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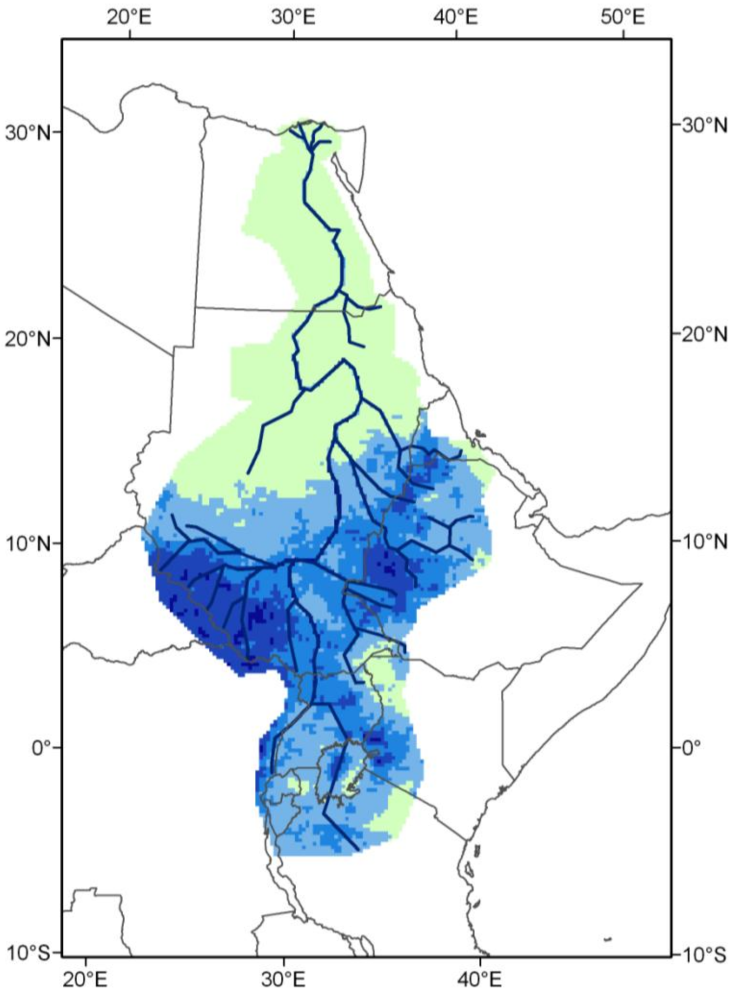
Developing a preliminary recharge model of the Nile Basin to help interpret GRACE data

Groundwater Resources Programme

Open Report OR/09/018



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HC Bonsor, M Mansour, AG Hughes, AM MacDonald and R Hipkin

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Front cover

Output of Nile Basin ZOODRM model in 2008.

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Contents

FIGURES

TABLES

Summary

This report describes the preliminary development of a recharge model of the Nile River Basin using ZOODRM (Mansour and Hughes, 2004), to help interpret GRACE gravity data. This work was undertaken as part of the BGS Groundwater Research Programme and in collaboration with Edinburgh University.

GRACE data provide a new and exciting opportunity to gain a direct and independent measure of water mass variation on a regional scale, but the data must be combined with hydrological modelling to indicate in which part of the water cycle the mass change has occurred. GRACE data has predominantly been used in other investigations to assist basin-scale water balance calculations and there has been little focus on groundwater when interpreting the GRACE data. There is, however, a clear need to assess GRACE data from a groundwater perspective because the gravity data could provide a unique means to monitor real time, seasonal groundwater mass variation.

The primary aim of this project was to develop a preliminary recharge model (ZOODRM) of the Nile River Basin, to help interpret the GRACE data. To achieve this aim, the following work was carried out: 1) source and collate the required data (including daily rainfall and evapotranspiration (ET) data), 2) manipulate data into a useable form for ZOODRM and 3) construct a recharge model. It was also important to examine observed data of the hydrology of the Nile, so as to develop an understanding of the most important processes to the hydrology of the Nile Basin.

- Rainfall (National Oceanic and Atmospheric Administration (NOAA) data) and ET data were sourced from the US Aid Famine Early Warning Systems Network (FEWS NET) African Data Dissemination Service. Geological data was sourced from the digital geology map of the world, landuse data from the US Geological Survey (USGS) and the Digital Elevation Model (DEM) data from ESRI.
- Several difficulties arose in getting the data into a usable format for ZOODRM. The main data issues were: 1) the original spatial reference of the rainfall data was unclear, 2) the daily ET data, obtained for 2002-2007, were only complete for 2003, and 3) all data had to be transformed to UTM zone 36N projection, to ensure area was conserved within the ZOODRM model.
- Using the formatted data, a preliminary recharge model (ZOODRM) of the Nile River Basin was developed. GRACE data indentifies monthly water mass changes of 5 – 7 mm within the Nile Basin, and it was hoped the recharge model would enable identification of how much, if any, of this water mass variation related to groundwater recharge.
- Cursory modelling indicated groundwater recharge of 0-4 mm/yr across the basin. It was not possible, however, to model seasonal groundwater mass change within the river basin to help interpret the GRACE data, as hoped at the outset of the project. This was as a result of the current version of ZOODRM being unable to represent the transfer of runoff to rivers over timescales of greater than one day, that occurs in large river basins, such as the Nile (which has a river basin area of ~$3x10^6$ km^2).

Despite, only a qualitative interpretation of the GRACE data having been achieved within this initial study, the work of this project has indicated that the ZOODRM model can be used with entirely remotely-sensed data, and that sufficient data exists for the Nile Basin to construct a

recharge model. Future work is now required to properly calibrate the model and to enable closer comparison of the Nile GRACE data.

1 Background

GRACE data provide an opportunity to gain a direct and independent measure of water mass variation on a regional scale. While direct monitoring can provide good localised information, the density of ground-based observations is rarely sufficient to determine the balance between precipitation and losses through run-off and evaporation for the whole area of a major river drainage basin.

Groundwater resource assessment is often hampered by a lack of data, or difficulty in obtaining existing data (Brunner et al., 2007). Such restrictions to data availability are typical within developing countries, or within large trans-boundary river basins, where several countries are reliant on one river and the distribution of water resources is highly contentious. The ability to use remotely sensed data to develop accurate, independent hydrological models has, therefore, the potential to be a significant advancement in hydrological science and to have high impacts for the management of water resources (Brunner et al., 2007).

The problem with the GRACE data is that it cannot distinguish between the air, soil, surface or groundwater water masses. Using the GRACE data in isolation, it is therefore impossible to identify what proportion of the water mass in a region is stored where, or what proportion of a seasonal water mass variation relates to change in which water mass. Hence, hydrological modelling is required to interpret the GRACE data.

The primary aim of this project was to develop a preliminary recharge model (ZOODRM) of the Nile River Basin, to help interpret the GRACE data. Of prime interest was to determine what proportion of the GRACE gravity mass variation within the Nile Basin, if any, corresponded to groundwater recharge (mass storage), as well as to ascertain what proportion of the total water mass is recycled within the catchment and how much water mass is lost (evaporation and runoff).

ZOODRM is an appropriate model to use for this work, due to the lower data demands of the model, relative to other groundwater models, and the ability of the model to use entirely remotely-sensed input data. The lack of observational data within the Nile Basin did not therefore compromise the accuracy of the model or the modelling outputs.

