Comparison of groundwater recharge estimation methods for the semi-arid Nyamandhlovu area, Zimbabwe

Tenant Sibanda · Johannes C. Nonner · Stefan Uhlenbrook

Abstract The Nyamandhlovu aquifer is the main water resource in the semi-arid Umguza district in Matebeleland North Province in Zimbabwe. The rapid increase in water demand in the city of Bulawayo has prompted the need to quantify the available groundwater resources for sustainable utilization. Groundwater recharge estimation methods and results were compared: chloride mass balance method (19–62 mm/year); water-table fluctuation method (2–50 mm/year); Darcian flownet computations (16–28 mm/year); ^{14}C age dating (22–25 mm/year); and groundwater modeling (11–26 mm/year). The flownet computational and modeling methods provided better estimates for aerial recharge than the other methods. Based on groundwater modeling, a final estimate for recharge (from precipitation) on the order of 15–20 mm/year is believed to be realistic, assuming that part of the recharge water transpires from the water table by deep-rooted vegetation. This recharge estimate (2.7–3.6% of the annual precipitation of 555 mm/year) compares well with the results of other researchers. The advantages/disadvantages of each recharge method in terms of ease of application, accuracy, and costs are discussed. The groundwater model was also used to quantify the total recharge of the Nyamandhlovu aquifer system (20×10^6–25×10^6 m^3/year). Groundwater abstractions exceeding 17×10^6 m^3/year could cause ecological damage, affecting, for instance, the deep-rooted vegetation in the area.

Keywords Groundwater recharge/water budget · Groundwater age · Groundwater flow · Nyamandhlovu area · Zimbabwe

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Introduction

The problem of estimating groundwater recharge in semi-arid areas is that recharge amounts are normally small in comparison with the resolution of the investigation methods (e.g. Allison et al. 1984). The greater the aridity of the climate, the smaller and potentially more variable in space and time is the recharge flux. Direct groundwater recharge from precipitation in semi-arid areas is generally small, usually less than about 5% of the average annual precipitation, with a high temporal and spatial variability (Gieske 1992).

Lerner et al. (1990) concluded that determination of groundwater recharge in arid and semi-arid areas is neither straightforward nor easy. This is a consequence of the temporal variability of precipitation and other hydro-meteorological variables in such climates, and the spatial variability in soil characteristics, geology, topography, land cover characteristics and land use. Holman (2006) points out that climate change, also in arid and semi-arid areas, may affect recharge in the near future.

De Vries and Simmers (2002) classified natural groundwater recharge mechanisms according to the origin into three types: direct/diffuse recharge, localized recharge, and indirect/non-diffuse recharge. Direct recharge refers to water that is added to the groundwater reservoir from precipitation by direct percolation through the unsaturated zone in excess of soil moisture deficits, interception, surface runoff and evapotranspiration. Indirect recharge refers to water that percolates to the groundwater through the beds of surface watercourses. Localized recharge is an intermediate form of groundwater recharge resulting from horizontal (near) surface concentration of water (ponding) in the absence of well-defined channels.

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Groundwater recharge studies in arid and semi-arid regions of Southern Africa have been carried out by different researchers. Larsen et al. (2002), Gieske (1992), Beekman and Sunguro (2002) concluded that recharge in semi-arid regions in Southern Africa is a small component of the water balance (usually <5% of the average annual rainfall). Nyagwambo (2006) demonstrated that as the potential evapotranspiration is higher than the rainfall, the recharge is dependent on rainfall intensity and the existence of fractures, fissures and cracks in the tropical crystalline basement aquifers of Zimbabwe.

The influence of vegetation on recharge is also very important. Studies by De Vries et al. (2000) in the Kalahari Desert have detected acacia species with deep tap-root systems exceeding 50 m. Capillary rise and uplift induced by deep-rooted vegetation has been reported to cause upward movement of water from large depths (Obakeng 2007).

Within this framework, the main objectives of this article are, first, to report on the application of different methods (tracer and physical methods) to estimate recharge rates in the semi-arid Nyamandhlovu aquifer, Zimbabwe. Second, the recharge estimation results have been compared, along with the methods themselves with regard to the accuracy of the method, the costs involved, and the ease of application. The studied Nyamandhlovu aquifer is located near Bulawayo, the second city of Zimbabwe, in the semi-arid western part of the country (see Fig. 1). The groundwater demand is growing in this area and the determination of the recharge rate is crucial for the groundwater management in that region.

The Nyamandhlovu aquifer

Physiographic and geologic setting

The Nyamandhlovu aquifer is located in the Umguza district of Matebeleland North Province of Zimbabwe, about 40 km northwest of the city of Bulawayo. The Nyamandhlovu aquifer is part of the much larger Forest Sandstone aquifer system. The coordinates X_{min} 598000, X_{max} 6780000 and Y_{min} 7795000, Y_{max} 7833000 give the position of the boundaries of the Nyamandhlovu aquifer. The boundaries partly coincide with the local boundaries between the Khami River and the Umguza River catchments, and other small catchments of rivers in the north, east and southwest, and with the Gwayi River in the west (Fig. 2). This region experiences a typical semi-arid savannah climate characterized by low annual precipitation and high evapotranspiration. The long-term average annual precipitation is about 555 mm/year and the potential evapotranspiration can go up to 2,000 mm/year.

