone consists of the Pila Spi, Aivanah, Sinjar, Baj Hassan and part of the Mukdadiyah formations in the Foothill Zone, the Bekhme, Kometan, Qamchuqa and Balambo formations in the High Folded Zone, the Balambo formation in the Imbricated zone and the Qulqula formations in the Thrust zone. This implies that the groundwater system of the study area is regulated through infiltration and discharge of this zone. Therefore, the hydrological characteristics of these formations are directly linked to the behavior of the springs emerging from these formations (Krásný et al., 2006; UN-ESCWA and BGR, 2013).

non-infiltrative zone

This zone consists of impermeable or almost impermeable layers and is characterized by high runoff rates. The flow regimes of these areas are governed by overland flow and for a much less extend depression storage. This means that a small amount of the total rainfall stays in the area as depression storage. The main part of the rainfall drains fast to the streams and rivers, causing peak flows during periods with high rainfall.

The main formations included in this zone are the Mukdadiyah, Gercus, Khurmala, Kolosh, Tanjero and Shiranish formations in the High Folded Zone, the Tanjero formation in the Imbricated zone and the Qulqula formations in the Thrust zone. The non-infiltrative zone is the main driving factor behind the fast runoff mechanism of the area. High rainfall rates in this zone are closely linked to flash floods and discharge peaks in the rivers (Al-Manmi, 2013a).

alluvial zone

The alluvial zone includes all the areas where the hydrology is determined by recent alluvial deposits. These deposits can vary from gravel and very coarse sediments in the alluvial fans in the higher areas, to sand and clay soils in the low lying areas. The main area of these zones are covered by fine sediments as clay and silt, which have low infiltration rates. Therefore, fast runoff processes play an main role, but also depression storage is an important factor in the lower lying areas.

The alluvial zone is mainly part of the lower Foothill Zone, close to the Tigris river, but consists also of the synclines of the higher Foothill Zone, where sediment layers are formed. Further it
Infiltrative / Non-Infiltrative
Alluvial

Figure 2.9: Division of Northern Iraq in a alluvial and an infiltrative/non-infiltrative zone. The Alluvial zone is indicated by the yellow area and the Infiltrative/Non-Infiltrative zone by the blue area.

includes the intermontane basins, close to Derbendikhan and Dukan lake and several smaller areas in the High Folded Zone. The alluvial area contributes to both the groundwater flows as the fast runoff flows in the area. Total river flows generated from the alluvial zone are relatively small, due to low rainfall and high evaporation rates.

**Total area zones**

With the different geological formations and the hydrologic zoning known, it is possible to define the zones using geologic maps. However, for this research there were only a few detailed geologic maps available of the Iraqi region and none of the Iranian and Turkish parts of the catchments. Therefore, it is chosen to separate the area into two zones, the alluvial and the combined infiltrative/non-infiltrative zone, as shown in figure 2.9. This separation could be done more easily, because these zones are also indicated on less detailed geological maps. Afterwards the share of the infiltrative zone of the catchment is estimated, based on the more detailed geological maps and finally calibrated within the rainfall runoff model.

**2.4 Present water management in Tigris catchment and future perspective**

The Tigris river is regulated by an extensive network of dams and water diverting structures. An oversight is given in figure 2.10. Also many dams are planned in all riparian countries. The most important and influencing plan is the GAP (Southeastern Anatolia Project), which is initiated by
the Turkish government, to give an economical impulse to the less developed southwestern part of Turkey. In this paragraph first the present water infrastructure is discussed, followed by the effect of these structures on river flows and some insight in future development in water management.

Water availability

Total water availability in the Tigris catchment is still under debate in literature, therefore it is difficult to give exact numbers. In most literature the total share of Turkey to the Tigris river flow is about the same as the total share from Iraq and Iran (Beaumont, 1998; Al-ansari and Knutsson, 2011; UN-ESCWA and BGR, 2013). The total flow is about 50 cubic kilometer per year (Altinbilek, 2004; Brooks, 1997; Al-ansari and Knutsson, 2011). The main flows in Iraq upstream of Baghdad originate from five main tributaries, but these rivers have also their headwaters in Turkey or Iran. This means that a large amount of the available Tigris water in Iraq, originates from neighbouring countries, which makes Iraq strongly dependent on neighbouring countries.

Due to development and building of water infrastructure projects in Turkey, Iraq and Iran the total discharge of the Tigris river is highly influenced. The building of regulating dams can be divided in a few main periods:

1954-1969 In this period the main water infrastructure in Northern Iraq was constructed. The Lesser Zab was dammed by the Dibis and Dukan dams and the Diyala river by the Derbendikhan and Diyala dams. These dams have a total capacity of about 12 BCM. Further the Tharthar dam was build, which diverts water to lake Tharthar (UNEP, 2001; Altinbilek, 2004). Throughout this period the flow from Turkey remained more or less natural and the Tigris river itself was not dammed, except for the diversion works to lake Tharthar.

1981-1999 During this stage also the main river was dammed and the current largest reservoir at Mosul was constructed in 1985, with a capacity of 11 BCM. Also the upstream parts of the Tigris river in Turkey were dammed by the Goksu, Kralkizi, Dicle, Batman and Garzan dams with a total storage of about 9 BCM (UN-ESCWA and BGR, 2013). Also the Hemrin and Adhaim dams were build in Iraq with a total storage of about 4 BCM.

1999-now The last 15 years there are no large dams constructed. A few small dams where constructed along the upstream Iranian part of the Diyala river, but the total storage of those dams is small (Al-Manmi, 2013b).

Future In the next years many dams are planned, of which the Ilisu dam (10 BCM), Badush dam (10 BCM) and the Bekhme dam (17 BCM) are the largest. This could almost double the total storage of the reservoirs in the Tigris river upstream from Baghdad (UN-ESCWA and BGR, 2013).

Although most of these dams are meant for generation of hydropower, large amounts of water are used for irrigation or water supply of large cities in the region. Additionally, lake water evaporation causes a large loss of water storage every year. The construction of those dams has a large influence on the streamflow regime of the Tigris river and its tributaries. Obviously, it reduces the total yearly streamflow, but at the same time it guarantees a more constant streamflow over the year, because the high water flows in the spring are stored in the reservoirs and released during summer for hydropower generation. While there is still some seasonality in the Tigris river at the moment, it is likely that it will diminish when the Bekhme dam is constructed and the flow of the Greater Zab river is regulated.
Figure 2.10: Overview of the Euphrates and Tigris catchments, constructed and planned dams in Iraq, Turkey and Syria in 2000 (UNEP, 2001)
The GAP project

To develop the Southeastern part of the country, Turkey has initiated the GAP, which partly consists of the plan to build an extensive irrigation scheme in the upstream parts of the Tigris river. This project involves about 600,000 ha irrigated agriculture, with an estimated water consumption of about 5.6 to 7.7 BCM. Currently only 42,000 ha is operational, which means that a decrease of water inflow at the Turkish-Iraqi border of at least 5 BCM can be expected as a result of this project Altinbilek (1997); UN-ESCWA and BGR (2013). A total number of eight dams with a storage of about 16 BCM are planned as part of the GAP project.

2.5 Transboundary water management and water politics

Almost all tributaries of the Tigris river are transboundary river catchments and significant parts of the upstream areas of these catchments lie in Iranian and Turkish territory. Together with the sharing of several groundwater basins (UN-ESCWA and BGR, 2013) and the growing water needs of all riparian countries, it shows clearly that transboundary water management in these areas is important. At the moment there are several agreements between those countries about the division of water, which are taken from UN-ESCWA and BGR (2013) and Al-Manmi (2013b); Ali (2007) and presented in table 2.1.

In general the agreements between Turkey and Iraq state that a joint commission should be installed to allocate the water from the Tigris and Euphrates rivers. In 1980 there was indeed a Joint Technical Committee installed to discuss the water allocation, which was joined by Syria in 1983. But from 1992 onwards the commission does not function any more, because of disagreements in the commission about water allocation (UN-ESCWA and BGR, 2013). Also the agreements state that Turkey should inform Iraq about the discharge of the Tigris river and planned infrastructure projects, but till now this agreement is not applied by both Turkey and Iraq as stated by Scheumann (1998).

Agreements between Iraq and Iran state that there should be an equal divide in water use by those countries, based on either equal shares or established water rights. But although these agreements are formally active, the neighbouring countries do not act accordingly, which is a recurring point of discussion (Al-Manmi, 2013b; Ali, 2007). Also, it is not possible to check whether the agreements are met, because there is no sharing of information or measuring network to monitor river flows.

The most promising agreement are the Iraqi-Syrian agreement, which also specifies total area and the volume of extraction.

Outlook

Because of the Syrian crises it is likely that trilateral meetings will be postponed. Tension between Turkey and Iraq about water allocation will likely increase, because the construction of the Ilisu dam in Turkey and growing water needs of both countries. It is likely that the tension between Iran and Iraq on water resources will increase, as Iran is developing its water infrastructure in the upstream parts of the shared Tigris tributaries.
Table 2.1: Oversight of transboundary water agreements

<table>
<thead>
<tr>
<th>Year</th>
<th>Name</th>
<th>Significance</th>
<th>Signatories</th>
</tr>
</thead>
<tbody>
<tr>
<td>1914</td>
<td>Protocol of Constantinople</td>
<td>The protocol states that the Al-Wand, Kunchan Chum, Teeb and Diwarech rivers were to be shared according to the established water rights.</td>
<td>Iran, Ottoman Empire</td>
</tr>
<tr>
<td>1946</td>
<td>Treaty of Friendship and Good Neighbourly Relations</td>
<td>This was the first legal instrument of cooperation. Both parties agreed that Turkey shall install and operate permanent flow measurement facilities and inform Iraq periodically about the recorded data (article 3) and water infrastructure projects.</td>
<td>Iraq, Turkey</td>
</tr>
<tr>
<td>1975</td>
<td>Algeria Agreement</td>
<td>The agreement stated that Banaw- Suta, Quarato and Gangir rivers shall be shared equally.</td>
<td>Iraq, Iran</td>
</tr>
<tr>
<td>1980</td>
<td>Protocol for Technical and Economic Cooperation</td>
<td>The protocol mandates establishment of a joint technical committee to study the issue of regional waters particularly the Euphrates and Tigris Rivers.</td>
<td>Iraq, Turkey (Syria signed in 1983)</td>
</tr>
<tr>
<td>1987</td>
<td>Protocol on Economic Cooperation</td>
<td>Article 7 of the protocol states that Syria and Turkey shall work together with Iraq to allocate Euphrates and Tigris water within the shortest possible time frame. Article 9 asserts the intention of the two states to construct and jointly operate irrigation and hydropower projects on the two rivers.</td>
<td>Syria, Turkey</td>
</tr>
<tr>
<td>2002</td>
<td>Agreement on the Creation of a Pumping Station in Syria on the Tigris</td>
<td>The agreement governs the establishment of a Syrian pumping station on the Tigris River. It also specifies project area and volume of water extracted.</td>
<td>Iraq, Syria</td>
</tr>
<tr>
<td>2009</td>
<td>Turkish-Syrian Strategic Cooperation Council Agreement</td>
<td>The agreement states that water is a focus point for cooperation between the two countries with specific emphasis on improvements to water quality, the construction of water pumping stations (on the Syrian stretch of the Tigris) and joint dams, as well as the development of joint water policies</td>
<td>Syria, Turkey</td>
</tr>
</tbody>
</table>
Chapter 3

Water mass changes from GRACE

3.1 Introduction

The GRACE (Gravity Recovery And Climate Experiment) mission is a joint mission from the NASA and the German Aerospace Center. By measuring gravity, GRACE can determine the mass changes of the earth's surface. From March 2002 till now this satellite is operating in a nearly monthly repeat cycle. The GRACE satellite mission uses the distance between two satellites, flying in the same orbit to calculate the gravity of the earth. Gravity measurements are based on acceleration of the satellites, caused by the mass or gravity force of the earth's surface. Because the two satellites are at different locations their accelerations are different, which can be translated to mass of the earth's surface underneath the satellites.

The most important applications of GRACE are research on the ice caps at the poles and continental hydrology. As almost all mass changes are caused by movement of water, data from GRACE can give valuable information about groundwater reserves around the world and can be implemented in hydrologic models Awange et al. (2011); Schmidt et al. (2008); Ramillien et al. (2008). But because the spatial resolution of this satellite is coarse (± 300 km), only larger areas can be isolated from the surroundings. This makes the Euphrates and Tigris catchments a suitable study case.

