DEVELOPING A RECHARGE MODEL OF THE NILE BASIN TO HELP INTREPRET GRACE DATA

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ABSTRACT

The Gravity Recovery and Climate Experiment (GRACE) data provide a new opportunity to gain a direct and independent measure of water mass variation on a regional scale. Processing GRACE data for the Nile Basin through a series of spectral filters indicates a seasonal spatial variation to gravity mass (±0.005 mGal). To understand how this gravity mass variation relates to the different components of the hydrosphere within the Nile Basin, and particularly what proportion, if any, relates to groundwater recharge, a recharge model was developed for the Nile catchment using the ZOODRM model and remotely sensed data. Results indicate: a significant proportion of the annual water mass variation indicated by GRACE in the Nile Basin (~$5.0\text{x}10^{11}$ m^3/yr) is related to seasonal groundwater mass change (~$1.2\text{x}10^{11}$ m^3/yr); annual water mass variation in the Nile Basin as indicated by GRACE is an order of magnitude less than observed rainfall input minus river outflow; evaporative losses of surface water are significant within the Nile Basin; and relatively little water is lost by outflow from the Nile delta. The results of this study show the value of using groundwater models to interpret subtle variations in GRACE data, to gain an insight into the partitioning of water cycle within river basins, and also the ability to develop a plausible recharge model using remotely sensed data.

1. BACKGROUND

GRACE data have been used successfully to assist basinal-scale water balance calculations (e.g. Syed et al. 2005; Rodell et al. 2004), and to estimate change in groundwater mass where large mass storage changes are occurring (e.g. Rodell et al. 2009). However, there have been fewer attempts to try to interpret how smaller, seasonal, GRACE gravity mass variations relate to the different components of the water cycle in a river basin. Of prime interest in this study, was to determine what proportion of the seasonal GRACE gravity mass variation in the Nile Basin, if any, related to groundwater recharge (mass storage), as well as what proportion of the total water mass is recycled within the catchment and how much water mass is lost seasonally (evaporation and runoff).

To gain an understanding of these more subtle seasonal variations in water mass indicated by GRACE data requires the use of hydrological models which are able to simulate the partitioning of effective precipitation between surface and groundwater masses on a basin-scale. Combining GRACE data with groundwater modelling to estimate seasonal water mass changes in the water cycle will enable more robust water resource assessments, particularly in large transboundary basins such as the Nile, where distribution of water resources is highly contentious (Brunner et al. 2007; Karyabwite 2000; Nicol 2003).

2. THE NILE BASIN

2.1 The Nile Basin catchment

Approximately 3 million km^2 in extent, the Nile River Basin drains approximately 10% of Africa and includes over 10 countries (Sutcliffe and Park 1999; Nicol 2003). As a result of the length and size of the basin, the upper and lower catchments of the basin are characterised by very different climates and hydrological regimes. The upper catchment has a humid, equatorial tropical climate, and it is here, as well over the Ethiopian and Sudanese Highlands, where the majority of water in the Nile is sourced (Sutcliffe and Park 1999). To the north, away from the equator, the lower catchment is largely arid or semi-arid, with very low effective precipitation (Karyabwite 2000). As a result the Nile River is an important source of water for up to 2.5 million people within Egypt and Sudan and sustainable water resource management is vital in this large transboundary basin (Conway 2005; Karyabwite 2000). Lack of data, or difficulty in obtaining data, however, makes such management difficult (Brunner et al. 2007). The ability to use remotely sensed data to develop accurate, independent hydrological models that can quantify seasonal distributions of water mass in a basin, has therefore high impact potential to water resource management in the Nile (Abdalla 2009; Mileham et al. 2008).

2.2 Hydrology of the Nile Basin

The hydrology of the Nile Basin is complex. The hydrology of any particular reach is directly influenced by the landuse adjacent to the Nile (e.g. irrigation abstraction) and the hydrological regime of major tributaries (Sutcliffe and Park 1999).

