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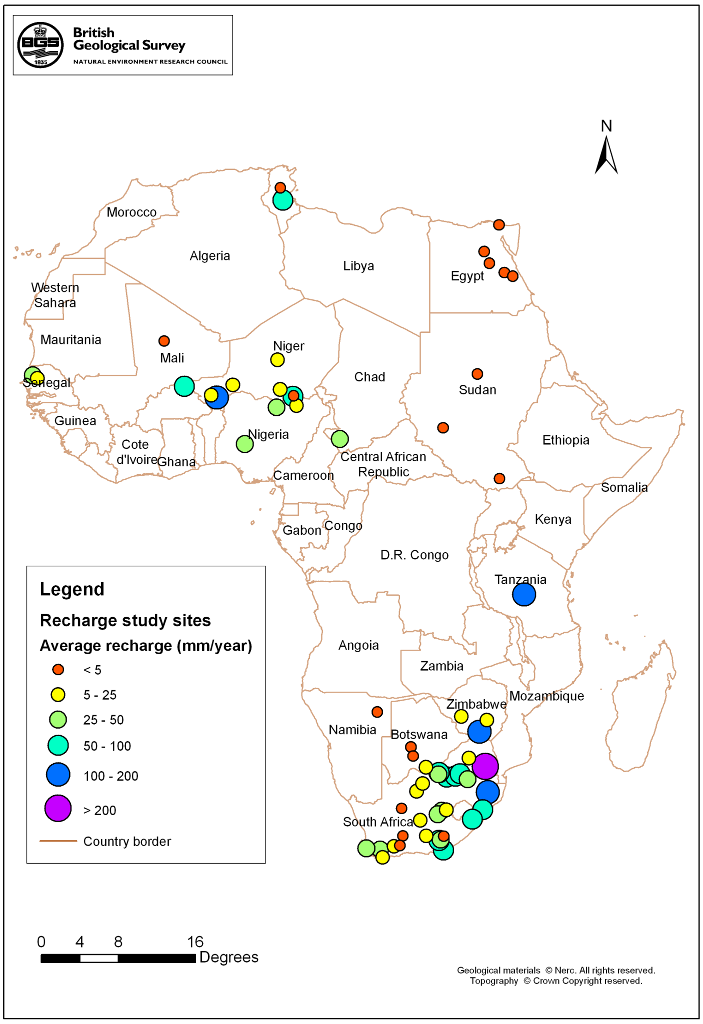
A literature review of recharge estimation and groundwater resource assessment in Africa

Groundwater Resources Programme

Internal Report IR/10/051



BRITISH GEOLOGICAL SURVEY

GROUNDWATER RESOURCES PROGRAMME

INTERNAL REPORT IR/10/051

A literature review of recharge estimation and groundwater resource assessment in Africa

Lei Wang, Brighid Ó Dochartaigh, David Macdonald

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Summary

This report reviews the available literature on groundwater recharge and groundwater resource assessment in Africa. The purpose of this review is to identify estimates of groundwater recharge that have been undertaken either in Africa, or outside Africa but in similar environments and climates to those found in Africa.

The first part of the report highlights the importance of groundwater recharge modelling to the study of climate change impacts on groundwater resources in Africa. Section 2 discusses groundwater recharge mechanisms, and challenges in recharge estimation, particularly in arid and semi-arid regions. Sections 3, 4, 5, and 6 largely describe groundwater recharge studies in arid and semi-arid areas, especially in Africa, which used different methods at different scales. In the final part of the report we emphasize our main conclusion:

- There is a gap in information on the scale and temporal and spatial distribution of groundwater recharge across much of Africa. Most existing recharge estimates have been done on an *ad hoc* basis using very different methods and data, so that there is no consistency between estimates in different regions. The distribution of these estimates across Africa is also patchy and unequal.
- There is potential value in producing a process-based quantitative continental scale recharge estimate that uses a consistent approach and data, as the basis for studying potential climate change impacts on groundwater resources in Africa. The only existing continental scale recharge model, the WaterGAP Global Hydrology Model (WGHM) (Döll et al. 2003, Döll and Flörke 2005, and Döll and Fiedler 2008), was originally designed to estimate global runoff, and does not fully quantitatively account for detailed hydrogeological processes, in particular for soil moisture change processes related to groundwater recharge.
- Developing a continental-scale recharge model that accounts for the highly variable climate zones across Africa, with the limited available data, is a great challenge. Modelling recharge is particularly difficult in arid and semi-arid areas.

1 Introduction

Groundwater is an important source of water supply in Africa because of its capacity to buffer short-term climatic variability; its comparatively good quality; and the affordability of infrastructure for groundwater abstraction, compared to surface water (Macdonald et al., 2009; Calow and Macdonald, 2009). However, estimating groundwater recharge has long been one of the most difficult challenges in hydrological science.

The occurrence of groundwater depends on geology, geomorphology and rainfall. Precambrian basement rocks, consolidated sedimentary rocks, unconsolidated sediments, and volcanic rocks are the four major hydrogeological environments in Sub-Saharan Africa (Macdonald et al., 2008). Low permeability aquifers with limited storage occupy about 80% of the African land area. Macdonald et al. (2009) propose there are three broad rainfall recharge zones in Africa: negligible groundwater recharge in zones with less than 200 mm/a rainfall; about 50 mm/a recharge in the zones with rainfall range of 200-500 mm/a; and greater than 50 mm/a recharge in zones where rainfall exceeds 500 mm/a. Although there is considerable uncertainty about the future of African climate (Christensen et al., 2007), there is some confidence that there will be increased average temperatures and reduced annual rainfall in Africa. One of the challenges in water resources management in Africa is how to sustainably manage groundwater resources in semi-arid and arid regions under climate change. This requires better information on the impacts of climate change on renewable groundwater resources. Therefore, a much better understanding of recharge processes and aquifer response to a changing future is necessary (Adelana and MacDonald, 2008; Foster et al., 2008; Calow and MacDonald, 2009).

The purpose of this review is to identify estimates of groundwater recharge that have been undertaken in Africa or from outside Africa but that could be applied to the climates found in Africa. These estimates are at a range of scales, from site specific to regional. The approaches used include tracer studies, soil moisture budgets, a combination of these two, and others. Semi-quantitative approaches are also referenced which use index methods for assessing groundwater availability and vulnerability.

2 Groundwater recharge: mechanisms and estimation approaches

Groundwater recharge estimation is a fundamental part of groundwater resources management. In semi-arid and arid parts of Africa, where groundwater is often the major water resource, and is likely to be prone to depletion under projected future climate trends, groundwater recharge estimation is even more important.

Sources of recharge include direct recharge from precipitation, localised recharge from depressions (e.g. ponds) and rivulets, indirect recharge from rivers, irrigation losses, and urban recharge. Recharge can be quantified using several methods (Lerner et al., 1990; Allison et al., 1994):

- direct measurement
- water balance methods
- Darcian approaches
- tracer techniques
- empirical methods

According to Lerner et al. (1990), a “good” recharge model should have five essential ingredients:

- water balance – explicitly account for the water that does not become recharge
- recharge processes – an appropriate conceptual model
- error of estimate – it will not be sensitive to parameters which are hard to estimate accurately
- ease of use – data and skill
- extrapolation – spatio-temporal monitoring data inputs

Many factors affect the complex groundwater recharge processes, such as rainfall intensity, rainfall frequency, temperature, wind speed, solar radiation, soil type, seasonal vegetation coverage change, irrigation, topography, permeability of vadose zone, and the groundwater level (Figure 1). These factors control groundwater recharge processes in different ways across climates. For example, groundwater is generally considered to occur in topographic highs and discharge in topographic lows in humid regions, whereas in arid alluvial-valley regions groundwater recharge is usually focused in topographic lows, such as channels of ephemeral streams (Scanlon et al., 2002; Sanford, 2002). Groundwater recharge modelling faces particular challenges in arid and semi-arid areas. Here, potential evapotranspiration generally exceeds rainfall, and groundwater recharge depends on high intensity rainfall events, the accumulation of rain water in depression and streams, and the ability of rain water to escape evapotranspiration by rapid infiltration through cracks and fissures. Therefore, ***direct recharge is likely to be less important than localised and indirect recharge***, in terms of total aquifer replenishment. Howard and Lloyd (1979) demonstrate that a 10-day or monthly time-step can lead to a significant underestimation of groundwater recharge. Since groundwater recharge results from only infrequent large rainfall events, and even during these events generally only occurs in small amounts, annual rainfall totals are not good predictor of annual potential recharge (De Vries and Simmers, 2002; Eilers et al., 2007).

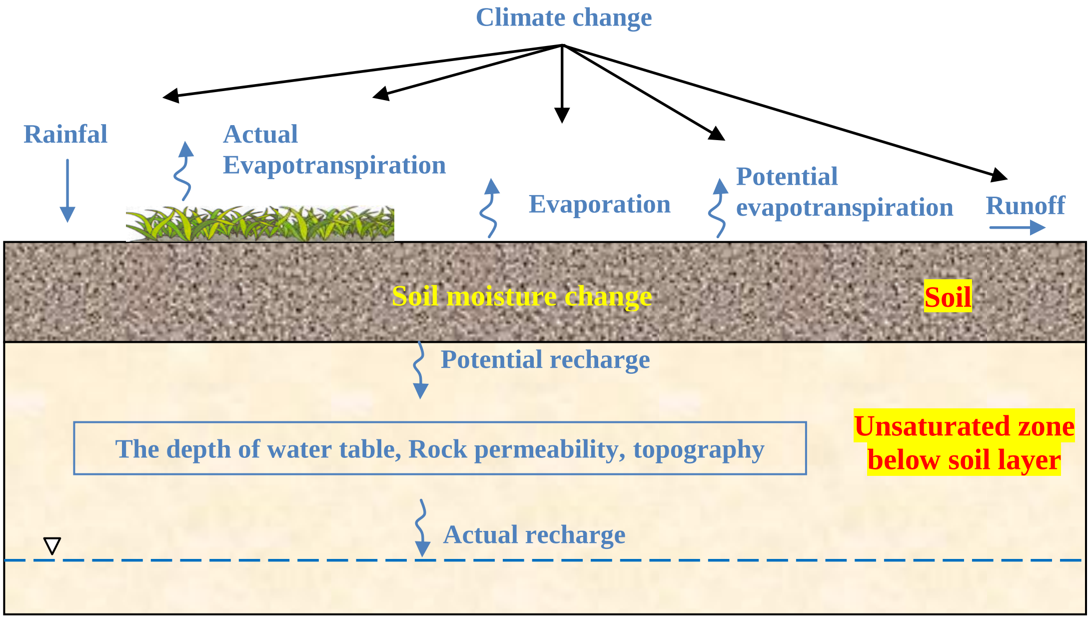

Figure 1. Sketch of groundwater recharge processes

3 Recharge studies in Africa

Groundwater recharge studies in Africa have usually been done at a small-scale (i.e. focussing on a small area) on an *ad hoc* basis, in order to define local fundamental aspects of groundwater recharge, such as its source, timing, magnitude, and distribution. Details of known recharge studies in Africa and in equivalent arid and semi-arid environments in other parts of the world have also been collated for this review and are presented in Table 1. Estimated recharge in these studies ranges from 0.08 mm/a to 288 mm/a. The majority of existing groundwater recharge studies in Africa have focused on arid and semi-arid environments (Table 1), but a small number of regional groundwater recharge studies covering tropical, arid, and semi-arid environments have also been identified (Table 1). The information in Table 1 does not include reference to any literature published after August 2009.