In this chapter first the methods to derive total mass change are presented. Then calculation areas are chosen based on hydrology and calculation methods. In the result paragraph, mass variations of the study area and differences between different regions are presented. Finally these results and the used calculation methods will be discussed.
3.2 Derivation of mass from GRACE

The main issue in GRACE data calculations is that it cannot easily be translated into mass changes of the earth's surface. Mainly because the satellites measure gravity at an orbit height of 500 kilometers, which means that the measured gravity can be caused by mass changes spread out over huge areas. Also, while the measurements are precise, there are many processes in the atmosphere or on the earth which cause noise in the signal. And even if this noise could entirely be removed from the dataset, it is not possible to derive mass change from a single measurement, due to spread of the signal.

During the last years several methods are developed to calculate the total mass change in different areas. Most methods comprise different processing steps, which are mainly meant to reduce noise and to improve the ability of GRACE to see spatial details. For this study a numerical solution of basin functions is used (Schrama and Wouters, 2011). The basic concept of this method is that the area is split up in a finite number of basins, which have only one variable surface water level. Then the influence functions of those water levels on the gravity field are implemented in a system of equations, to model the gravity field. Finally the water levels of the basins are changed in such a way, that the error between the modeled and the measured gravity field is minimized.

Although many other studies use Gaussian smoothing and Empirical Orthogonal Filtering (EOF), to reduce noise in the signal, such methods are not implemented in this research (Schrama et al., 2007; Wouters and Schrama, 2007). Firstly because not only noise, but also real data is removed during those processes. Secondly because those methods are not strictly necessary, while most of the noise or random errors average out when longer time series are used.

In this study so called mascons are used, which are basin functions of circular influence zones, with a diameter of approximately 2 degrees latitude. These circles are divided over the globe in such a way that the whole globe is covered, which causes small difference in diameters of adjacent mascons. See figure 3.3. Although the figure suggest that the mascons do not cover some small areas, the whole area is covered because mascons do not represent a closed area, but the main influence zones of the basin functions. The main advantage of this method is that the mascons are more mass conservative then the simple grids and the method is a good alternative for the method of Swenson and Wahr (2006). The size of two degrees per measuring point can be seen as a disadvantage, because other methods use a one by one grid. But in practice this does not make a difference, because reliable calculations need a minimal grid size of three by three degrees. For
this region will be shown that final results are only slightly different.

To translate the 1x1 degree GRACE raster data to results for our study area, the shapes of this area are rescaled to a 0.1 by 0.1 degree grid. Then the total contribution of the 1x1 degree grid cells to the study area, is used as a weight function to calculate the change in WHE (Water Height Equivalent). For the GRACE mascon data the same approach is used, where the empty spaces between the mascons are evenly divided over the different mascons. This approach can be expressed in the following formula:

\[
WHE_{area} = \sum \frac{A_{\%} WHE_{mas} A_{mas}}{A_{tot}}
\]

Where \( WHE_{area} [m] \) is the WHE of the total study area, \( A_{\%} [-] \) the percentage of the mascon inside the study area, \( WHE_{mas} [m] \) the WHE of a mascon, \( A_{mas} [m^2] \) the total area of a mascon and \( A_{tot} [m^2] \) the total area of the study. The total mass change can easily be derived by multiplying \( WHE_{area} \) with the total area \( A_{tot} \).

Because level variations of large lakes and reservoirs in the region play an important role in the results, the study area has to be chosen in such a way, that both the hydrology and the lakes and reservoirs can be accounted for. For a complete description of the hydrology see paragraph 2.1 and for the reservoirs and lakes paragraph 4.1. The chosen study area is presented in the next paragraph.

### 3.3 Chosen study area

To choose a correct study area, the mascon coverage, hydrology and lakes in the study area should be taken into account. The study area (fig 3.2 and 3.3) is chosen based on the following considerations:

- Every mascon can be used as a more or less independent mass unit, but the mass variation within a mascon is unknown. Therefore it is not preferable to split up a mascon and divide it over different areas, which is only correct if there is no mass variation inside the mascon. And as there is almost always mass variation within a cell, such a division of a mascon will introduce errors in the result.

- Because hydrologic models perform best on catchment scale, the study area should mostly be defined by catchment boundaries.

- Especially in the Euphrates and Tigris river basins, the total water mass is highly influenced by reservoirs and inland (salt) lakes (UN-ESCWA and BGR 2013)(Altinbilek, 2004). This water mass has to be subtracted from the GRACE signal to find the groundwater mass. But when the lakes are situated at the borders of a mascon, an unknown part of the mass change due to this lakes leaks to adjacent mascons. Therefore, it is preferable to include adjacent mascons if there are important water masses at the borders.

The study area mainly consists of the Tigris catchment upstream from the confluence point of the Tigris and Diyala rivers and the Urmia catchment. The Urmia catchment is included because lake Urmia has a large contribution to the total change in mass of the area and lies close to the border of the Tigris catchment. The study area is expanded to the southwest to include the total signal of lake Qadisiyah, Tharthar, Habbaniyah and Razazzah. Although this area is part of the Euphrates catchment, it is expected that there are no large groundwater level changes in this area, because of flat terrain, deep groundwater levels and absence of agriculture.
Figure 3.2: Mass calculation zone. Study area is indicated by the gray line, the Euphrates and Van catchments by the light blue area, and the Tigris catchment upstream from Baghdad by the darker blue. Inside the study area the Tigris tributaries are indicated by green, the Desert part by yellow and the Urmia catchment by the dark blue. Large lakes and reservoirs are indicated by red dots.

Figure 3.3: Mascon coverage of the study area an its surroundings. The study area consist of six mascons.
3.4 Result for the study area and regional differences

In this paragraph the results of the mascon and grid data for the study area are presented. Then a comparison between different parts of the region is made, to give more insight different contribution of these regions to the total signal. Finally a comparison between the GRACE signal and rainfall in the area is given, to show the correlation between GRACE and hydrology of the area.

The difference between raster data and mascon data is generally small as can be seen from the first graph of figure 3.4. While the long trend is almost the same, there are some differences at a smaller time scale. The mascon data shows more irregularities and spikes than the raster data, which looks more smooth. On the one hand this could mean that the mascon method is better capable of capturing local effects on smaller time scales. On the other hand it could be caused by random errors, which are present in the mascon data but filtered out with the raster data.

The second graph from picture 3.4 shows that there are significant differences between the different regions in our study area. The desert area function differs from the other two because the seasonal effect is much smaller, which is likely because the water flows in this area are much smaller. The decline of mass in the Desert area has a strong dependency on water storages in the area, especially lake Tharthar (see paragraph A and figure A.1 for comparison). The Urmia catchment shows a similar trend as the Tigris catchment, but there are a few differences in the trend. At the start there is a slight increase instead of a stable situation, in the middle part there is less decrease in signal and at the end of the period there is more decrease in signal. This last trend is in agreement with lake level measurements of lake Urmia, which show a negative trend for this period in contrast to other lakes and reservoirs (see section A).

The third and fourth graph of figure 3.4 shows the monthly and yearly rainfall. As the main thriving factor in catchment hydrology, rainfall can be used as an indicator for the availability of water in the catchment. Between 2006 and 2009 there is a clear dry period, which is directly correlated with a decrease in water mass in this period and a smaller yearly variation. Further there is a clear lag in the yearly cycles of rainfall and GRACE data, which can be explained by the accumulation of rainwater in the catchment throughout the rainy season. This shows us that there is a strong evidence for coupling the GRACE mass signal and hydrology.

The total yearly variation in equivalent water height is about \(171 \pm 8\) mm and the total decline between 2006 and 2009 is about \(130 \pm 14\) mm. Where the total yearly variation is based on the yearly difference between the maximum and minimum GRACE value. The total decline is based on the average low values of 2009-2011 minus the average low values of 2004-2006. It is chosen to compare the yearly low values instead of the yearly average values, to isolate the decline of the deep groundwater from the effect of yearly variation.

The given bandwidth is based on an average error in the GRACE signal of \(17\) mm, as given in Schrama et al. (2007). Then, if the errors are randomly distributed, the bandwidth for ten years is two times this deviation for the minimum and maximum value divided by the square root of the total number of values: \(\frac{(17+17)}{\sqrt{20}} = 8\) mm. For the bandwidth of the total decline the same method is used but now for six values: \(\frac{(17+17)}{\sqrt{6}} = 14\) mm.

3.5 Discussion

An important notion when working with GRACE data is that it is still very difficult to determine from which location or factor the change of signal comes. To reduce mass leakage at the boundaries, mascons were used instead of raster data to make a better approximation for the total mass. But while using mascons a new error was introduced because the study area does not cover all the
Figure 3.4: GRACE and rainfall in study area. From top to bottom: A comparison between calculated GRACE signal for mascon and raster data, GRACE time series for different parts of the study, yearly rainfall and monthly rainfall.
mascons exactly. This problem can be solved by using mascons with exactly the same size as our study area, but it is not likely that it would reduce mass 'leakage' at the boundaries significantly.

Further it is disputable how the mass of lakes can be subtracted from the GRACE signal and how the border of the study area is chosen based on this knowledge. One could argue that also lake Van, Keban and Ataturk should be included in this data and the study area should be expanded. But it is chosen to exclude this lakes, because these lakes have much smaller variations than lake Urmia and Tharthar and are generally not included in the same mascons as the study area (figure 3.3). Further would the included areas have a much larger impact on the result than the desert area, because of larger groundwater and soil moisture variations.

Finally the explanations of the variations given in the results section are not the only possible explanations of the given signal, but from hydrologic perspective the most simple explanations. Further it is stated that there is a relation between hydrology and GRACE but the exact relation cannot be given from this data.
Chapter 4

Derivation of surface and groundwater

4.1 Introduction

As stated in paragraph 3.3, the water mass of lakes and reservoirs in the region has a large influence on the GRACE signal. Therefore, the total signal of all the large lakes and reservoirs is calculated and subtracted from the GRACE signal to find groundwater mass. This process is described in paragraph 4.2, 4.3 and 4.4. Beside the mass of surface water also the mass of snow and plant water has an influence on the results for groundwater. Although these changes are mainly seasonal and do not have much effect on the long trend, these are still included to show the influence of these parameters and to optimize model performance. Derivation of these parameters is described in paragraph 4.5.

4.2 Surface water levels

Surface water levels are obtained from Hydroweb Crétaux et al. (2011). This database contains water levels of large reservoirs and lakes obtained from satellite altimetry missions (Topex-Poseidon, GFO, ERS-2, Jason-1, Jason-2 and Envisat). In this research preferably time series of water levels from 2002 till 2012 are used, but a part of the time series is only available till the end of the Envisat mission in 2010. In table 4.1 an overview is given of all the available altimetry data in the region, including maximum water level variation, mean lake area and approximated variance. Figure 3.2 indicates the locations of the lakes. To calculate the total mass change from surface water, lake Van, Atatürk, Karakaya and Keban are excluded because they lie outside our study area.

4.3 Surface areas of lakes and reservoirs

To calculate the total volume change of the lakes and reservoirs, we also need the surface area of the lakes. It is possible to obtain average values from literature, but it has several advantages to have time series of lake areas. In the first place it generates data to calculate lake hypsometry and accurate volume variation. Secondly, it can be used as validation data on surface water levels. Finally, it enables us to to fill in gaps in time series of surface water levels using a stage-area relation.

To calculate surface areas and surface area variations the following datasets are used:

- SRTM digital elevation map at a 250 meter resolution.
- MODIS MOD09A1 reflectance band 5 at a 500 meter resolution and 8 day repeat cycle.
- MODIS MOD09Q1 reflectance band 2 at a 250 meter resolution and 8 day repeat cycle.

First the MODIS datasets are merged into datasets with a repeat cycle of 24 days, to reduce the number of errors and missing data in the datasets. For every repeat cycle the following calculation steps are performed (see figure 4.1 for an example). First, a subset of the MODIS reflectance band 2 is selected in which the lake lies. Secondly, this subset is filtered using the digital elevation map of the same area and the pixels at lower or higher elevation than the lake are removed. This is done to filter out small water surfaces and erroneous data. Thirdly, the pixel values of the MODIS reflectance band 5 are used to filter out all the areas without water at a 500 meter resolution. This additional filter is used, because this reflective band seems to be more accurate in determining surface water than the other reflective band and can filter out errors in reflective band 2. Fourth, all non-water pixels at 250 meter resolution are filtered out, using the pixel values of reflectance band 2. Finally the total area can be calculated by multiplying the total number of water pixels by the pixel surface area.

