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PAPER

Review: Groundwater recharge estimation in arid and semi-arid southern Africa

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Abstract
Groundwater recharge estimation in arid and semi-arid southern Africa is reviewed based on four decades of recharge investigation in the region. This paper updates an earlier review by incorporating emerging and grey literature from a wide range of research sectors in southern Africa, collected during the past decade. For ease of comparison, methods commonly used are critically reviewed with a rating provided in terms of accuracy, application and costs. These include, but are not limited to, the methods of chloride mass balance (CMB), rainfall infiltration breakthrough (RIB), Extended model for Aquifer Recharge and moisture Transport through unsaturated Hardrock (EARTH), water-table fluctuation (WTF), water balance in the saturated zone (including equal volume spring flow (EVSF) and saturated volume fluctuation (SVF)), and groundwater modelling (GM). As the methods based on mass balance and relationships between rainfall, water-level fluctuations and abstraction are proven to have the potential to simulate and forecast groundwater recharge, the EVSF and CMB methods are highly recommended for use in the southern African region according to this review. Caution on the uncertainty associated with error input and propagation for all the methods is advised, based on a case study in South Africa. The review provides an updated source of references related to recharge estimation in arid and semi-arid regions of Sub-Saharan Africa in general and to ongoing projects for the implementation for Resource Directed Measures (part of the National Water Resources Strategy) in South Africa in particular.

Keywords Arid regions · Groundwater recharge/water budget · Estimation methods · South Africa · Sub-Saharan Africa

Introduction

Groundwater recharge is a critical process in the provision of renewable fresh water resources in arid and semi-arid regions globally. There have been efforts made to investigate groundwater recharge in, for example, the Middle East (Marechal et al. 2006; Mohammadi et al. 2014; Izady et al. 2015; Rezaei and Mohammadi 2017) and in Africa, where efforts in the past have been made to determine recharge rates mainly for water supply purposes. There have been attempts to provide regional recharge estimates across disparate areas of Sub-Saharan Africa with the aim to promote the concept of Integrated Water Resources Management. Reviews of groundwater recharge include, but are not limited to, those of Bredenkamp et al. (1995), Beekman and Xu (2003), Wang et al. (2010), Bonsor and MacDonald (2010), Healy (2010) and Kim and Jackson (2011). These reviews were also based on Official Development Association (ODA) financed groundwater studies associated with the cross-research council Global Challenges Research Fund (GCRF). However, these attempts have been limited by difficulties experienced in accessing technical reports on isolated water projects in the region. Over the past decade, additional groundwater related projects had been carried out in southern Africa (JICA 2002; Nyagwambo 2006; Shamboko-Mbale et al. 2012; Stone and Edmunds 2011; Beekman and Sunguro 2015). This paper will focus on groundwater recharge estimation in arid and semi-arid southern Africa and includes both previous reviews and the results of more recent groundwater projects. Aridity is defined according to Lloyd (1986) on the basis of average annual rainfall:

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hyper-arid 0–50 mm/year, arid 50–200 mm/year, and semi-arid 200–500 mm/year. About 22% of southern Africa falls within the boundaries of aridity as shown in Fig. 1.

Four decades of recharge studies in Southern Africa

Data and information on groundwater recharge in Africa are limited (Xu and Beekman 2003a; Wang et al. 2010). In southern Africa, most regional and local recharge studies (including groundwater exploration projects) have been carried out in semi-arid Botswana, South Africa and Namibia, and in Zimbabwe and Zambia to a lesser extent, over the past four decades. Isolated studies of recharge were conducted in Zimbabwe and Zambia through overseas aid agencies such as BGR, the German Geological Survey (Nyagwambo 2006; Shamboko-Mbale et al. 2012).

Botswana

The first systematic study of groundwater recharge in the eastern part of Botswana was carried out by Jennings (1974) in collaboration with researchers at the University of Witwatersrand in South Africa. Although further studies were also carried out in the Kalahari during the 1970s and 1980s (Verhagen et al. 1974; Mazor et al. 1977; Foster et al. 1982; De Vries and Von Hoyer 1988), it was not until 1987 that a co-operative Groundwater Resources Monitoring and Recharge Study (GRES) was launched by the Botswana and Dutch governments. The study aimed to gain a better understanding of recharge processes in Botswana. The first phase of GRES, which concentrated on Precambrian aquifers in southeastern Botswana, was completed in 1991 (Gieske 1992). The second phase (GRES II) expanded into the Kalahari Basin was completed in 1997 (Selaolo 1998; Beekman et al. 1996, 1999; De Vries et al. 2000). Methods used in the GRES studies included analysis of precipitation and evapotranspiration, environmental isotopes and rainfall chemistry, and of transport processes in both saturated and unsaturated zones. The GRES investigations revealed that recharge, in the order of 10 to 50 mm/year, takes place under favourable conditions in the eastern part of Botswana. A decreasing recharge from the outskirts of the Kalahari to the central part of the Kalahari, was observed from 5 mm/year down to 1 mm/year. When rainfall is less than 350 mm/year, lower or completely insignificant recharge rates can be expected. A follow-up research project was carried out by the University of Twente (ITC) of the Netherlands focusing on evapotranspiration (Lubczynski 2006, 2009).

Namibia

Although Namibia is one of the driest countries in southern Africa, and therefore in need of water resources assessment, large-scale recharge studies were not conducted until the 1990s. Perhaps the earliest study on groundwater recharge that was ever published is an assessment of recharge due to a cloudburst experienced on 25 and 26 February 1960 in the Uhlenhorst and Derm settlements (Schalk 1961). The Namibian and German governments launched a joint co-