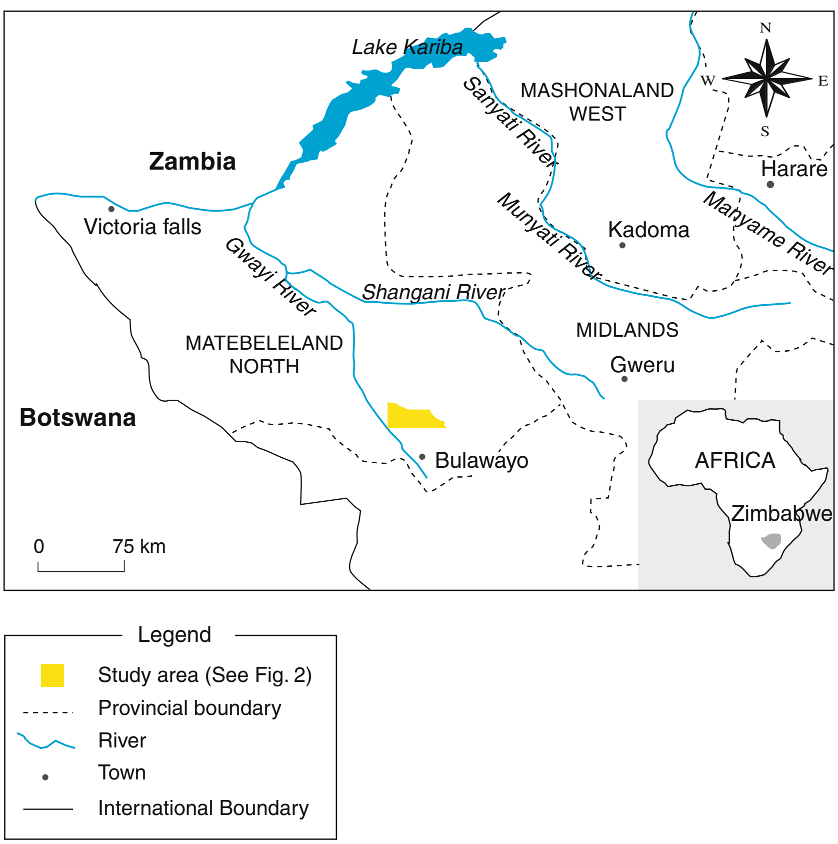

Fig. 1 Location map of study area in Zimbabwe

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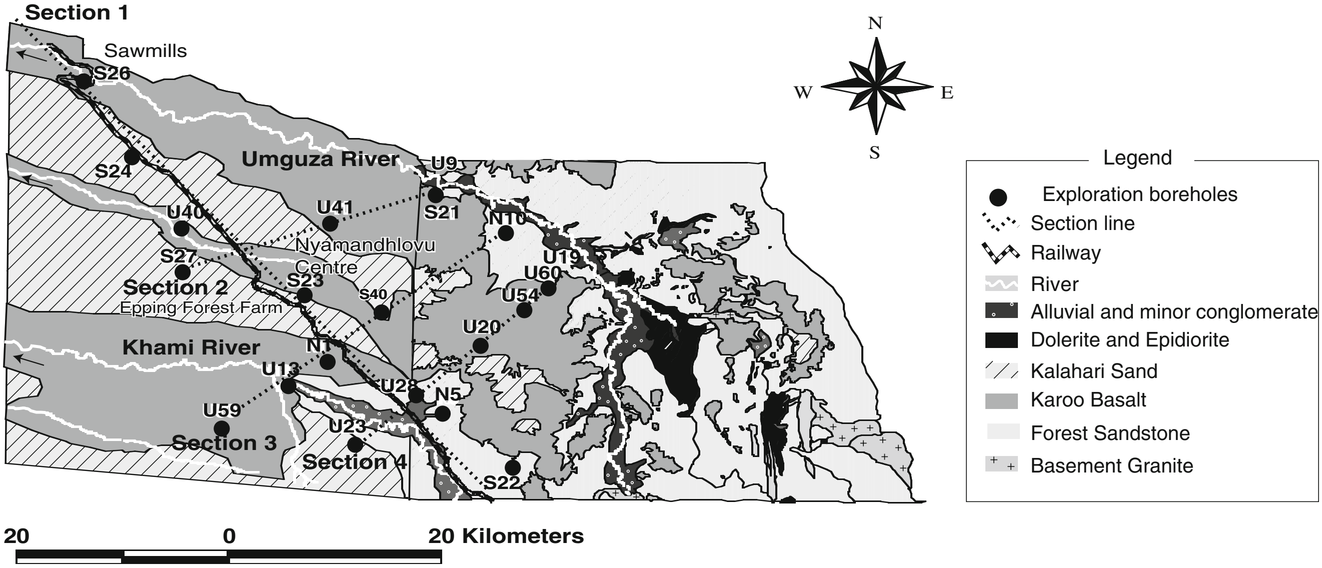

Fig. 2 Geology of the area showing traverses of cross sections

The land surface is flat with isolated ridges normally capped with basalts. Some isolated hills with silicified sandstone occur at the southeastern part of the area. The higher areas, occupied by savannah bush forest, are characterized by a low surface drainage density and the topographic gradient gently slopes downward in a northwestern direction. The main rivers (all ephemeral) in the area, the Umguza River and the Khami River, generally flow down gradient towards the northwest. These rivers join the Gwayi River which flows northwards into the Zambezi River.