Because there is no literature available on which threshold values should be chosen to decide whether a pixel is water or not, a method based on minimizing errors is used. First, a bandwidth for the values is defined based on visual inspection using satellite images. Then, the relation between lake area and lake level is predicted as described in paragraph 4.4 and for every lake the R-squared is calculated. Then the best performing threshold values are chosen based on the sum of the R-squared values:

$$\sum_{Lake=1}^{j} R_{square} = \sum_{Lake=1}^{j} \left(1 - \frac{\sum_{t=1}^{n}(A_{t,j} - \hat{A}_{t,j})}{Var(A_{t,j})}\right)$$

Where $A_{t,j}$ is the calculated area, $\hat{A}_{t,j}$ the predicted area from the lake area-level relation, $n$ the number of time steps, $j$ the number of lakes and $Var(A_{t,j})$ the variance of $A_{t,j}$. Using this technique the optimal threshold values are 730 for reflectance band 2 and 800 for reflectance band 5.

### 4.4 Derivation of lake mass and volumes

To obtain the stage-volume curves of the lakes, the surface areas and water levels from the previous two paragraphs are merged. First the surface areas at the measuring moments of the lake levels are calculated using linear interpolation. Then a stage-area relation is obtained by linear and cubic regression (see A for the curves). To decide whether a cubic regression gives a significant improvement in fitting the data in comparison with linear regression, a F-test is used.

The F statistic is calculated based on the following formula:

$$F = \frac{(RSS_{lin}-RSS_{cub})}{\frac{RSS_{cub}}{p_{cub}-n_{lin}} + \frac{RSS_{cub}}{n_{cub}}}$$

Where $RSS$ is the sum of the squares of the measured area values and the approximated area values, $p$ the degrees of freedom of the curves ($p_{cub} = 3$ and $p_{lin} = 2$) and $n$ the total number of

---

1The MOD09A1 and MOD09Q1 data products were obtained through the online Data Pool at the NASA Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota (https://lpdaac.usgs.gov/data_access).
Applicance of filtering method for Mossul Lake

Figure 4.1: Example of lake area calculation. By applying three filters the area of Lake Mosul is determined.
data points. Then the F statistic is used as input value for the cumulative F-distribution curve, with the parameters $d_1 = n - p_{cub}$ and $d_2 = p_{cub} - p_{lin}$. When this results in an uncertainty of less than 0.05, the linear model is accepted as the best model. When it is higher then 0.05 the cubic curve is used.

This approach resulted in a linear curve for almost all the stage-area regressions. Results for all the lakes included in this research are given in Appendix A and are clustered based on location. In the first figure the large lakes of central Iraq are given, in the second the large upstream lakes in Turkey and Syria, in the third the larger lakes in Northern Iraq and in the last, the lakes Van and Urmia. The lakes of central Iraq, Northern Iraq and lake Urmia are included in the calculations for our study area. But because lake Urmia and Razzazah are located close to the border of our study area, it is assumed that about one third of the total mass leaks away to other mascons. Therefore the mass contributions of these lakes are reduced with one third.

Using the stage-area relations, the stage-volume curves can now be derived by integration:

$$V(h_{lake}) = \int A(h_{lake}) \, dh_{lake}$$

From this curve also the area-volume relations can be derived. These can be used if there is only data on lake areas available. Still it is preferable to use lake levels instead of lake areas, because the measurement of lake levels is more accurate. To approximate the errors in the calculated water level from lake areas the error of the regression is used. The resulting values are presented in table 4.1. When we assume that the relationship between lake area and lake level is indeed linear/cubic, the standard deviation of the lake area calculation becomes:

$$\sigma^2_{h,Area} = \sigma^2_{h,Regression} - \sigma^2_{h,Satellite}$$

The resulting uncertainties are given in table 4.1. The lowest uncertainties in lake variation are mainly from the lakes in the relative flat desert area, which show large variations in total area. The total lake size also influences the relative error because of the raster size of the MODIS dataset. A special case is lake Van, which can be frozen for some time of the year which results in a large error. Further, it is important to notice that the total uncertainty in lake levels does not depend on the absolute errors, but on the errors relative to the total level difference. For example the relative error for lake Van $0.18 \pm 0.07 [-]$ is much larger then the relative for lake Dukan $0.66 \pm 0.29 [-]$ while the absolute error is three times smaller.

### 4.5 Mass from snow and plant water

Surface water and groundwater in the study area are not the only water storages. Also plant water, snow and ice are storages in this region. As there are no or only very small glaciers located in our study area (Dyurgerov et al., 2002) there are no significant changes in ice mass expected, so only plant water and snow storage are discussed here. These values are obtained from GLDAS models (Rodell et al., 2004), which include modules for calculating biomass growth, snowfall and snowfall accumulation. Afterwards the total snow mass is multiplied by 2.23, based on the precipitation calibrations based on measured rainfall data, given in paragraph 5.2. In figure 4.4 a graph is given for the water equivalent of snow water, plant water and surface water variations. It is clear that the amount of water in plants is small and the snow accumulation is only seasonal. Which is as expected because most of the area is scarcely vegetated and most of the snow melts away every summer. Snow melt can explain about 10 % of the yearly fluctuation derived from GRACE given in paragraph 3.4, but does not have effect on the long trend in summer time. A map of yearly fluctuations and long trends are given in figure 4.2.
Table 4.1: Lake characteristics of large lakes between 2002 and 2012. The lakes where 'Exclude' is added are situated outside the study and are excluded for the calculation.

<table>
<thead>
<tr>
<th>Name</th>
<th>Mean Area [km$^2$]</th>
<th>Max level difference [m]</th>
<th>Max volume change [km$^3$]</th>
<th>$\sigma_h$,Area</th>
<th>$\sigma_h$,Satellite</th>
<th>$\sigma_h$,Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tharthar</td>
<td>1700</td>
<td>12.9</td>
<td>23</td>
<td>0.81</td>
<td>0.09</td>
<td>0.82</td>
</tr>
<tr>
<td>Habbaniyah</td>
<td>220</td>
<td>5.1</td>
<td>1.6</td>
<td>0.64</td>
<td>0.86</td>
<td>1.07</td>
</tr>
<tr>
<td>Razazah</td>
<td>640</td>
<td>3.8</td>
<td>5.0</td>
<td>0.18</td>
<td>0.29</td>
<td>0.34</td>
</tr>
<tr>
<td>Hamrin</td>
<td>140</td>
<td>6.3</td>
<td>1.6</td>
<td>0.31</td>
<td>0.39</td>
<td>0.50</td>
</tr>
<tr>
<td>Adhaim</td>
<td>40</td>
<td>8.8</td>
<td>0.50</td>
<td>2.42</td>
<td>0.53</td>
<td>2.48</td>
</tr>
<tr>
<td>Darbandikhan</td>
<td>110</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Dukan</td>
<td>120</td>
<td>29.7</td>
<td>4.5</td>
<td>1.75</td>
<td>0.66</td>
<td>1.87</td>
</tr>
<tr>
<td>Qadisiyah</td>
<td>300</td>
<td>27.0</td>
<td>6.4</td>
<td>1.36</td>
<td>0.42</td>
<td>1.42</td>
</tr>
<tr>
<td>Van (Excluded)</td>
<td>3000</td>
<td>1.7</td>
<td>5.9</td>
<td>3.54</td>
<td>0.18</td>
<td>3.55</td>
</tr>
<tr>
<td>Urmia</td>
<td>3900</td>
<td>3.8</td>
<td>17</td>
<td>1.74</td>
<td>0.16</td>
<td>1.74</td>
</tr>
<tr>
<td>Mosul</td>
<td>240</td>
<td>30.2</td>
<td>7.5</td>
<td>1.59</td>
<td>0.58</td>
<td>1.69</td>
</tr>
<tr>
<td>Assad (Excluded)</td>
<td>620</td>
<td>3.1</td>
<td>7.5</td>
<td>0.93</td>
<td>0.14</td>
<td>0.94</td>
</tr>
<tr>
<td>Ataturk (Excluded)</td>
<td>620</td>
<td>10.0</td>
<td>3.9</td>
<td>2.63</td>
<td>0.13</td>
<td>2.63</td>
</tr>
<tr>
<td>Karakaya (Excluded)</td>
<td>210</td>
<td>11.4</td>
<td>9.3</td>
<td>1.56</td>
<td>0.25</td>
<td>1.58</td>
</tr>
<tr>
<td>Kebar (Excluded)</td>
<td>510</td>
<td>22.4</td>
<td>13</td>
<td>2.02</td>
<td>1.07</td>
<td>2.29</td>
</tr>
</tbody>
</table>
Figure 4.2: Mean yearly trend and variation of snow water equivalent

4.6 Validation of lake volumes

To validate the calculated relations between water level, lake area and lake volume the regression curve of lake Mosul is compared with data found in literature Issa et al. (2013). Only the lake areas of lake Mosul were validated, because data from other lakes were not available. In figure 4.3 a comparing graph is given for the stage-area. Two different curves are given from literature, one made by IVO from topographic maps dated before 1968 and one from 2011. Differences in those graphs can mainly be explained by sedimentation according to the authors. This means that our derived graph should be between those curves, but more closely to the curve from 2011, which is indeed the case for the lower water levels. For the higher water levels it is not, although the fitted linear function has about the same angle as the old IVO measurements for the high values. Generally, the used method seems to perform quite well but could give a bit lower values for higher water levels.

4.7 Results

The goal of this section was to derive the changes in groundwater levels over the whole study area. This is done by subtracting other water masses as snow water, plant water and surface water from the curves obtained from GRACE calculations (see paragraph 3.4). In this result paragraph the outcome of these calculations are presented. Further a first indication of the total changes in deep groundwater and soil moisture are presented.

From figure 4.4 can be seen that the largest contributor of snow, vegetation and surface water is the surface water. The total signal from surface water on the longer trend is about $74 \pm 4$ mm, using the mean minimal signal of the years before and after the drought period. The minimal mean is taken instead of the yearly mean because otherwise the yearly cycle would have a large influence, while this study wants to focus on the change of the longer trend. The total signal of the yearly variation of the lakes is about $55 \pm 5$ mm. The contribution of snow shows only a yearly cycle and no longer trend, because almost all snow melts away during the summer. This means that when the GRACE signal is corrected for snow it is only topped off and shows no changes for the
summer/low periods. The total contribution of the snow signal is about $20 \pm 3$ mm at the end of the winter. The vegetation signal has almost no influence at all. There are some differences but those are in the order of 1 mm.

Another interesting phenomenon, which can be seen from figure 4.4, is the lag between the peaks of the snow and surface water curves. This is caused by the hydrologic routing of water in the catchment. When the first snow falls in the winter the contribution of snow has a direct effect on the GRACE signal, but it takes till the end of the spring before the melt and rain water is routed to the reservoirs and lakes in the area.

In figure 4.5 the total effect of those reductions is given on the total GRACE signal. This shows that the pattern of the groundwater signal is still comparable with the total GRACE signal but mainly the amplitude of the signal is changed due to correction of the yearly cycle by surface water and snow water. Further the average signal is lower in the period before and higher in the period after the summer of 2007. This groundwater signal still contains a shallow soil moisture and deep groundwater component, which are modelled in section 6. The decline of soil moisture and groundwater between 2006 and 2009 is $56 \pm 14$ mm and the yearly variation is $144 \pm 8$ mm.

4.8 Discussion

In the derivations of the change in snow and lake masses, uncertainties can cause errors in the data. In the following part the main influencing factors and uncertainties are described.

Lake levels The lake levels are an important source of uncertainty in this study, because they have a strong influence on the results. Using satellite data an approximation can be made
Figure 4.4: Contribution of snow water, plant water and surface water to GRACE signal, smoothed over 60 days.