The Nile River Basin was chosen as a focus for this work, due to the availability of GRACE data for the Nile region from Edinburgh University. However, the Nile Basin was also an appropriate focus for this study due to the lack of observational data within the basin, and the need to better understand groundwater resources on a basin-scale within the large, trans-boundary basin.

2 The potential of GRACE gravity data to aid hydrological modelling

2.1 OTHER WORK USING GRACE DATA

This project is not the first attempt to validate the terrestrial water mass storage changes indicated by the GRACE data. This work is, however, the first attempt to interpret GRACE data from the Nile Basin. Most other published GRACE work has been focused on the Mississippi (e.g. Rodell et al., 2004; Rodell et al., 2006; Syed et al., 2005), the Amazon (Syed et al., 2005), the Congo (e.g. Crowley et al., 2006), the Rio Negro (Frappart et al., 2008) and the High Plains Aquifer of the USA (Strassburg et al., 2007).

In the main, GRACE data have been used in other studies to assist basin-scale water balance calculations, and there has been little or no focus on groundwater when interpreting GRACE data. Indeed, the groundwater storage component of a river basin is often only calculated as the 'remainder' in water balance calculations, rather than any attempt being made to model recharge processes over a time period. For example, Rodell et al., 2004, use the Global Land Data Assimilation System (GLDAS) to simulate soil moisture and snow water masses, and then isolate the groundwater storage anomalies from the GRACE data by a simple subtraction calculation. Other studies simplify water budget calculations further, by treating soil moisture and groundwater storage to be one water mass (e.g. Syed et al., 2005 and Rodell et al., 2004).

Few, if any, of the other hydrological modelling studies, validate the GRACE data, at the same resolution as the GRACE data (the spatial resolution of GRACE is a few hundred kilometres). For example, Rodell et al., 2006 evaluated the GRACE water storage changes within the Mississippi Basin, against water wells from only 58 wells within the unconfined aquifers of the basin.

There is an obvious need to assess GRACE data from a groundwater perspective, as the gravity data could provide a unique opportunity to monitor real time seasonal groundwater mass variation. Hydrological models must be able to simulate the partitioning of surface and groundwater masses on a basin-scale, to facilitate this interpretation. Yet to date, none of the hydrological modelling used with GRACE data, or used within the Nile (e.g. Mohammed et al., 2005) has, explicitly modelled this partitioning of surface and groundwater masses on a basin-scale.

GRACE gravity data have the potential to enable real time monitoring of water mass variation on a basin-scale. Up till now, there has been no way of measuring seasonal water mass variations on such a wide scale, or in real-time. Such data would provide invaluable information to improve our understanding of large river basin hydrologic processes. The independent nature of the data would also make the data highly useful with large trans-boundary basins, where data relating to water resources is highly contentious.

2.2 GRACE DATA

The GRACE gravity data, when appropriately processed, provides an independent measure of water mass variation over entire river basins. Direct monitoring can provide good localised information, but the density of ground-based observations is often not sufficient to determine the balance between precipitation and losses through run-off and evaporation for the whole area of a major river drainage basin.

Precipitation *P* and loss through run-off and evaporation *L* determine the rate of change of overall water mass, *dW/dT*

$$\frac{dW}{dt} = P - L \qquad (1)$$

The gravity satellite pair GRACE (http://www.csr.utexas.edu/grace/) can monitor integrated water mass *W* directly, so can, in principle, add an important constraint to the water balance equation. With gravity models available at 30 day intervals and now at 10 day intervals, it becomes possible in principle to find the time derivative of gravity and thence water mass (Gunter et al., 2007; Chen et al., 2006).

3 Nile GRACE data: Edinburgh University

In the initial GRACE gravity data, the pattern of gravity anomalies for features less than about 700 km across, was dominated by sensor noise, whose amplitude was nearly 4 orders of magnitude larger than the environmental signals being sought. Despite this, spectral filters for spherical data sets could extract information useful to hydrology and pilot studies at Edinburgh University using Nile GRACE data have been successful in determining the rate of change of total water mass within in the river basin that is consistent with measurements of precipitation and river flow.

A clear seasonal variation to gravity mass (±0.005 mGal) can be seen within the Nile Basin in the processed GRACE data, thought to relate to the downstream movement of water in the catchment following the wet season in the upper catchment (Figure 1). What is not known is how much of the water mass variation relates to groundwater recharge or how much water mass is recycled within the basin. This is why the combination of GRACE data with advanced hydrological modelling, as proposed by this work, is so important.

There is now, a new release of GRACE data in which the sensor noise is greatly reduced through the use of refined spherical harmonics to extract the gravity data. This data has yet to be applied to hydrological modelling, however based on the previous work of Edinburgh University the potential for using this data to constrain accurate hydrological models is considerable.

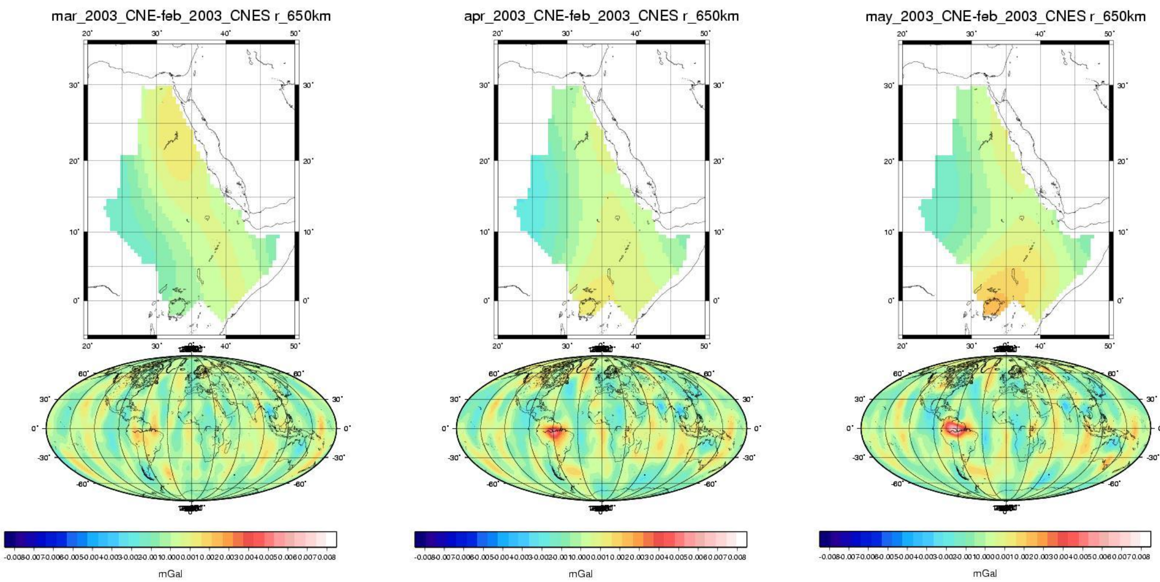


Figure 1 Preliminary modelling of Grace data for the Nile Basin showing mass changes between March, April and May (source: Edinburgh University)

4 Discharge regime of the Nile

4.1 OBSERVED DATA

No modern discharge data are readily available for the Nile and the most recent period for which there are data from all gauging stations on the Nile is 1976-1979. Data do exist for four gauging stations up to 1990, however, it is difficult to obtain any data beyond 1990. As a result, it was not possible in this initial study to obtain observed discharge data for the same time period as that of the Nile GRACE data (2002-2007). This was a key restriction to the quality of the model calibration possible within this preliminary study.