The Nile River extends from the head waters of Lake Victoria and Lake Albert in Uganda and the Democratic Republic of the Congo, to the Mediterranean Sea – Fig 1. The basin is divided into a number of sub-catchments: the Victoria Nile, Sudd, White Nile, Sobat, Blue Nile and the Main Nile – Fig. 1. The contribution of each of these sub-catchments to the Main Nile flow is markedly different. Whilst the Victoria Nile and White Nile, provide a constant annual baseflow to the Main Nile of approximately 6x10^{10} m^3/yr, as much as 70% of the annual discharge of the Main Nile is sourced seasonally from the Blue Nile, Sobat and Atbara tributaries which originate in the Ethiopian Highlands (Sutcliffe and Park 1999). These tributaries respond relatively rapidly to the wet season rainfall in the Ethiopian Highlands and provide a seasonal pulse of water to the Main Nile River in the lower catchment. This seasonal response is not observed within the White Nile, due to as much as half of the inflow from the Victoria Nile and Bahr el Ghazel sub-catchments, being lost to evaporation within the Sudd wetland (Sutcliffe and Park 1999) – Fig. 1.

Evaporative losses from the Nile river surface itself are also significant to the hydrology of the Nile. Within Sudan and Egypt, where published open water evaporative losses in the lower Nile catchment vary from 1700-2400 mm/yr, discharge of the Nile River decreases downstream by up to 1.0x10^{10} m^3/yr as a result of evaporation (Mohamed et al. 2004; Sutcliffe 2005; Vallet-Coulomb et al. 2001; Sutcliffe and Park 1999) – Fig. 1. Indeed, as a result of evaporative losses throughout the Nile catchment, discharge of the Main Nile River to the Mediterranean is comparatively small (~4x10^{10} m^3/yr) relative to the size of the river catchment.

Little is known to the quantity of groundwater, or modern recharge rates, on a catchment scale within the Nile Basin. Regional studies indicate the importance of the Nile River as a recharge source within 20 km from the river, and that some shallow groundwater is lost through evaporation (up 0.1mm/yr evaporative loss from groundwater <10m below ground surface) (Farah et al. 1999; Abdalla 2009).

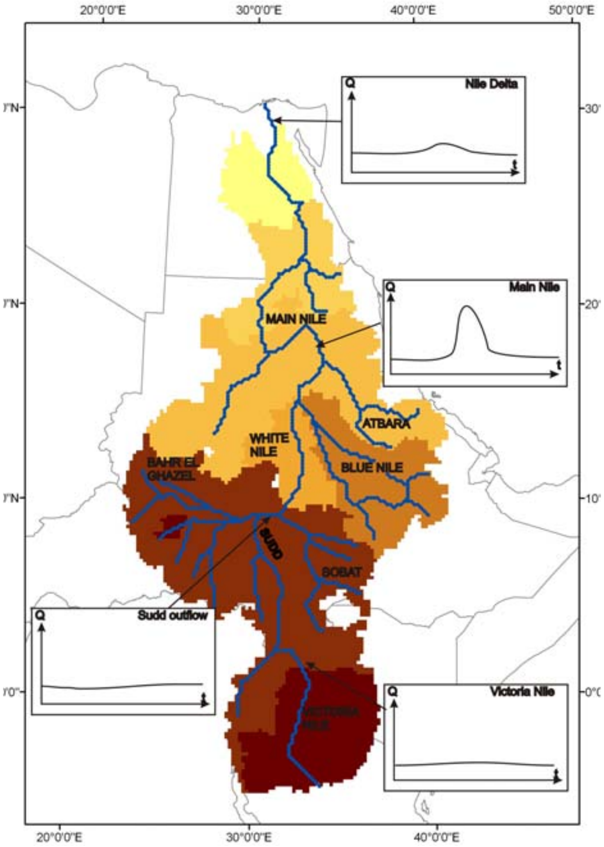

Figure 1 –Major sub-catchments of the Nile Basin: Victoria Nile, Sudd wetland, White Nile, Sobat, Blue Nile, Atbara and the Main Nile. Annual hydrographs indicate the seasonal pulse of discharge in the Main Nile river, downstream of the Sobat, Blue Nile and Atbara tributaries. In contrast outflow from the Sudd provides a constant annual baseflow to the Nile.