A GIS database for recharge estimates in Africa has been created based on the information in Table 1, so that the spatial distribution of these can be seen. Figure 2 shows locations and average values of available recharge estimates in Africa. These estimates using different methods vary greatly even in the same climatic region. The attribute table for this GIS database is presented in Appendix 1.

The available groundwater recharge estimates were done using a variety of methods, as mentioned above. More detail on these methods is given in the subsequent sections.

3.1 TRACER METHODS

Adanu (1991) used stable isotope tracers to study the source of groundwater recharge in the Zaria-Kaduna area, Nigeria (tropical climate), and found that the primary source of recharge in the area is the direct infiltration of rainfall at the soil surface.

Sami (1992) used chemical and isotopic tracer methods to study the groundwater recharge mechanisms and geochemical processes in a semi-arid catchment in the Eastern Cape, South Africa. The hypothesised recharge and salinisation mechanism is that large storm events periodically dissolve accumulated surficial meteoric salts and, after a period of evaporative enrichment at or near the soil surface, leach them into the groundwater. Geochemical variations imply that spatial differences exist in recharge volumes, in evaporative enrichment or in the extent of leaching of surficial salts.

Edmunds and Gaye (1994) estimated groundwater recharge in the arid Sahel using thirteen unsaturated zone interstitial water chloride profiles. Recharge estimates range from 0.1-1.3 mm/a.

Leduc et al. (2001) used an isotope tracer method to estimate groundwater recharge in semi-arid Niger. Their study showed that unexpected groundwater level rise (in spite of the severe droughts of the 1970s and 1980s) in the Continental Terminal in southwest of Niger may be explained by a change in land-use. Recharge in the study area was 5 mm/a during the 1950s and 1960s (before land clearance and deforestation), increasing to 20 mm/a since 1990. In this semi-arid area, intense land clearing has modified the hydraulic properties of the top few centimetres of the soil and has consequently increased surface runoff. As runoff concentrates in temporary endorheic (internally drained) ponds and then percolates to the water-table, higher runoff implies higher groundwater recharge and a subsequent rise in the water-table. Favreau et al. (2002) estimated the groundwater recharge in the same area using stable isotope tracer method and concluded that the groundwater recharge before land clearance was 1-5 mm/a, whilst recent groundwater recharge (since approximately 1990) ranges from 20 mm/a to 50 mm/a.

Edmunds et al. (2002) estimated groundwater recharge in northern Nigeria using chloride (Cl) mass-balance method at the plot scale, and then extrapolated the groundwater recharge results to

Table 1. Estimates of groundwater recharge in arid/semi-arid areas

Location	Climatic Type	Estimated Annual Recharge (mm/a)	Method	Reference
Sahel	Arid	0.1~1.3	Chloride Tracer	Edmunds and Gaye (1994)
Eastern Desert, Egypt	Arid	Tarfa: 0.08 Asyuti: 0.11 Qena: 0.09 Hammamat: 0.24	Water Balance	Gheith and Sultan (2002)
Sinai Peninsula, and Eastern Desert of Egypt	Arid	Sinai Peninsula: 15.7% of the annual rainfall; Eastern Desert: 21.2% of the annual rainfall	The combination of remote sensing and SWAT	Milewski et al. (2009)
Kajemarum Oasis, Northeast Nigeria	Arid	60	Steady-state unconfined flow equation	Carter (1994)
Northern Nigeria		14~49	Chloride tracer	Edmunds et al. (2002)
Upland in Northeast Nigeria	Arid	0.9	One dimensional flow equation	IWACO (1985)
Nigeria	Arid	15-54(unsaturated zone), and 200 (saturated zone)	Chloride tracer	Edmunds et al. (1999)
Amargosa Desert Basin, USA	Arid	-	The combination of streamflow data and tracer	Stonestrom et al. (2007)
Arroyo Hondo, New Mexico, USA	Arid	-	Inverse modelling and tracer	Moore (2007)
Westtern Mojave Desert, California, USA	Arid	-	Combing hydraulic, thermal, geomorphic, chemical, and tracer	Izbicki et al. (2007)
Tanzania	Semi-arid	100 (Forested-nondegraded), 133 (Deforested – nondegraded), 84 (Deforested-degraded); 15% reduction in rainfall resulted in a 40-50% reduction in recharge	Two-layer SMD	Sandström (1995)
Botswana	Semi-arid	0.5 (Chloride), 1.1 (Isotope), and 3.8 (^{3}H)	Chloride, isotope, and ^{3}H Tracers	Selaolo et al. (1996)
Botswana	Semi-arid	14~22 (Chloride), and 9 (^{3}H)	Chloride and ^{3}H Tracers	Gieske et al. (1995)
Botswana Kalahari	Semi-arid	5 mm/a at the eastern fringe of the Kalahari where annual rainfall exceeds 400 mm; 1 mm/a at the central Kalahari with lower precipitation	Modelling and tracer	De Vries et al. (2000)
Eastern Cape, South Africa	Semi-arid	-	Tracer	Sami (1992)
Sahelian, South-West Niger	Semi-arid	1~5 during 1950s-1960s, 20~50 from 1990-2000	Tracer	Leduc et al. (2001)
Southern Niger	Semi-arid	13 (unsaturated zone), 28 (saturated zone)	Chloride tracer	Bromley et al. (1997)
Niger	Semi-arid	6 during 1950s-1960s, 20 from approximately 1990-2000	Tracer	Favreau et al. (2002)
Iullemmeden basin,	Semi-arid	50~300	Tracer	Rueedi et

Location	Climatic Type	Estimated Annual Recharge (mm/a)	Method	Reference
South-West Niger				al.(2005)
Sahel in Niger	Semi-Arid	50~60	Groundwater level observation	Leduc et al. (1997)
Senegal	Semi-Arid	22 and 26 (^{3}H); 29 and 34 (Chloride)	Chloride and ^{3}H Tracers	Gaye and Edmunds (1996)
Senegal	Semi-Arid	15	Chloride and ^{3}H Tracers	Cook et al. (1992)
South-West Chad	Semi-arid	20~50	Tracer	Goni (2008)
North and central of Sudan	Semi-arid	-	Tracer	Vrbka et al. (2008)
Sudan	Semi-arid	0.3-1.3 (Interfluvial sandy clay); 2.8 (Sandstone ridge, possible surface runoff)	Chloride tracer	Edmunds et al. 1988
Karoo aquifers of South Africa	Semi-arid	2~5% of the annual rainfall	Neutron probe measurements and saturated volume fluctuation	Van Tonder and Kirchner (1990)
Tunisia	Semi-arid	1.3	Chloride Tracer	Edmunds (2001)
Tunisia	Semi-arid	61~108	The equation of Williams and Kissel (1991) (Empirical equation based on groundwater vulnerability ranks)	Hamza et al. (2007)
Continental Terminal 3 aquifer in Niger	Semi-arid	2 during 1950s-1960s, 23 from approximately 1995-2005	The combination of magnetic resonance soundings and water table fluctuation	Vouillamoz et al., (2008)
Northeast of Nigeria	Semi-arid	average 14, range 0-95	Improved single layer SMD	Eilers et al. (2007)
Southern Zimbabwe	Semi-arid	Rainfall between 141 and 162 mm during a week resulted in widespread groundwater recharge. Infiltration rate were from 104 mm to 161 mm for 17/18 February 1995.	Comparing rainfall, groundwater level, and soil moisture data monitored	Butterworth et al. (1999a,b)
Victoria province, Zimbabwe	Semi-arid	82, 11, 39, 27, 8, 9, 12, 7, and 3 (1975-1983), or 2-5% annual rainfall	River baseflow analysis, groundwater hydro-chemical analysis, and groundwater modelling	Houston (1990)
Northeast of Namibia	Semi-arid	1	Hydro-chemical data, satellite image, and Groundwater modelling	Klock (2001)
Southern Zimbabwe	Semi-arid	15~20	Tracer, Water table fluctuation method, Darcian flownet computations, and groundwater	Sibanda et al. (2009)

Location	Climatic Type	Estimated Annual Recharge (mm/a)	Method	Reference
			modelling	
Murray Basin, Australia	Arid/Semi-arid	3~30 (clay content ranges from 0-10% in the top 2 meter of soil profile)	Water Balance	Kennett-Smith et al. (1994)
western Saudi Arabia, Middle East	Arid/Semi-arid	3~4% of the annual rainfall	Tracer	Bazuhair and Wood (1996)
Southwestern Australia	Arid/Semi-arid	-	Water Balance	Lewis and Walker (2002)
Southwestern USA	Arid/Semi-arid	-	one-dimensional, variably saturated flow model based on Richards (1931) equation (water movement in unsaturated porous media)	Small (2005)
Inner Mongolia, China	Arid/Semi-arid	Rainfall recharge: 15; River leakage: 20~650; Irrigation returns: 350	Wetting Threshold (and SMB/water balance in irrigated areas)	Ó Dochartaigh and MacDonald (2005)
West Bank Mountain Aquifer, Middle East	Arid/Semi-arid	Wetting Threshold Method: 150; SMD Method: 105; The composite model (SMD+urban+irrigation): 144.	Water Balance	Hughes and Mansour (2005), and Hughes et al. (2008)
Southeastern Australia	Arid/Semi-arid	-	Remote sensing and GIS	Tweed et al. (2007)
Abo Arroyo, New Mexico, USA	Arid/Semi-arid	-	Tracer	Stewart-Deaker et al. (2007)
Southern Africa	Tropical, Arid, and Semi-arid	Runoff calculation	Water Balance	Alemaw and Chaoka (2003)
Nile Basin	Tropical, Arid, and Semi-arid	0~5	Water Balance	Bonsor et al.(2009)
Western Cape, Africa	Mediterranean	17.4% of mean annual rainfall at the Table Mountain Group (TMG) Aquifer	Chloride and δ^{18}O tracers	Weaver and Talma (2005)

a regional scale. The estimated groundwater recharge based on point-source data in northern Nigeria ranges from 14-49 mm/a.