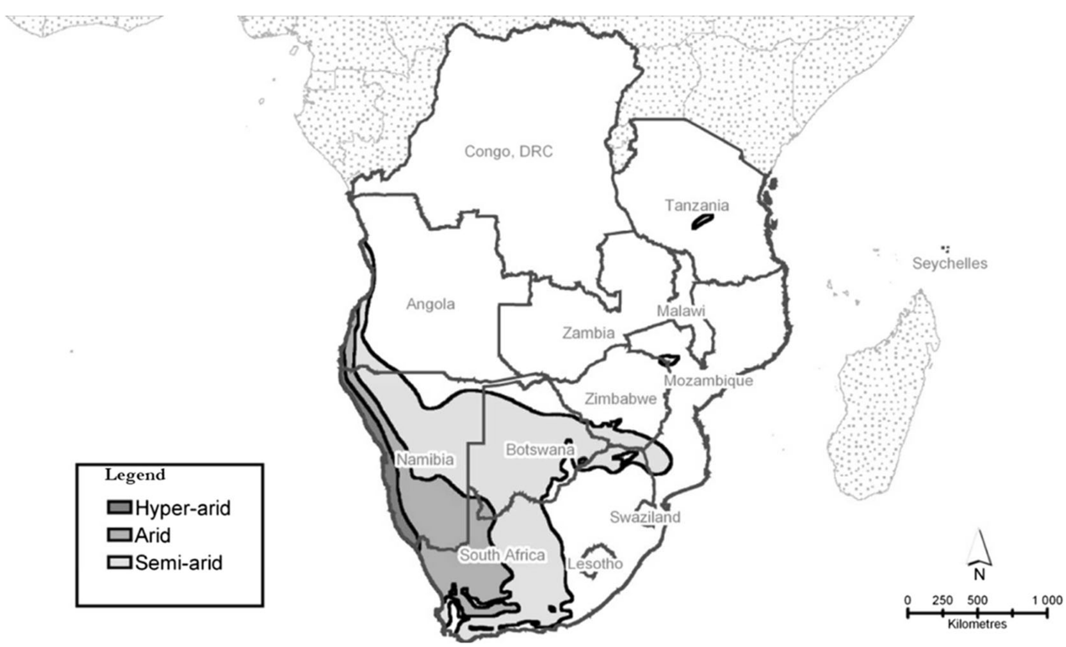


Fig. 1 Aridity in southern Africa (Beekman and Xu 2003)

operation program in 1992 focusing on recharge in the north-eastern part of the country in the karst areas of Otavi Mountain Land (Schmidt and Ploethner 2000). Over the past two decades, annual rainfall has been below the long-term mean of 550 mm, resulting in recharge of less than 10 mm/year. For the adjacent Kalahari Catchment to the east, Klock (2001) determined recharge to be 1 mm/year. This figure was based on regionalized site-specific hydrochemical data and satellite imagery, and was verified by a groundwater model. Recharge in the area may range from 0.2 to more than 100 mm/year. Central Namibia will urgently need additional secure water resources within the next decade. Therefore, a groundwater investigation was initiated in northern Otavi Mountain Land in 1999 to determine the long-term sustainable abstraction and short-term emergency bulk groundwater abstraction from the promising Tsumeb aquifers (Bufler et al. 2000). Recharge is also being investigated in the Stampriet Artesian Basin (JICA 2002; Stone and Edmunds 2011).

South Africa

The first systematic recharge studies in South Africa date back to the early 1970s, which were carried out in the western Transvaal (Bredenkamp and Vogel 1970; Bredenkamp et al. 1974) and the Northern Cape (Smit 1978). Recharge studies were mostly conducted at a local scale as part of a larger groundwater resources assessment project. It was during an international groundwater recharge workshop in Turkey in 1987 that an urgent need was expressed for developing new, and improving existing, practical methods for recharge estimation in arid and semi-arid areas (Simmers 1988). In South Africa, the growing need for reliable recharge estimation originated from a desire to better (sustainably) manage its limited groundwater resources. The Water Research Commission of South Africa therefore initiated the project "Preparation of a Manual on Quantitative Estimation of Groundwater Recharge and Aquifer Storativity". The manual (Bredenkamp et al. 1995) presents a great variety of well-tested (semi-empirical) methods that are widely employed in South Africa and contains a wealth of recharge case studies and data covering the work over two decades prior to 1995. This was followed by the UNESCO publication entitled "Groundwater Recharge Estimation in southern Africa", which summarizes recharge investigations in the region (Xu and Beekman 2003a). A later study by Van Wyk et al. (2011), funded by the South African Department of Water Affairs, provides valuable data on chloride monitoring over decades. This study illustrates the importance of spatial and temporal distribution of chloride in both rain water and groundwater for recharge estimates. Accuracy of recharge estimates becomes increasingly an issue of concern as it is critical for the determination of Groundwater Resource Directed Measures, which are part of the National Water Resources Strategy (Xu et al. 2003; Parsons and Wentzel 2007; Levy and Xu 2012; Xu et al. 2015).

Overview of results

Figure 2 shows all reported recharge rates determined up to 2015, including those from more humid southern African regions, as a function of annual rainfall. The rainfall limits range from as low as 215 mm to 1500 mm annually, whereas the recharge estimates range from as low as 0.23 mm to as high as 990 mm. These values are mostly from Botswana (Beekman et al. 1996), South Africa (Bredenkamp et al. 1995; Xu et al. 2007; Van Wyk et al. 2011), Namibia (JICA 2002; Stone and Edmunds 2011) and Zimbabwe (Houston 1988; Nyagwambo 2006; Shamboko-Mbale et al. 2012). As very few papers or reports are readily available from Zambia in the past decades, limited data sets are drawn from isolated reports such as BGR reports and meeting documents, which are analysed and captured in Fig. 2. The diagram shows up to a factor of 100 difference in recharge rates for the same annual rainfall. The methods which have most consistently been applied over the range of annual rainfall values illustrated here are the chloride mass balance (CMB) and the equal volume spring flow (EVSF) method (modified water balance). The results of other methods, such as saturated volume fluctuation modelling, mostly fall within the same range of results. Some characteristics of these results are demarcated using a number of elongated circles. For instance, results obtained in the Little Karoo in South Africa share some resemblance with that of the Botswana due to rainfall constraints. The fact that the recharge rates obtained in Little Karoo in South Africa are higher than those of Botswana evidently confirms that the recharge is enhanced by outcrops of fractured Table Mountain Group aquifers. Three areas of recharge rates in high rainfall regions can be identified in Fig. 2, including the CMB results at the top of the graph and the baseflow results at the bottom of the graph, with the results of the spring flow analysis going between. The ellipse at the bottom represents results of the hydrograph separation method, which were mostly obtained from the river baseflow analysis. The top area in Fig. 2, above the spring flow data, indicates some anomalous recharge values determined through chloride profiling in St. Lucia, South Africa (Bredenkamp et al. 1995). It seems that this method consistently overestimates recharge in this range of rainfall. One of the reasons would be that the estimated amount of drainage may not fully percolate to the water table of interest. The recharge estimated from the baseflow method is more conservative than that of the chloride profiling in this case. In reality, opposite results can also be given. As baseflow represents the effect at a catchment scale, recharge estimates using the baseflow method can be used for