There are five main geological formations that have been mapped in the Nyamandhlovu aquifer area. Figure 2 presents the geological map and Fig. 3 shows cross sections based on borehole information. The geological formations include the alluvial deposits, Kalahari Sands, Karoo Basalts, Forest Sandstone, and the Basement Complex. The alluvial deposits are only mapped close to the rivers or old river channels. Thin patches of aeolian Kalahari Sands cover the Karoo Basalts in places. The basalts overlay the Forest Sandstone which rests directly on the granitic-gneissic Basement Complex. The lithological stratigraphy of the five principal geological formations in the study area is summarized in Table 1 (Macgregor 1937).

Previous hydrogeological investigations

Beginning in the 1970s, different researchers have studied the Nyamandhlovu aquifer. The studies are multi-disciplinary encompassing preliminary hydrogeological investigations. Beasley (1983) carried out a study on the groundwater potential of the area. The main aquifer unit was identified as the permeable Middle and Lower division of the Forest Sandstone. The overlying Karoo Basalt is permeable where the rock is weathered and fractured. Kalahari Sands locally occur as unconsolidated sediments on top of the basalt. They have a high permeability thus enhancing direct recharge through porous material.

Beasley (1983) carried out further studies on the hydrogeology of the area. He found transmissivity values for the Forest Sandstone aquifer in the range of 4–94 m^2/day with an average value of 35 m^2/day for the Nyamandhlovu area. The aquifer thickness was between 51 and 119 m resulting in a permeability range of 0.10–0.85 m/day with an average of 0.34 m/day. It was shown that the groundwater flow system forms a regional system flowing to the northwest. It was also noted that there are some local flow systems influenced by changes in the stream discharges in the area. Direct groundwater–surface water interactions occur at the Umguza and the Khami Rivers. Furthermore, several hints indicated that recharge takes place mainly at the high plateaus.

Banda et al. (1977) carried out a study in the Umguza sub-catchment focusing on the exploration of groundwater through the drilling of exploratory boreholes. Within the frame of the study reported here, 25 boreholes were drilled into the Forest Sandstone and pump tested, yielding a weighted average for the transmissivity of 40 m^2/day and a storativity of 5×10^{-4}.

Martinelli and Hubert (1996) carried out a desk study and made an inventory of the available information pertaining to groundwater in the Nyamandhlovu aquifer. They also carried out step-drawdown and constant discharge tests and obtained values for the transmissivity in the range of 0.2–230 m^2/day for the Forest Sandstone. They recommended executing further geophysical investigations, drilling of production and monitoring boreholes, geophysical borehole logging, pumping tests, hydrochemical sampling and age dating of water, groundwater flow modeling, re-designing the monitoring program and aquifer recharge studies.