Observed discharge data, from 12 gauging stations on the Nile (Figure 2) were used to calibrate the preliminary recharge model. The discharge data related to the period 1976-1979 and were obtained from Sutcliffe and Parks (1999) and from the online resource of SAGE (Centre for Sustainability and Global Environment, Gaylord Institute, University of Wisconsin-Madison: www.sage.wisc.edu/riverdata/).

Techniques for using satellite radar altimetry to determine surface water in lakes and rivers are being developed (e.g. Berry and Pinnock, 2003), and their application to the Nile Basin could have a large impact on the available data on river flows.

4.1 HYDROLOGY OF THE NILE

The hydrology of the Nile is complex. Annual flows of any river reach are of the order of 10^7 Ml/yr (1×10^7 Ml/yr – 5×10^7 Ml/yr), however the hydrology of any particular reach is directly influenced by the landuse adjacent to the Nile and the hydrological regime of major tributaries.

The White Nile, originating from Lake Victoria and Lake Albert in Uganda and the Congo, provides a constant baseflow to the Nile, whilst the seasonal Sobat and Blue Nile tributaries provide over 70% of the river flow within the wet season. These tributaries join the Nile downstream of the Sudd wetland, at Malakel and Jebel Aulia.

The discharge regime is complicated further by significant evaporative losses from areas of saturated ground in the basin, e.g. irrigated areas below the Aswan Dam (area ~3.42×10^5 km^2) and the Sudd and Bahr el Ghazal swamps (~1.0×10^4 km^2 and 2×10^4 km^2, respectively). Evaporative losses from these regions are of the order of 2×10^7 Ml/yr and they lead to a significant reduction of the Nile discharge (Figure 3). The losses however, vary seasonally as the area of the swamp changes between the wet and dry season. Furthermore, it is uncertain what proportion of the evaporative losses is permanent and how much of the water mass is recycled within the Nile Basin. Previous modelling work by Mohammed et al. (2005) suggests only 11% of the water mass is recycled within the Nile basin.

Evaporative losses from the Nile river surface itself are also significant. Sutcliffe and Parks (1999) state that annual channel evaporative losses are approximately 2.4 km^3 from a river surface area of 900 km^2 (2.7×10^6 m^3/km^2/yr) in the Atbara. This, however, seems a very high evaporative loss. Other work states evaporative losses from open water in SSA are much less, e.g. Vallet-Coulomb et al. (2001) state an evaporation rate of 1.78 m/yr is typical from lake surfaces within the Main Ethiopian Rift.

Regardless of the seasonality of channel losses, the losses mean that a progressive downstream increase in discharge is not observed in the Nile River, as is commonplace for many rivers around the world. The discharge of the Nile River is in fact reduced through the

Sudd (by evaporation losses) and downstream of Aswan (by irrigation abstraction and evaporative losses).

It is worthy of note, that the amount of water mass loss downstream of Dongola and Aswan, corresponds, in crude terms, to the volume of water abstracted for irrigation purposes in Sudan and Egypt, as recorded in FAO aquastat database: www.fao.org/nr/water/aquastat/dbase/index.stm.

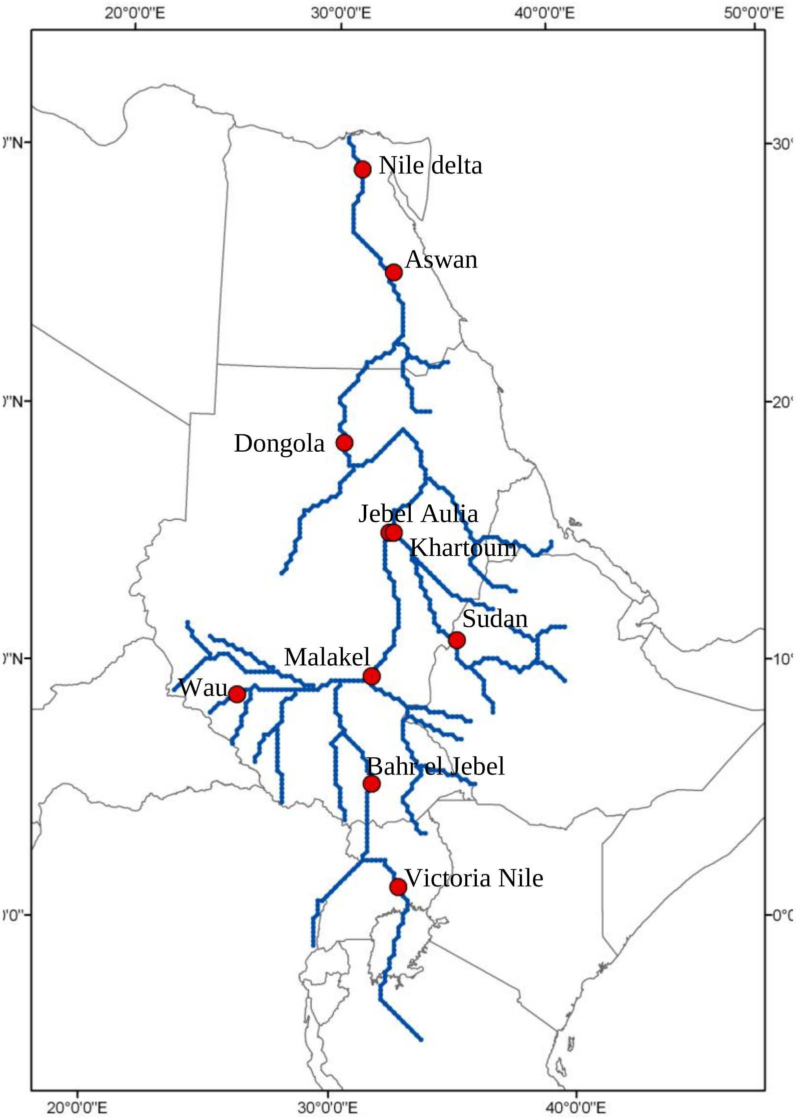
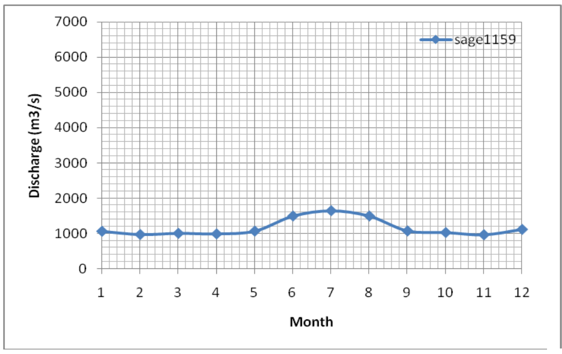
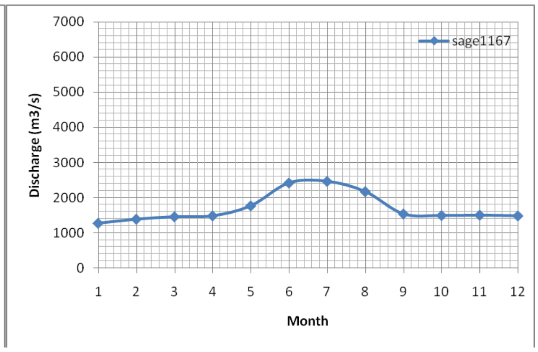