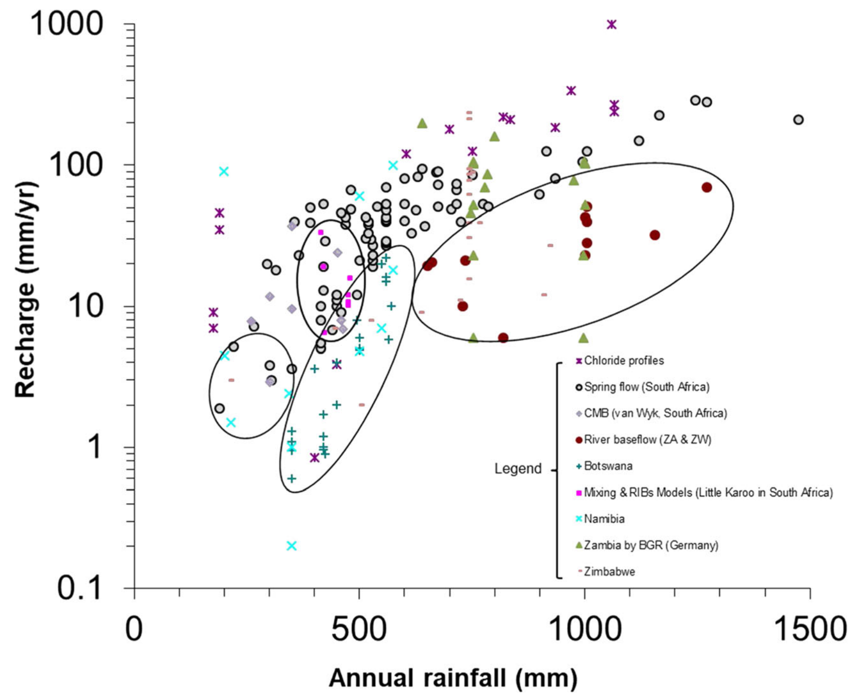


Fig. 2 Typical results of recharge studies in southern Africa (updated after Beekman et al. 1996; Beekman and Xu 2003)

comparison with the estimates obtained from other methods that are often related to the study at a local scale.

Analysis of measurements and other information revealed that each *method* has its own specific applicability over a range of recharge and rainfall. On an average basis, the chloride profile (CP), spring flow and baseflow methods can be used to determine recharge rates of approximately 0–383, 28–232 and 11–54 mm/year over rainfall ranges of approximately 175–1605, 190–1475 and 650–1270 mm/year, respectively.

Statistical analyses of the *regional data* (southern Africa) shown in Fig. 2 indicate that a method may be applied for a wide range of recharge rates within a limited range of rainfall. On an average basis, the CP, spring flow and baseflow methods may be used to determine recharge rates of approximately 0–584, 0–237 and 0–70 mm for rainfall ranges of approximately 236–1500, 328–1500 and 495–1500, respectively. There are rainfall limits where recharge estimates cannot be valid for some methods. For instance, for annual rainfall less than 200 mm, recharge would be undetected using the chloride profile method. For annual rainfall less than 300 mm, recharge would be undetected by using the SVF and EVSF methods. It is noticed that there are cases exceptional to this observation in the region, as they might be influenced by many factors. In the case of Namibia, where annual rainfall is less than 300 mm, large differences exist between the values found. Key factors, such as episodic rainfall events and evapotranspiration and geomorphology, may have contributed to these variations. Annual recharge estimates would become meaningless, as recharge cannot take place unless there is a major rainfall event, which occurs once over many years (Schalk 1961).

Recharge concepts and terminology

Broadly, groundwater recharge can be defined as an addition of water to the saturated zone. Four main modes of recharge can be distinguished:

- Downward flow of water through the unsaturated zone reaching the water table,
- Lateral and/or vertical inter-aquifer flow,
- Induced recharge from nearby surface-water bodies resulting from groundwater abstraction, and
- Artificial recharge such as from borehole injection or man-made infiltration ponds, dams, etc.

This paper focuses on the first mode: natural recharge by downward flow of water through the unsaturated zone, which is generally the most important mode of recharge in arid and semi-arid areas. Main sources of recharge are rainfall, surface-water bodies (ephemeral or seasonal rivers, lakes, estuaries, etc.) and irrigation losses.

Recharge can be expressed in various forms, e.g. as a percentage of annual rainfall, or in mm/year. Figure 3 conceptualizes different modes of recharge according to the origin of water, flow mechanism through the unsaturated zone, areas on which it acts, and time frame over which it occurs (Beekman et al. 1999; Lloyd 1986; Lerner et al. 1990; De Vries and Simmers 2002; Ford and Williams 2007; Healy 2010):

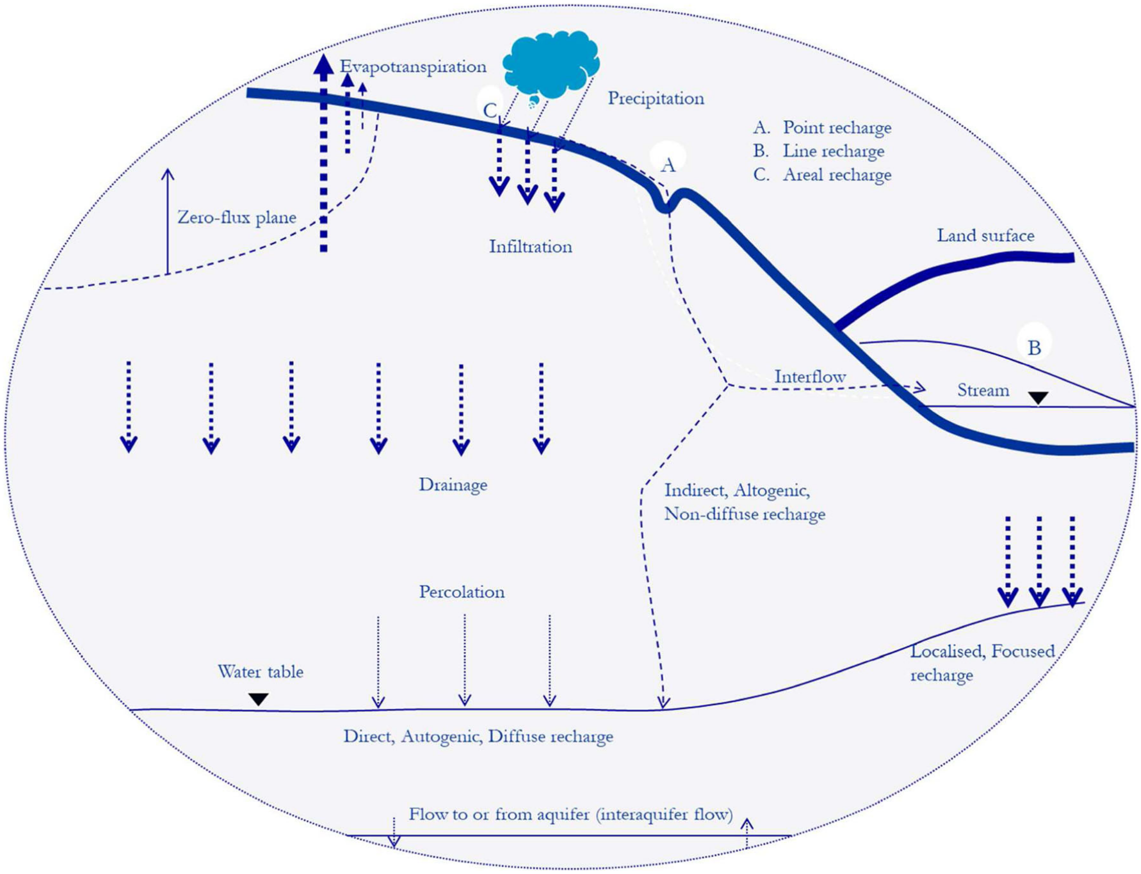


Fig. 3 Recharge mechanisms and terminology (after Healy 2010)

I. Origin of water:

- Direct, autogenic/diffuse recharge: direct infiltration of precipitation and subsequent percolation through the unsaturated zone to a groundwater body, i.e. water added to the groundwater reservoir in excess of soil-moisture deficits and evapotranspiration
- Indirect, allogenic/non-diffuse recharge: percolation to the water table through depressions and fault zones,
- Localized/focused recharge: accumulation of precipitation in surface-water bodies, and subsequently concentrated infiltration and percolation through the unsaturated zone to a groundwater body.