Rueedi et al. (2005) estimated the average groundwater recharge in Niger at 50-300 mm/a, using an isotope tracer method.

Goni (2008) estimated the average recharge in the south-western sector of the Chad basin using a chloride mass-balance method, at 20-50 mm/a.

Vrbka et al. (2008) and Oga et al. (2008) used a stable isotope tracer to reveal groundwater recharge sources respectively in north and central Sudan, and Abidjan (southern Ivory Coast). No actual recharge values were reported.

Tracer methods, both physical and chemical, have been the most successful in estimating groundwater recharge in arid and semiarid areas (Allison et al., 1994). However, these expensive and plot-scale based tracer methods are not suitable for routine estimation of regional groundwater recharge, especially on a continental scale. Nevertheless, the results of tracer methods for recharge estimation could provide useful values for the calibration and validation of

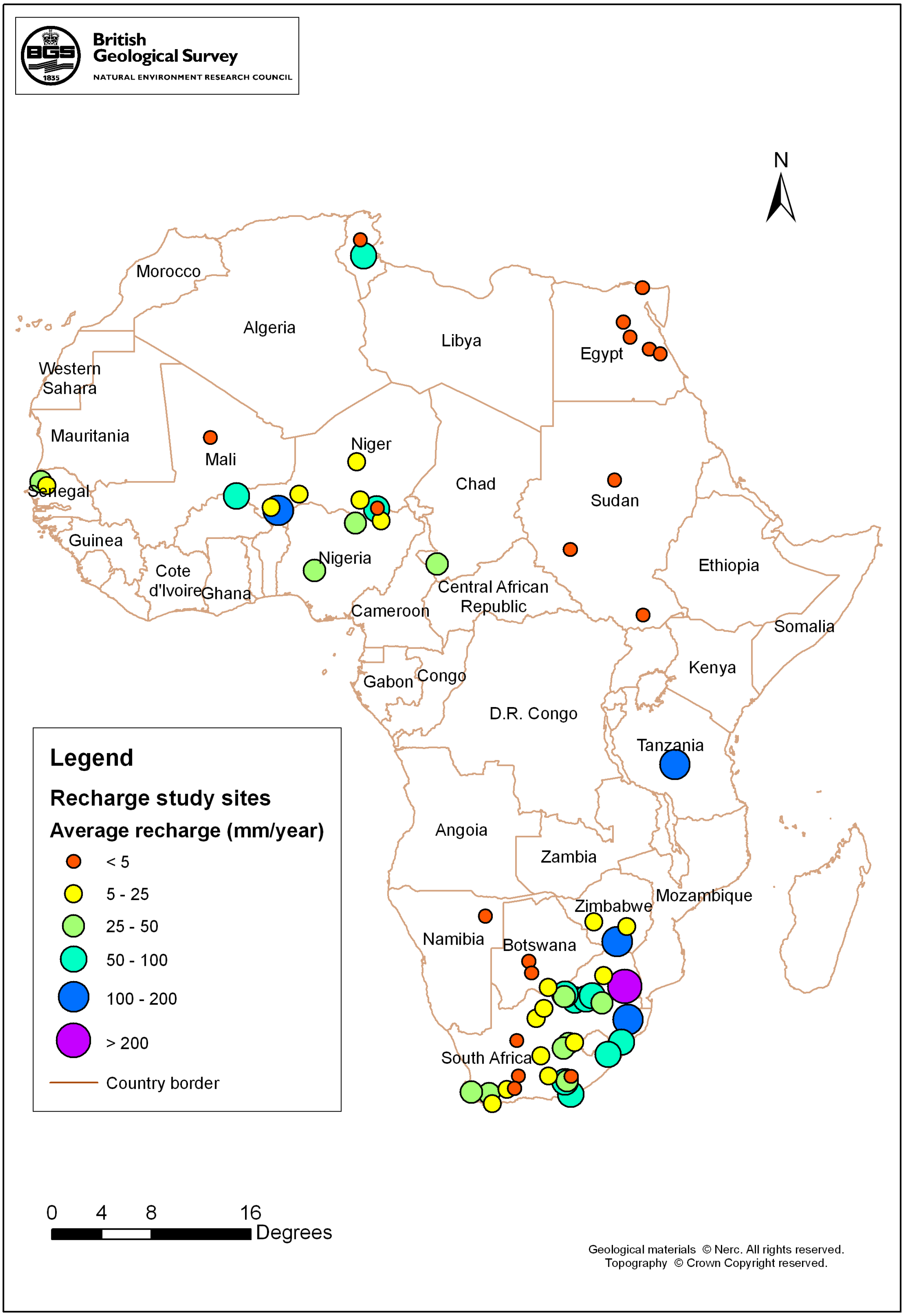

Figure 2. The locations and the average value of recharge estimates in Africa

an African-wide recharge model. For example, Scanlon et al. (2006) made a global synthesis of the findings from about 140 recharge studies in semi-arid and arid regions (including Africa) that provides important information on recharge rates, controls, and processes. According to Scanlon et al. (2006), average recharge rates in semi-arid and arid regions range from 0.2 to 35 mm/a, representing 0.1-5 % of long-term average annual precipitation. However extreme local variability in recharge, with rates up to about 720 m/a, could be resulted from focussed recharge beneath ephemeral streams, lakes, and preferential flow path. Climate variability at decadal to century scales recorded in chloride profiles in Africa results in recharge rates of 30 mm/a during the Sahel drought (1970–1986) to 50 mm/a during non-drought periods. Land use changes could affect the rate of groundwater recharge. For example, the impact of land use change was much greater than climate variability in Niger, where replacement of savanna by crops increased recharge by about an order of magnitude. Sensitivity of recharge to land use changes shows that recharge maybe controlled through management of land use.

3.2 WATER BALANCE METHODS

The advantages of water balance methods include using readily available data, such as rainfall and land use; and not being hindered by any presuppositions as to the mechanisms that control the individual components in water balance. Hence, they can be applied over a range of space and time scales, ranging from lysimeters (centimetres, seconds) to global climate models (kilometres, centuries). The disadvantages of water balance methods include: the fact that groundwater recharge is the residual, which is a small difference between large numbers, with potentially high cumulative errors from component fluxes, especially in arid and semi-arid environments; and the fact that some fluxes, such as runoff and evapotranspiration, cannot be measured easily (Lerner et al., 1990; Scanlon et al., 2002). Doubts over the suitability of water balance methods in arid and semi-arid areas have been expressed. For example, Hendrickx and Walker (1997) argued that soil moisture budgeting models are of limited use in such areas, since they are prone to large errors in calculating recharge because potential evapotranspiration is invariably much larger than rainfall. This is a valid criticism when the water balance model ignores soil and crop conditions, or uses too long a time step. As mentioned above, groundwater recharge in arid and semi-arid depends on rainfall events with high intensity. The longer a time step, the closer the amount of infiltration water and actual evapotranspiration resulting in small potential groundwater recharge and high potential errors. However, ***carefully designed water balance methods are powerful tools to understand the main processes of groundwater recharge, if short a time step and spatial variability of components in water balance is taken into account*** (Lerner et al., 1990; De Vries and Simmers, 2002; Eilers et al., 2007). The combination of a water balance method, local data, remote sensing, and GIS technology offers scope for a better understanding and quantification of regional groundwater recharge (Lerner et al., 1990; De Vries and Simmers, 2002).

A Soil Moisture Deficit (SMD) water balance method can be used to estimate groundwater recharge. SMD methods assume that groundwater recharge occurs when the amount of effective precipitation (precipitation minus evapotranspiration) at the surface raises the soil moisture to field capacity. When a SMD method is used for recharge estimation, a critical feature is the estimation of actual evapotranspiration when the crop is under stress (Lerner et al., 1990). Actual evapotranspiration depends on the moisture holding properties of the soil, the growth and harvesting of the crop and evaporation under bare soil conditions. Allen et al. (1998) provided valuable information about crop, and soil types. There are important differences in soil moisture conditions between a temperate climate where rainfall recharge generally occurs during the winter when crop growth is minimal, a semi-arid climate with a distinctive rainy season during which both the main crop growth and recharge occur, and a humid climate where crop growth and recharge can occur throughout the year (Rushton et al., 2006).

Taylor and Howard (1996) applied a SMD method to estimate groundwater recharge in the Aroca catchment of the Victoria Nile basin in central Uganda, and verified the calculated recharge using stable isotope data and groundwater flow modelling. The study revealed that estimated groundwater recharge averages in the order of 200 mm/a, and is more dependent on the number of heavy (more than 10 mm/day) rainfall events than the total annual volume of rainfall. Daily values of potential evapotranspiration were generated by applying a pan factor of 0.9 to monthly rates of pan evaporation, which has demonstrated as suitable in the Nile Basin region (Shahin, 1985), and dividing this by the number of days in the month. Runoff was generated based on study results from the Nile Basin (Shahin, 1985). In this study, a runoff factor of 3% was used when annual rainfall was less than the average for the period, and a value of 4% was used when annual rainfall exceeded the period average.

Taylor and Howard (1999) carried out a study of the impacts of tectonic setting on the hydrological characteristics of deeply weathered terrains in Uganda (equatorial tropical climate) using groundwater recharge estimates from SMD and stable isotope tracer methods. In south-western Uganda under a runoff-dominated regime, where stripping of the land surface has occurred since the mid-Pleistocene, groundwater recharge is restricted to years of exceptionally high rainfall. Annual surface runoff (34 mm/a), generated mainly from monsoon rainfall events, exceeds calculated recharge (8-15 mm/a).

Gheith and Sultan (2002) constructed a hydrological model to estimate the groundwater recharge rate for alluvial aquifers of the Eastern Desert from sporadic precipitation over the Red Sea Hills in Egypt. Annual groundwater recharge was estimated by assuming: i) initial loss (rain water lost before reaching stream) does not contribute to recharge to the alluvial aquifer; ii) recharge from smaller storms can be ignored; and iii) a large storm event of the magnitude of a 1994 flood event occurs once very 40 months. Runoff was calculated using the Curve Number (CN) method of the United States Department of Agriculture-Soil Conservation Service (USDA-SCS) (USDA-SCS, 1985). The flood hydrograph at the basin outlet was calculated as a function of lag time, i.e., the time from the centroid of a rain event to the peak discharge. According to Riverside County Flood Control and Water Conservation Distract (RCFC & WCD) (1978), lag time is a function of the length of the longest water course, the length along the longest water course to the sub-basin centroid, and the overall slope of the longest water course.