Figure 2 Location of key gauging stations on the Nile and tributaries

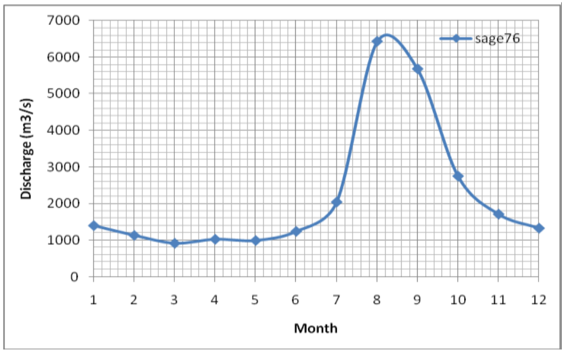


Nile Delta
~2.0x107 Ml/yr water loss from Aswan

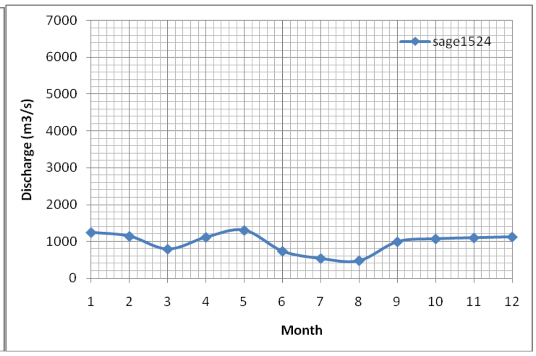


Aswan
(immediately downstream of dam)
1.06x10^7 Ml/yr water loss from Dongola

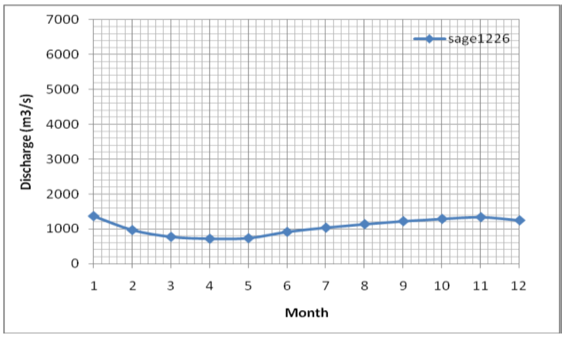
Irrigated area below Aswan 3.4x10^5 km^2
Irrigation water abstraction south of Aswan: 5x10^7 Ml/yr (source: FAO aquastat)



Dongola
(upstream of Aswan, after Blue Nile and Atbara confluences)
3.6x10^7 Ml/yr water gained from Jebel Aulia

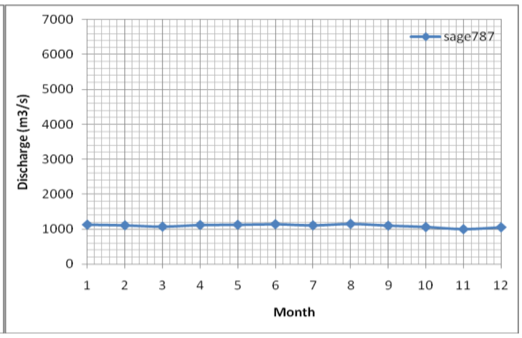


White Nile at Jebel Aulia
(immediately upstream of Blue Nile confluence)
3.2 x10^6 Ml/yr water gain from Malakel.



White Nile at Malakel
(downstream of Sudd and Sobat confluence)
5.5x10^7 Ml/yr water loss from Bahr el Jebel (upstream of Sudd)

Mass loss is greater than stated; Bahr el Ghazel and Sobat tributaries input into the Nile before Malakel gauge.



Victoria Nile

Figure 3 Hydrographs of key gauging stations on Nile, in sequential order – downstream to upstream ordering.

5 ZOODRM recharge model

5.1 MODELLED DATA

ZOODRM requires daily rainfall and evaporation data, as well as land surface, aspect, geological and digital elevation data for the modelled area. Due to the size of the Nile Basin and difficulties in obtaining gauged data from individual countries, entirely remotely sensed data were used for the modelling work. Daily rainfall (National Oceanic and Atmospheric Administration (NOAA) source) and daily evapotranspiration data were obtained from the US Aid Famine Early Warning Systems Network (FEWS NET) African Data Dissemination Service. Land use data were downloaded from the USGS, whilst geological data for Africa was based on digital geology of the world. Several forms of freely downloadable DEM data were obtained, however these datasets could not be manipulated within ArcMap or ArcCatalogue without incurring corruption, so the actual DEM used within the modelling work was the ERSI world DEM grid.

Links to all the data sources are listed below.

- Daily rainfall data: http://earlywarning.usgs.gov/adds/dwndailyrfe.php
- Daily evaporation data: http://earlywarning.usgs.gov/Global/product.php?image=pt
- Landuse data: http://edc2.usgs.gov/glcc/af_int.php
- Aspect data: ESRI – ArcImageData, world data
- Geology data: UNESCO, Africa Geological Map Scale (1:5,000,000), 6 Sheets, UNESCO, Paris, 1991.
- DEM data: ESRI – ArcImageData, world data
- Other DEM data – USGS (not used):
  http://edc.usgs.gov/products/elevation/gtopo30/e020n40.html
  http://edc.usgs.gov/srtm/data/seamlesshelp.html

The ET data is, however, incomplete for 2004 and 2005, which resulted in the model being run for only the year 2003. Alternative sources of ET data should be sought.

5.1.1 Data issues

ZOODRM requires all data files to be in ASCII. Numerous difficulties were encountered in manipulating the remotely sensed Nile data into a usable form for the ZOODRM model.

BIL files:

- The daily rainfall and ET data from FEWS NET were only downloadable as .BIL grid files. BIL files are sequential binary files, which do not hold coordinate information. The required header information, detailing the original spatial reference of the data was not supplied by the FEWS NET source. Without this header information, the coordinates of the data were ambiguous. However, looking at the data and comparing to other datasets it was decided, with reasonable certainty that the data was of the WGS84 coordinate system. This appeared to be a valid assumption, as the BIL files, when assigned WGS84 coordinate, aligned exactly to the other projected Nile datasets of known spatial reference systems.

  Each BIL file of daily rainfall and evapotranspiration had to be projected (see section 5.1.2.) and then converted to ASCII format for the modelling work. ArcGIS (version 9.2) does not have the facility to undertake batch conversions, and manual conversion was too time consumptive due to the large number of data files involved (two for each day in the 1-year model). Instead, the rainfall and ET BIL files projections were transformed using a UNIX script. The xyz data files produced by the UNIX script were then converted to ASCII files.

Corruption of DEM data:

- All readily downloadable grids of DEM data (GTOPO30, SRTM and USGS Streamless data) appeared to corrupt within GIS Arc and within Imaging software, as a result of the programs being unable to differentiate between the pixel values and the Z (elevation) values of the DEM files.

  To circumvent data corruption, a USGS specialist advised that the DEMs must be manipulated within ArcInfo, rather than ArcMap or ArcCatalogue. However, due to the time constraints of this preliminary study, rather than the manipulating the STRM or GTOPO30 DEM data within ArcInfo, the ERSI world DEM grid was found to be a suitable alternative DEM. Although, the ERSI world DEM grid is not as advanced as the STRM or GTOPO30 data, the ERSI DEM grid was of sufficient resolution for the needs of the ZOODRM model (of 20×20km resolution), and modelling outputs were not compromised.