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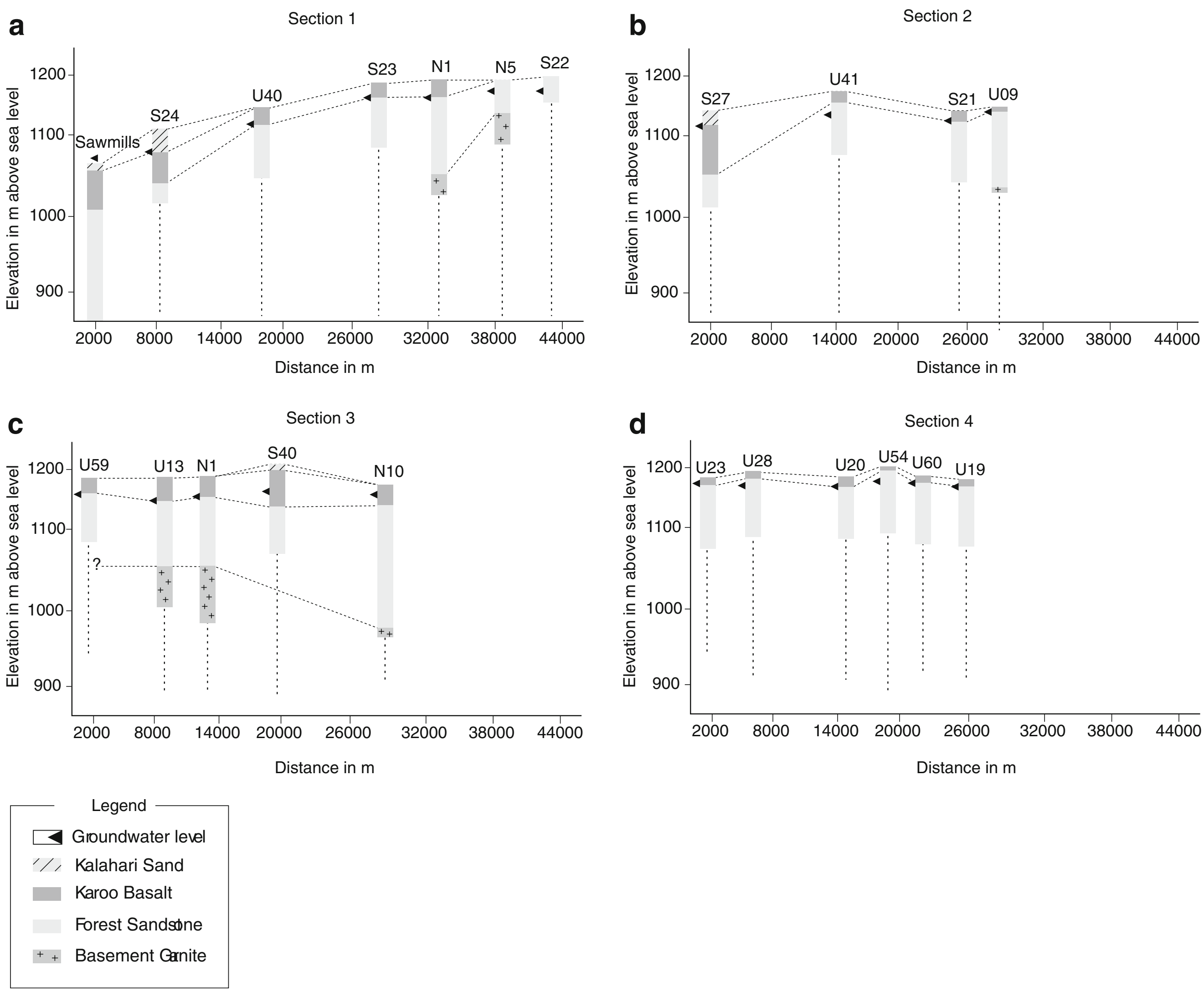

Fig. 3 Cross sections (see Fig. 2 for locations)

Siwadi (2001) carried out a study on re-designing the groundwater level monitoring network for the Nyamandhlovu aquifer. For his investigation period from 1989 to 1999, it was shown that the groundwater levels are declining at a rate of about 0.2–1.5 m/year, experiencing a high decline in areas of intense groundwater exploitation around the Bulawayo City well field.

Hydrogeological conceptualization

The previous studies indicate that the main aquifer in the Nyamandhlovu area is contained in the Middle and Lower division of the Forest Sandstone Formation. The Forest Sandstone only crops out in the eastern part of the study area and elsewhere this unit is overlain by Karoo Basalt and Kalahari Sands. The occurrence of artesian wells in the Forest Sandstone at Sawmills indicates that the Karoo Basalt can act as a confining aquiclude. However, the Karoo Basalt can also form a secondary aquifer where the rock is weathered and fractured. These conditions were found at Epping Forest Farm where geophysical investigations indicated that the rock is also very patchily developed. The unconsolidated Kalahari Sands, which mainly developed on the higher plateaus in between the local rivers in the study area, have a high permeability and can be considered as aquifers in the few places where the local water table is positioned within this unit (Fig. 3).

Recharge into the Forest Sandstone aquifer is believed to consist of contributions from precipitation, from the groundwater–surface water interaction at parts of the

Table 1 Lithological stratigraphy of the area (after Macgregor 1937)

Lithological unit	Geological age
Alluvial deposits	Pleistocene and Recent
Kalahari Sand	Early and middle Tertiary
Karoo Basalt and interbedded sandstones	Early and middle Tertiary
Forest Sandstone	Upper Triassic
Basement Complex	Pre-Cambrian

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Umgazi and Khami rivers and from return flows at irrigated fields. Precipitation amounting to a long-term average of 555 mm/year is the largest contributor of recharge and takes place in a direct way where the Forest Sandstone is exposed (Fig. 2). In the areas where Karoo Basalt, overlaying the Forest Sandstone crops out, recharge takes place where the basalt is weathered and fractured. Also recharge may take place through the Kalahari Sand into underlying permeable Karoo Basalt and Forest Sandstone.

Where the sandstone and the basalt are exposed, the vegetation is rather sparse and the drainage density is not that large with, in places, no connections of gullies to the major streams. This confirms the occurrence of groundwater recharge. The Kalahari Sands on the other hand show a densely vegetated terrain with abundant vegetation. When soil moisture limits are exceeded after heavy rain, percolation takes place through the sands and downward to the Karoo Basalt.