Rushton et al. (2006) developed an improved single layer daily SMD method, based on a single soil store, for estimating groundwater recharge in a wide variety of climatic conditions. Both transpiration from crops and evaporation from bare soil are included in the conceptual and computational models. A concept of “near surface soil storage” was introduced to account for continuing evapotranspiration on days following heavy rainfall even though a large soil moisture deficit exists. This study concluded that a single layer store model can be used to represent all the important processes if the additional a feature of near surface soil storage is introduced. The flexibility of this model was illustrated by two contrasting field studies: a rainfed crop in semi-arid northeast Nigeria, and a location where the long-term average rainfall and potential evapotranspiration are of similar magnitudes in England. The application of this method in semi-arid Nigeria was described by Eilers et al. (2007). The model can represent well the physical processes involved in groundwater recharge, including rainfall, runoff, evapotranspiration from bare land, rooting depths in vegetation yearly life cycle (i.e., sowing, seed germination, early development, mid-development, late development, and harvest), and a detailed description of the soil moisture deficit (Figure 3). The study described the estimation of model parameters, including daily rainfall, reference crop evapotranspiration, crop coefficient, soil evaporation coefficient, moisture content, field capacity, wilting point, depth of roots, depth for drying for evaporation, total available water, total evaporable water, depletion factor, readily available water, readily evaporable water, water stress coefficient, fraction for near surface storage, and runoff. It is worth noting that this method is a plot-scale based method requiring many parameters, and much work would be needed before using it to estimate the groundwater recharge for the whole of Africa.

Mileham et al. (2008) studied the effects of using different rainfall interpolation methods (spatial gridding based on rainfall station data) on groundwater recharge estimates in the humid tropics of equatorial Uganda. Runoff was calculated as a percentage of daily precipitation above a 10 mm threshold (Taylor and Howard, 1999). Potential evapotranspiration was calculated from pan evaporation, instead of by the Penman-Monteith method, because of the dearth of hydro-meteorological data for the study area. Actual evapotranspiration was calculated as a function of precipitation, runoff, recharge, antecedent SMD, and the actual current SMD. This study estimated a mean annual recharge of 104 mm/a and mean annual surface runoff of 144 mm/a.

Alemaw and Chaoka (2003) developed a continental-scale GIS hydrological model using SMD to calculate runoff for Southern Africa. Water balance components (precipitation infiltration, overland runoff, actual soil moisture and actual evapotranspiration) were calculated. The Curve Number (CN) method of USDA-SCS (1985) was adopted to estimate runoff using data for soil and land cover. Southern Africa includes arid, semi-arid, and humid regions. The suitability of a SMD method for these different climate regions was not addressed. This uncalibrated model estimated the mean annual generated runoff in Southern Africa as 151 mm/a.

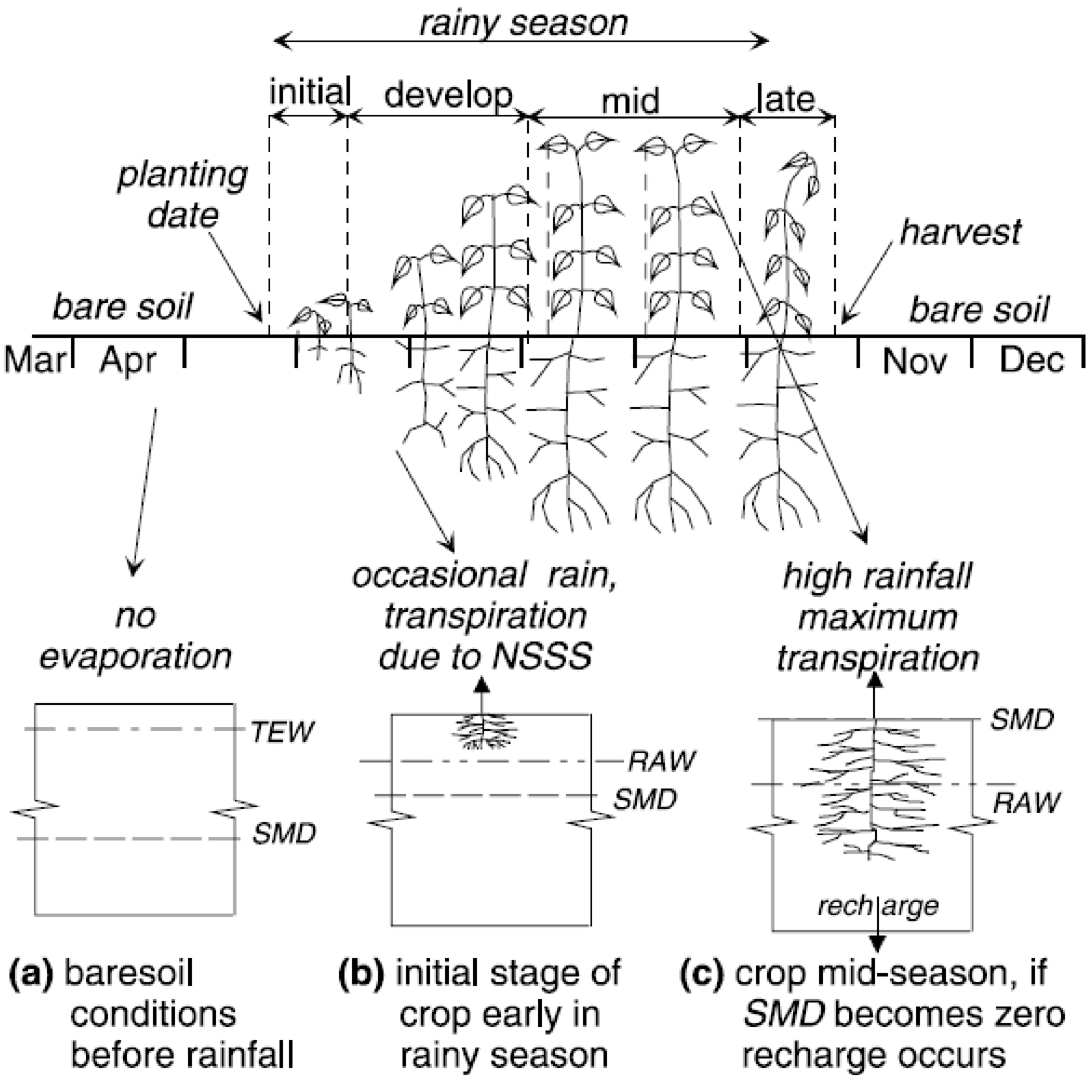

Figure 3. The impacts of the timing of millet crop growth on soil moisture at an experimental plot in north-eastern Nigeria (*Rushton et al., 2006*)

(NSSS: near surface soil storage, TEW: total evaporable water, RAW: readily available water)

Bonsor et al. (2009) estimated groundwater recharge in the Nile River Basin using ZOODRM (Mansour and Hughes, 2004), an object oriented distributed recharge model, hoping to interpret GRACE (Gravity Recovery And Climate Experiment (http://www.csr.utexas.edu/grace/)) data by separating groundwater mass from total water mass variation on a regional scale. Estimated annual groundwater recharge in the study area ranges from 0 to 5 mm/a. The recharge model was run for three full hydrological years from 2003 to 2005, and calibrated to observed annual discharge data for 1976-79 at 10 gauging station along the Nile and its tributaries. The model simulates observed annual Nile discharge to within 40% in all areas, and to within 20% in most areas, using realistic values of runoff (varying seasonally from 0.1 to 0.27) and overland losses (2% of runoff). The model reproduces observed evaporative losses from the river surface satisfactorily, and simulates a good water balance in each hydrological year. However, the authors point out that better calibration would be facilitated by access to modern river discharge data, which is lacking. They also point out that the lag time of runoff routing, evaporative losses from open water bodies, and pond open water storage are not considered by ZOODRM.

3.3 OTHER OR COMBINED SMD-TRACER METHODS

Houston (1990) investigated groundwater recharge in Zimbabwe (semi-arid climate) using both chloride tracers and an SMD method, and concluded that the amount of recharge depends upon rainfall, soil, and vegetation type; and the timing of recharge corresponds to the heaviest rainfalls of monsoons when rates of incoming precipitation (400 mm/a) temporarily exceed the intense evapotranspirative flux.

Van Tonder and Kirchner (1990) used neutron probe measurements and saturated volume fluctuation (groundwater fluctuation) methods to estimate groundwater recharge in the semi-arid Karoo aquifers of South Africa. The study showed that most recharge occurred along preferred pathways. Recharge in the study area varies from 2 to 5 % of annual rainfall. In areas which are overlain by a thick soil cover, recharge is less than 3%, while recharge in hilly areas with a thin soil cover may be of the order of 5%.

Carter (1994) used a steady-state unconfined flow equation to calculate groundwater recharge at 60 mm/a in the Manga Grasslands, northeast Nigeria. Based on this study, Carter et al. (1994) carried out groundwater modelling in the same area.

Carter and Alkali (1996) estimated groundwater recharge at 0.9 mm/a in the northeast arid zone of Nigeria, using a one dimensional flow equation.

Leduc et al. (1997) qualitatively analysed groundwater recharge in the arid Sahel in Niger based on four years of groundwater level observation data from an extensive network of wells and boreholes. In the study area, recharge is dominated by infiltration from temporary drainage networks, such as pools and streams, and aquifer response depends on aquifer hydraulic characteristics and distance from the nearest infiltration zone. Initial estimates of regional recharge are from 50 to 60 mm/a.