5.1.2 Model-data issues

The size of the Nile Basin and the reliance on remotely-sensed data, resulted in several modelling issues during the development of the Nile recharge model.

Projections

- The ZOODRM model integrates water fluxes over area, and it was therefore crucial to preserve area within the model, particularly due to the size of the Nile Basin, which extends from ~6° south of the equator to ~32° north of the equator. At this scale, the curvature of the earth would induce significant error to the area of the basin presented in conformal or equidistant projections. Projecting data into an equal area projection to conserve area within the model was not a valid option as ZOODRM is unable to read projected data; the model assumes any ASCII array to be of uniform x, y spacing. To circumvent this feature of ZOODRM and to ensure area was preserved within the model, data was projected into UTM zone 36N projection. The meridian of this projection is aligned with the centre of the Nile River Basin, and as a result there is minimal scalar, or areal, distortion of data within the modelled area. Area was therefore preserved within the model and ZOODRM would accurately locate spatial data.

Modern discharge data

- It is very difficult to obtain modern discharge data of the Nile to calibrate any modelling work. Monthly long-term average (LTA) discharge data is readily available for approximately 20 gauging stations along the Nile from 1970-1983, but it is only for the period 1976-1979 that data exists for all gauging stations. There is therefore a 30 year gap between the observed data which we are using for calibration, and the time frame of the model.

5.2 MODEL SETUP

ZETUP (Jackson and Spink 2004) was used to devise the catchment and river grids of the ZOODRM model (Figure 4). A coarse cell size of 20×20km was assigned to the model to ensure a reasonable computational runtime, with a total catchment area of approximately 3.0×10^6 km^3. This model resolution, although coarser than that of the GRACE data, is of a greater resolution than that achieved by previous modelling work in the Nile (e.g. modelling work by Mohammed et al., 2005, achieved a 50×50km resolution). To ensure no error was introduced into the model when the model read the spatial input data, all spatial data files were gridded to be of the same 20km x 20km cell size as the model grid (Figures 5 and 6). In addition, spatial data were projected to UTM zone 36 to ensure the preservation of the area within the model (see section 5.1.2.).

Once the model had been successfully run for one day, the routing component of ZOODRM (Figure 7) was corrected to ensure all surface water was routed to the Nile and its tributaries, rather than collecting as surface ponds. Despite the aspect and topography (DEM) data files being reduced to the same 20×20km resolution of the model, there were still a significant number of ponds generated by the model (hundreds) and correction of the routing took a significant period of time. However, it was particularly important to correct the surface ponding of water within the upper Nile Basin, where the majority of the rainfall occurs.

Other modelling factors were kept as simple as possible within this preliminary stage of model development. River losses were set to zero, as were irrigation losses, so that no water was lost from the Nile River to groundwater recharge, or irrigation, respectively. This ensured that the most important factors determining river discharge and groundwater recharge, (i.e. the partitioning of surface runoff and soil moisture) were the only factors modelled with this preliminary recharge model. River losses and irrigation abstractions may be considered more significant to the hydrology of the Nile Basin at a more advanced stage of modelling and included within the model at a later date.

It was deemed valid to include runon within this preliminary recharge model of the Nile Basin, due to the semi-arid nature of the lower half of the catchment, and runon has proved to be an important factor to previous ZOODRM models within semi-arid areas (e.g. Hughes et al., 2008). The runon factor within ZOODRM is in basic terms, the percentage of runoff lost per metre length, and it is a means of including overland water losses. The runon was initially set to be 0.0002 within the Nile model, which when multiplied by the length of a grid cell (20km), means that 40% of the runoff from a grid cell becomes runon.

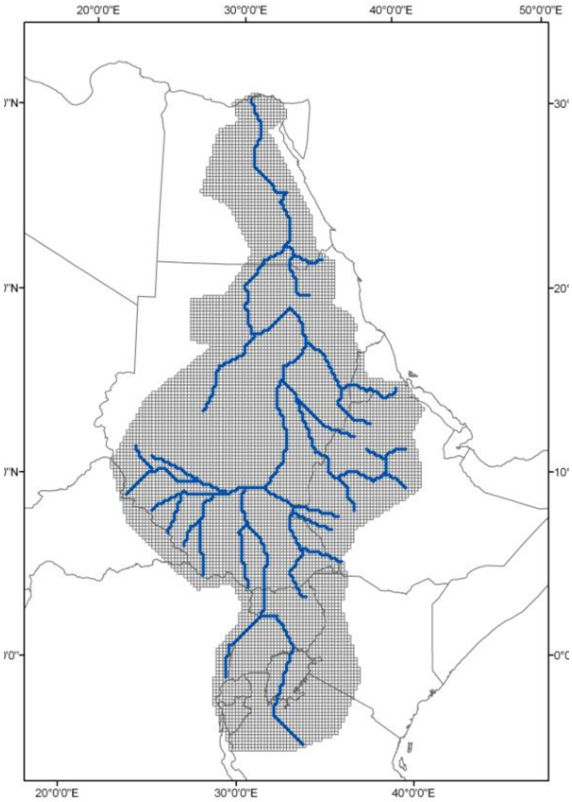


Figure 4. Catchment and river grid of ZOODRM model

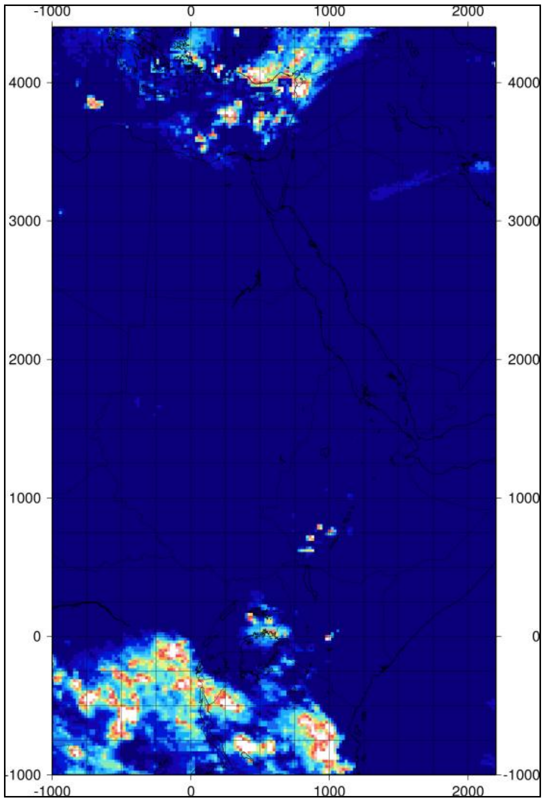


Figure 5. Gridded rainfall data, of 20 x 20 km resoltuion, and of UTM zone 36N projection