3. NILE GRACE DATA

The satellite mission Gravity Recovery and Climate Experiment (GRACE) has provided independent monthly models of the Earth's gravity field since 2002 (Tapley et al. 2004). GRACE lacks spatial resolution better than a few hundred kilometres but, when averaged over regions of this size, it detects consistent mass changes equivalent to the effect of a few millimetres of water. Gravity changes due to short period geological events, like volcanic eruptions or earthquakes, are detectable in extreme cases but produce a step-like change preceded and followed by a slow build-up or recovery (Han et al. 2006). Processes in the hydrosphere, atmosphere and cryosphere are believed to be the only ones capable of generating the mass changes with the seasonal timescale observed in the variability of the gravity field. Month to month changes seen in the gravity field over a low latitude continental region correspond to changes in all sources of sub-satellite water, integrated over the whole vertical column including aquifers, flooding and surface water, rainfall and other moisture in the atmosphere. For this study of the hydrology of the Nile Basin, GRACE gravity data have been synthesised from the CNES model, although we have made comparisons with other models generated by groups in the Texas Centre for Space Research, the Geoforschungszentrum in Potsdam and the Jet Propulsion Laboratory in Pasadena (Lemoine et al. 2007). Intercomparison of models produced by laboratories using different processing techniques compared with their average shows residuals with standard deviations equivalent to 3-6 mm of water (Bedada 2007). Note that to predict monthly water mass changes from the GRACE gravity models, time changes of gravity must be identified within GRACE data from an arbitrary datum. This datum is defined by the particular month chosen as reference. In this study March 2004 – the driest hydrological month of the modelled period – was used as the reference month.

4. COMPARISON OF GRACE DATA WITH OBSERVED DATA

GRACE data is a measure of monthly water mass change and, as such, the data responds to the component of the hydrosphere in which the largest mass change is observed within any given month. Comparison of the amplitude of change in the GRACE data to observed hydrological data can therefore help to delineate which component of the water cycle GRACE is measuring.

Within the Nile Basin GRACE data indicate an annual water mass change of approximately ~5.0×10^{11} m^3. Total annual rainfall minus river outflow from the basin is on average ~2.0×10^{12} m^3/yr. There is therefore a large difference between the annual water mass variation indicated by GRACE and the annual rainfall minus river outflow from the Nile – Fig 2. This mass difference can be explained by either a large amount of moisture recycling within the Nile Basin, or by a continual atmospheric input and output of water within the basin during the wet season. More likely, both will contribute to the mass difference between annual mass variation and net annual water input. If there is little atmospheric throughput of water within the Nile Basin, then the data indicates moisture recycling to be highly significant within the Nile Basin. To gain a better understanding of the functioning of the Nile Basin however, demands the use of hydrological modelling and better observed atmospheric data.

Observed atmospheric data (NCEP/NCAR R-2 source) indicate seasonal change within the atmospheric water mass. However, the high level of uncertainty within the data means a meaningful comparison with GRACE data is not possible.

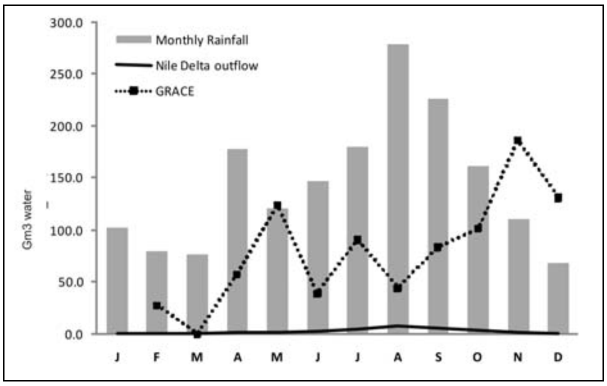

Figure 2 – Comparison of 2004 monthly rainfall, river outflow to Mediterranean Sea, and GRACE data (presented as water volume relative to March 2004)