The middle and eastern part of the study area could well receive larger amounts of recharge than the western part. One of the reasons is that, partially, the middle and eastern parts contain the exposed Forest Sandstone, but even more important is that the Karoo Basalt seems to become thicker in a westerly direction (Fig. 3). The large thickness of the basalt in the west makes it unlikely that this unit is weathered from top to bottom. The resulting less permeable nature of the basalt in these areas as demonstrated by the confining nature of the rock at Sawmills substantially reduces the scope for recharge from precipitation.

The recharge contribution from surface water is believed to be small since the major streams in the area are intermittent, only flowing after heavy rainfall. The contact area with the underlying Forest Sandstone or Karoo Basalt is relatively small and flood water carries an appreciable sediment load thereby clogging fractures in the hard rock. Return flows from fields are difficult to estimate but in view of the small size of the irrigated area of less than 2,000 ha, the overall quantities are considered to be small.

Recharge into the Forest Sandstone aquifer results in a groundwater flow in a northwesterly direction as indicated on groundwater level contour maps prepared on the basis of information from boreholes where groundwater levels are monitored. Along a flow path the dissolution of calcite present in the sandstone is one of the main hydro-chemical processes taking place. This yields a predominantly calcium-bicarbonate type of groundwater which is also fresh in most places.

Need for additional analyses

Previous studies in the Nyamandhlovu area have tackled to some extent the recharge issue, but so far the distribution of recharge across the area and the related recharge processes have only been described in general terms. Beasley (1983) and Martinelli and Hubert (1996) tried to quantify recharge for their groundwater potential and groundwater assessment studies and adopted recharge rates on the order of 125 and 14–28 mm/year correlating with 22% and 2.5–5% of the long-term average precipitation, respectively. However, they did not carry out detailed investigations. The study reported here, however, overcomes this lack and presents a number of methods to address the analysis of the recharge process and the estimation of recharge rates for the Nyamandhlovu aquifer.

Methodology and applicability

Four methods have been selected to estimate groundwater recharge in the study area: The *chloride mass balance*, the *water-table fluctuation method*, the *Darcian flownet computation,* and the *groundwater age dating* method (e.g. Kinzelbach et al. 2002; Scanlon et al. 2002). These methods have been selected based on the availability of data and the hydrogeological set up of the study area. In addition, *groundwater flow modeling* has been undertaken to complement and confirm the findings of the mentioned recharge estimation methods.

Chloride mass balance method

This is a tracer balance method whereby the amount of chloride entering into the root zone system is balanced by the amount of chloride leaving the system (Nonner 2006). The chloride mass balance equation can be described as follows:

$$\mathrm{Cl_{gw}}Q_{\mathrm{perc}} = \mathrm{Cl_p}P + D - \mathrm{Cl_e}E - \mathrm{Cl_r}R \quad (1)$$

where:

- Q_{perc} Rate of percolation at the lower boundary of the root zone (m^3/day)
- $\mathrm{Cl_{gw}}$ Chloride concentration in percolating groundwater (g/m^3)
- P Precipitation rate (m^3/day)
- $\mathrm{Cl_p}$ Chloride concentration in precipitation (g/m^3)
- D Dry chloride deposition (g/day)
- E Total evapotranspiration from the root zone (m^3/day)
- $\mathrm{Cl_e}$ Chloride concentration in evapotranspiration water (g/m^3)
- R Surface runoff (m^3/day)
- $\mathrm{Cl_r}$ Chloride concentration in runoff water (g/m^3)

To work out a simplified relation for recharge estimation, it will be assumed that the chloride concentration in the evapotranspiration water is virtually zero and that areas are being studied with very little surface runoff. In the longer run, the percolation rate also equates to the recharge rate which can then easily be determined by calculating the ratio of the chloride concentration in precipitation and the chloride concentration in groundwater (Gieske 1992). Working out the balance equation and assuming that the dry deposition is also determined in the collected precipitation water, the following formula for recharge estimation can be established:

$$Q_{\mathrm{perc}} = \frac{\mathrm{Cl_p} P}{\mathrm{Cl_{gw}}} \tag{2}$$

The successful application of this method depends on the following assumptions:

- Chloride is a conservative tracer in the system. This means that its concentration is neither diminished nor increased through chemical reactions in the soil
- There is no other source of chloride in the soil or groundwater (incl. dry deposition) other than precipitation
- Steady-state conditions of atmospheric solute input (constant chloride concentrations in space and time) and solute flux in the subsurface in the long term prevails
- No surface runoff is present, or its flux can be accounted for
- In the long run, the percolation at the lower boundary of the root zone equals groundwater recharge

The chloride mass balance method has successfully been used before in the semi-arid hard rock regions of Botswana and Zimbabwe (Beekman et al. 1996; Beekman and Sunguro 2002; Nyagwambo 2006). The assumptions underlying the application of the method are largely satisfied for the study area. For example, another source of chloride could be fertilizer used on agricultural fields. However, commonly used fertilizers in Zimbabwe are Compound D and ammonium nitrate which do not contain chloride and it is reasonable to assume that these chemicals were also used in the Nyamandhlovu area. Surface runoff as discussed in the previous section is thought to be rather small and to neglect this amount in the recharge computation following the chloride mass balance method is justified.