II. Flow mechanism through the unsaturated zone:

- Piston/translatory flow: precipitation which is stored in the unsaturated zone, is displaced downwards by the next infiltration/percolation event without disturbance of the moisture distribution,
- Preferential flow: flow via preferred pathways/macro-pores, which are sites (e.g. abandoned root channels, burrows, fissures) or zones (e.g. stream beds) in the unsaturated zone with a relatively high infiltration and/or percolation capacity.

III. Area on which it acts:

- Areal recharge: recharge over an area (C in Fig. 3),
- Point recharge: recharge at a site, with no areal extent (A in Fig. 3),
- Line recharge: recharge from a line source, such as a drainage feature or river (B in Fig. 3).

IV. Time frame over which it occurs (for both episodic and perennial recharge):

- Seasonal, annual and interannual recharge: recharge occurring within a time period of days, months or years as often observed in tropical and subhumid regions,
- Episodic recharge: recharge occurring once in several years,
- Palaeo recharge: recharge over a longer period, often tens up to thousands of years, in the past (accounting for climate change) within a time frame of a geological period.

In arid and semi-arid regions, recharge according to the above time scales may coexist (Braune and Xu 2010). Determination and differentiation of individual groundwater recharge events within an aquifer system in arid and semi-arid areas is neither straightforward nor easy. This is a consequence of the temporal variability of precipitation in arid and semi-arid climates and spatial variability in soil characteristics, topography, vegetation and land use (Lerner et al. 1990). Moreover, recharge amounts are normally small in comparison with the resolution of the investigation methods. The greater the aridity of the climate, the smaller and potentially more variable is the recharge flux (Allison et al. 1994).

Overview of recharge estimation methods

Classification of recharge estimation methods

Recharge estimation methods may be classified according to three types: (1) hydrogeological provinces, (2) hydrologic zones and (3) physical and tracer approaches (Lerner et al. 1990; Bredenkamp et al. 1995; Beekman et al. 1999; Scanlon et al. 2002; Kinzelbach et al. 2002, Beekman and Xu 2003). Based on the way the data are acquired, the recharge estimation methods can also be classified according to:

- Data from surface processes: remote sensing techniques, methods based on surface-water data, land-use change and evapotranspiration;
- Data from subsurface processes: unsaturated zone methods, methods based on groundwater data, and tracer methods including heat as a tracer;
- Data related to conceptual processes: conceptual model of recharge processes, water budget methods, inverse modelling simulations.

Commonly used methods (overview)

An overview of commonly used recharge estimation methods in southern Africa is given in Table 1. The methods are grouped according to hydrologic zones and further subdivided into physical and tracer approaches. A brief description of the principle and references is given for each method. Methods referring to surface-water and unsaturated zones estimate potential recharge whereas methods referring to the saturated zone can estimate actual recharge. Methods excluded from this overview, due to either a too qualitative nature, large inaccuracy or a too complicated nature for application in the (semi-)arid environment, are the rainfall-recharge relationship methods, soil-moisture/water budget methods (Schulze 1995), seepage meter methods, heat tracer methods and (semi-)quantitative methods, which involve the isotopes ^{2}H, ^{18}O (Beekman et al. 1996) and ^{4}He (Selaolo 1998). To the authors' knowledge, application of ^{36}Cl has not yet been reported in this region for recharge estimation.

Examples of integrated approaches, i.e. combining various methods, are the combined chemical and isotope mass balance approach (Beekman et al. 1999) and "Recharge" Excel spreadsheet model (Van Tonder and Xu 2000; Sun et al. 2013; Ahmadi et al. 2014). The former (combined chemical and isotope mass balance) is based on dating moisture and groundwater using the chloride mass balance (CMB) and ^{14}C groundwater dating methods. The "Recharge" spreadsheet model facilitates analysis of hydrogeological data with commonly used estimation methods from Table 1 and provides an opportunity to calculate a weighted average recharge rate after having assigned weighting factors to each of the methods used.

Furthermore, a semi-quantitative approach has also been applied to crystalline basement aquifers of central Namaqualand in South Africa to define the recharge potential (Adams 2004). The approach is based on integrating spatial climatic and (hydro-)geologic datasets in a geographic information system (GIS) environment and can be considered a derivative of the DRASTIC approach (Aller et al. 1987) used for aquifer vulnerability mapping. The approach has the potential to become quantitative once it is combined with recharge estimation methods of Table 1.

Mapping of recharge at a country level and at a continental level was carried out with the aim of developing indicators of groundwater availability (Doll and Fiedler 2007; DWA 2010). With a GIS platform, isolated data points established using CMB are connected to generate a spatially distributed map of recharge that is a function of space at any point of the x- and y-coordinates. The generated recharge map can be easily integrated with other GIS based information layers for strategic planning and education. However, it must be cautioned that recharge does not occur everywhere as the map would imply. Even in an identified area where recharge did take place, recharge may not be available annually, especially in the arid and semi-arid Sub-Saharan Africa where average annual recharge is not applicable. One of the research gaps identified during this review is that the recharge needs to be calibrated with case studies on the ground in order to prevent it from becoming a misleading "recharge bible".

Forecasting recharge

There are several models available for recharge simulation. Forecasting groundwater recharge has become increasingly important, particularly with regard to the envisaged climate change impacts on southern Africa's limited water resources (Kirchner 2003; Cavé et al. 2003; Sun et al. 2013). Methods that have great potential to forecast recharge are those that interrelate rainfall, abstraction and water-level fluctuations, such as the CRD, EARTH, autoregressive–moving average (ARMA) and empirical methods. Critical in reliable forecasting of recharge is the

Table 1 Recharge estimation methods applied in (semi-)arid southern Africa (after Beekman and Xu 2003)