5. ZOODRM GROUNDWATER RECHARGE MODEL

5.1 The ZOODRM model

The ZOODRM model is a distributed recharge model code for calculating spatial and temporal variations in groundwater recharge, and has been applied successfully in semi-arid areas (e.g. Palestine and Inner Mongolia) and in wet temperate areas (e.g. Europe) (Hughes et al. 2008). ZOODRM calculates recharge at distributed node objects by applying the soil moisture deficit recharge method over daily time steps (Penman 1948; Grindley 1967). Separate objects are used to represent different entities such as soil, rivers and springs. These nodes are, in turn, held in a two layer grid structure comprised of an unsaturated and saturated grid. The ZOODRM model is therefore able to represent the numerous flow processes controlling the partitioning of surface water and groundwater, as well as the delay time required for water in the unsaturated zone to reach the water table (Hughes et al. 2008). ZOODRM is also able to simulate evaporative losses from open water surfaces, such as the Sudd wetland, which are known to be important to the hydrology of the Nile Basin (Sutcliffe and Park 1999). ZOODRM outputs monthly estimates of rainfall, evapotranspiration (ET), change in soil moisture deficit, groundwater recharge, surface runoff and river discharge.

The ZOODRM model is a suitable model for this study due to its lower data demands relative to other hydrological models; the ability of the model to use largely remotely sensed data; and the added functionality of routing of runoff water according to topography. The data needs of the model are: daily rainfall and potential evapotranspiration (PET), land use, aspect, geological and digital elevation data. Due to the size of the Nile Basin and difficulties in obtaining gauged river flow data from individual countries, largely remotely sensed input data were used for the modelling work. Daily rainfall (NOAA data) and PET were sourced from the FEWS NET African

Dissemination Service for 2003-2005. Geological data were sourced from the Digital Geological Map of the World, land-use data from the USGS and elevation data from the Shuttle Mission (STRM).

A 20x20 km cell size was adopted for the model grid as a compromise between model accuracy and model run time. This model resolution, although coarse, is greater than that achieved by previous basin-scale modelling work in the Nile (e.g. Mohamed et al. 2005, whose modelling work was of 50x50 km resolution), and by other hydrological models used with GRACE data (e.g. Fukuda et al. 2009). All input data were gridded to be of the same 20 km^2 resolution and projected to a UTM zone 36 projection to ensure no error was introduced into the ZOODRM model when input data files were read. The projection of input data was required to ensure minimal scalar, or areal distortion of the data within the modelled area. This preservation of area within the model was important to model accuracy, as the ZOODRM model integrates water fluxes over area. Due to the size of the Nile Basin the curvature of the Earth would induce significant error to the area of the basin presented within conformal or equidistant projections.

Surface routing of runoff water is calculated according to a slope aspect map generated from digital elevation model data (DEM). The aspect direction at any node determines the direction of movement of surface runoff water, which is generated as a proportion of the effective precipitation plus any water received from an adjacent node. Although this surface water routing calculation is simple it is adequate for a time step of one day, and the tributary catchment areas simulated by the model according to the aspect map were realistic (Hughes et al. 2008). Calculation of recharge according to the Soil Moisture Deficit (SMD) method (see Penman and Grindley 1967), used root constant and wilting point values for the different vegetation types within the Nile Basin, according to published values for vegetation types (see FAO; Lerner et al. 1990).

Other modelling factors were kept as simple as possible in this preliminary stage of model development. Irrigation losses were set to zero to ensure that it was only the partitioning of surface water to run-off and recharge which determined the modelled river discharge and groundwater water mass. Open water evaporation rates from the Sudd wetland, and the Nile river surface were modelled as 3-7 mm/day according to published values (e.g. Sutcliffe 2004; Mohamed et al. 2004).

5.2 Model calibration

The ZOODRM model was run for three full hydrological years from 2003 to 2005, and calibrated to observed annual discharge (1976-79) at 10 gauging stations along the Main Nile and tributaries. The recharge model simulates observed annual discharge of the Nile River to within 40%, using realistic values of run-off (modelled to vary seasonally from 0.1-0.27) and overland losses (2% of run-off) – Table 1. These modelled values of run-off are comparable to other published estimates (e.g. Mohamed et al. 2005). It was deemed valid to include overland losses (simulated by the RunOn parameter within the recharge model) due to the semi-arid nature of the lower catchment and overland losses have proved to be important to previous ZOODRM models within semi-arid areas (e.g. Hughes et al. 2008).