Water-table fluctuation method

Groundwater recharge from precipitation may be estimated from an analysis of water-table fluctuations in an unconfined aquifer (Scanlon et al. 2002; Nonner 2006). Recharge causes a rise in the water table which consequently causes an increase in the amount of water stored. Recharge is equal to the amount stored plus an amount that is added to discharge. To assess recharge with the water-table fluctuation method, a hydrograph of the water table is considered to determine the so-called modified rise in water table elevation. The modified rise in the water table is equal to the rise taken from the extended recession curve to the peak of the table. The modified rise accounts for both the water stored and the amount drained laterally during the recharge event. The following equation can then be used to compute the recharge rate:

$$Q_{\mathrm{prec}} = S_{\mathrm{y}} \frac{\Delta\phi_{\mathrm{mod}}}{\Delta t} \tag{3}$$

where:

Q_{prec} Rate of recharge from precipitation (m/day)
S_{y} specific yield (-)
$\Delta\phi_{\mathrm{mod}}$ Modified rise in water table (m)
Δt Observation period (days)

In cases where more than one recharge event occurs within the observation period, modified rises in water table can be summed up for the estimation of an average recharge rate. This approach may be applicable for larger time steps ranging from months to seasons where natural discharge is quite substantial.

The water-table fluctuation method has been used for crystalline rock in Zimbabwe where, in parts of the area, the hard rock was overlain by Kalahari Sands (Nyagwambo 2006). The availability of long time series of groundwater levels justifies the application of the water-table fluctuation method for the Nyamandhlovu area, but there are also disadvantages. Perhaps the main drawback is the uncertainty in obtaining a representative value of the specific yield S_{y} which is difficult to establish in the fractured hard sandstone and basaltic rock present in the study area. As a result of the well screen setting in the Forest Sandstone aquifer for which the water levels may not exactly reflect water table behavior, the correct water table rises may also be difficult to establish.

Flownet computation

Regional groundwater flow computations based on groundwater flow equations may be used to assess groundwater recharge. The approach follows the Dupuit-Forchheimer assumption whereby groundwater flow is assumed to be horizontal in aquifers and vertical in aquitards. Flownets can be prepared by drawing a set of flow lines perpendicular to equipotential contour lines on groundwater level contour maps. The flow lines will then form boundaries of stream tubes whereby it is assumed that groundwater flowing through an individual stream tube is neither loosing nor gaining water from the neighboring tube (Fetter 2001).

Darcy's law can be used to compute the flow rate through a cross-sectional area of the aquifer by summing up flow rates through individual stream tubes. The groundwater flow rate through a stream tube at a selected cross-section can be computed by taking into consideration the discrete difference in hydraulic head for two successive contour lines, the width of the stream tube and the thickness of the aquifer. Darcy's law equation for the flow rate computation can be written as follows:

$$Q_{\mathrm{s}} = -KHw_{\mathrm{s}} \frac{\Delta\phi}{\Delta s} \tag{4}$$

where:

Q_{s} Flow rate (horizontal) through the stream tube (m^3/day)

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K Horizontal coefficient of permeability (m/day)
H Saturated aquifer thickness (m)
w_s Width of the stream tube (m)
$\Delta\phi$ Discrete difference in groundwater level (m)
Δs Discrete distance between contour lines (m)

The flownet computation method has not been used much in Zimbabwe. Presumably, the dominance of hard crystalline rock with a very uneven distribution of transmissivities and a lack of sufficient monitoring wells has prevented scientists from performing this type of recharge assessment. However, the application of the method appears to be justified for the Nyamandhlovu aquifer. Although there is a reasonable variation in the transmissivity of the Forest Sandstone across the area, a reliable average can be determined from pumping tests carried out at a large number of wells. The large number of groundwater level monitoring wells with suitable data and with a reasonable distribution over the study area allows the preparation of groundwater level contour maps.

Groundwater dating

Groundwater recharge to aquifers can be evaluated from carbon-14 ages according to the Bredenkamp and Vogel (1970) model. The equation for the recharge estimation is:

$$Q_{\mathrm{prec}} = \phi_{\mathrm{e}} \frac{H}{t} \ln \frac{H}{h} \tag{5}$$

where:

Q_{prec} Recharge rate (mm/year)
ϕ_{e} Effective porosity of the saturated zone in the aquifer (-)
h Saturated thickness of the aquifer (m)
H Total thickness of the aquifer (m)
t Carbon-14 age of water (years)

The approach assumes only vertical water fluxes, thus the developed relationship takes only the depth of sampling into account. The approach can be applied for particular boreholes in a recharge area. The model has been applied successfully in several groundwater recharge studies in Southern Africa by various researchers (e.g. Bredenkamp and Vogel 1970; Bredenkamp et al. 1995; Beekman et al. 1996).