Zone	Approach	Method	Principle	References
Surface water	Physical	HS	Stream hydrograph separation: outflow, evapotranspiration and abstraction balances recharge	11
		CWB	Recharge derived from difference in flow upstream and downstream, accounting for evapotranspiration, in- and outflow and channel storage change	4
		WM	Numerical rainfall-runoff modelling; recharge estimated as a residual term	5, 6
Unsaturated	Physical	Lysimeter	Drainage proportional to moisture flux/recharge	2
		UFM	Unsaturated flow simulation, e.g. by using numerical solutions to Richards equation	2, 4
		ZFP	Soil moisture storage changes below ZFP (zero vertical hydraulic gradient) proportional to moisture flux/recharge	2, 3,7
	Tracer	CMB	Chloride mass balance – profiling: drainage inversely proportional to Cl in pore water	1, 2, 3, 7
		Historical	Vertical distribution of tracer as a result of activities in the past (^{3}H)	1, 2, 3, 7
Saturated – Unsaturated	Physical	CRD, RIB	Water-level response from recharge proportional to cumulative rainfall departure	2, 10, 12
		EARTH	Lumped distributed model simulating water-level fluctuations by coupling climatic, soil moisture and groundwater-level data	3, 8
		WTF	Water-level response proportional to recharge/discharge	2
	Tracer	CMB	Amount of Cl into the system balanced by amount of Cl out of the system for negligible surface runoff/runon	1, 2, 3, 7, 13
Saturated	Physical	GM	Recharge inversely derived from numerical modelling groundwater flow and calibrating on hydraulic heads/groundwater ages	2, 3
		SVF	Water balance over time based on averaged groundwater levels from monitoring boreholes	2
		EVSF	Equal volume spring flow water balance at spring catchment scale	2
	Tracer	GD	Age gradient derived from tracers, inversely proportional to recharge; Recharge to unconfined aquifer based on vertical age gradient (^{3}H, CFCs, $^{3}H/^{3}He$); recharge to confined aquifer based on horizontal age gradient (^{14}C)	1, 7, 9

HS Hydrograph separation – baseflow, *WM* Watershed modelling, *UFM* Unsaturated flow modelling, *ZFP* Zero flux plane, *CMB* Chloride mass balance, *CRD* Cumulative rainfall departure, *EARTH* Extended model for Aquifer Recharge and moisture Transport through unsaturated Hardrock, *WTF* Water-table fluctuation, *GM* Groundwater modelling, *SVF* Saturated volume fluctuation, *EVSF* Equal volume – spring flow, *GD* Groundwater dating

[1] Beekman et al. 1996

[2] Bredenkamp et al. 1995

[3] Gieske 1992

[4] Lerner et al. 1990

[5] Sami and Hughes 1996

[6] Albhaisi et al. 2013

[7] Selaolo 1998

[8] Van der Lee and Gehrels 1997

[9] Weaver and Talma 1999

[10] Xu and Van Tonder 2001

[11] Xu et al. 2002

[12] Sun et al. 2013

[13] Van Wyk et al. 2011

accuracy of forecasting rainfall in terms of frequency of events, quantity and intensity. In southern Africa there is a wealth of rainfall records, often dating back to the beginning of the previous century, and this should form a sound basis for future predictions. Note that the accuracy of forecasting recharge is complicated by the non-linear behaviour of groundwater systems in response to rainfall. Note also that forecasting should accommodate for the propagation of uncertainty in input parameters.

Review of recharge estimation methods

Commonly used methods (review)

A review of commonly used recharge estimation methods in (semi-)arid southern Africa is presented in Table 2. Methods are evaluated in terms of limitations, applicability (range of fluxes, spatial and temporal scales) and ratings (accuracy, ease of application, cost).

Table 2 Review of commonly used recharge methods in (semi-)arid southern Africa

Zone	Method	Limitation	Applicability[b]			Rating[c]			
			Flux (mm/yr)	Area (km^2)	Time	Accuracy	Ease	Cost	Score
SW	HS	Ephemeral rivers	400–4000 (0.1–1000)	1–1300 (10–1000)	0.3–50 (1–100) yr	2–3	1–2	1–2	53%
	CWB	Inaccurate flow measurements	100–5000	0.001–10	1 d–1 yr	2–3	2	3	39%
	WM	Ephemeral rivers	1–400	0.1-5 × 10^5	1 d–10 yr	2	2–3	3	43%
Unsaturated[a]	Lysimeter	Surface runoff	1–500 (0–200)	0.1–30	0.1–6 yr	2	3	3	42%
	UFM	Poorly known relationship, hydraulic conductivity -moisture content	20–500	0.1–1	0.1–400 yr	3	2	2	42%
	ZFP	Subsurface heterogeneity, periods of high infiltration	30–500	0.1–1	0.1–6 yr	3	2	2	42%
	CMB	Long-term atmospheric deposition unknown	0.1–300 (0.6–300)	0.1–1	5–10,000 yr	2	1	1	67%
	Historical	Poorly known porosity, present ^{3}H levels almost undetectable	10–50 (10–80)	0.1–1	1.5–50 yr	2–3	2–3	3	38%
Sat-Unsat	CRD, RIB	Deep (multilayered) aquifer, sensitive to specific yield (Sy)	(0.1–1000)	(1–1000)	(0.1–20) yr	2	1–2	1	70%
	EARTH	Poorly known Sy	(1–80)	(1–10)	(1–5) yr	1–2	2	1	76%
	WTF	In/outflow and Sy usually unknown	5–500	5 × 10^{-5} to > 0.001	0.1–5 yr	2	1	1	75%
	CMB	Long-term atmospheric deposition unknown and low Cl background value	0.1–500	2 × 10^{-6} to > 0.01	5- > 10,000 yr	2	1	1	75%
Unsaturated[a]	GM	Time consuming, poorly known transmissivity, sensitive to boundary conditions	(0.1–1000)	10^{-6} to 10^6	(1 d–20 yr)	1–2	3	3	50%
	SVF	Flowthrough region, multilayered aquifers	(0.1–1000)	(1–1000)	(0.1–20 yr)	1–2	1–2	2	61%
	EV-SF	Confined aquifer	(0.1–1000)	(1–100)	(1–100 yr)	1–2	1–2	1–2	67%
	GD	^{14}C, ^{3}H/^{3}He, CFC: poorly known porosity/correction for dead carbon contribution	^{14}C: 1–100; ^{3}H/^{3}He, CFC: 30–1000	^{14}C, ^{3}H/^{3}He, CFC: 2 × 10^{-6} to > 0.001	^{14}C: 200–200,000; ^{3}H/^{3}He, CFC:2–40	3	2–3	3	34%

[a] All methods for estimating fluxes through the unsaturated zone assume diffuse vertical flow whereas in reality flow along preferred pathways is the rule rather than the exception. These methods therefore tend to overestimate the diffuse flux

[b] Data in brackets are estimates from southern Africa; rainfall may be up to 2000 mm/year; other data represent global values and are taken from Scanlon et al. (2002)

[c] Ratings for methods applied to semi-arid southern Africa

The aim of rating is to advance an on-going discussion among groundwater professionals on the selection of appropriate methods for recharge estimation. The ratings are based on the authors' experience and based on ratings given by Bredenkamp et al. (1995), van Tonder and Xu (2000), Kinzelbach et al. (2002) and a workshop, the "Framework for recharge estimation in southern Africa", in 2003 (Beekman et al. 2003).