Greatest error between observed and modeled river discharge occurs in the simulation of river flow within the Sudd wetland, at Bahr el Jebel, in the upper catchment (modelled river flow is 43% greater than observed). Elsewhere, the model simulates observed annual discharge to within 20%, and models observed evaporative losses from the river surface satisfactorily. Furthermore, a good water balance is simulated within the model throughout each hydrological year. Better calibration would however be facilitated by access to modern discharge data.

Annual discharge (Gm^3/yr)	Aswan	Dongola	Bahr el Jebel	Lake Victoria
Observed	58.4	69.0	48.3	38.5
Modelled	60.1	80.6	69.1	42.6

Table 1 – calibration results of the ZOODRM model.

5.3 Modelling results

Annual rainfall within the Nile Basin is observed to be ~2.0×10^{12} m^3/yr. Interpretation of how much of this seasonal rainfall becomes retained, recycled, or lost from the Nile Basin water cycle, requires the use of hydrological modeling. The ZOODRM modeling work simulated the partitioning of the observed rainfall mass between other components of the water cycle in the river basin, and calculated the daily quantities of ET, groundwater recharge, runoff and river outflow within the Nile throughout each hydrological year from 2003-2005.

Monthly volumetric estimates of ET, groundwater recharge, run-off and river outflow in the Nile as calculated by ZOODRM are displayed in Fig 3. The results indicate: water mass loss from the Nile Basin by river outflow (~6.0×10^{10}m^3/yr) is small in comparison to evaporative losses (~1.0×10^{12} m^3/yr); and a significant proportion of run-off and river flow is lost to evaporation (up to 3.8×10^{11} m^3/yr).

Groundwater recharge is modelled to be greatest within 20 km of the Nile River, and within the Ethiopian and Sudanese Highlands – Fig 4. The total annual groundwater recharge simulated by ZOODRM is

2.4×10^{11} m^3/yr (or 0-400mm/yr) – a figure greater than river outflow from the Nile Basin. This estimate is comparable and of a higher resolution (20x20km) to other large-scale recharge estimates in Africa by Döll and Fiedler (2008) who calculate 0-200 mm/yr of recharge in the Nile Basin on a 50x50km resolution. The recharge estimate is also comparable to estimates (0-200 mm/yr recharge) from regional studies in the Nile which use isotope and chloride concentrations as indicators of groundwater recharge and discharge (e.g. Taylor and Howard 1996).

Assuming that recharge equals discharge over the hydrological year, and that discharge is constant year-round, the seasonal mass change in the Nile Basin due to recharge is estimated by this work to be ~1.2×10^{11} m^3/yr, half the total recharge estimated (Farah et al 1999).

6 INTREPRETATION OF RESULTS

GRACE data indicate a seasonal water mass change of approximately ~5×10^{11} m^3/yr within the Nile Basin. Total observed rainfall minus river outflow from the Nile Basin is, however, on average ~2.0×10^{12} m^3. The annual mass change as indicated by GRACE is therefore an order of magnitude smaller than the rainfall input into the catchment minus river outflow. This large difference between annual water mass variation and the net annual water mass input into the Nile catchment indicates either a large amount of moisture recycling within the Nile Basin, or a continual atmospheric input and output of water during the wet season. If rainfall was simply retained within the basin as groundwater recharge, soil moisture, or in vegetation, such a large difference between annual mass variation and the net annual water input into the basin would not be observed. Previous work in Nile Basin by Mohamed et al. 2005 estimated 11% recycling of the water mass within the Nile Basin. If there is no significant atmospheric throughput of water during the wet season, results of this work, would however, indicate much greater moisture recycling in the Nile Basin, as inferred by Fontaine et al. 2002, within West African river basins.

Aside from moisture feedbacks, the modelling work of this study has indicated that storage of water in soil moisture, shallow groundwater, and vegetation, is significant to the seasonal variation of water mass within the Nile Basin – Fig 4. Up to ~1.2×10^{11} m^3/yr of the ~5×10^{11} m^3 seasonal mass change indicated by GRACE data is calculated to relate to seasonal groundwater recharge.