Figure 4.5: Total GRACE signal and groundwater signal, smoothed over 60 days.
about the uncertainty of this data (table 4.1). Further it is important to notice that the errors only apply for one lake at one moment of time, which means that the total error for all the lakes is much smaller. From the table can also be seen, that especially the larger lakes, like Tharthar, Urmia and Razazah, have much smaller errors than the smaller lakes. And for the larger lakes with substantial errors, like Dukan, Mosul and Qadisiyah, the relative errors are small due to large level variations. The mean relative error is calculated using the absolute error in water level, divided by the total water level change and weighted by the total mass contribution of every single lake. This result in a total error of 3%.

**Lake areas** The average errors for the lake areas are larger then the errors for lake elevations, but the total influence of these errors is small. Firstly a large part of the errors is filtered out by using the a regression line for the stage-area curves. (Appendix A). The remaining error was about 5% for lake Mosul. Because the largest mass variations are caused by lakes with about the same or smaller errors, this percentage can be used as a maximum error for single lakes. By combining all the lakes the maximum total error will be 6%, based on the errors and mass contributions of table 4.1.

**Snow mass** The total snow mass is calculated based on the GLDAS model, but because the total precipitation and snow accumulation is much higher then calculated by GLDAS it is multiplied by a factor of 2.23. However, in reality are the processes of snow accumulation and snow melt not linearly related to precipitation. It is likely that there is slightly more snow accumulation during the winter period, but this error is small related to the error made in snow melt calculations. This is mainly because snow melt is not related to precipitation but to temperature and solar radiation. Therefore it is expected that the snow melt will take longer than modeled, which causes a few millimeters more snow mass in the melting period. Snow accumulation in the model is mainly dependant on precipitation, so the error can be derived from uncertainties in precipitation calculations given in 5.5, which is 23% for monthly precipitation. Snow accumulation takes place in minimal 2 months so the total error is about \( \frac{23}{\sqrt{2}} = 16\% \).

The total error for the reduced signal given in figure 4.5 is based on the errors from GRACE calculations (17 mm), lake mass (6%) and snow mass (16%). The total error is calculated using the following formula:

\[
\sigma_{\text{total}} = \sqrt{\sigma_{\text{GRACE}}^2 + \sigma_{\text{snow}}^2 + \sigma_{\text{lake}}^2}
\]

This results in a total error of 14 mm for the longer trend and 8 mm for the yearly variation.
Chapter 5

Water Fluxes

5.1 Introduction

In the two previous chapters we discussed the main water storages in our study area, which include lake mass, snow mass and groundwater mass. In this section we focus on the main water fluxes in the study area. Three important fluxes are discussed and presented. Rainfall in paragraph 5.2, evaporation and transpiration in 5.3, river discharge in 5.4. The fluxes presented here help to understand the hydrologic behavior of the area, but will also be used as forcing parameters for a rainfall runoff model presented in chapter 6.

5.2 Rainfall

The most important forcing parameter of rainfall runoff models is rainfall. To find the amount of precipitation in our study area, precipitation data of the TRMM satellite and the GLDAS model (Huffman et al., 2007; Rodell et al., 2004) are compared and calibrated with data from four rainfall stations in the region (Agro-meteorological department Kurdistan, 2013). These stations are situated close to or in the cities of Sulaymaniyah, Dukan, Derbendikhan and Penjwen.

To find out which dataset represents the rainfall regime of the area better, monthly and yearly rainfall of the four rainfall stations are compared with TRMM and GLDAS data using regression curves. Because there is too much variation in this data to obtain reliable higher degree fits, only linear regression lines through the origin are used, which means that no offset value is expected (figure 5.2 and 5.3). For all four rainfall stations a comparison of monthly data is made between TRMM or GLDAS datasets and the measurements of the rain stations. Daily and yearly measurements are also plotted, but are given in the appendix. From the monthly graphs can be seen that TRMM and GLDAS datasets performs equally. For Dukan and Sulaymaniyah GLDAS gives slightly better results, while the TRMM dataset fits the Penjwen data better. The fit for Durbandikhan is worse in both cases. More remarkable is the absolute difference between the datasets and rainfall stations. While the GLDAS dataset gives rainfall amounts of about half the measured values, TRMM data shows a small overestimation of the monthly rainfall. Also the difference between the different gauging stations is remarkable. Both GLDAS and TRMM datasets give much smaller differences in rainfall amounts between Penjwen and the other stations than in situ data. This can be caused by the relation between the GLDAS and TRMM datasets, because TRMM measurements are included in the GLDAS dataset. But possibly it reflects the large variations within every satellite measurement cell of 0.25 x 0.25 degrees. This means that TRMM, GLDAS measurements and rain gauge measurements can both be correct, because the first measures over an area and the second at a point.
Because differences are small between the TRMM and GLDAS dataset an additional fit is made for all datasets (figure 5.1). Again there is only a small difference between the TRMM and GLDAS measurements. Still, the TRMM dataset is chosen because it gives more accurate absolute values and a more independent measurement. The total amount of rainfall of this dataset, multiplied by the factor resulting from the yearly results (1.07), is used as the forcing parameter of the hydrologic model.

After application of the calibration parameter, average monthly rainfall rates can be obtained for the period 2002 till 2012, figure 2.2. An oversight of the mean yearly rainfall rate over the whole catchment is shown in figure 2.2. This is done by averaging the daily rainfall satellite measurements of every 0.005 x 0.005 degrees grid cell inside the catchments, which are calculated from the 0.25 x 0.25 degree grid cells of the TRMM dataset using nearest neighbour interpolation. Using the same method also the monthly average rainfall of the Foothill Zone and High Folded Zone of our study area are calculated and given in figure 5.4. This shows that the average rainfall at higher elevation is indeed much more than in the Foothill Zone. Further a clear wet and dry period can be distinguished, with the wet period from November till April and the dry period from May till October.

As a last step the total precipitation is adjusted for snowfall and snow melt, available from the GLDAS model. First the snowfall values are subtracted because and becomes part of the snow mass in the model. When the snow melts, it is added to the rainfall values and the snow water enters the rainfall runoff model. Because snowfall is part of the precipitation in the catchment, the calibration parameter of 2.23 for the yearly precipitation from the GLDAS model is used as given in figure 5.1.

5.3 Potential evaporation

Especially in dry and hot areas as Iraq evaporation and transpiration are hydrologically very important. In the first hours after every rainfall event, a considerably amount of water is lost due to interception and soil evaporation. And during months after the rain event this water can be transpired by plants. An important parameter used by evaporation or transpiration calculations is potential evaporation, the total amount of water which can be evaporated during the day if there is enough water available. In this research the potential evaporation of every 0.25 x 0.25 GLDAS grid cell is calculated using the Penman-Monteith equation, applied for grass evaporation (Allen et al.):

\[
\lambda ET_0 = \frac{\Delta (R_n - G) + \rho_a c_p (e_a - e_s)}{\Delta + \gamma (1 + \frac{r_s}{r_a})}
\]

Where \(\lambda\) [J/m³] is the energy needed to evaporate water, \(ET_0\) [m/s] is the potential evaporation per day, \(R_n\) [J/m²/s] the net solar radiation at the surface, \(G\) [J/m²/s] the soil heat flux density, \(\rho_a\) [kg/m³] is the mean air density at constant pressure, \(c_p\) [J/K/kg] is the specific heat of the air, \(\Delta\) [Pa/K] the slope of the vapour pressure curve, \(\gamma\) [Pa/K] the psychometric constant, \(e_s\) [Pa] the saturation vapour pressure, \(e_a\) [Pa] the actual vapour pressure, \(r_s\) [s/m] the aerodynamic resistance and \(r_a\) [s/m] is the surface resistance. From these parameters \(\lambda, \rho_a, c_p\) and \(\gamma\) are given constants. Additionally, \(r_s, r_a, e_s\) and \(\Delta\) are calculated using the temperature at 2 meter height and wind speed at 2 meter height. Because temperature, wind speed and further needed parameters are all available in the GLDAS model (Rodell et al., 2004), calculation is straightforward. A map of the yearly potential evaporation of Northern Iraq is given in figure 5.6. This map shows that potential evaporation also decreases towards the north and the east, where the terrain is higher.
Figure 5.1: Relation between TRMM, GLDAS and measured rainfall at all four gauging stations. Data between 2002 to 2012
Figure 5.2: Relation between monthly rainfall from GLDAS dataset and gauging stations between 2002 and 2012
Figure 5.3: Relation between monthly rainfall from TRMM dataset and gauging stations between 2002 and 2012.
Figure 5.4: Average monthly and yearly rainfall of Foothill Zone and High Folded Zone
and more mountainous. Monthly variation is given in figure 5.5, where the average monthly mean of the High Folded and Foothill Zone are given from 2002 till 2012. During the dry and hot summer the potential evaporation reaches rates of more then 200 mm/month, while the potential evaporation can be lower then 50 mm/month during winter. And these differences are even small when compared with the daily evaporation rates, which vary between 1 and 10 mm/day.

Although the potential evaporation give some interesting insight in the climatic condition of the region, it does not mean that the given rates comes even close to the observed evaporation and transpiration rates. Beside the lakes and reservoirs in our study area, most other areas show only evaporation in the weeks after rainfall events. Mainly because the available soil moisture rapidly disappears by high evaporation, infiltration or runoff rates. And as there is only water available in the winter and spring season, almost all transpiration occurs in this seasons. This means that in contrary to the potential evaporation rates, most actual transpiration and evaporation occurs during winter and spring.

5.4 River Discharge

The most important quantity to calibrate our models is river discharge. River discharge into Dukan and Derbendikhan lakes is obtained from Directorate of Derbendikhan Dam (2013); Directorate of Dukan Dam (2013). These dams including their catchment areas are shown in figure 5.7. The catchments consist of the upstream part of the Diyala river catchment in the case of Derbendikhan lake and the Lesser Zab for Dukan lake. Both dams were built in the period from 1956-1961 by European and Russian companies. The dams are mainly built for hydropower generation, which means that they store river discharges in summer and spring to be able to generate energy in summer and autumn. Therefore, data downstream of these dams is not suitable for rainfall runoff model calibration, because all discharge peaks are eliminated from the data and lagged for several months (figure 5.8). Because there are reservoirs in the Iranian part of the Diyala river catchment
upstream of Derbendikhan dam, the discharge measured at this dam is less suitable for model calibration. Additionally, there is only monthly data available for the Derbendikhan dam, while there is daily data available for Dukan dam. Therefore it is chosen to calibrate the model based on the river discharge into Dukan lake.

In figure 5.8 an overview is given of the monthly and yearly inflow in the years 2002-2012. From these graphs can directly be seen that during the period 2007 till 2010 there is much less discharge, which is directly linked with the total rainfall during this period, as mentioned in paragraph 5.2. The maximum difference in discharge between different years is a factor of 3 to 4 and the mean low flow during summer and high flow during winter differs almost a factor of 10.

5.5 Discussion

Looking at the calibration graphs for rainfall, the question raise, whether these datasets are still suitable for modeling applications or not. For exact daily calculation these datasets are indeed not suitable. But in this study the main goal is to capture the general hydrologic behavior of the system, which has generally a much longer timescale than one day. The shown error in the data can be misleading, because it can be caused by several other factors, like scale factors and measurement errors at the rainfall stations. Additionally a part of the local errors, are averaged out because aggregates of large areas are used instead of local data. This means that the calculated errors are likely to be a maximum value. The monthly error for the average rainfall of the measuring stations is 23 % and the error for the average yearly rainfall is 9 %.

The formula for potential evaporation mainly suffers from a lack of information about the ground surface. Therefore, the simplified formula was implemented using a well watered grassland as reference surface, which is different from the real conditions in the study area. Mainly in the summer, when almost all grass dies, there is a large difference between the model and reality. But during winter and spring when there is actual evaporation and transpiration, it fits these conditions quite well, because the area will mainly be covered by grass during that period. This means that
Figure 5.7: Catchments of Dukan and Derbendikhan dams. The light blue area is the Tigris catchment upstream from Baghdad. The darker blue inside the black lines shows the total upstream area of Dukan dam in the Lesser Zab catchment and Derbendikhan dam in the Diyala catchment. The dam locations are indicated by black dots.
Figure 5.8: In the upper graph a comparison between inflow and outflow of Dukan Lake obtained from Directorate of Dukan Dam (2013). Data is smoothed over 3 months. In the lower left graph a comparison of average monthly precipitation and discharge between 2002 and 2012, where precipitation is an average value of the whole catchment and discharge is measured at the inflow of lake Dukan. In the lower right graph yearly precipitation and discharge are given. The axis are scaled in such a way that the water amounts are proportional.
while there are errors made in this calculation, the main errors are in the period where it does not affect modeling results. Other small errors in this calculation also do not have much effect, because the total evaporation is mainly driven by water availability and not by potential evaporation.