Analyses and results

The recharge estimation following the chloride mass balance method requires data on precipitation, total chloride deposition from the atmosphere and the chloride concentration in the percolating groundwater. A long-term average annual precipitation of 555 mm/year was obtained from a record of 31 years duration at two stations in the study area, the Nyamandhlovu Rail and Umguzani stations. The total chloride deposition from the atmosphere, mainly from precipitation and measured over only two years in the study area, ranged between 0.5 and 1.0 mg/L. Larsen et al. (2002) proposed for the total chloride deposition from the atmosphere an average value of 0.5 mg/L for western Zimbabwe. For the computation of the recharges a value of 0.6 mg/L has been used. For the determination of the chloride concentration in percolating groundwater, water samples have been collected at well screens in the saturated Forest Sandstone aquifer. Chloride concentrations ranging from 2.5 to 76.5 mg/L, determined in samples from a selection of 24 wells, have been used for recharge computations.

Figure 4 shows the aerial distribution of recharge rates computed with Eq. (2). The rates vary between a high of 133 mm/year for an observation point in the middle of the area to a low of 4.4 mm/year near Sawmills. Since water samples for the determination of chloride rates in groundwater have been taken at well screens not exactly

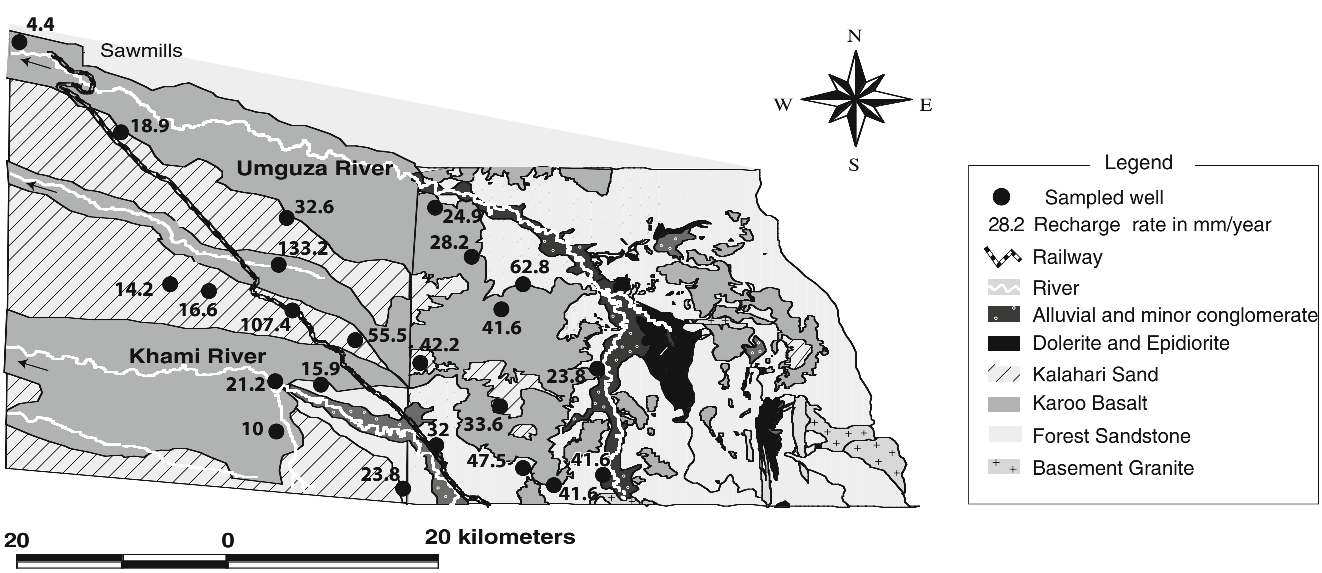

Fig. 4 Recharge determined with the chloride mass balance method

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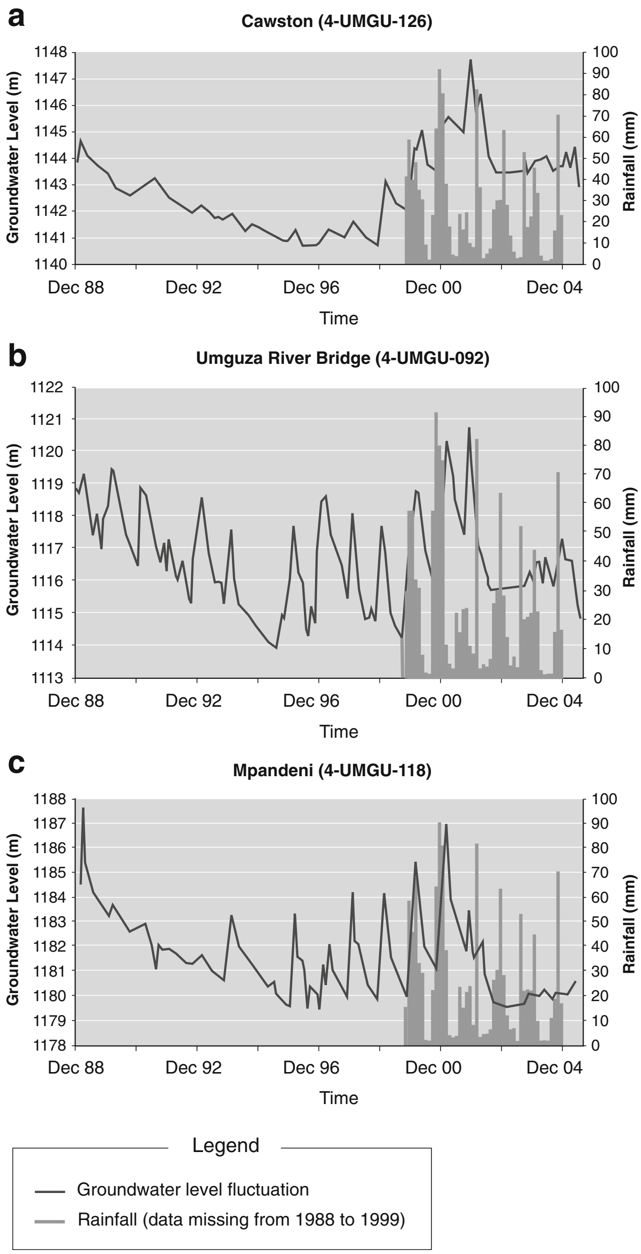

Fig. 5 Precipitation–groundwater level relationships

tapping the water table, the recharge rates rather apply to some point 'upstream' of the wells. This makes it difficult to correlate recharge rates determined at wells located in the Karoo Basalt and Kalahari Sand areas with direct recharge into these formations, since recharge may also have taken place in 'upstream' areas where Forest Sandstone is exposed. However, the general trend seems to be that in the middle and eastern parts of the study area, the recharge rates tend to be higher than in the western section. Finally, it can be concluded that for the entire study area, a recharge range of 19–62 mm/year yielding an average rate of 38 mm/year can be computed with the chloride mass balance method. This average recharge value represents 6.7% of the total annual precipitation.

For the computation of recharge using the water–table fluctuation method, specific yields and groundwater level time series are required. The calculations have been based on the lower and upper limits of specific yield values of 0.002 and 0.008, which were interpreted from the two pumping tests in the area clearly showing water-table conditions. The wells are located in the Forest Sandstone and Karoo Basalt Formations. Groundwater levels at four monitoring wells are continuously recorded with pressure transducers whereas in another 37 monitoring wells monthly measurements have been carried out since the 1988–1989 rainy season.