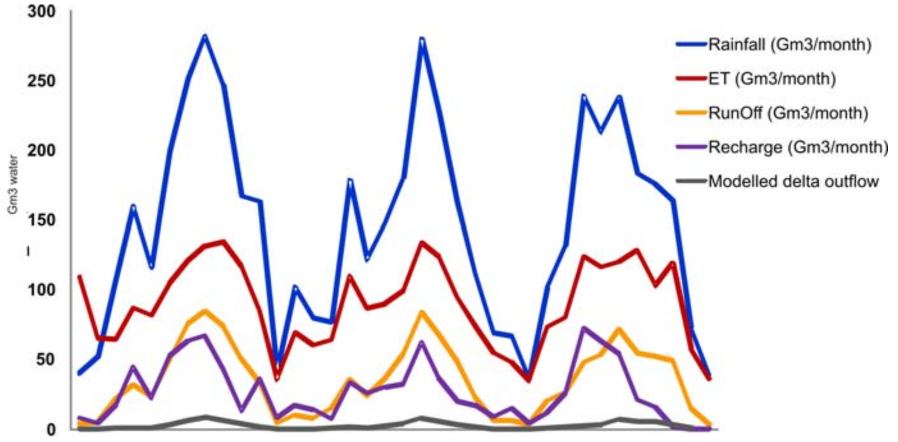

Figure 3 – Monthly volumetric estimates of the partitioning of rainfall within the Nile Basin.