With regard to the applicability of methods, data have been adopted from Scanlon et al. (2002). Regarding ratings, the approach of *accuracy* rating is adopted from Kinzelbach et al. (2002): class 1: difference from true value within a factor of 2; class 2: within a factor of 5; and class 3: within a factor of 10 or more. *Ease of application* is related to data requirements and data availability and is rated from 1 (easy to use) to 3 (difficult to use). *Cost* is rated from 1 (inexpensive) to 3 (expensive). A combined rating for each method was established by applying the following weighting factors for *ease*, *cost* and *accuracy*: 15%, 35% and 50%, respectively.

Promising methods

The following methods can be applied with reasonable confidence in arid and semi-arid southern Africa: EVSF, CMB, RIB, EARTH, WTF, SVF and GM. These methods have in common that they estimate recharge based on linking specific information from the atmosphere, and unsaturated and saturated zones. Greater certainty in the results from the GM method is obtained when groundwater levels and ages are used in the calibration process. Four of these methods (EVSF, CMB, RIB and GM) are widely applied and are discussed in more detail. They represent a list of preferred methods but an increasing complexity in their use and data requirements.

Equal volume spring flow (EVSF)

The EVSF method is based on a water balance principle within a spring catchment that contributes flow to the spring (sometime referred to as ZOC). The spring flow volume accumulated over a flow period between two equal flow points in a given spring flow time series is compared with the rainfall volume of a period that is identified to be responsible for the spring flow of the period. Excel-based software is often used to quantify recharge in South Africa (Van Tonder and Xu 2000). If a spring catchment or ZOC can be delineated, this method would be used to give most accurate recharge estimates. A time lag between the rainfall period and spring flow period is a critical parameter to be considered for use of this method.

Recharge estimates obtained from spring flow simulation largely lie between those of the chloride profile and baseflow methods (see Fig. 2). The chloride mass balance method gives the upper limit of recharge potential, while the baseflow method represents the lower limit of recharge due to possible water loss prior to discharge along rivers. A liner best fit between annual rainfall and average annual recharge estimates for the EVSF is plotted in Fig. 4. The upper line and bottom line in the graph represent annual recharge plus and minus its standard deviation, respectively. Note that the range of recharge (plus and minus its standard deviation) covers most recharge estimates obtained in southern Africa, with the exception of those of Namibia (see Fig. 2). The equation $Y = 0.202X - 67$ may be used for initial estimates of recharge prior to a detailed investigation, where Y is the recharge estimate and X the mean annual rainfall.

In terms of *applicability, limitations, data requirements,* and *ratings* as presented in Table 2, EVSF can be used wherever spring flow series are available. The method cannot be applied in areas where the spring catchment cannot be delineated, nor can it be used for no record of the flow series. Monthly rainfall records and spring flow time series are essential. The ratings are as follows: accuracy: 1; ease of application: 1–2; cost: 1–2, with an overall score of 67%.

Chloride mass balance (CMB)

This method is based on the assumption of conservation of mass between the input of atmospheric chloride and the chloride flux in the subsurface (Eriksson and Khunakasem 1969). It can be used for estimating a drainage or moisture flux in the unsaturated zone by means of a profiling technique when diffuse (piston) flow is assumed. It can also be used for recharge estimation in the saturated zone. Comparison of moisture flux and recharge provides insight into the mechanism of recharge. Note that mechanisms of recharge and recharge rates can be considered crucial in the assessment of vulnerability of groundwater resources to pollution. The use of the CMB method is readily facilitated, as chloride (Cl) concentrations in both precipitation and groundwater are recorded in selected monitoring stations all over South Africa (Van Wyk et al. 2011).

Recently, van Wyk et al. (2011) highlighted seasonal signals in the application of the CMB method. The work demonstrates the importance of incorporating Cl sampling and analysis pertaining to rain and groundwater into government groundwater monitoring networks to allow for the estimation of recharge in South Africa. It would be possible to take into account typical geological settings when using the CMB method where and if data and information permits.

Applicability, limitations, data requirements, and *ratings* of the CMB method applied to both unsaturated and saturated zones are summarized in Table 2. Most reliable estimates of site-specific drainage or moisture fluxes may be obtained through a multiple tracer profiling approach (Simmers et al. 1997). This approach aims at deducing and quantifying where possible relevant transport processes occurring in the unsaturated zone. For example, the CMB method may reveal the thickness of the evapotranspiration zone and moisture fluxes, ^{18}O and ^{2}H profiling may provide insight into the evaporation process and moisture fluxes (Beekman et al. 1996), and ^{3}H profiling may highlight zones of preferred pathways, thereby either validating or invalidating the use of the various methods (Selaolo et al. 2003). The CMB method for the saturated zone may be especially useful in areas where groundwater levels do not fluctuate or data on groundwater levels are lacking. For the unsaturated zone, preferential flow seems to be the rule rather than the exception. Moisture fluxes may therefore be overestimated. The CMB method should not be applied in areas underlain by evaporates or areas where upconing or mixing of saline groundwater occurs. The method should be applied with great caution in areas close to the sea where rainfall chloride contents are highly variable. In fractured rock systems, the applicability of the CMB method is complicated (1) if additional chloride is produced through weathering of the rock matrix and (2) when time is needed to develop a new equilibrium between groundwater chloride concentrations in the rock matrix and fractures following a change in environmental conditions (Cook 2003). If additional chloride is being produced, a recharge rate derived from a CMB should be considered a minimum. In the case of a larger fracture spacing it takes longer to develop a new equilibrium in chloride concentrations. The estimated recharge may therefore not represent changed environmental conditions (e.g. climate or land-use). The CMB method requires long-term averages of precipitation,

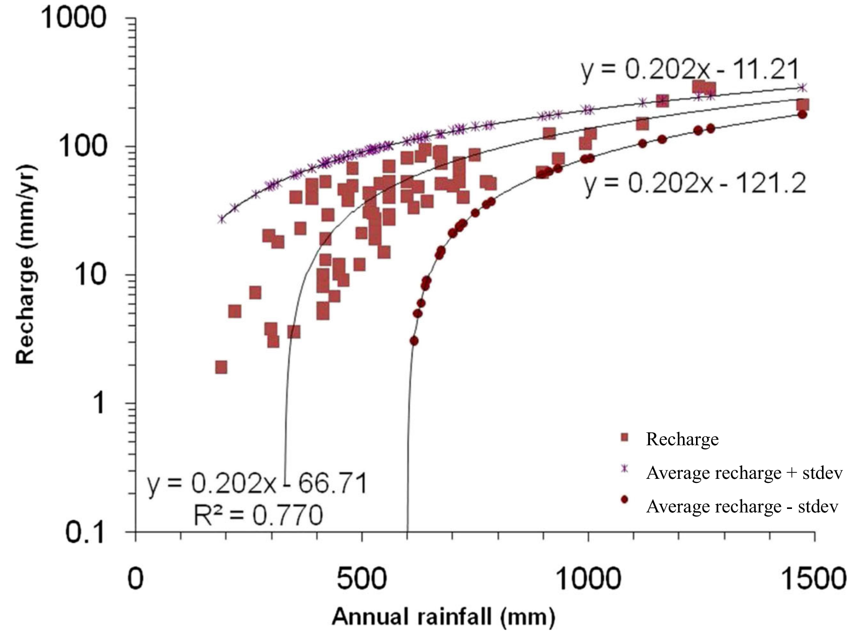


Fig. 4 Typical range of recharge estimates with the spring flow method

chloride content of precipitation and dry deposition; chloride content of soil moisture and volumetric moisture content, and chloride content of groundwater. The ratings for the CMB method are as follows: accuracy: 2; ease of application: 1; cost: 1, and the score ranges from 67% for its application to the unsaturated zone and 75% for the saturated zone.