For the river discharge, possible errors in the data are only caused by measurement errors. These errors can be separated in random errors and systematical errors. Random errors are mainly caused by every measuring moment and systematical errors by the derivation discharges from water velocities and water heights. During this study most errors of the first kind are averaged out by using long time series and have only low influence on model results. Errors of the second kind are more problematic because they can cause underestimations or overestimates over long periods. But in this case these errors can only be small because the total water flow to and from the lakes is checked by the total water balance of the lake. Which means that instead of measuring just one water flux, different water fluxes and the lake storage can be evaluated using a water balance of the whole system.
Chapter 6

Rainfall-Runoff models

6.1 Introduction

Rainfall runoff models are a common tool in hydrology to give insight in hydrologic behavior of catchments and predicting stream flow data. Since the launch of the GRACE satellite several studies are done on the relation between water storage in those models and GRACE satellite data (Awange et al., 2011; Hinderer et al., 2006; Ngo-Duc et al., 2007; Schmidt et al., 2008). Most models show indeed similar behavior as the derived signal from GRACE data, but mainly with smaller peaks then the GRACE data. Common thoughts are that these differences are caused by other water storages beside of groundwater basins like snow, surface water and vegetation water. And although it is possible to measure the first two quite accurately, vegetation water is difficult to measure. Our study area is barely vegetated, which reduces the impact of vegetation water. Therefore, we can assume that the results for the GRACE signal in the Tigris catchment upstream from Baghdad are quite accurate and indeed represent the groundwater and lake water mass.

Other differences between GRACE observations and rainfall runoff models comes from the used assumptions in those models. One important assumption in most hydrological model is that the catchment is pristine. Therefore, evaporation and transpiration are calculated using a combination of vegetation and soil moisture.

In this section a rainfall runoff model is developed and calibrated based on GRACE and runoff data to show that the observed GRACE signal can be simulated using rainfall runoff models. This hypothesis is mainly based on characteristics of the groundwater system in the catchment, which were discussed in section 2.2. The area can be characterised by high infiltration and recharge rates and large groundwater reservoirs, which drain relatively fast (UN-ESCWA and BGR, 2013). Also other possible causes, like overpumping in the area, cannot have such a strong influence on the total water mass in the area. In paragraph 6.2 first the used concepts are shortly explained, then in paragraph 6.3 the selected optimal model is discussed and in the result part the final results are presented.

6.2 General setup of rainfall runoff model

In this research the so-called lumped-model approach using flex models is used (Fenicia et al., 2011). This means that the model consists of lumped reservoir storages, which have one rainfall rate, evaporation rate, reservoir flow and reservoir level for a whole area. The disadvantage of these models is that the spatial distribution of the input data, as specific geology, rainfall and potential evaporation is lost. But because the used input data has already quite some uncertainty, there is
only small information loss by integration over larger areas. Also this approach is used to prevent uncertainties and equifinality of the model (Beven, 2001, 1993; Savenije, 2001).

To represent the large geological differences in our study area the flex-topo approach is used, where different geological or hydrological zones are classified and lumped (Savenije, 2010). In this research the catchments are divided in three zones, the alluvial zone, the infiltrative geologic formations and the non-infiltrative geologic formations. These zones are also described and illustrated in paragraph 2.2. For every catchment the total area, rainfall and evaporation of the alluvial zone and the combined infiltrative/non-infiltrative are calculated. A division parameter is used to calculate the total contribution of the the infiltrative and non-infiltrative zone. The main hydrologic processes in these different zones are:

**alluvial zone** The hydrology in the alluvial zone is mainly governed by the present sediment layers. While small areas consist of coarse materials, like alluvial fans, the most areas consist of clayey soils. This results in mainly low infiltration rates and most water leaves the area as surface runoff. Also, parts of these alluvial sediments are underlain with impermeable geologic formations, which also prevent deeper percolation of groundwater Al-Manmi (2013a). A large part of the surface runoff ends up in the stream of rivers in the area, but a considerable amount flows into local depressions, from where the water evaporates or infiltrates. In addition to these local depressions, more and more small dams are constructed to use the water for local agriculture.

**Infiltrative geological formations** These formations are mainly located in the High Folded Zone, but also parts of the Foothill Zone are included in this area. These geological formations mainly consist of well fractured and karstified limestone or conglomerates. The main formations included in the study area are the Bai Hassan, Pila Spi, Bekhme, Qamchuqa, Balambo, Garagu and Sarmord formations. While small parts of these formations generate surface runoff, the main area is strongly fractured and jointed, which results in high infiltration rates. Most of these areas are sloping and have only thin soil layers with little vegetation.

**non-infiltrative geological formations** These formations are mainly located in the High Folded Zone. There are some small areas in the Foothill Zone, but their share is not significant. These formations consist of mixed tertiary sandstones, siltstones and claystones and the less fractured limestone from the Cretaceous and Jurassic period. The hydrology of this region can be characterized by high runoff rates and low infiltration rates. Because of shallow soil layers and steep slopes, soil water and depression storage are also relatively small. Compared to the infiltrative geological formation, these formations cover a larger area of Northern Iraq.

For each of these zones a unsaturated reservoir is included in the model, but for the fast reacting reservoirs and groundwater reservoirs the infiltrative and non-infiltrative areas are coupled. This is done because these areas are both mainly located in the High Folded Zone and share the underlying aquifers and top soils. This means that they contribute to the same groundwater reservoirs and have similar fast runoff processes. From the unsaturated reservoir water is routed to either:

**Evaporation/Transpiration** Water that remains in the top soil layers after rainfall events is partly evaporated and transpired.

**Fast Runoff** The main fast runoff process in these areas is surface runoff. Because the soil is saturated or not able to take up all the precipitation, water flows over the rocks and soils to open water. Another fast runoff process, which occurs in combination with or additionally to surface runoff is flow through the unsaturated reservoir to surface water (interflow). To
model the flow of water between the moment it rains and the moment that is reaches open water a fast reservoir is added.

**Slow Runoff** The slow runoff part is the groundwater flow to and from groundwater reservoirs. Groundwater reservoirs are filled by percolation from the unsaturated reservoir and emptied through springs to the open water. Generally, the slow runoff reservoirs fill during the winter period and are the main source for streamflow during summer.

After the fast runoff and slow runoff enters a flow or a river, it still takes some time for the water to arrive at the location where runoff is measured. Therefore a lag function is added to account for this process. For calibration using GRACE data this lag function should include riverflow till the point where the water leaves the study area.

### 6.3 Mathematical implementation of model elements

In this section the mathematical implementation of the general setup of the rainfall runoff model is given. First a schematization of all reservoir and fluxes is given, then the used parameters are shown and quantified. A schematization of the rainfall runoff model is given in figure 6.1 and the final table of parameters in table 6.1. The schematization is split up in the three zones by lines (alluvial, infiltrative and non-infiltrative) and in three reservoir types by colours (Unsaturated reservoir, Fast reactive reservoirs and Slow reacting reservoirs). All calculations for this model are done on a daily basis.

**Unsaturated reservoir**

The unsaturated reservoir is split up in three areas with their own precipitation, potential evaporation and runoff rates. The model for these zones consists of three steps; adding precipitation,
runoff calculation and evaporation/transpiration. First the precipitation on a particular date is added to the storage of the unsaturated reservoir, or \( Su^t = Su^{t-1} + \int_{t-1}^t P dt \), where \( Su^t \) [m] is the storage of the unsaturated reservoir at time \( t \) and \( P \) [m/day] the precipitation during timestep \( t \). Then the total runoff is calculated using two different methods.

For the alluvial zone, the daily runoff and infiltration of the unsaturated reservoir is calculated using the parameters \( \beta_A [-] \), \( Su_{\text{max},A} [\text{m}] \) and \( \gamma_A [\text{m/m}] \). The total flow out of the unsaturated reservoir is calculated for every time step, if the new storage does not exceed the maximum storage (Moore, 1985):

\[
Q_{Su,A}^t = P_A^t \times \left( 1 - \left( 1 - \frac{Su_A^t}{Su_{\text{max},A}} \right)^{\beta_A} \right) \quad \text{(6.1)}
\]

Where \( Q_{Su,A} [\text{m/day}] \) daily flow out of the alluvial unsaturated reservoir, \( P_A(t) [\text{m/day}] \) is the daily rainfall, \( Su_A(t) [\text{m}] \) is the current amount of water stored in the unsaturated reservoir, \( Su_{\text{max},A} [\text{m}] \) is the maximum storage in the unsaturated reservoir and \( \beta_A [-] \) is the exponent which determines the relation between storage and flow out of the reservoir. If the maximum storage is exceeded the formula changes to \( Q_{Su,A}(t) = P_A(t) \). Important to notice about this formula is that the total runoff can never be more than the total rainfall in a certain time step, which means that if some soil water is left in the unsaturated reservoir, it will stay there till it is evaporated or transpired. This is in correspondence with the natural mechanism that a part of the water will stay in the soil due to capillary forces. The bounds of the parameter \( Su_{\text{max},A} \) are \([0.05, 0.10]\) based on experience of local experts (Al-Manmi, 2013a). And the bounds of \( \beta_A \) are \([2, 4]\) because of low infiltration capacity of the soils.

When the total outflow of the unsaturated reservoir is calculated, this flow is divided into fast runoff and percolation using the parameter \( \gamma_A \):

\[
Q_{Su,A,F} = Q_{Su,A} \gamma_A \quad \text{(6.2)}
\]

\[
Q_{Su,A,G} = Q_{Su,A} (1 - \gamma_A) \quad \text{(6.3)}
\]

Where \( Q_{Su,A,F} [\text{m/day}] \) is the outflow towards the fast reservoir and \( Q_{Su,A,G} [\text{m/day}] \) is the outflow to the groundwater reservoir. Based on the low infiltration rate, the bounds of \( \gamma_A [-] \) should be high, but because of the amount of depression storage the bounds are a bit lower \([0.6, 0.8]\).

To calculate evaporation from the unsaturated reservoir, the potential evaporation in a time step, \( ET_0^t \), is multiplied by a factor based on saturation. Although in most studies almost the full potential evaporation is used to calculate evaporation, another approach is used here. This is mainly based on a different hydrology of the study area compared to the countries where most studies are done. While in this study there is only little vegetation, which cannot develop because of a long dry period, the common study areas consist of areas where water available year round and vegetation is fully developed. This means that soil evaporation becomes very important in the total evaporation and transpiration term. But soil evaporation is dependent on the amount of water available in the topsoil. Therefore is chosen to calculate the total evaporation and transpiration using the same approach as in equation 6.1:

\[
E_{Su,A}^t = \frac{ET_0^t}{\epsilon_A} \left( 1 - \left( 1 - \frac{Su_A^t}{Su_{\text{max},A}} \right)^{\epsilon_A} \right) \quad \text{(6.4)}
\]

Where \( E_{Su,A} [\text{m/day}] \) is the evaporation in the current time step and \( \epsilon_A [-] \) is the exponent which regulates the relation between storage and evaporation in the unsaturated reservoir. The bounds of \( \epsilon_A \) are \([1, 3]\) because the evaporation is at least proportional to the amount of soil moisture and probably larger.
Calculation methods for the unsaturated reservoir in the infiltrative and non-infiltrative zone are basically the same as for the alluvial zone. Therefore, the same parameters names are used, but the parameter values are different. The only formula which differs from the alluvial zone is for the total outflow of the unsaturated reservoir as in equation 6.1. For the infiltrative and non-infiltrative zone the modified logistic curve is used (Clark et al., 2008; Fenicia et al., 2011):

$$Q_{Su,I} = P_I \left(1 + \frac{e^{-\beta_I(1-\lambda_I)}}{(1 + e^{-\beta_I((1-\lambda_I) - x)})} \right) \frac{e^{-\beta_I x} - 1}{(1 + e^{-\beta_I(x-\lambda_I)})}$$

Where $x = \frac{Su_I}{Su_{max,I}}$ and $\lambda_I$ [-] an additional parameter, which represents the amount of soil saturation needed to generate overland flow. In figure 6.3 a few examples of the logistic curve are given. While the parameter $\beta$ determines the slope and bend of the logistic curve, the parameter $\lambda$ determines location of the slope based on the saturation degree $x$. The reason to use this approach is the nature of sloped terrain with high overland runoff. During rainfall events the top soil layer will fill up to a certain level and suddenly starts to overflow, generating overland flow. This means also that the maximum amount of water in the unsaturated can never be much higher than the $\lambda Su_{max}$. Therefore, the bounds of the parameters $Su_{max,I}$ and $Su_{max,N}$ are chosen [0.08, 0.12], a bit higher then the values given by local experts of 0.08 Al-Manmi (2013a). The values of $\lambda_I$ and $\lambda_N$ are fixed at 0.8, because otherwise $\lambda$ and the values for the unsaturated reservoir will only correct for each other, causing equifinality. The values of $\beta_I$ and $\beta_N$ mainly accounts for the spread in overflow values over the whole area and lies in the interval [10, 40]. The largest difference between the infiltrative and non-infiltrative zone are the factors $\gamma_I$ and $\gamma_N$, which divide the flow from the unsaturated reservoir to the slow and fast reservoirs (see formula’s 6.2 and 6.3). The chosen bounds for $\gamma_I$ are [0.05, 0.15] because almost all water from this areas will infiltrate. Therefore, the total runoff flow from this area is small. The bounds for $\gamma_N$ are [1, 1] because the bedrock is impermeable, which actually means that there is no percolatin to the groundwater in this area.