A hydrological study was carried out in the Romwe Catchment in semi-arid southern Zimbabwe to improve the understanding of links between climate, land use and hydrology in communal land areas, which are mostly underlain by crystalline basement aquifers (Bromley et al., 1999). As part of the Romwe catchment study, Butterworth et al. (1999b) investigated the redistribution of rainfall in different soil types (a red clay soil and a mixed soil of sand over clay) by measuring runoff in sub-catchments over an entire cropping season and the following dry season. Results indicate that surface water redistribution is of particular importance for groundwater recharge in years with low or evenly distributed rainfall. Butterworth et al. (1999a) analysed groundwater recharge and recession in the shallow weathered aquifers of the study area using rainfall data, groundwater level monitoring data from 65 boreholes, and soil moisture data. Results showed that where the soil profile was freely draining, groundwater levels typically responded within a few days of major rainstorms. In areas where a thick clay layer exists, annual fluctuations were smaller and groundwater levels rose more gradually in response to rainfall. In cultivated areas, vertical drainage was an important recharge mechanism. Butterworth et al. (1999c) evaluated the effects of variations in rainfall on groundwater level using soil water balance model, and a cumulative rainfall departure method. The soil water balance model simulated drainage (recharge) from daily rainfall and evaporative demand. Groundwater levels were then predicted, using monthly rainfall, as a function of drainage, specific yield and water table height, using the cumulative rainfall departure method (CRD) (Bredenkamp et al., 1995). The CRD method is analogous to a simple bucket type soil water balance model where the mean rainfall defines the size of soil water store. When the mean rainfall is exceeded, this store overflows, resulting in drainage and groundwater rise. For periods when rainfall is below the mean value, groundwater levels fall by an amount related the difference between rainfall and the mean. Results indicated that large perturbations in groundwater levels are a normal feature of the response of a shallow aquifer to variations in rainfall. The modelling methods described may be applied in the development of guidelines for groundwater abstraction schemes to help ensure safe long-term yields and to predict future stress on groundwater resources in low rainfall periods.

Hamza et al. (2007) carried out groundwater recharge estimation in semi-arid Tunisia using the equation of Williams and Kissel (1991) in GIS. This empirical equation links groundwater recharge to precipitation within the definition of four hydrological soil groups. The estimated recharge in the study area ranged from 61 to 108 mm/a.

Vouillamoz et al., (2008) used magnetic resonance soundings (MRS) to determine water table depth, aquifer transmissivity, aquifer total porosity, and specific yield; and then use the water table fluctuation method to estimate groundwater recharge in semi-arid Niger, where the Continental Terminal 3 aquifer's water table has continuously risen by 4 m in the past four decades. In the study area, groundwater recharge was about 2 mm/a before land clearance (1950s), whilst recent groundwater recharge rates have been about 23 mm/a from approximately 1995-2005.

Milewski et al. (2009) identified relatively large rainfall events from remote sensing datasets, and then input these climate data into a catchment-based hydrological model - Soil Water and Analysis Tools (SWAT) (Arnold, 1998), to estimate runoff and groundwater recharge in the arid Sinai Peninsula and the Eastern Desert of Egypt.

Sibanda et al. (2009) compared groundwater recharge estimation methods in the semi-arid Umguza district, Matebeleland North Province, Zimbabwe: a chloride mass balance method (19–62 mm/a); a water table fluctuation method (2–50 mm/a); Darcian flownet computations (16–28 mm/a); ^{14}C age dating (22–25 mm/a); and groundwater modelling (11–26 mm/a). It was concluded that the flownet computational and modelling methods provided better estimates for aereal recharge than the other methods. Based on the groundwater modelling method, the most realistic groundwater recharge for the area is 15–20 mm/a.

Vegter (1995) developed a national groundwater map for the Republic of South Africa, which included estimates of groundwater recharge. These are presented in Table 2.

4 Relevant recharge studies in arid and semi-arid regions outside Africa

Kennett-Smith et al. (1994) built a simple SMD water balance model to study the importance of factors affecting diffuse recharge in the arid southwestern Murray Basin, Australia. Generally, as the texture of the soil became heavier, the calculated recharge decreased. Under cropped land, as the clay content in the top 2 m of the soil profile increased from 0 to 20 %, recharge decreased by one order of magnitude (from about 30 to about 3 mm/a, for a mean annual rainfall of 310–380 mm). As mean annual rainfall increased, the mean annual recharge also increased. Sites with an average clay content in the top 2 m of about 10 % and a mean annual rainfall of 270 mm had an estimated recharge of about half that of sites with a mean annual rainfall of 310–380 mm. Data from land which was grazed but not cropped showed similar patterns.

Bazuhair and Wood (1996) used a chloride tracer method to study groundwater recharge in the wadi systems of the Asir and Hijaz mountains in western Saudi Arabia. In general, recharge was found to be between about 3 and 4 % of precipitation.

Table 2. Groundwater recharge estimates (derived from Vegter (1995))

Location	Longitude (degrees)	Latitude (degrees)	Mean annual rainfall (mm)	Mean annual recharge (mm)	Reference
Atlantis	E18.40	S33.56	375	Range from 32-70; mean 42.5	Bredenkamp et al. (1993); and Kok (1992)
Bedford	E26.10	S32.67	605	36.2	Kok (1992)
Bloemendal	E30.50	S29.55	910	65.4	Kok (1992)
Bosberg	E25.95	S32.73	700	50.4	Kok (1992)
Bredasdorp	E20.12	S34.52	460	22	Kok (1992)
Cape Padrone	E26.4	S33.75	640	53	Kok (1992)
De Aar	E24.0	S30.65	280	16.4	Kirchner et al. (1991); Vegter (1992)
Dewetsdorp	E26.68	S29.56	530	21.3	Kirchner et al. (1991)
Dorpsrivier	E29.06	S24.2	580	Range from 9.2– 17.8; mean13.1	Bredenkamp et al. (1993)
Hlobane	E31.0	S27.72	720	117	Van Wyk (1963)
Klein Swartberg	E21.3	S33.36	245	12.5	Vegter (1995)
Kokstad	E29.42	S30.55	760	55	Kok (1992)
Koo	E19.85	S33.68	535	47.7	Vegter (1995)
Kuruman	E23.63	S27.63	460	15	Bredenkamp et al. (1992);
Louwna-Coetzersdam	E24.23	S26.85	450	12	Botha and Bredenkamp (1992)
Marydale	E22.08	S29.42	185	0.8	Vegter (1995)
New Bethesda	E24.62	S32.28	315	21.9	Kok (1992)
Pretoria Fountains	E28.13	S25.83	675	74.3	Kok (1992)
Reddersburg	E26.25	S29.67	480	38.1	Kok (1992)
Rietpoort	E25.95	S25.70	530	Range from 48-67.2; mean 56.7	Botha (1993)
Sabie	E30.75	S25.08	1250	288	Kok (1992)
Schoonspruit	E26.75	S26.16	660	82.1	Kok (1992); Polivka (1987)
Steenkoppies	E27.63	S26.05	650	Range from 70.4-87.5; mean 81.1	Bredenkampn (1986); Enslin and Kriel (1967); and Fleisher (1981)
Trompsburg	E25.80	S30.03	370	25.2	Kok (1992)
Upper Molopo	E25.88	S25.88	570	Range from 46-49.3; mean 47.8	Bredenkamp et al. (1987); and Bredenkamp et al. (1993)
Vicinity Leandra	E28.92	S26.38	700	35	Vegter (1995)

Lewis and Walker (2002) used a simple water balance model to assess the potential recharge at 53 sites throughout Western Australia. Their model calculated the difference between daily rainfall and evapotranspiration. If there is a rain excess, it is added to the available soil storage. If the evapotranspiration cannot be satisfied by daily rainfall, it is taken from soil water storage. Recharge occurs when the available soil water store becomes full. The results showed that a substantial proportion of the recharge in drier parts of the agricultural areas occurred episodically, and that direct episodic recharge could be as important in some semi-arid areas as in arid regions. Mean annual rainfall is not a strong predictor of the percentage of episodic recharge to total recharge at a site.

Small (2005) investigated the climatic controls on diffuse recharge in semi-arid environments of the southwestern USA using a one-dimensional, variably saturated flow model based on the Richards equation (Richards, 1931). The model is driven by a stochastic parameterisation of climate that includes storm size distribution and seasonality of precipitation and potential evapotranspiration.

ZOODRM has been applied both in humid and arid/semi-arid regions for estimating groundwater recharge, such as the West Bank Mountain Aquifer, Palestine (Hughes and Mansour, 2005; Hughes et al., 2008) with estimated recharge 143.5 mm/a, and Inner Mongolia, China (Ó Dochartaigh and MacDonald, 2005) (estimated direct recharge at 15 mm/a).

Tweed et al. (2007) combined remote sensing data and GIS techniques to map groundwater recharge and discharge areas in an unconfined basalt aquifer in a drought prone region of southeastern Australia. A set of index indicators was built up to indentify the recharge and discharge areas.

A series of groundwater recharge studies in arid and semi-arid southwestern United States focused on understanding the interacting processes that modulate recharge, in order to improve understanding of recharge dynamics. For example, Stewart-Deaker et al. (2007) investigated groundwater recharge in arid/semi-arid Abo Arroyo, New Mexico using a chloride tracer method in the unsaturated zone. Stonestrom et al. (2007) examined groundwater recharge derived from ephemeral flows in rivers in the arid Amargosa Desert Basin by using streamflow data and chloride tracer. The Amargosa Desert portion of the rivers are dry more than 98 % of the time, but infiltration losses during ephemeral flows of these rivers provide the main sources of groundwater recharge on the desert basin floor. Moore (2007) examined streambed infiltration rates in Arroyo Hondo, New Mexico through use of an inverse modelling technique that fits simulated to measured subsurface temperatures. Cumulative streambed infiltration rates were estimated from streambed infiltration rates, channel widths, and the downstream extent and duration of streamflow. Environmental tracers (chloride and bromide) were used to investigate the presence of recharge at selected sites. Izbicki et al. (2007) assessed recharge from intermittent stream sources in the Westtern Mojave Desert, California using hydraulic, thermal, geomorphological, chemical, and isotopic data. The rate of downward movement of water through the unsaturated zone underlying Oro Grande Wash and Sheep Creek Wash was estimated on the basis of tritium data.

5 A global hydrological model

A global-scale hydrological model has been developed to estimate long term runoff and subsequently to derive groundwater recharge based on the estimated runoff. This is the WaterGAP Global Hydrology Model (WGHM), at a grid scale of 0.5 degree × 0.5 degree (Döll et al. 2003, Döll and Flörke 2005, and Döll and Fiedler 2008). The model uses meteorological inputs of monthly values of precipitation, temperature, number of wet days per month, cloudiness, and daily sunshine hours. **Daily potential evapotranspiration** is computed using the method of Priestley and Taylor (1972), following the recommendation of Shuttleworth (1993). Vertical water balances for open water bodies and land areas are calculated separately, taking into account canopy evaporation, soil water content, effective rainfall, actual evapotranspiration, and runoff from the land surface. The runoff from open water bodies is assumed to be the difference between precipitation and potential evapotranspiration. Actual evaporation is assumed to be equal to potential evapotranspiration in the model. The vertical water balance of land areas is described by a canopy water balance and a soil water balance (Figure 4).