Although this method may not be as accurate as other methods, differences in recharge estimation are still within a factor of three. Measured atmospheric input of chloride (often only short-term records are available) is assumed to be representative for a long period and is thus an area of concern as rainfall and chloride deposition during the past may be different from today. Other areas of concern include the uncertainty in the measured chloride content of rainfall and rainfall amount, depending on the type of rain gauge used, pollution and analytical errors when measuring relatively low chloride concentrations (Beekman and Sunguro 2002; Adams 2002). Despite these shortcomings, the CMB method is highly recommended, also for fractured rock systems (Cook 2003), as it is relatively simple in its application and the least expensive method.

Rainfall infiltration breakthrough (RIB)

Initially based on the cumulative rainfall departure (CRD) method, the rainfall infiltration breakthrough (RIB) method was developed to include both hydrogeological and rainfall dynamics (Xu and Van Tonder 2001; Xu and Beekman 2003b). The RIB method was used to accommodate for trends in rainfall time series. The RIB method, along with an associated spreadsheet program, was recently reviewed for ease of application (Sun et al. 2013; Ahmadi et al. 2014)

The RIB method is based on the assumption that groundwater recharge has a linear relationship with water-level fluctuations under natural conditions, while stressed conditions, including abstraction, are accommodated by a simple water balance approach. The RIB method can be used for rainfall-recharge simulations and typical percolation scenario analyses. Three rainfall percolation mechanisms can be distinguished for different time scales. The mechanisms are listed below in terms of the duration of the time lag:

- Mechanism a: water-level fluctuations resulting from preceding rainfall events. This is often observed at places with relatively quick infiltration in forms of direct, point, preferential flow (ranging from hours to a day).
- Mechanism b: water-level fluctuations resulting from the cumulative effect of all previous rainfall events, such as direct, autogenic/diffuse recharge. This often represents the combination of point and diffuse recharge mechanisms.
- Mechanism c: water-level fluctuations which are caused by limited rainfall events and which are subjected to a certain time lag (ranging from one month to a number of months depending on local hydrogeological conditions).

Applicability, limitations, data requirements, and *ratings* of the RIB method are summarized in Table 2. The method cannot be applied in areas where there are no groundwater-level fluctuations and the method should only be applied to unconfined aquifers. Monthly rainfall records, water levels, borehole abstractions and aquifer properties including storativity and size of the recharge area are required. The ratings for the RIB method are as follows: accuracy: 1–2; ease of application: 1–2; cost: 2, and the overall score is 70%.

Groundwater levels of fractured aquifers with small storativity are particularly sensitive to rainfall recharge. Simulation of water levels based on the RIB method and hence recharge estimation is fairly accurate in these cases, provided that storativity can be determined. The uncertainty in recharge estimation increases with increasing depth to the water table. Rainfall, water levels and abstraction rates must be representative for the recharge area of the aquifer. By taking into account different ranges of rainfall, the RIB method will give reasonable estimates of recharge rates. The accuracy of estimation increases with increased spread of boreholes over the recharge area of the aquifer and with increased frequency of monitoring data.

Groundwater modelling (GM)

The aim of modelling groundwater flow is usually to predict the aquifer piezometry (water levels) under various groundwater stress situations. The general three-dimensional groundwater flow equation, assuming uniform fluid density and viscosity, was formulated by Bear (1972). In inverse modelling, recharge is a function of water levels, inflow and outflow (e.g. sub-surface drainage and abstractions), hydraulic conductivity and storativity. Changes of the parameters over time in a given aquifer domain should be known. Confidence in calculated recharge will improve when the velocity distribution of groundwater or groundwater ages is calibrated based on the hydraulic model matching groundwater ages derived from radionuclide (^{14}C) transport modelling.

Applicability, limitations, data requirements, and *ratings* of the groundwater modelling are summarized in Table 2. Groundwater modelling is time consuming, sensitive to boundary conditions and difficult to calibrate and validate. A conceptual hydrogeological model, daily/monthly rainfall records, water levels, borehole abstractions, aquifer characteristics (including storativity, hydraulic conductivity, porosity, dispersion characteristics) and radionuclide concentrations (e.g. ^{14}C) are required. Ratings for the groundwater modelling are as follows: accuracy: 1–2; ease of application: 3; cost: 3, and the overall score is 50%.

The accuracy of recharge estimation relates directly to the degree of discretization of the groundwater system and to the accuracy of the parameter values. Once the age or velocity distribution in an aquifer based on the flow model matches the age distribution of groundwater, a higher degree of confidence is gained in the recharge estimate. With regard to ^{14}C dating of groundwater, correction models may have to be constructed to account for sources or sinks of carbon. These correction models require a proper insight into the hydrochemistry of water-rock interactions operating in the aquifer, hence ^{14}C dating and thus recharge estimation is a challenging task. Both flow and transport modelling require advanced hydrogeological and hydrochemical skills, and costs involved are usually high due to the vast amount of hydrogeological and hydrochemical data required.

Discussion and recommendations

The following discussion and recommendations focus on possible improvements and expansion of the use of selected methods such as the EVSF and CMB method. The uncertainty associated with recharge estimates and possible guidelines are discussed, and recommendations are put forward for future work.

Use of other spectator ions as tracers

The essence of the use of Cl in the CMB method is the assumption of Cl as a conservative tracer, i.e. the ion does not react with other species. The principle of using spectator ions such as Cl can be extended to include other ions, e.g. (1) anion spectator ions, such as SO_4, ClO_4, I and NO_3; (2) cation spectator ions, for example, cations of metals such as K and Mg. Similar environmental tracers (Lin et al. 2013) include halogens (fluoride) and sulphate, nitrate and sodium. The application of this principle at the Campus Site Aquifer near the Cape Town International Airport in South Africa gave comparative results as shown in Table 3. The results are compatible with that of Cl except for NO_3, which was found to be non-conservative. As Fluhler et al. (1982) and Lin et al. (2013) advised, caution must be exercised as some species are locally sensitive to certain types of soils.