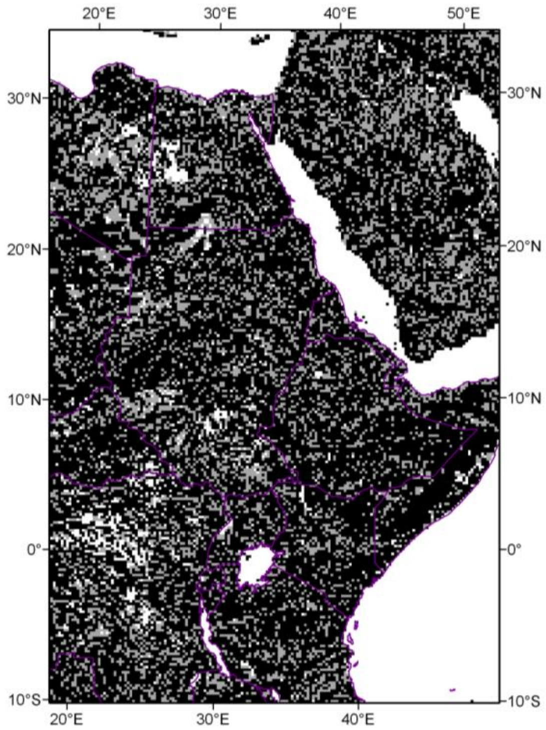


Figure 6. Gridded aspect data, of 20 x 20 km resolution from which ZOODRM computes the routing of water

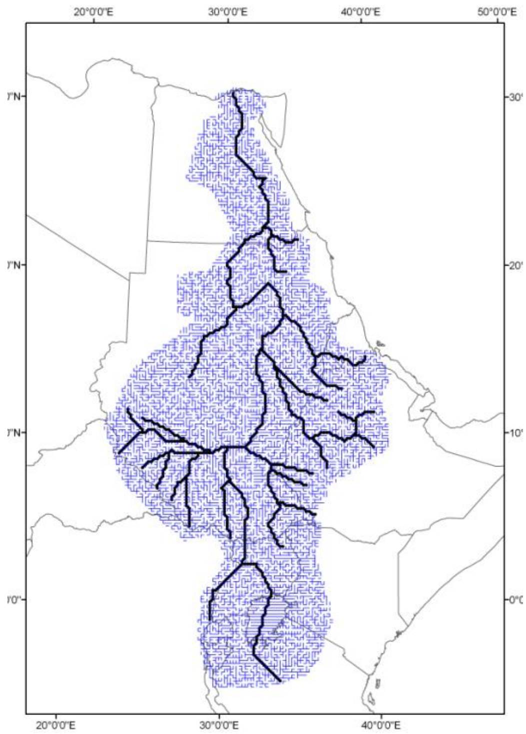


Figure 7. Surface routing paths (blue) computed by ZOODRM from the aspect and DEM data

5.3 MODELLING OUTPUTS

5.3.1 Results

The recharge model was run for the complete year of 2003, this being the year for which there was the most complete rainfall and evapotranspiration data. Comparison of observed and simulated annualised discharge at selected gauge points along the Nile, indicated the model to be replicating observed discharge to within the same order of magnitude (Tables 1 and 2 and Figure 8). The gauging stations modelled include all major reaches and tributaries (except the Atbara) of the Nile River. However, it should be remembered that the observed discharge data are that recorded from 1976-1979, whilst the model is simulating the Nile discharge during 2003. The comparison and calibration is therefore somewhat ambiguous.

The model was calibrated to annualised discharge data, due to the recharge model being unable to simulate a time-lag in surface routing. At present, all rainfall reaching the ground must reach the Nile gauging stations within one day. The most valid method of calibrating the model was therefore to calibrate simulated annual discharge to observed annual discharge.

The best model calibration was achieved setting the runoff coefficient to 0.1 and the runon coefficient to 0.00002 m^{-1}. As a result of this runon factor, runoff is actually significantly less than 10%. River catchments determined by the model appear reasonable (Figure 9) and long-term average (LTA) groundwater recharge was calculated to range from 0-4 mm/yr. Groundwater recharge was modelled to be highest in SW Sudan and W Ethiopia, where rainfall is highest (Figure 10). The groundwater recharge estimates are reasonable and are comparable to those derived in other studies (e.g. Mohammed et al., 2005).

A good model calibration was also achieved, however, when runon was not included, and runoff was set to 0.05. Under this set of input parameters, annualised discharge was again simulated to within the same order of magnitude as observed discharge. Presently, there is therefore some doubt over what is the most valid way to calibrate the model (refer to section 6.4). Both runoff coefficients simulated compare reasonably to other work in the Nile Basin, which suggests it is a basin typified by low runoff (Conway and Hulme, 1993; Mohammed et al., 2005; Sutcliffe and Parks, 1999).

Table 1 Location of key gauge stations included within the ZOODRM model.

Easting	Northing	Gauging Station
322392	3323581	Delta
462392	2863581	Aswan
242392	2103581	Dongola
442392	1703581	Jebel Aulia
462392	1703581	Khartoum
742392	1223581	Sudan border
362392	1063581	Malakel
362392	583581	Bahr el Jebel
482392	123581	Lake Victoria
-237608	983581	Wau

Table 2 Comparison of observed (1976-1979) and modelled data for the main Nile River Basin.

ANNUAL FLOW (Ml/yr)	**GAUGE**			
	Main Nile Nile Delta	Aswan	Dongola	Malakel
Observed	4.06E+07	5.84E+07	6.90E+07	3.29E+07
Modelled	**4.80E+07**	**4.79E+07**	**4.78E+07**	**3.46E+07**

ANNUAL FLOW (Ml/yr)	**GAUGE**			
	Blue Nile Khartoum	**Blue Nile** Sudan border	**Bahr El Ghazel** Wau	
Observed	**3.68E+07**	**7.67E+07**	**1.18E+07**	
Modelled	**7.85E+06**	**5.01E+06**	**1.18E+06**	

ANNUAL FLOW (Ml/yr)	**GAUGE**			
	White Nile **Jebel Aulia**	Malakel	Bahr El Jabel	Lake Victoria
Observed	**2.33E+06**	3.30E+07	4.83E+07	3.85E+07
Modelled	**3.64E+07**	**3.46E+07**	**1.037E+07**	**4.60E+06**

Data for the Main Nile are shown in the upper table, whilst data for the Blue Nile are shown in the middle table and data for the White Nile and Bahr El Ghazel tributaries are shown in the lowermost table. In all tables, the gauges are displayed downstream to upstream, as you read left-right. Except for the Blue Nile, all simulated discharge data are of the same order of magnitude as observed.