Canopy evaporation (E_c) is computed as a function of potential evapotranspiration, amount of water stored in the canopy, the maximum amount of water that can be stored in the canopy, and one-side leaf area index. **Actual evapotranspiration** is calculated as a function of potential evapotranspiration, E_c, soil water content in the effective root zone, and total available soil water capacity in the effective root zone.

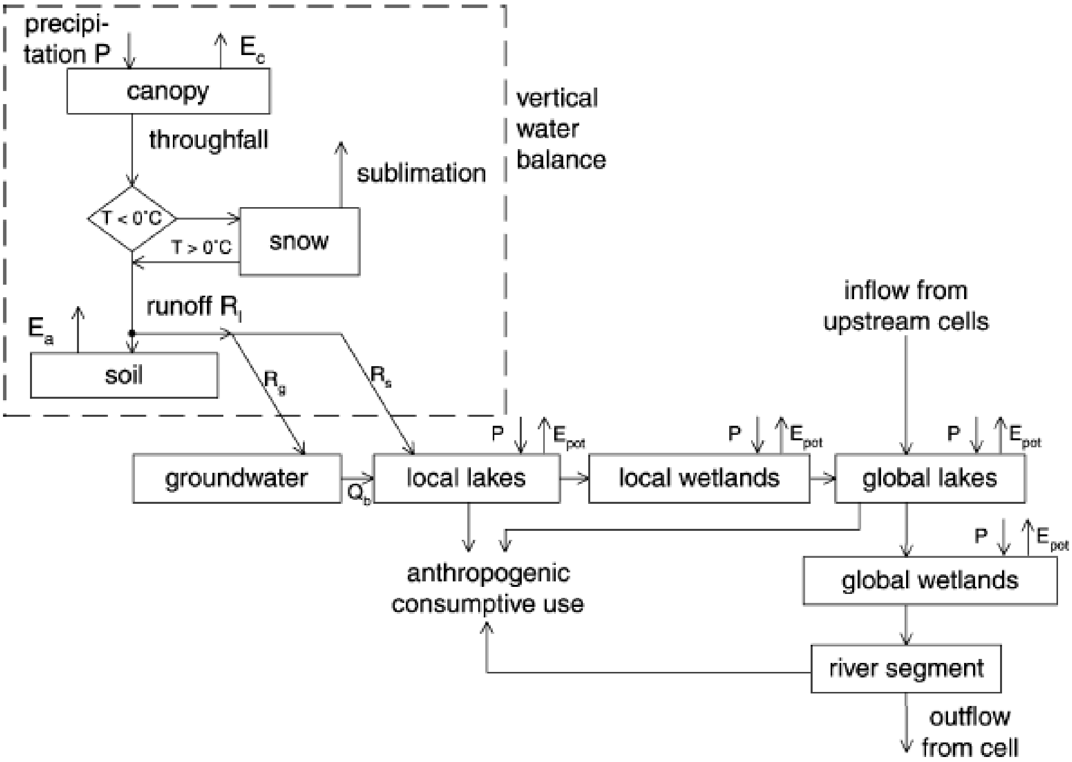

Figure 4. Schematic representation of the global hydrological model WGHM, a module of WaterGAP 2 (Döll et al., 2003)

(Epot: potential evapotranspiration, Ea: actual evapotranspiration from soil, Ec: evaporation from canopy, Rg: recharge, Rs: surface runoff). The vertical water balance of the land and open water fraction of each cell is coupled to a lateral transport scheme, which first routes the runoff through a series of storages within the cell and then transfers the resulting cell outflow to the downstream cell. The water volume corresponding to human consumptive water use is taken either from the lakes (if there are lakes in the cell) or the river segment.

Total runoff is calculated as a function of effective rainfall, runoff coefficient, soil water content in the effective root zone, and total available soil water capacity in the effective root zone. The total runoff resulting from WGHM is divided into surface runoff and groundwater recharge. The groundwater recharge R_g is expressed as:

$$R_g = \min(R_{g\max}, f_g R_l) \qquad f_g = f_r\, f_t\, f_h\, f_{pg} \qquad \textbf{Equation 1}$$

where Rg max = soil texture-specific maximum groundwater recharge (infiltration capacity) (mm/day)

R_l = total runoff from land area in cell (mm/day)

f_g = groundwater recharge factor [0, 1)

f_r = topography factor (0, 1)

f_t = soil texture-related factor [0,1]

f_h = hydrogeology-related factor (0, 1)

f_{pg} = permafrost/glacier-related factor [0,1]

The values of these factor coefficients depend on a qualitative understanding of the influence of these factors on the partitioning of total runoff. The final groundwater recharge result is therefore subjective. For example, in the process of identifying hydrogeological factors, a global geological map was compared with a European hydrogeological map (named Pan-Europe) to make a rough classification of global hydrogeological units. These were (with the assigned hydrogeological factor in brackets):

- Cenozoic and Mesozoic sedimentary rocks with high hydraulic conductivity (f_h=1);
- Paleozoic and Precambrian sedimentary rocks with low hydraulic conductivity (fh = 0.8 in hot and humid climates; 0.7 in other regions); and
- non-sedimentary rocks with very low hydraulic conductivity (fh = 0.7 in hot and humid climates; 0.5 in other regions).

It was assumed that groundwater recharge increases proportionally to annual temperature and precipitation, because high temperature and precipitation enhance weathering. The values of f_h were therefore modified based on the long-term (1961-1990) average annual temperature and precipitation in each cell.

Döll and Fiedler (2008) conclude that the conceptual model of groundwater recharge in their study is more appropriate for humid than for semi-arid areas. To partially address this, their model uses add-on reduction criteria (allowing groundwater recharge in soil with a medium to coarse texture, only if daily precipitation is greater than 10 mm/day) in order to match the calculated groundwater recharge values for semi-arid areas more closely to recharge values derived from other independent studies. Figure 5 shows long-term average groundwater recharge (1961-1990) in Africa from Döll and Flörke (2005).

A strength of Döll’s study is the introduction of factors for topography, soil texture, and geological weathering in calculating actual recharge. However, these factors have been estimated based on expert qualitative opinion, rather than being based on measured quantitative data, which is likely to lead to uncertainty in calculating actual recharge. Where measured data are available, it may be possible to include these and so reduce uncertainty

The concept of splitting runoff into groundwater recharge and surface runoff (Figure 4, and Equation 1) used by Döll and Fiedler (2008) needs to be checked, before applying it to the development of a new Africa-scale groundwater recharge model. Groundwater recharge, the downward water flow reaching the water table, can be defined by Equation 2 in a general sense (Lerner et al., 1990).

Recharge = rainfall – runoff – actual evapotranspiration
± moisture storage change above the water table **Equation 2**

The simplified processes for groundwater recharge are shown in Figure 1. Direct groundwater recharge is the water reaching the water table through a vertical percolation process in the unsaturated zone in excess of soil moisture deficits and evapotranspiration after some water is removed from rainfall in a form of surface runoff. Indirect groundwater recharge occurs at the localised surface water courses, such as rivers and ponds. Between direct and indirect groundwater recharge, there is an intermediate category of groundwater recharge (Lerner et al., 1990) that occurs during the horizontal movement of runoff before reaching at rivers or ponds. The indirect and intermediate groundwater recharge implies that some of runoff could end up with groundwater recharge before or after joining in surface water courses. But, it would not be conceptually correct if groundwater recharge were simply estimated as a portion of surface runoff in each modelling cell by ignoring the actual groundwater recharge processes.

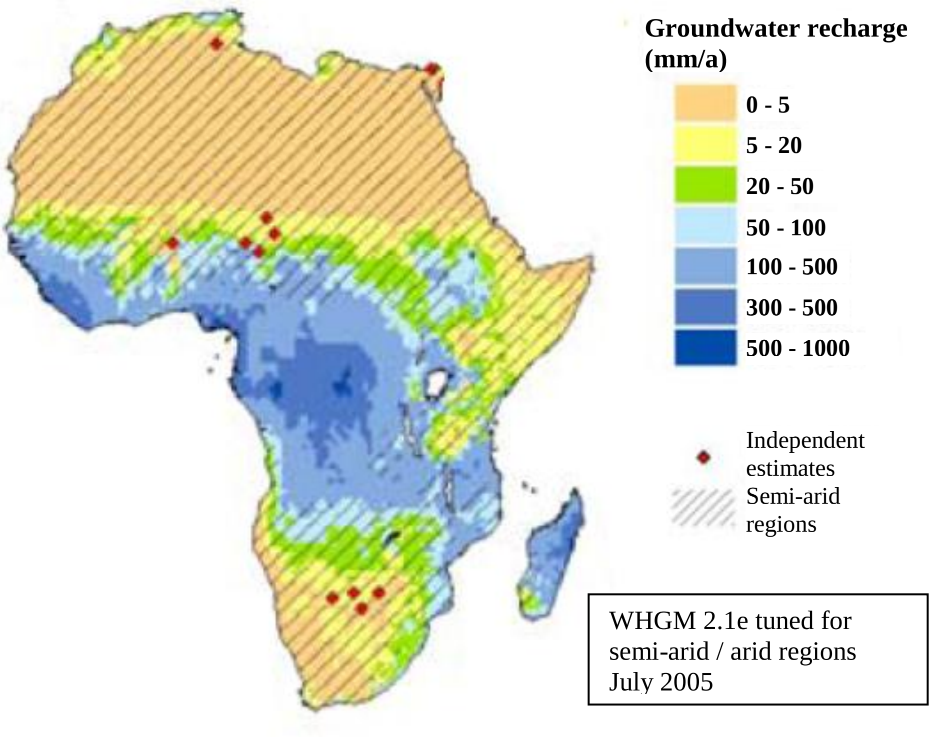

Figure 5. Long-term average groundwater recharge for the period 1961-1990 as computed by WHGM 2.1e (version tuned for semi-arid/arid regions) (*Adapted from Döll and Flörke (2005)*)

6 Index methods for assessing groundwater resource vulnerability

Döll (2009) calculated the impact of climate change on groundwater recharge using WGHM, and the number of affected people, based on four climate scenarios. The vulnerability of populations to decreased groundwater resources was computed using three indices: a water scarcity index, an index of the dependence of water supply on groundwater, and a human development index. In the A2 (B2) emissions scenario (A2: equivalent CO2 emission increase from 11 Gt C /a in 1990 to 25 Gt C/a in 2050s; B2: CO2 increase only to 16 Gt C/a in 2050), 18.4–19.3% (16.1–18.1%) of the global population of 10.7 (9.1) billion would be affected by groundwater recharge decreases of at least 10%, and 4.8–5.7% (3.8–3.8%) of the global population would be in the two highest vulnerability classes. The highest vulnerabilities, with moderate to high senstivitiy, are found at the North African rim of the Mediterranean Sea; in southwestern Africa; in north-eastern Brazil; and in the central Andes.