Because the topsoil of the infiltrative and non-infiltrative areas are quite similar, the parameter groups $\lambda_I$, $\lambda_N$, $Su_{max,I}$, $Su_{max,N}$ and $\epsilon_I$, $\epsilon_N$, $\epsilon_A$ are coupled, which means that they have the same values in the final model. This also helps to reduce the total number of parameters in the model. This brings the total number of parameters in the unsaturated reservoirs to ten.

**Fast runoff reservoir**

The interflow and overland runoff of the High Folded Zone and the alluvial zone to the surface water, is modeled as a fast runoff reservoir. As a first step the inflow is added to the reservoir levels:
The modified logistic curve $L(β, λ)$

$\frac{Q_t}{P(t)}$

$L(50, 0.3)$
$L(10, 0.3)$
$L(50, 0.8)$
$L(10, 0.8)$

Figure 6.3: Logistic curve with different $β$ and $λ$ values

\[ S_{f,A}^t = S_{f}^{t-1} + \int_{t-1}^{t} Q_{Su,A}^t dt \]

\[ S_{f,H}^t = S_{f,H}^{t-1} + \int_{t-1}^{t} (Q_{Su,I}^t + Q_{Su,N}^t) dt \]

Where $S_{f,A}$ [m] is the fast runoff reservoir in the alluvial and $S_{f,H}$ [m] is the fast runoff reservoir in the High Folded Zone. The outflow of the reservoirs is based on two parameters for each reservoir, the parameter $K_f$ and the parameter $α$:

\[ Q_{Sf}^t = \left( \frac{S_f^t}{S_f} \right)^α K_f \]

Where the parameter $K_f$ [−] represents the outflow as part of the fast reservoir storage and $α$ [−] the difference in flow between high storage levels and low storage levels. $S_f$ is only there to normalize the equation in order to get an easier calibration and does not have to be the exact mean. The $α$ is added because the fast runoff reservoirs do not act like groundwater flows, but more like channel flow. The bounds of $K_{f,A}$ and $K_{f,H}$ lay in the interval $[0.01, 0.1]$ based on observed river discharge and the bounds of $α_{f,H}$ and $α_{f,A}$ are $[1, 2.5]$ based on coefficients for open water flow. As for a part of the parameters of the unsaturated reservoir, the parameter pair $[α_{f,H}, α_{f,A}]$ is coupled, because the process behind these parameters is more or less the same and there is not enough information available to identify $α_{f,A}$ correctly. The $K_f$ parameters are kept separate because they are related to the slope and distance to nearest drainage, which is different in both cases. The only restriction for these values is that $K_{f,A}$ should always be lower then $K_{f,H}$, because the slopes are smaller and the distance rivers are larger in the alluvial zone.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Bounds</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Su_{max,I,N}$</td>
<td>Maximum storage of unsaturated reservoir in infiltrative and non-infiltrative zone</td>
<td>[m]</td>
<td>[0.08, 0.12]</td>
<td>Personal communication Al-Manmi (2013a)</td>
</tr>
<tr>
<td>$Su_{max,A}$</td>
<td>Maximum storage of unsaturated reservoir in alluvial zone</td>
<td>[m]</td>
<td>[0.05, 0.10]</td>
<td>Personal communication Al-Manmi (2013a)</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Threshold value for runoff generation from unsaturated reservoir</td>
<td>[-]</td>
<td>[0.8, 0.8]</td>
<td>Factor multiplied with $Su_{max,I,N}$ should be 0.08 on average</td>
</tr>
<tr>
<td>$\beta_I$</td>
<td>Shape factor for runoff generation from unsaturated reservoir infiltrative zone</td>
<td>[-]</td>
<td>[10, 40]</td>
<td>High variation of soil saturation over the catchment</td>
</tr>
<tr>
<td>$\beta_N$</td>
<td>Shape factor for runoff generation from unsaturated reservoir non-infiltrative zone</td>
<td>[-]</td>
<td>[10, 40]</td>
<td>High variation of soil saturation over the catchment</td>
</tr>
<tr>
<td>$\beta_A$</td>
<td>Shape factor for runoff generation from unsaturated reservoir alluvial zone</td>
<td>[-]</td>
<td>[2, 4]</td>
<td>Low infiltration capacity of the soils</td>
</tr>
<tr>
<td>$\epsilon_{I,N,A}$</td>
<td>Shape factor for evaporation from unsaturated reservoirs</td>
<td>[-]</td>
<td>[1, 3]</td>
<td>Lower evaporation and transpiration due to little vegetation</td>
</tr>
<tr>
<td>$\gamma_I$</td>
<td>Share of fast runoff in total runoff of infiltrative zone</td>
<td>[-]</td>
<td>[0.05, 0.15]</td>
<td>High infiltration but small losses due to interflow and high rainfall intensity</td>
</tr>
<tr>
<td>$\gamma_N$</td>
<td>Share of fast runoff in total runoff of non-infiltrative zone</td>
<td>[-]</td>
<td>[1, 1]</td>
<td>No infiltration due to impermeable rocks</td>
</tr>
<tr>
<td>$\gamma_A$</td>
<td>Share of fast runoff in total runoff of alluvial zone</td>
<td>[-]</td>
<td>[0.6, 0.8]</td>
<td>Low infiltration but depression storage Al-Manmi (2013a)</td>
</tr>
<tr>
<td>$K_{SH}$</td>
<td>Discharge factor of slow reservoir storage in the High zone</td>
<td>$[d^{-1}]$</td>
<td>[0.0015, 0.004]</td>
<td>Literature Ali and Stevanovic (2010); Ali et al. (2009b,a)</td>
</tr>
<tr>
<td>$K_{SA}$</td>
<td>Discharge factor of slow reservoir storage in the alluvial zone</td>
<td>$[d^{-1}]$</td>
<td>[0.0005, 0.004]</td>
<td>Similarity with groundwater in other zones</td>
</tr>
<tr>
<td>$K_{fH}$</td>
<td>Discharge factor of fast reservoir storage in the High zone</td>
<td>$[d^{-1}]$</td>
<td>[0.005, 0.015]</td>
<td>Estimation from hydrograph</td>
</tr>
<tr>
<td>$K_{fA}$</td>
<td>Discharge factor from fast reservoir storage in the alluvial zone</td>
<td>$[d^{-1}]$</td>
<td>[0.002, 0.01]</td>
<td>Estimation from hydrograph</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Flow from High to alluvial slow reservoir</td>
<td>[-]</td>
<td>[0.05, 0.2]</td>
<td>Link between reservoirs but mainly spring discharge in study area</td>
</tr>
<tr>
<td>$\alpha_{H,A}$</td>
<td>Exponent for fast reservoir discharge</td>
<td>[-]</td>
<td>[1, 2.5]</td>
<td>Based on physics of open water flow</td>
</tr>
<tr>
<td>$Div$</td>
<td>Division between infiltrative and non-infiltrative zone</td>
<td>[-]</td>
<td>[0.4, 0.6]</td>
<td>Geologic maps of Northern Iraq (Geosurv, 1997)</td>
</tr>
</tbody>
</table>
Groundwater reservoir

The groundwater flow from the slow runoff reservoir is described by a linear reservoir Fenicia et al. (2011). This means that the outflow of both slow reservoirs can be described using one parameter:

\[ Q_{Ss} = S_s K_s \]

The bounds of the parameter \( K_{s,H} \) are \([0.0015, 0.004]\) based on literature (Ali et al., 2009a,b; Ali and Stevanovic, 2010). The bounds of \( K_{s,A} \) are \([0.001, 0.006]\) chosen a bit wider, because most of the deeper limestone aquifers in the alluvial zone are similar to the high zone Jassim and Tibor (2006), but characteristics of other aquifers are unknown. To include the connection between these two aquifers, a part of the flow from the High slow reservoir is directly routed towards the alluvial slow reservoir. This results in the following flow towards the slow reservoirs:

\[
S_{s,H}^t = S_{s,H}^{t-1} + \int_{t-1}^{t} (Q_{Su,N} + Q_{Su,I}) \, dt
\]

\[
S_{s,A}^t = S_{s,A}^{t-1} + \int_{t-1}^{t} (Q_{Ss,H}\delta + Q_{Su,A}) \, dt
\]

With \( \delta \) as a dividing parameter of the flow from the slow high reservoir, to streamflow and the slow alluvial reservoir. The flow between the reservoirs is limited because of the irregular geology, therefore the bounds for \( \delta \) are \([0.05, 0.2]\).

Division of infiltrative/non-infiltrative zone

An important parameter in the rainfall runoff model is the division parameter \( Div \). This parameter represents the total share of the infiltrative zone compared to the non-infiltrative zone:

\[
Div = \frac{A_{\text{Infiltrative}}}{A_{\text{Non-Infiltrative}}}
\]

Ideally, this parameter is not needed because the share of the total infiltrative zone and non-infiltrative zone can be calculated beforehand, using geological maps. But because there are no detailed maps available for large areas of the three contributing countries, it is chosen to introduce this as a calibration parameter in the model. Beforehand an approximation is made based on the available geological maps, which resulted in a value of around 0.5. In the model the boundaries for this parameter are chosen \([0.4, 0.6]\).

Lag function

For the lag function the incomplete gamma function is used (Clark et al., 2008). The lag function for the hydrologic model is added because it takes some time for river water to end up at the measurement station. And because the calculations for the GRACE and streamflow data are not in the same location, it is not possible to calibrate on the lag function. Therefore it is chosen to calculate the lag function manually based on the travel time of water in the main rivers. Using the fact that almost all water in these rivers originate from the far upstream parts, mean travel time is calculated using the total river length and mean river velocity. The mean river velocity of 0.85 m/s is chosen based on Schulze and Hunger (2005). In table 6.2 an oversight of the river length and lag time is given.
Table 6.2: Approximate river length from upstream areas to Baghdad and total calculated lag (UN-ESCWA and BGR, 2013)

<table>
<thead>
<tr>
<th>River Name</th>
<th>Length [km]</th>
<th>Lag [days]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feesh Khabour</td>
<td>650</td>
<td>9</td>
</tr>
<tr>
<td>Greater Zab</td>
<td>800</td>
<td>11</td>
</tr>
<tr>
<td>Lesser Zab</td>
<td>550</td>
<td>7.5</td>
</tr>
<tr>
<td>Adhaim</td>
<td>300</td>
<td>4</td>
</tr>
<tr>
<td>Diyala</td>
<td>500</td>
<td>7</td>
</tr>
<tr>
<td>Desert area (Mosul)</td>
<td>450</td>
<td>6</td>
</tr>
<tr>
<td>Lesser Zab till Lake Dukan</td>
<td>120</td>
<td>1.5</td>
</tr>
</tbody>
</table>

6.4 Calibration method rainfall runoff model

The calibration of the rainfall runoff model is done using a combination of GRACE data given in section 4 and streamflow measurements into lake Dukan, which are given in paragraph 5.4. Because it is not possible to compare the two datasets directly, first a few modifications are made to the GRACE dataset allow a valid comparison:

Desert area outside catchment As can be seen from figure 6.5, a large part of the Iraqi desert is included in the calculation, which is not a part of the Tigris catchment. This desert area consists mainly of large uninhabited areas with almost no rainfall. Therefore it is assumed that the changes in deep groundwater levels are only small and do not contribute significantly to the total GRACE signal of the area. Also the large lakes and reservoirs in the area are already taken into account using the methods given in 4.4. This leaves only the soil moisture in the shallow ground layers, which are modeled by GLDAS (Rodell et al., 2004). Using this assumption, the total mass signal of this area is calculated, which is shown in figure 6.4. Then a new GRACE signal of the area without the desert signal is derived, by subtracting the total mass change of the desert area. See figure 6.4.