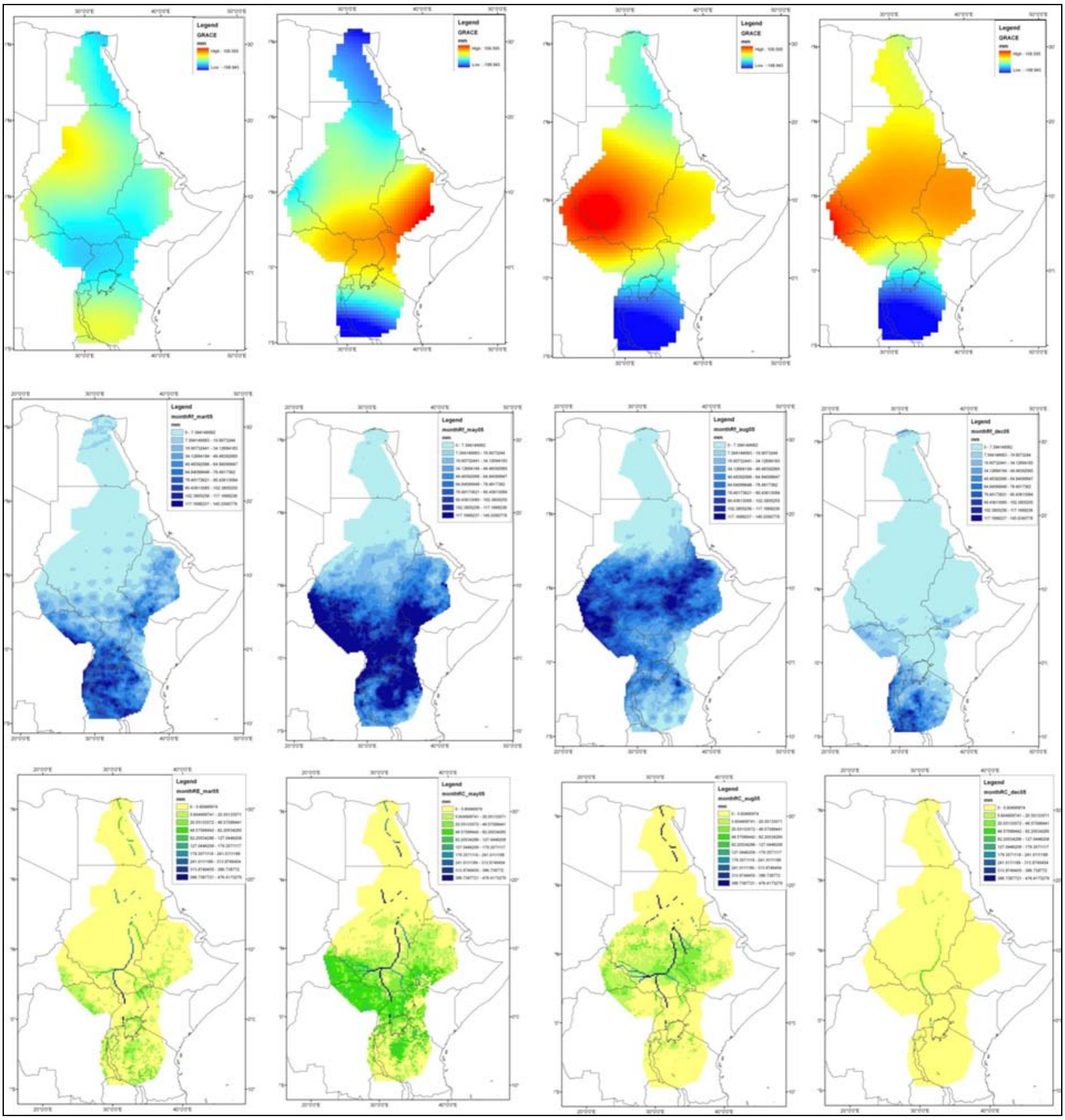

Figure 4 – Comparison of Nile GRACE data, with modelled monthly rainfall and groundwater recharge.

7 FUTURE WORK

This work has shown it is possible to develop a groundwater recharge model on a basinal-scale using largely remotely sensed data and to use groundwater modelling to interpret subtle, seasonal variations in GRACE data. The main limitations to the current Nile ZOODRM model include: the poor simulation of run-off routing time within the Nile Basin (at present only annualised flows can be compared); storage of water in surface water bodies is underestimated and as a result the Sudd wetland is poorly simulated; the model has been calibrated to discharge data from 1976-79 due to lack of available discharge data from 1990 onwards; and the model does not include storage of water in reservoirs, or known irrigation abstraction losses. None of these limitations are thought to invalidate the findings of the modelling, however, future work is required to advance the calibration of the recharge model. Techniques for using satellite radar altimetry to determine surface water levels in lakes and rivers are being developed, and their application to the Nile Basin could provide modern estimates of river flows (e.g. Berry and Pinnock 2003) and improve the level of attainable model calibration. The largest uncertainty is the estimates of atmospheric water changes not related to precipitation.

8 CONCLUSIONS

This work is one the first attempts to try to interpret how subtle, seasonal gravity mass changes indicated in GRACE data, relate to seasonal distribution of water within a river basin. Processing GRACE data for the Nile Basin through a series of spectral filters indicates a seasonal spatial variation to gravity mass (±0.005 mGal) in the basin, thought to relate to seasonal rainfall within the basin. A recharge model was developed to quantitatively estimate how the seasonal rainfall mass is partitioned between other components of the water cycle. Of particular interest was to estimate how much of the seasonal GRACE mass change, if any, relates to groundwater recharge in the Nile Basin. Results indicate:

- the annual water mass variation in the Nile Basin is ~$5.0\text{x}10^{11}$ m^3/yr;
- annual water mass variation is an order of magnitude smaller than the rainfall input into the catchment minus river outflow (~$2\text{x}10^{12}$ m^3/yr);
- evaporative losses are significant within the Nile Basin and relatively little water is lost by outflow from the Nile delta. If there is little atmospheric throughput of water within the Nile Basin, then the results of this work indicate moisture recycling to be highly significant within the Nile Basin. Comparison of the modelling results to accurate atmospheric data is required to better understand the importance of moisture recycling within the Nile Basin.
- Annual groundwater recharge is calculated to be ~$2.4\text{x}10^{11}$ m^3/yr, which is comparable to other large-scale recharge estimates in the Nile Basin (e.g. Döll and Fiedler 2008; Taylor and Howard 1996). Accounting for year-round discharge of groundwater, the seasonal groundwater mass change is calculated to be ~$1.2\text{x}10^{11}$ m^3/yr within the Nile Basin. A significant proportion of the annual water mass variation (~$5.0\text{x}10^{11}$ m^3/yr) indicated in the Nile GRACE data is therefore inferred to reflect groundwater recharge in the Nile Basin.

The results of this study show the value of using groundwater models to interpret subtle variations in GRACE data, to gain an insight into the partitioning of water cycle within river basins. Future work is required to advance the calibration of the ZOODRM model to enable closer comparison with the GRACE data, and to interpret the GRACE data with better estimates of the non-precipitated atmospheric water mass.

8 ACKNOWLEDGEMENTS

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