The British Geological Survey developed a practical index method to produce a map of groundwater availability for Ethiopia during drought, indicating the degree of groundwater availability under different rainfall and aquifer conditions, in order to guide groundwater resources management. This index method made allowances for groundwater recharge, groundwater recharge acceptance, and groundwater storage. Groundwater recharge acceptance and storage were assumed to be controlled by aquifer (rock) permeability and by porosity and permeability type. High aquifer permeability means that groundwater can move more freely through the unsaturated zone to the water table. Aquifers dominated by intergranular porosity/permeability, storing groundwater in pore spaces, have a larger storage capacity than fractured or karstic aquifers. Aquifer permeability and storage were estimated from available hydrogeology and geology maps. Long term average rainfall was used as a proxy for recharge, assuming that long-term rainfall is more important in controlling long-term recharge to aquifers than short term variations, because aquifers react slowly to changes in rainfall. Long term average rainfall was derived from a 3 minute grid of monthly rainfall for Africa for 1951-1995 (New and Hulme, 1997), and was divided into four rainfall categories: less than 250 mm/a; 250 mm/a to 500 mm/a; 500 mm/a to 1000 mm/a; and greater than 1000 mm/a (Calow et al., 2006).

7 Conclusions

This review has highlighted a gap in information on the scale and temporal and spatial distribution of groundwater recharge across much of Africa. Most existing recharge estimates have been done on an *ad hoc* basis using very different methods and data, so that there is no consistency between estimates in different regions. There is a need for a process-based continental scale recharge estimate that uses a consistent approach and data, as the basis for studying potential climate change impacts on groundwater resources in Africa. The only existing continental scale recharge model, WGHM, was originally designed to estimate global runoff, and does not fully quantitatively account for detailed hydrogeological processes, in particular for soil moisture change process related to groundwater recharge.

Developing a continental-scale groundwater recharge model for Africa, with its highly variable climate zones (hyperarid, arid, semi-arid, dry sub-humid, humid, tropical, and Mediterranean), is a major challenge. Groundwater recharge modelling is particularly challenging in arid and semi-arid areas, where small amounts of groundwater recharge derive from infrequent large rainfall events, and where annual rainfall totals are therefore not a good predictor of annual potential recharge. A process-based quantitative groundwater recharge model based on a robust conceptual model is essential for reducing uncertainty in groundwater recharge estimates in arid and semi-arid regions.

Data availability is a major issue in developing a continental-scale groundwater recharge model. Any process-based model will have extensive data requirements, which could include meteorological (rainfall, evapotranspiration); hydrological (river flow); land use; soil; and geology. Unsurprisingly there are no consistent datasets at a continental scale; at larger scales, much of this information is also patchy, both spatially and temporally. Non-traditional data sources such as remotely sensed data (for example, GRACE), may be useful substitutes for some traditional data sources.

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Appendix 1

Table A1. The attribute table of the GIS database of recharge studies in Africa

Latitude	Longitude	Location	Location accuracy	Scale	Climatic type	Number of estimates	Recharge component	Recharge (mm/a)	Average recharge (mm/a)	Min recharge (mm/a)	Max recharge (mm/a)	Average recharge accuracy	Method	If validated	Confidence level	Reference	Comment
N19.062118	W2.548828	Sahel	Estimated	Site	Arid	Range	Direct rainfall recharge	0.1-1.3	0.7	0.1	1.3	Average from range	Tracer	Self_validated	High	Edmunds and Gaye (1994)	
N28.386488	E30.629416	Tarfa, Eastern Desert, Egypt	Estimated	Catchment-scale	Arid	1	Direct rainfall recharge	0.08	0.08	0.08	0.08	Single value	Water balance	results were compared with that from reports	Medium	Gheith and Sultan (2002)	
N27.183847	E31.185036	Asyuti, Eastern Desert, Egypt	Estimated	Catchment-scale	Arid	1	Direct rainfall recharge	0.11	0.11	0.11	0.11	Single value	Water balance	results were compared with that from reports	Medium	Gheith and Sultan (2002)	
N26.170345	E32.72383	Qena, Eastern Desert, Egypt	Estimated	Catchment-scale	Arid	1	Direct rainfall recharge	0.09	0.09	0.09	0.09	Single value	Water balance	results were compared with that from reports	Medium	Gheith and Sultan (2002)	
N31.120742	E32.160866	Hammamat, Eastern Desert, Egypt	Estimated	Catchment-scale	Arid	1	Direct rainfall recharge	0.24	0.24	0.24	0.24	Single value	Water balance	results were compared with that from reports	Medium	Gheith and Sultan (2002)	
N25.839449	E33.612671	Eastern Desert of Egypt	Estimated	Catchment-scale	Arid	Precentage of rainfall	Direct rainfall recharge	21.2% of annual rainfall				Indirect	RS&SWAT	SWAT was calibrated using runoff data	Medium	Milewski et al. (2009)	
N13.329494	E10.806427	Kajemarum Oasis, Northeast Nigeria	Estimated	Site	Arid	1	Direct rainfall recharge	60	60	60	60	Single value	Steady-state unconfined flow equation	GWLs were used in modelling	Medium	Carter (1994)	
N13.394963	E10.870972	Upland in Northeast Nigeria	Estimated	Basin	Arid	1	Direct rainfall recharge	0.9	0.9	0.9	0.9	Single value	One dimensional flow equation	GWLs were used in modelling	Medium	IWACO (1985)	
S23.039298	E23.027344	Botswana Kalahari	Estimated	Region	Semi-arid	2	Direct rainfall recharge	1 and 5	3	1	5	Average	modelling and tracer	Self_validated	High	De Vries et al. (2000)	
S32.301063	E26.444092	Eastern Cape, South Africa	Estimated	Basin	Semi-arid	Recharge mechanism study	Direct rainfall recharge					No estimated value	Tracer	Self_validated	High	Sami (1992)	
N13.475106	E2.329102	Sahelian, South-West Niger	Estimated	Region	Semi-arid	two ranges	Direct rainfall recharge	1-5 (1950s-1960s), and 20-50 (1990-2000)	25	1	50	Average from ranges	Tracer	Self_validated	High	Leduc et al. (2001)	
N17.14079	E9.206543	Niger	Estimated	Region	Semi-arid	2	Direct rainfall recharge	6 (1950s-1960s), and 20 (1990-2000)	13	6	20	Average	Tracer	Self_validated	High	Favreau et al. (2002)	

Latitude	Longtude	Location	Location accuracy	Scale	Climatic type	Number of estimates	Recharge component	Recharge (mm/a)	Average recharge (mm/a)	Min recharge (mm/a)	Max recharge (mm/a)	Average recharge accuracy	Method	If validated	Confidence level	Reference	Comment
N13.223904	E2.889404	Iullemmeden basin, South-West Niger	Estimated	Region	Semi-arid	Range	Direct rainfall recharge	50-300	175	50	300	Average	Tracer	Self_validated	High	Rueedi et al.(2005)	
N14.397439	W0.461426	Sahel in Niger	Estimated	Site	Semi-arid	Range	Direct rainfall recharge	50-60	55	50	50	Average	Groundwater level observation	compared with other studies	Low	Leduc et al. (1997)	
N8.928487	E15.644531	South-West Chad	Estimated	Basin	Semi-arid	Range	Direct rainfall recharge	20-50	35	20	50	Average	Tracer	Self_validated	High	Goni (2008)	
N15.665354	E29.926758	North and central of Sudan	Estimated	Region	Semi-arid	Indentify groundwater recharge sources	Direct rainfall recharge					No estimated value	Tracer	Self_validated	High	Vrbka et al. (2008)	
S32.277845	E22.208862	Karoo aquifers of South Africa	Estimated	Region	Semi-arid	Precentage of rainfall	Direct rainfall recharge	2-5% of the annual rainfall				Indirect	Neutron probe measurements and saturated volume fluctuation	compared between different methods	High	Van Tonder and Kirchner (1990)	
N33.706063	E9.755859	Tunisia	Estimated	Region	Semi-arid	Range	Direct rainfall recharge	61-108	84.5	61	108	Average	The equation of Williams and Kissel (1991) (Empirical equation based on groundwater vulnerability ranks)	No validation	Low	Hamza et al. (2007)	
N14.51978	E4.54834	Continental Terminal 3 aquifer in Niger	Estimated	Region	Semi-arid	2	Direct rainfall recharge	2 (1950s-1960s), and 23 (1995-2005)	12.5	2	23	Average	The combination of magnetic resonance soundings and water table fluctuation	compared with other studies	Medium	Vouillamoz et al., (2008)	
S21.473518	E30.124512	Southern Zimbabwe	Estimated	Region	Semi-arid	Range	Direct rainfall recharge	104-161	132.5	104	161	Average	Comparing rainfall, groundwater level, and soil moisture data monitored	Not_sure	Medium	Butterworth et al. (1999a,b)	
S19.877809	E28.273315	Nyamandhlovu aquifer, Umguza district in Matebeleland North Province in Zimbabwe	Estimated	Region	Semi-arid	Range	Direct rainfall recharge	15-20	17.5	15	20	Average	Tracer, Water table fluctuation method, Darcian flownet computations, and groundwater modelling	compared results from different methods and with other studies	High	Sibanda et al. (2009)	
N4.806365	E32.233887	Nile Basin	Estimated	Region	Tropical, Arid, and Semi-arid	Range	Direct rainfall recharge	0-5	2.5	0	5	Average	Water Balance	No	Low	Bonsor et al.(2009)	
S33.254767	E21.873779	Western Cape, Africa	Estimated	Region	Mediterranean	Precentage of rainfall	Direct rainfall recharge	17.4% of mean annual rainfall				Indirect	Chloride and δ18O tracers	Self_validated	High	Weaver and Talma (2005)	