Urmia catchment Another part of the study area, which is not included in the upstream parts of the Tigris river, is the Urmia catchment, which drains into Lake Urmia. This area is also part of the Zagros mountain range and has the same climatic conditions as the upper parts of the Tigris catchment. The only differences are slightly less precipitation than the western side of the mountain range and less karstification. On the one hand this could indicate that the effect of dry periods will have less effect on the total water mass. But on the other hand there is more intensive agriculture and more water use for irrigation purposes. This means that water is used for agriculture, even if there is no rain. The enormous water loss of the lake Urmia during dry years is illustrative for the water depletion in those years. Taking into consideration these aspects and the fact that it was not possible to get additional information on this area, it is assumed that the GRACE signal for this area is the same as for the Tigris tributaries. This means that no additional changes are made to the found GRACE signal derived in the former calculation step.
Mass signal from soil moisture desert

Signal from groundwater with and without desert area

Figure 6.4: Soil moisture in desert area, the old GRACE signal and the new GRACE signal. The old GRACE signal is already corrected for lake mass.
Adding catchments together As a result of the two former steps, the study area is now reduced to a stretch of desert along the Tigris river and five Tigris tributaries, Adhaim, Diyala, Feesh Khabour, Greater Zab and Lesser Zab. To compare with the GRACE signal model runs are done for all six areas and added together to one signal. For every signal separate rainfall, evaporation and zonal areas are used. The GRACE signal and the results are evaluated, using the Nash-Sutcliffe efficiency (equation 6.5) for the period of 2002 till 2012.

Additionally to the GRACE signal from all six areas, also the modeled discharge from the area upstream from Dukan Dam is compared with measured data at the inflow of Dukan lake. For this purpose also the catchment, evaporation, rainfall and zonal areas upstream from the Dukan Dam are calculated. The simulated discharge is evaluated using the Nash-Sutcliffe efficiency for the high flow and the Log Nash-Sutcliffe efficiency for the low flows:

$$NS_Q = 1 - \frac{\sum_{t=1}^{T} (Q_t^o - Q_t^m)^2}{\sum_{t=1}^{T} (Q_t^o - Q_t^o)^2}$$  \hspace{1cm} (6.5)

$$LogNS_Q = 1 - \frac{\sum_{t=1}^{T} (\log(Q_t^o) - \log(Q_t^m))^2}{\sum_{t=1}^{T} (\log(Q_t^o) - \log(Q_o)^2)}$$  \hspace{1cm} (6.6)

Where $NS_Q$ is the Nash-Sutcliffe and $LogNS_Q$ the log Nash-Sutcliffe efficiency, $\overline{Q_o}$ the average measured value, $Q_t^o$ the measured value and $Q_t^m$ the modeled values at time step $t$. For the Dukan area both the Nash-Sutcliffe and Log Nash-Sutcliffe are used as objective functions. For the GRACE signal only the Nash-Sutcliffe is used:

$$NS_G = 1 - \frac{\sum_{t=1}^{T} (G_t^o - G_t^m)^2}{\sum_{t=1}^{T} (G_t^o - G_o)^2}$$  \hspace{1cm} (6.7)

Where $NS_G$ is the Nash-Sutcliffe, $\overline{G_o}$ the average measured value, $G_t^o$ the measured value and $G_t^m$ the modeled values at time step $t$.

6.5 Results

The optimal results for the rainfall runoff model of the Dukan catchment and are chosen based on a Monte Carlo simulation and the three objective functions, which are given at the end of section 6.4. First 60.000 random parameter sets are chosen within the bounds for each parameter given in table 6.1. These parameter are used as an input for the rainfall-runoff models of the Dukan catchment and the other tributaries in Northern Iraq (see fig 2.1 and 5.7). Then the total discharge of the Dukan catchment is compared to the measured discharge values and the total mass variation of Northern Iraq is compared with the resulting GRACE values for the same area. This means that the model is calibrated on two independent datasets, the river flow into Dukan lake and the observed mass from GRACE.

In figure 6.6 a scatter plot is given with the mean values of the Nash-Sutcliffe and Log Nash-Sutcliffe efficiency for the Dukan discharge curve at the x-axis, and the values of the Nash-Sutcliffe efficiency of the water mass variations on the y-axis. Higher values mean better performance, so
Figure 6.5: Separation of study area in Desert area, Urmia catchment and Tigris tributaries. The border of the study area is indicated by the dotted line, the Euphrates and Van catchments by the light blue area, and the Tigris catchment inside Turkey by the darker blue. Inside the study area the Tigris tributaries are indicated by green, the Desert part by yellow and the Urmia catchment by the dark blue. Large lakes and reservoirs are indicated by dots.
the best performing datasets are represented by the lower-left dots in the scatter plot. There is a trade off between better performance for the total water mass and the best discharge curve. This is because that a model is never totally correct and GRACE values are related to reservoir storages and discharges to water fluxes. Therefore, the model with the highest total value of the two objective functions is chosen as the best performing. In figure 6.7 the results for the water mass and in figure 6.10 the results of the discharge curve are given.

**Mass variations**

Figure 6.7 shows that the model is able to reproduce both the yearly variations and the long trend. Especially the long trend is clearly represented through variations in the total water storage in groundwater reservoirs, figure 6.8. In this figure the total signal is split into three main parts, where the groundwater storages are represented by the slow reservoir. While the slow reservoir is more or less stable till the first half of 2006, it shows a strong decline till the end of 2009, which corresponds with the observed GRACE signal.

As expected, the yearly variations of the model and the GRACE signal show comparable behavior, but the total variation in the model is smaller than in reality. Especially, the yearly lows are different from the modeled values, which can be related to errors in the model and human activities in the catchment. From the different storages can be seen that the yearly cycle is mainly related to the water storage in the unsaturated and fast reservoir. Where the unsaturated reservoir is a constant factor, because it represent the increased soil moisture in the top layers, and the fast reservoir shows more variation because it mainly represents fast runoff processes, with a much shorter time scale.

The fast storage shows a large similarity with the sharp peaks in the GRACE signal (compare
Deviation of model from GRACE signal on longer trend

A closer look on the curves of the GRACE signal and the modeled water mass of figure 6.7, suggest also a long term difference. Over the whole period, the model underestimates the GRACE signal in the first years and overestimates it in the last years. This means that the total trend from GRACE cannot totally be explained by natural variation and could be influenced by groundwater extraction in the area. In the left graph of figure 6.9 the yearly deviation of the GRACE signal from the modeled value is given, which could be caused by human influence on the total water balance. It is chosen to calculate the values for the hydrologic years of 2005 till 2011, where the hydrologic years start in October of the year before and ends in September. The years 2003 and 2012 were excluded because they are only partly included in the data and 2004 is assumed to be part of the spin-up period of the model.

It shows an ongoing decline in water mass in the whole area of about 10 mm per year. While this water decline was presumed in literature Voss et al. (2013), the numbers are about three to four times smaller and more constant over the whole period. It also is in agreement with the declining
Figure 6.8: Total modelled mass variations and contributions of groundwater, unsaturated and fast reservoirs.

Water levels and the drying out of some springs in Northern Iraq, which cannot be caused by a drought period Al-Manmi (2013a).

**Discharge curves**

In figure 6.10 the modeled and measured discharges are presented, together with the used TRMM rainfall curve for the upstream catchment of Dukan lake. To get a closer look, the same is done for a period of two years in figure 6.11. The discharge curve shows that there is a large difference in accuracy between the high flows and low flows. The low flows in the dry period fit almost perfectly with the measured ones, which suggests that the storage and flows of the deeper groundwater are correctly modeled for the Dukan catchments. This also indicates that the depletion of the deep groundwater reservoirs are correctly modeled, which was the main goal of the rainfall runoff model.

Contrary to the low flows, large flows can differ largely from the measured ones. A simple explanation of this model behavior is that the calculated rainfall from TRMM measurements does not always coincide with the real rain events. And for some rain events this is indeed likely, with the large rain event at the end of 2006 as a good example. Further, it is likely that the spreading of rain over the catchment due to coarse TRMM data and the lumped model approach, causes a difference in the discharge curves. But although some individual rainfall events can differ, the overall rain patterns and rainfall amounts are comparable with the real ones and are a good base for hydrologic processes on longer timescales.

**6.6 Discussion**

To give more insight in the model errors when compared to GRACE, the error distribution of the signal is given in figure 6.12. This graph shows that the signal does not suffer from random
errors only, but that also systematic errors are involved. This could mean that there are important processes in reality, which are not included in the model. The curve is also not symmetrical, which means that the GRACE signal is more often lower than the modeled signal than vice versa.

**Random errors**

There are many random errors that disturb the modeled signal. The most important ones are given below:

**TRMM_rainfall** As shown in paragraph 5.2, it is possible that the TRMM data contributed to the random error in the model, because the total monthly rainfall can deviate more than 100 mm at particular rainfall stations. Possibly, this is caused by differences between point measurements at rainfall stations and measurement over larger areas using satellites, but the error can be about 25% of the total monthly rainfall. This means that monthly errors can occur of up to 25 mm for the wet season, where monthly rainfall is about 100 mm.

**GRACE signal** A large and more or less random error is the noise in the GRACE signal. This is also the reason that in many GRACE studies sophisticated methods are used to remove this noise. Examples are Gaussian smoothing or Empirical Orthogonal Filtering (EOF) (Swenson and Wahr, 2006; Schrama et al., 2007). However, in this study such methods are left out because also a part of the mass signal can be lost by removing noise. Therefore, some noise remains in the signal, but the signal for the longer trend is more trustworthy. The average errors using this method lie between 8 and 20 mm Schrama et al. (2007), but are possible reduced due to integrating the signal over larger areas.

**GRACE step size** Due to the monthly repeat cycle of the GRACE satellites, random errors are introduced in the dataset. Which is because the mass variation in the model is daily and the GRACE signal is interpolated between monthly measurements. Estimates of this error cannot be made from the GRACE dataset, but the daily deviation from the monthly mean of the modeled dataset can be used as an estimate. Using this assumption, the average error due to step size differences is estimated to be about 4 mm.

**Lake volume** The random errors in the lake levels and lake areas also causes an error in the derived GRACE groundwater signal. An oversight of the derived errors is given in table 4.1.
Figure 6.10: Measured and modeled data for Dukan dam together with average rainfall rates in Dukan catchment
Figure 6.11: Discharges and rainfall for 2006 till 2008
The maximum random error in the derived GRACE signal for groundwater is about 10 mm.

**Geologic classification** Due to wrong geological classification also random errors are introduced, because rainfall or evaporation rates are wrongly assigned to different areas. However, the random error due to this classification is believed to be small, because the geologic classification is much more detailed than the rainfall datasets. This means that most errors due to wrong allocation of rain and evaporation values, are caused by the implementation of the rainfall and evaporation data and not by wrong classification.

**Systematic errors**

A significant part of the model errors are made by systematic errors. These systematic errors can be part of the input data of the model, but can also be caused by processes that are not included in the model. A good example of this error is the assumption that the catchment behaves as a pristine natural area, while in reality there are human influences. Figure 6.12 shows that there is not a clear mean of the probability curve, but the highest probabilities are spread over the interval [-0.05,0.05] meter. The main driving factors behind the systematic error are given below:

**Groundwater extraction** The presence of a large number of wells in the study area could cause a decline in groundwater levels. Although most of the extracted groundwater is replenished during wet periods, there is also a clear negative trend in the last years, which could be explained by overpumping of the aquifers (figure 6.9). The total negative trend during the period 2005-2011 is about 0.04 meter, which is a cause of equal probabilities over the interval [-0.05,0.05]. This process could also explain the lower values from GRACE in the dry season, which are probably caused by ongoing groundwater extraction.