Dealing with uncertainty

To illustrate the sensitivity of error propagation associated with recharge calculations using simple interval mathematics, the CMB method was applied to the Campus Site Aquifer at the University of the Western Cape. Cl concentrations of groundwater samples taken from a borehole, and Cl concentrations of rain samples taken from data for a station located near Cape Town International Airport were used. Nine parameters were considered including the rainfall amount and Cl concentrations of both rain water and groundwater over three different periods. Errors of the nine input values are introduced by assigning a percentage error to each measured value involved in calculation to propagate a corresponding error output each time. As is shown in Fig. 5, input errors must be controlled within a limit of less than 25% in order to guarantee that errors of recharge estimates are contained within a 100% error. The error propagation process may vary from one method to another. But it is essential to make an evaluation of order of magnitudes of possible errors generated from a given method.

Table 3 Comparison of Cl with other ions for recharge estimation

Ion	Recharge (mm/year)	Recharge (%)	Calibrated I (mm/year)	Calibrated I (%)	Calibrated II (mm/year)	Calibrated II (%)
Cl	284	46%	212	32%	157	25%
F	450	73%	n/a	n/a	124	20%
Na	208	34%	208	34%	142	23%
SO_4	250	40%	204	32%	229	37%
NO_3	6974	1128%	n/a	n/a	n/a	n/a

The uncertainty often reflected in different recharge estimates obtained through various methods can arise from the inaccuracy of measurements (or imprecision) and the use of suboptimal models (bias). The combination of these two factors, bias and precision, gives rise to four scenarios. Neither the high bias nor low precision would generate a realistic estimate. An ideal scenario of the low bias and high precision is hardly achieved in practice. A pragmatic combination of low bias and low precision might yield acceptable results. This could be achieved through the adaptation of multiple methods whose results can be cross-checked by realistic conceptual models for the aquifers of interest.

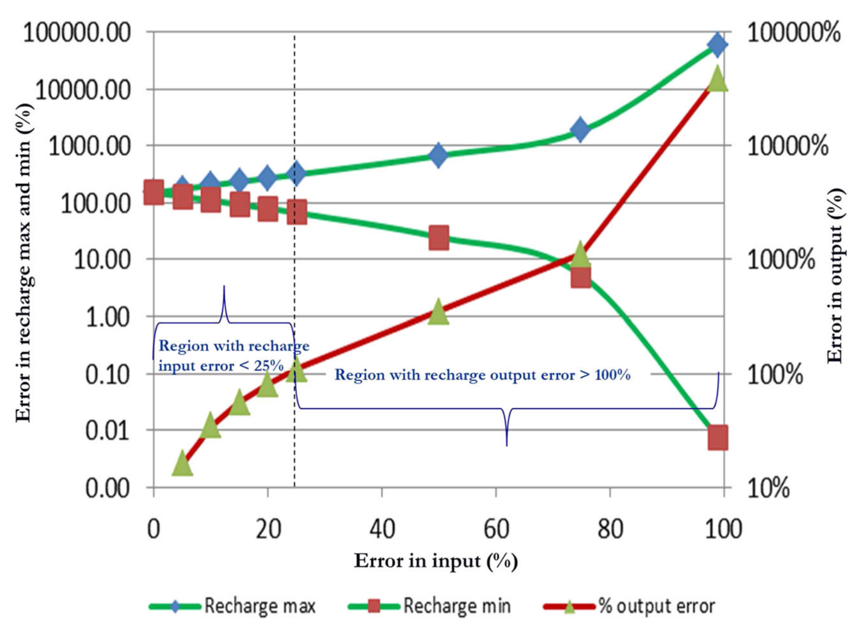
Guidelines

There are as many methods available for quantifying groundwater recharge as there are different sources and processes of recharge. Each of the methods has its own limitations in terms of applicability and reliability. The objective of the recharge study should be known prior to selection of the appropriate method for quantifying groundwater recharge as this may dictate the required space and time scales of the recharge estimates (Scanlon et al. 2002). Water resource evaluations, for instance, would require information on recharge at large spatial and temporal scales, whereas assessments of aquifer vulnerability to pollution would require more detailed information at local and shorter time scales.

Development of a conceptual model of recharge in an area of interest should also precede selection of the appropriate recharge estimation method in order to reduce both the uncertainty and costs of quantifying recharge as illustrated. Such a model should describe the location, timing and probable mechanisms of recharge and provide initial estimates of recharge rates based on climatic, topographic, land use and land cover, soil and vegetation types, and geomorphological and (hydro-)geological data (including recharge sources, flow mechanisms, piezometric surface, groundwater exploitation).

An initial guess of recharge can be made prior to a detailed investigation in southern Africa using the equation $Y = 0.202X - 67$ for rainfall range from 328 to 1500 mm, where Y is the recharge and X a mean annual rainfall value of the range, although some part of the rainfall range (< 328 mm) falls out of the algorithm's range. It is essential to have recharge estimates cross-checked. As a recharge estimate, the groundwater contribution to baseflow is determined, which must be cross-checked with the other methods such as

Fig. 5 Relationship between input error (horizontal axis) and output error (vertical axis)



CMB to verify their consistence. It is often found out that those results do not match with each other, especially estimates that are made from different datasets. Some guidelines for recharge estimation are given in Lerner et al. (1990) and Scanlon et al. (2002), but a user-friendly framework for recharge estimation does not yet exist.

Recommendations

In arid and semi-arid areas, assessment of groundwater recharge is a key challenge in determining the sustainable yield of aquifers. In particular, in South Africa, the recharge estimations during the implementation for Groundwater Resource Directed Measures is often the issue of much debate. This is not only because recharge rates are generally much lower than those of average annual rainfall or evapotranspiration, and thus difficult to determine precisely, but also due to the different connotation of recharge concept adopted between surface-water and groundwater groups.

A host of recharge estimation methods for semi-arid and arid areas is currently available with each method having its own limitations. According to Table 2, whereas one method can be applied in site specific studies, another can better be used in regional studies; whereas one method represents a short time scale, e.g. from event based recharge to daily/monthly/yearly recharge, another represents a much longer time scale, ranging from decades to thousands of years. Upfront, understanding the objective of the recharge determination is prerequisite for choosing appropriate methods for recharge estimation. The uncertainty due to the low precision and high biased methods in recharge estimation can get improved when multiple methods are applied for cross-check (Beekman et al. 1996; De Vries and Simmers 2002; Scanlon 2000; Lubczynski 2009; Xu 2012).

In southern Africa, experience in recharge estimation covers a time span of at least four decades. This experience formed the basis for this paper. It is concluded that the following methods can be applied with greater certainty in the arid and semi-arid parts of the region: the EVSF, CMB, RIB, EARTH, SVF, WTF and GM methods. From these methods the CMB remains the easiest to apply and the least expensive whereas GM is the most difficult and expensive method.

Future work should focus on quantifying the time lag between rainfall events and water-level responses, on episodic recharge and on forecasting in the context of climate change. The decades of work on recharge assessment in the region should be collated, synthesized and translated into user-friendly products (such as manuals, databases, decision support systems and analysis programs) to better serve the groundwater practitioner and the water manager in properly and effectively using the results for various purposes. This would pave the way also for dealing with issues including water-sensitive urban design (WSUD) and managing aquifer recharge (MAR), which are receiving increasing attention in southern Africa.

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