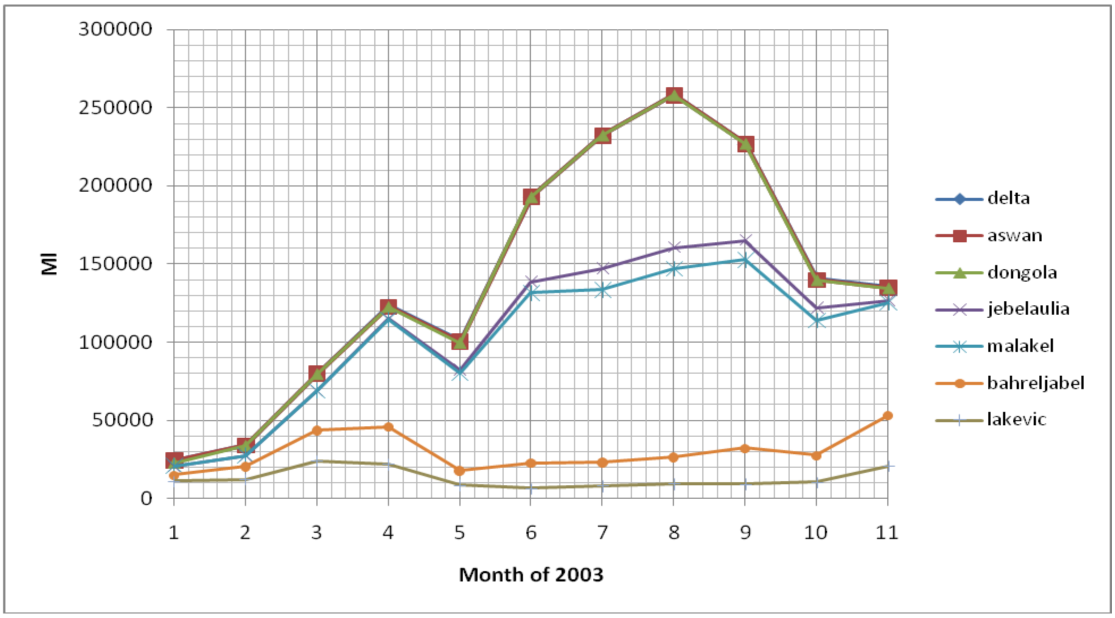


Figure 8. Simulated Nile River discharge by the ZOODRM recharge model for 2003.

In general these simulated discharges compare well to observed data (i.e. same order of magnitude). The model replicates the difference between the constant baseflow of the Victoria Nile and the seasonal flows of the lower Nile (influenced by the Sobat and Blue Nile tributaries) well. However, the model is not able to simulate the loss of discharge downstream of Aswan, due to exclusion of irrigation abstraction losses within the initial ZOODRM model.

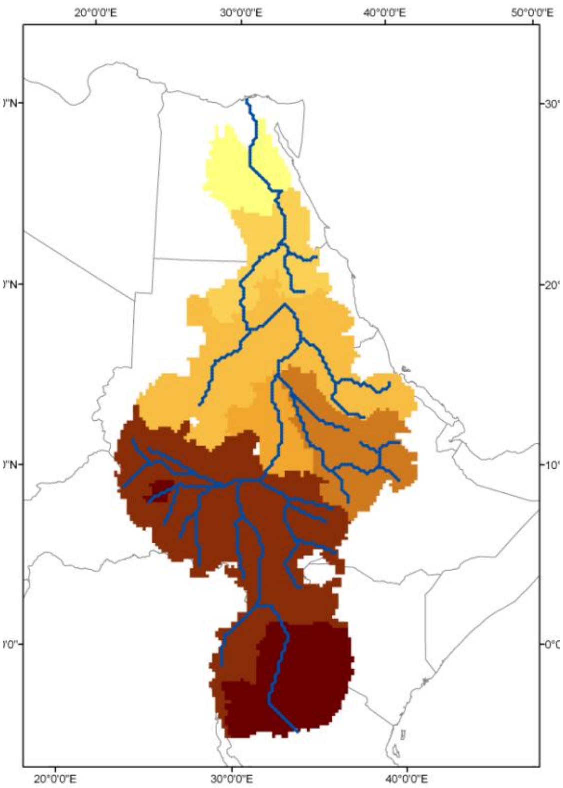


Figure 9. Calculated catchment areas within the Nile basin.

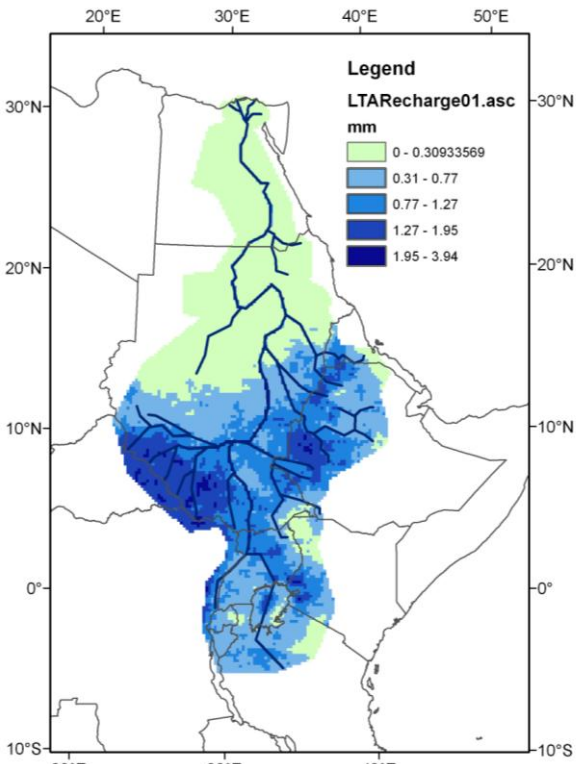


Figure 10. Groundwater recharge calculated by initial modelling work. Green = 0-0.3 mm recharge, dark blue 2-4 mm recharge.

5.4 MODELLING ISSUES

There are several significant limitations to the current Nile ZOODRM model:

1. *Runoff routing: time-lag*

   At present, all rainfall reaching the ground, must reach the gauging stations within one day – i.e. there is no lag time built into the runoff routing, to enable a realistic 3-month travel time between rain falling in Ethiopia and reaching the Nile delta. It is for this reason that we are calibrating to annualised flows at present.

2. *RunOn*

   Without inclusion of the RunOn parameter within the recharge model, runoff is generated as a simple fraction of the rainfall, rather than being linked to both rainfall and the soil moisture. Inclusion of RunOn within the Nile model circumvents this limitation. However the validity of the inclusion of RunOn within the model is ambiguous when a good calibration can be achieved both with, and without it.

   RunOn has proved an important model parameter within other ZOODRM models in semi-arid areas (e.g. Palestine) and it seems logical to need to include this parameter, particularly within arid areas of the Nile Basin. When the Nile model is run with a time-lag built into the runoff routing, inclusion of RunOn may be necessary for calibration of the model.

3. *Evaporative losses*

   ZOODRM has limited capabilities to simulate large evaporative losses from the river surface, from extensive saturated areas, such as the Sudd and Bahr el Ghazal swamps in the central Nile Basin, or from irrigated land. Evaporative losses are significant within the Nile Basin and need to be included within the recharge model (e.g. it is estimated from observed data that approximately 2×10^7 Ml/yr of water is lost through evaporation within the Sudd wetland alone (Sudd area ~1 $x10^4$ km^2)).

4. *Surface water storage*

   ZOODRM has limited capabilities to simulate surface water storage, such as Lake Victoria. All the water arriving at a node, which is a pond, goes to rainfall over that node in the next day and then the Soil Moisture Deficit (SMD) procedure is applied. The amount of recharge and runoff simulated from these nodes may not therefore be realistic. This may, in part, be why the model consistently underestimates discharge immediately downstream of Lake Victoria by an order of magnitude, in all calibrations.

5.5 FUTURE MODELLING DEVELOPMENT

1. Need to develop a robust method of calibration

Inclusion of time-lag to surface routing

The model at present probably does not require RunOn due to all the water being routed into the Nile River in one day. When a time-lag is built into the routing component of ZOODRM, the model will probably need to include RunOn. It would be best to build in a time-lag component to routing before the method of calibration is decided.