**Agriculture and irrigation** An important water flux in Northern Iraq is the transpiration of water from (irrigated) agriculture. The yearly water cycle for agricultural areas and especially
irrigated agriculture, is different from that of a natural environment in Northern Iraq. Firstly, farmers prepare their land in such a way that it absorbs more water than the areas which are not cultivated. Then, this water is mainly transpired by the crops during the growing season. This means that the GRACE signal is higher at the start of the growing season and declines faster and longer at the end of the growing season. For irrigated agriculture this behavior is even stronger, but the difference is that most irrigation water is stored in reservoirs, which are corrected for by the model. The main difference is that the water stays in the area after it is withdrawn from the lakes, because irrigation water does not directly leave the area, as assumed in section 4. Instead of directing the water directly out of the catchment, which is generally true for hydropower generation, the water is first used as irrigation water and leaves the area later as transpired crop water. The effect of irrigation is very difficult to quantify, but does contribute to higher and later peaks in the derived GRACE signal for groundwater.

Reservoir storage Beside the random errors from reservoir storages, there is also a small systematic error, because small lakes are not included in the correction for surface water. Because these reservoirs do not have large storage capacities, they are practically filled and emptied every year. Therefore, these lakes contribute mainly to the yearly signal and is not relevant for the longer trend. The total storage variation is approximately 10% of the total yearly storage variation of 50 mm, based on satellite images. This means that the yearly variation of the groundwater signal from GRACE is overestimated by about 5 mm.

Sensitivity of model parameters

One of the tools to see whether the model represents reality, is by analyzing the sensitivity of the model on the used parameters. In figure 6.13 the model performance of the hundred best parameter sets is given. In the following a short analysis of the observed variations is given, based on different components in the model.

Unsaturated reservoirs_infiltrative/non-infiltrative zone The parameter with the highest influence on the final result is $S_{u\text{max},I,N}$, the maximum water storage in the unsaturated reservoirs of the infiltrative and non-infiltrative areas. It is likely that this influence is mainly linked with the maximization of the yearly water mass variation in the model, to fit the GRACE curve. Possibly, the maximum capacity of the soil is indeed larger, but to be sure that the model reflects reality the maximum bounds are fixed. Different values for the shape factors $\beta_I$ and $\beta_N$ of the logistic curves do not have a large influence, but give better results for higher values. Which is in correspondence to the large spread in soil saturation over the catchment. Further, the shape factors show similar behavior, which indicate comparable soil characteristics. The division between runoff and infiltration $\gamma_I$ and the division between the infiltrative and non-infiltrative zone show a tendency to higher runoff and lower infiltration values. But the total variation between the bounds is relatively small and no reason to change the boundary values.

Unsaturated reservoir alluvial zone The alluvial variables $S_{u\text{max},A}, \beta_A$ and $\gamma_A$ do not show large variations or influence, which can be caused by the model setup. Because the alluvial zone in the Dukan catchment is relatively small, it has only minor influence on the discharge at Dukan lake. Rainfall in the alluvial zone is also smaller than in the other areas and most rainfall in the area is quickly discharged through surface runoff. This also means that the unsaturated reservoir in the area does not reach its maximum in most circumstances, which reduces the influence of this parameter on the final mass variations.
Evaporation The resulting low values of the evaporation/transpiration parameter $\epsilon_{I,N,A}$ show indeed that soil water evaporation plays an important role in our study area. In contrast with transpiration by vegetation, which generates transpiration rates comparable to potential evaporation and high $\epsilon$ values. This means that the total evaporation/transpiration is strongly dependent on the amount of soil moisture in the unsaturated reservoir.

Slow runoff reservoirs The optimal parameter value for the discharge of the High zone $K_{s,H}$ has indeed a maximum around the given literature values, which gives confidence in the model results for this groundwater reservoir. The parameter for the slow reservoir $K_{s,A}$ performs better for lower values, which indicates lower discharge and longer retention times of the water. Possible explanations for these lower values are aquifers with lower hydraulic conductivities, longer distances from the infiltration zones, smaller slopes and less connections of the aquifer to the surface. Therefore, it is likely that this tendency for lower values is based on reality.

Fast runoff reservoirs As shown in the hydrographs in figures 6.11 and 6.10, it is difficult to model the discharge of the catchment using the given rainfall datasets. This mainly means that the optimal values found in the model are adequate approximates of the real values, but it is not well possible to determine this from the optimal parameter values. Therefore, it is advisable to improve the rainfall datasets and include the spreading of rainfall over the catchment, to improve the modeling of peak flows and find the optimal parameter values.
Figure 6.13: Parameter performance plots for the hundred best performing model runs. On the y-axis the mean of the two objective functions given in figure 6.6. On the x-axis the parameter values.
Chapter 7

Conclusions

The main goal of this research was to address and explain the water mass variation in the area. Therefore, the total mass variation from GRACE was calculated over an extended surface area to ensure minimal mass leakage. Thereafter, important contributions to the water mass variations where identified and quantified, of which the total mass variation of groundwater could be calculated. Finally, the variation in groundwater mass was compared with a rainfall runoff model of the total area, to see whether the mass decline between 2005 and 2011 could be explained by natural variation. The main conclusions of this research are separated in two groups; the more general conclusions about the used methodology and the specific conclusions about the hydrology of the study area.

Hydrology of Northern Iraq

This study has given several valuable insights in the water balance and water fluxes in the Tigris tributaries of Northern Iraq:

**Lake water mass** Reservoir storages in the area are an important water source during dry periods and play an important role in the yearly variations and longer trends of the total water balance. The total contribution in the yearly cycle is 40 to 50 mm for the study area, about one third of the total yearly variation. Influence on the longer trend is even more important with a decline of about 80 mm over the whole period, which is at least half of the total decline in water mass.

**Snow and ice water mass** Although in many areas around the world the total water mass is declining due to change total ice and snow masses, the effect in the studied area are small because of high summer temperatures and absence of ice masses. There is abundant snowfall in winter, but almost all snow melts away during the summer, which means that it only has an effect on the yearly cycle. Yearly snow mass variations are 20 mm on average, but can vary from year to year.

**Deep groundwater** Due to highly infiltrative and karstified areas, the water levels of the aquifers in Northern Iraq are very responsive to changes in rainfall regimes. Therefore, the groundwater levels in the area strongly declined in the drought period of 2006-2009. Almost 60 mm of water storage left the area through natural discharge of the karstic aquifers, which accounts for about 60 % percent of the total groundwater decline.

**Unsaturated and fast reservoir storage** The largest contribution to the yearly water mass variations are related to storage of water in the unsaturated reservoir, streams and depressions
in the area. This storage generally contributes about 100 mm to the yearly variations, but can be higher during and shortly after large rainfall events.

**Groundwater decline due to pumping** Several sources in the area indicate that groundwater pumping in the study area intensified during the last years. It is likely that the total pumping rates exceed recharge rates over large areas, as groundwater tables are declining. During this study also a negative residual term was found of about 10 mm per year. But because of the possible errors in other water masses, it is not certain whether this decline represents the over pumping of local aquifers or errors in model calculations.

**Conclusions about the used methodology**

In this study several approaches were combined to address and quantify the total mass variations in the study area. Here a few conclusions are made about the used methods.

**GRACE mass calculations** To obtain trustworthy results for total mass calculations from GRACE, it is very important to choose a study area that minimizes the leakage of mass. The used approach in this study, by expanding the area and correcting for this expansion later on, is a good example for that and works seemingly well. But it is inevitable that there is mass leakage at the borders, which was in this study mainly related to the mass influence of several large lakes.

**Mass variations from lakes** The used method to calculate lake mass changes worked well in the study area where large lake level and lake area variations are common. The used methods were not applicable for some lakes due to small lake level variations, steep terrain, branched shapes and ice cover.

**Satellite data as forcing for hydrologic models** During this study it was possible to describe the hydrological behavior of the catchment using satellite data as forcing data, but calibration is still needed. This means that satellite data is valuable in hydrologic modeling of large catchments, although additional climate and geologic data remains crucial.

**GRACE and hydrologic model behavior** Based on the final results of this research there is a close relationship between the observed GRACE signal and the modeled hydrology of the catchment. This could give more confidence in both the usefulness of GRACE in hydrologic modeling and the realism of the applied hydrologic model.
Chapter 8

Recommendations

Most of the approaches used in this study can possibly be improved to reduce errors and gain accuracy in the results. Of course, a very detailed study of the area with lots of data acquisition will give the best result, but in this recommendations the main focus is on how to improve results with less effort:

**GRACE mass calculations** As mentioned earlier, it is only possible to calculate the GRACE signal for large areas. and because the minimum size to get a more or less independent signal is about 3 by 3 degrees, it is not possible to calculate for independent parts of the study area. A possible way to improve GRACE results is to use a basin function for the exact shape of the study area. This basin can then be used instead of the six mascons in the current approach, but it is not likely that it would significantly improve the results.

**Lake mass variations** To improve the accuracy of the lake mass variations, more accurate lake area calculations are useful. The best method to gain accuracy is to use satellite datasets with lower resolutions, of which the ASTER and LANDSAT satellites are a good example. Another method is to calibrate the used filtering values separately for every lake. This could improve the lake area calculations because there are large differences in lake characteristics, like lake depth, temperature and salt content, which could influence the lake area calculation.

**Model forcing data** The largest errors in the model are caused by the model forcing data. Therefore, it is very likely that higher quality of the rainfall and evaporation datasets will improve model performance. By combining several different rainfall datasets, instead of using just one, it is likely that rainfall data will improve. Also, additional rainfall data of gauging stations in the study area can improve the dataset, because in the used model only rainfall stations in the South East part of the catchment are used. Further, a more accurate method for calculation of evaporation should be used, because evaporation plays a key role in the water mass variations in the catchment. During this study it was tried to come up with a calculation method using NDVI and soil moisture rates, but because of little vegetation and many uncertainties in soil moisture this method was inaccurate. Therefore, it is advised to use a calculation method which uses the energy balance at the ground surface instead. In this way the accuracy of the catchment evaporation and transpiration can be improved and the number model parameters decreased.

**Geologic classification** A more extensive study on geologic classification of the catchment areas is an important step in further research. This will not only give the ability to implement characteristics of the different catchments in the model, but also give more insight in the hydrology of the area. Acquisition of Iranian and Turkish geologic maps will be the first step.
to take. Further research on the geology in Iran and close to the Iranian border will fill an important gap in the geologic description and classification.

**Model layout** Still many improvements are possible for the used model in this study. But adding more calibration parameters should be avoided, because overparametrization is a real threat. As mentioned in the discussions, the spreading of rainfall over the catchment is an important source of errors in this model. Therefore, it is advised to use a more distributed model approach for the unsaturated reservoir, to utilize the distribution of the rainfall dataset. This will prevent spreading of local rainfall events over large areas, but can be done without adding model parameters. However, if someone wants to stay with the lumped model approach, an additional parameter could be introduced to influence the runoff generation based on rainfall differences inside the catchment. This rainfall variance parameter can be calculated from the datasets, so there will be no extra calibration parameters needed. Additionally, if it is chosen to expand the current model, inclusion of snowfall and snow melt is a promising step.

**Calibration data** Because the Dukan catchment included only a small part of the alluvial zone, the inclusion of calibration data for the alluvial parts of the catchment is preferable. The most straightforward method to do this is to include streamflow data of gauging stations downstream of alluvial areas.
Chapter 9

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Appendixes
Appendix A

Resulting graphs lakes and reservoirs
Figure A.1: Stage area curves and change in volume of lakes in desert area
Figure A.2: Stage area curves and change in volume of lakes in Northern Iraq
Figure A.3: Stage area curves and change in volume of lake Van and Urmia
Figure A.4: Stage area curves and change in volume of lakes in the upstream part of the Euphrates catchment
Appendix B

Daily and yearly TRMM calibrations
Figure A.1: Comparison between daily rainfall from GLDAS and gauging stations
Figure A.2: Comparison between daily rainfall from TRMM and gauging stations
Figure A.3: Comparison between Yearly rainfall from GLDAS and gauging stations
Figure A.4: Comparison between Yearly rainfall from GLDAS and gauging stations