Latitude	Longtude	Location	Location accuracy	Scale	Climatic type	Number of estimates	Recharge component	Recharge (mm/a)	Average recharge (mm/a)	Min recharge (mm/a)	Max recharge (mm/a)	Average recharge accuracy	Method	If validated	Confidence level	Reference	Comment
S33.56	E18.4	Atlantis, South Africa	Accurate	Not sure	Not sure	Range	Direct rainfall recharge	32-70	42.5	32	70	Single value	Not sure	Not sure	Not sure	Bredenkamp et al. (1993); and Kok (1992)	
S32.67	E26.1	Bedford, South Africa	Accurate	Not sure	Humid	1	Direct rainfall recharge	36.2	36.2	36.2	36.2	Single value	Not sure	Not sure	Not sure	Kok (1992)	
S29.55	E30.5	Bloemendal, South Africa	Accurate	Not sure	Humid	1	Direct rainfall recharge	65.4	65.4	65.4	65.4	Single value	Not sure	Not sure	Not sure	Kok (1992)	
S32.73	E25.95	Bosberg, South Africa	Accurate	Not sure	Humid	1	Direct rainfall recharge	50.4	50.4	50.4	50.4	Single value	Not sure	Not sure	Not sure	Kok (1992)	
S34.52	E20.12	Bredasdorp, South Africa	Accurate	Not sure	Mediterranean	1	Direct rainfall recharge	22	22	22	22	Single value	Not sure	Not sure	Not sure	Kok (1992)	
S33.75	E26.4	Cape Padrone, South Africa	Accurate	Not sure	Humid	1	Direct rainfall recharge	53	53	53	53	Single value	Not sure	Not sure	Not sure	Kok (1992)	
S30.65	E24	De Aar, South Africa	Accurate	Not sure	Semi-arid	1	Direct rainfall recharge	16.4	16.4	16.4	16.4	Single value	Not sure	Not sure	Not sure	Kirchner et al. (1991); Vegter (1992)	
S29.56	E26.68	Dewetsdorp, South Africa	Accurate	Not sure	Humid	1	Direct rainfall recharge	21.3	21.3	21.3	21.3	Single value	Not sure	Not sure	Not sure	Kirchner et al. (1991)	
S24.2	E29.06	Dorpsrivier, South Africa	Accurate	Not sure	Humid	Range	Direct rainfall recharge	9.2– 17.8	13.1	9.2	17.8	Single value	Not sure	Self_validated	High	Bredenkamp et al. (1993)	
S27.72	E31	Hlobane, South Africa	Accurate	Not sure	Humid	1	Direct rainfall recharge	117	117	117	117	Single value	Not sure	Not sure	Not sure	Van Wyk (1963)	
S33.36	E21.3	Klein Swartberg, South Africa	Accurate	Not sure	Mediterranean	1	Direct rainfall recharge	12.5	12.5	12.5	12.5	Single value	Not sure	Not sure	Not sure	Vegter (1995)	
S30.55	E29.42	Kokstad, South Africa	Accurate	Not sure	Humid	1	Direct rainfall recharge	55	55	55	55	Single value	Not sure	Not sure	Not sure	Kok (1992)	
S33.68	E19.85	Koo, South Africa	Accurate	Not sure	Mediterranean	1	Direct rainfall recharge	47.7	47.7	47.7	47.7	Single value	Not sure	Not sure	Not sure	Vegter (1995)	
S27.63	E23.63	Kuruman, South Africa	Accurate	Not sure	Semi-arid	1	Direct rainfall recharge	15	15	15	15	Single value	Not sure	Not sure	Not sure	Bredenkamp et al. (1992); Smit (1978)	
S26.85	E24.23	Louwna-Coetzersdam, South Africa	Accurate	Not sure	Semi-arid	1	Direct rainfall recharge	12	12	12	12	Single value	Not sure	Not sure	Not sure	Botha and Bredenkamp (1992)	
S29.42	E22.08	Marydale, South Africa	Accurate	Not sure	Semi-arid	1	Direct rainfall recharge	0.8	0.8	0.8	0.8	Single value	Not sure	Not sure	Not sure	Vegter (1995)	
S32.28	E24.62	New Bethesda, South Africa	Accurate	Not sure	Semi-arid	1	Direct rainfall recharge	21.9	21.9	21.9	21.9	Single value	Not sure	Not sure	Not sure	Kok (1992)	

Latitude	Longtude	Location	Location accuracy	Scale	Climatic type	Number of estimates	Recharge component	Recharge (mm/a)	Average recharge (mm/a)	Min recharge (mm/a)	Max recharge (mm/a)	Average recharge accuracy	Method	If validated	Confidence level	Reference	Comment
S25.83	E28.13	Pretoria Fountains, South Africa	Accurate	Not sure	Humid	1	Direct rainfall recharge	74.3	74.3	74.3	74.3	Single value	Not sure	Not sure	Not sure	Kok (1992)	
S29.67	E26.25	Reddersburg, South Africa	Accurate	Not sure	Humid	1	Direct rainfall recharge	38.1	38.1	38.1	38.1	Single value	Not sure	Not sure	Not sure	Kok (1992)	
S25.7	E25.95	Rietpoort, South Africa	Accurate	Not sure	Humid	Range	Direct rainfall recharge	48-67.2	56.7	48	67.2	Single value	Not sure	Not sure	Not sure	Botha (1993)	
S25.08	E30.75	Sabie, South Africa	Accurate	Not sure	Humid	1	Direct rainfall recharge	288	288	288	288	Single value	Not sure	Not sure	Not sure	Kok (1992)	
S26.16	E26.75	Schoonspruit, South Africa	Accurate	Not sure	Humid	1	Direct rainfall recharge	82.1	82.1	82.1	82.1	Single value	Not sure	Not sure	Not sure	Kok (1992); Polivka (1987)	
S26.05	E27.63	Steenkoppies, South Africa	Accurate	Not sure	Humid	Range	Direct rainfall recharge	70.4-87.5	81.1	70.4	87.5	Single value	Not sure	Not sure	Not sure	Bredenkampn (1986); Enslin and Kriel (1967); and Fleisher (1981)	
S30.03	E25.8	Trompsburg, South Africa	Accurate	Not sure	Humid	1	Direct rainfall recharge	25.2	25.2	25.2	25.2	Single value	Not sure	Not sure	Not sure	Kok (1992)	
S25.88	E25.88	Upper Molopo, South Africa	Accurate	Not sure	Humid	Range	Direct rainfall recharge	46-49.3	47.8	47.8	47.8	Single value	Not sure	Not sure	Not sure	Bredenkamp et al. (1987); and Bredenkamp et al. (1993)	
S26.38	E28.92	Vicinity Leandra, South Africa	Accurate	Not sure	Humid	1	Direct rainfall recharge	35	35	35	35	Single value	Not sure	Not sure	Not sure	Vegter (1995)	
N35.003003	E9.503174	Tunisia	Estimated	6 sites	Semi-arid	1	Direct rainfall recharge	1.3	1.3	1.3	1.3	Single value	Chloride Tracer	Self_validated	High	Edmunds (2001)	Sand, natural agricultural
N15.538376	W16.193848	Senegal	Estimated	2 sites	Semi-arid	4	Direct rainfall recharge	22 and 26 (^{3}H); 29 and 34 (Chloride)	27.75	22	34	Average	Chloride and ^{3}H Tracers	Self_validated	High	Gaye and Edmunds (1996)	Sand, Dry land agricultural
N15.199386	W15.732422	Senegal	Estimated	19 sites	Semi-arid	1	Direct rainfall recharge	15	15	15	15	Single value	Chloride Tracer	Self_validated	High	Cook et al. (1992)	Dry land agricultural
N14.072645	E9.470215	Niger	Estimated	1 site	Semi-arid	2	Direct rainfall recharge	13 (unsaturated zone), 28 (saturated zone)	20.5	13	28	Single value	Chloride Tracer	Self_validated	High	Bromley et al. (1997)	Tiger bush (banded woodland and bare soil)
N8.407168	E5.800781	Nigeria	Estimated	345 sites	Arid	Range and value	Direct rainfall recharge	15-54(unsaturated zone), and 60 (saturated zone)	37.5	15	60	Average	Chloride Tracer	Self_validated	High	Edmunds et al. (1999)	Grasslands, interdune laskes and playas
N10.055403	E26.367188	Sudan	Estimated	14 sites	Semi-arid	Range and value	Direct rainfall recharge	0.3-1.3 (Interfluvial sandy clay); 2.8	3.05	0.3	5.8	Average	Chloride Tracer	Self_validated	High	Edmunds et al. (1988)	

Latitude	Longtude	Location	Location accuracy	Scale	Climatic type	Number of estimates	Recharge component	Recharge (mm/a)	Average recharge (mm/a)	Min recharge (mm/a)	Max recharge (mm/a)	Average recharge accuracy	Method	If validated	Confidence level	Reference	Comment
								(Sandstone ridge, possible surface runoff)									
S24.006326	E23.269043	Botswana	Estimated	6 sites	Semi-arid	3	Direct rainfall recharge	0.5 (Chloride), 1.1 (Isotope), and 3.8 (^{3}H)	1.8	0.5	3.8	Average	Chloride, isotope, and ^{3}H Tracers	Self_validated	High	Selaolo et al., 1996	
S25.125393	E24.587402	Botswana	Estimated	2 sites	Semi-arid	Range and value	Direct rainfall recharge	14~22 (Chloride), and 9 (^{3}H)	15.5	9	22	Average	Chloride and ^{3}H Tracers	Self_validated	High	Gieske et al. (1995)	
N12.382928	E11.162109	Northeast of Nigeria	Estimated	2 sites	Semi-arid	Range and value	Direct rainfall recharge	average 14, range 0-95	14	0	95	Single value	Improved single layer SMD	Validated using observed soil moisture	High	Eilers et al. (2007)	
S19.394068	E19.555664	Northeast of Namibia	Estimated	Catchment-sacle	Semi-arid	Range and value	Direct rainfall recharge	average 1, range 0-100	1	0	100	Single value	Hydro-chemical data and Groundwater modelling	Validated using groundwater modelling	Medium	Klock (2001)	
S20.269927	E30.907288	Victoria province, Zimbabwe	Estimated	Catchment-sacle	Semi-arid	Range and values	Direct rainfall recharge	82, 11, 39, 27, 8, 9, 12, 7, and 3 (1975-1983), or 2-5% annual rainfall	22	3	82	Average	River baseflow analysis, groundwater hydro-chemical analysis, and groundwater modelling	Validated mutually using different methods	High	Houston (1990)	
S7.2099	E34.782715	Tanzania	Estimated	Catchment-sacle	Semi-arid	Range and values	Direct rainfall recharge	100 (Forested-nondegraded), 133 (Deforested – nondegraded), 84 (Deforested-degraded); 15% reduction in rainfall resulted in a 40-50% reduction in recharge	105.7	84	133	Average	Two-layer SMD	Validated using observed soil moisture	High	Sandström (1995)	
N12.21118	E9.09668	Northern Nigeria	Estimated	Site	Arid	Range	Direct rainfall recharge	14-49	31.5	14	49	Average	Chloride Tracer	Self_validated	High	Edmunds et al. (2002)	