Lack of modern discharge data

The lack of modern discharge data is a significant limitation to our calibration capabilities. Significant year-to-year variation in discharge (±50%) is observed from the longer gauging stations records at certain stages. If no modern discharge data can be obtained, it would perhaps be better to calibrate to fewer gauging stations, for which there is discharge data up until 1990. However, there are only 3 gauging stations with such long-term records, and even 1990 data is 10-15 years older than the time frame of the Nile GRACE data.

2. **Representation of surface water storage: Lake Victoria**

The outflow from Lake Victoria is at present significantly underestimated by the ZOODRM model, and this has a large knock-on effect on downstream calibration. There is therefore a need to develop a better modelling capability to simulate surface water storage within model. An alternative would be to model only the catchment area downstream from Lake Victoria. This may, however, have serious consequences for the water balance of the model, due to this area of the river basin being where the majority of rainfall occurs.

3. **Evaporative losses**

Wetland areas change significantly through the wet and dry season, and as a result so do the evaporative losses. This probably needs to be included within the recharge model, otherwise the evaporative flux and river discharge will be under- and overestimated within the wet and dry season, respectively.

6 Conclusions

6.1 SUMMARY

Previous hydrological modelling using GRACE data has been focused on quantifying the water balance of major river basins within the world (e.g. The Amazon and Congo). However, none of these hydrological studies have used GRACE data from the Nile, nor has the hydrological modelling tried to interpret the GRACE data from a groundwater perspective. There is, however, a clear need to assess GRACE data from a groundwater perspective, as the gravity data could provide a unique opportunity to monitor real time seasonal groundwater mass variation.

Using remotely sensed data, a preliminary recharge model of the Nile River Basin was developed using ZOODRM to help interpret GRACE data of the basin. By incorporating surface routing, the ZOODRM model is able to not only quantify daily changes in water mass within the Nile Basin, but also what proportion of the water mass goes to groundwater recharge and soil moisture, and how much of the water mass within the basin is recycled.

The initial modelling work has demonstrated that sufficient data exist to create a working ZOODRM model of the Nile Basin. The ZOODRM model produced reasonable simulations of the observed Nile discharge over an entire hydrological year, and groundwater recharge estimates are comparable (0-4 mm/yr) to those derived in previous studies. It was not possible, however, to model seasonal groundwater mass change within the river basin and future work is required to properly calibrate the model and to enable closer comparison of the GRACE data.

6.2 RECOMMENDATIONS FOR FUTURE WORK

More detailed work is required to develop a calibrated ZOODRM model of increased spatial resolution. Key model limitations include the inadequate simulation of surface runoff, surface water storage and evaporative losses from saturated ground within the ZOODRM model. All of these are significant to the observed hydrology of the Nile Basin.

Some assumptions of ZOODRM are invalid within a river catchment as large as the Nile. It is of utmost importance that any further work includes a time-lag component to surface water routing, so that there can be a realistic 3-month travel time of surface water from the upper to lower Nile catchment. At present ZOODRM assumes all rainfall falling within the catchment must reach the river gauging stations within one day.

Lack of observed discharge data is a major limitation to the validity of model calibration possible at present. Techniques for using satellite radar altimetry to determine surface water in lakes and rivers are being developed, and their application to the Nile Basin could be of great potential to available data on river flows. There is the possibility of collaborating with PA Berry, a leading researcher in Altimetry techniques at Simon de Montford University, who holds altimetry data for the Nile River Basin, to develop a technique of remote gauging of real time river discharge within the Nile.

References

BERRY, P. A. And PINNOCK, R. A. (2003) The potential contribution of satellite altimetry to retrieval of the global hydrology runoff budget , *Geophysical Research Abstracts*, Vol. 5, 04389.

BRUNNER, P. HENDRICKS FRANSSEN, H-J., KGOTLHANG, L., BAUER-GOTTWEIN, P. and KINZELBACH, W. (2007) How can remote sensing contribute in groundwater modelling? *Hydrogeology Journal,* **15;** 5-18.

CHEN, J. L., WILSON, C. R., FAMIGLIETTI, J. S. and RODELL, M. (2007) Attenuation effect on seasonal basin-scale water storage changes from GRACE time-variable gravity, *Journal of Geodesy,* **81;** 237-245.

CONWAY, D. and HULME, M. (1993) Recent fluctuations in precipitation and runoff over the Nile sub-basins and their impact on main Nile discharge, *Climatic Change* **25:127** 151, 1993.

CROWLEY, J. W., MITROVICA, J. X., BAILEY, R. C., TAMISIEA, M. E. and DAVIS, J. L. (2006) Land water storage within the Congo Basin inferred from GRACE satellite gravity data, *Geophysical Research Letters*, **33**; L19402.

FRAPPART, F., PAPA, F., FAMIGLIETTI, J. S. PRIGENT, C. And ROSSOW, W. B (2008) Interannual variations of river water storage from a multiple satellite approach: A case study for the Rio Negro River basin, *Journal of Geophysical Research*, **113**; D21104

GUNTNER, A., SCHMIDT, R. and DOLL, P. (2007) Supporting large-scale hydrogeological monitoring and modelling by time-variable gravity data, *Hydrogeology Journal,* **15:** 167–170.

HUGHES, A. G., MANSOUR, M. M. AND ROBINS, N. (2008) Evaluation of distributed recharge in an upland semi-arid karst system: the West Bank Mountain Aquifer, Middle East, *Hydrogeology Journal*, 16; 5, pp 845-854.

MANSOUR, M. M. and HUGHES, A. G. (2004) User's manual for the distributed recharge model ZOODRM. *British Geological Survey*, Internal Report, IR/04/150.

MOHAMMED, Y. A., VAN DEN HURK, B. J. J. M., SAVENIJE, H. H. G. And BASTIAANSSEN, W. G. M. (2005) Hydroclimatology of the Nile: results from a regional climate model, *Hydrology and Earth System Sciences,* **9**; 263–278.

RODELL, M., CHEN, J., KATO. H., FAMIGLIETTI, J. S., NIGRO, J. and WILSON, C. R. (2006) Estimating groundwater storage changes in the Mississippi River Basin (USA) using GRACE. *Hydrogeology Journal,* **15;** 159-166.

RODELL, M., FAMIGLETTI, J. S., CHEN, J. SENEVIRATNE, S. I., VITERBO, P., HOLL, S. and WILSON, C. R. (2004) Basin scale estimates of evapotranspiration using GRACE and other observations, *Geophysical Research letters,* **31;** L20504.

STRASSBURG, G., SCANLON, B. R. and RODELL, M. (2007) Comparison of seasonal terrestrial water storage variations from GRACE with groundwater-level measurements from the High Plains Aquifer (USA), *Geophysical Research Letters*, 34, L14402.

SUTCLIFFE, J. V. and PARK, Y. P. (1999) The Hydrology of the Nile, *IAHS Special Publication no.5* , IAHS Press.

SYED, T. H., FAMIGLIETTI, J. S., CHEN, J., RODELL, M., SENEVIRATNE, S. I., VITERBO, P. and WILSON, C. R. (2005) Total basin discharge for the Amazon and Mississippi River basins from GRACE and a land-atmosphere water balance. *Geophysical Research letters,* **32;** L24404.

VALLET-COULOMB, C., LEGESSE, D., GASSE, F., TRAVI, Y. And CHERNET, T. (2001) Lake evaporation estimates in tropical Africa (Lake Ziway, Ethiopia), *Journal of Hydrology,* **245;** 1-18.