Figure 5 shows time series of groundwater levels of three of these wells and Fig. 6 presents the locations of these wells. The time series based on monthly measurements show a similar pattern as the continuous registration of levels in the same wells. The Cawston and Mpandeni wells are located in the Karoo Basalt, but screened in the Forest Sandstone aquifer, and the Umguza River Bridge well is located and screened in the Forest Sandstone. Without the presence of a thick dampening zone of unconsolidated material, the rather rapid reaction to precipitation events, within 1 or 2 months (Fig. 6), indicates preferential flow through fractured rock. Considering the whole time series the reaction to rain events in the rainy season is evident and it is clearly shown that after a number of dry years, with little recharge from 1990 to 1999, groundwater levels were restored in the much wetter period from 1999 to 2002. In particular the groundwater level time series in the wells at inland Mpandeni and Umguza River Bridge show a similar behavior which could indicate that the influence of the seasonal floods in the latter well (at about 20 m from the river) is not that large. The well at Cawston is different in the sense that the restoration of the groundwater levels after 1999 is more evident than in the other two wells. The more pronounced restoration in the former well is a result of a lack of direct recharge in the area around this well in the preceding dry period when soil moisture deficits were apparently not exceeded. Lack of groundwater level data, like in the 2002–2003 rainy season, can be a reason for a poor correlation between these groundwater levels and precipitation.

Figure 6 also shows the locations of the other four wells that have been used for the recharge computations using the water-table fluctuation method. These wells are located in the Karoo Basalt and screened in the Forest Sandstone whereby it has been assumed that the measured groundwater levels reflect the water table. Some justification for this assumption is given by the statements made on the hydrogeological conceptualization of the area, describing the Karoo Basalt as highly weathered and fractured in places. The recharge computations carried out with Eq. (3) for the period 1989–2002 show that the recharge rates vary between 2 and 12 mm/year when a specific yield of 0.002 is used. They range from 9 to 50 mm/year for a specific yield of 0.008. The locations of the monitoring wells are in most places not that far away from production wells with mutual distances ranging between

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50 and 1,000 m. However, during groundwater level measurements production wells are usually switched off for a period of at least 24 h and the recovered 'static' levels allow a reasonable computation of recharge values. Nevertheless, the effects of incomplete recovery at some wells (Mpandeni, Dillkosh and Khami; see Fig. 6) were noted and corrections were made to come up with more accurate recharge rates. In view of the above, the limits that can be set for the recharge estimation using the water table fluctuation method are 2 and 50 mm/year corresponding to 0.4% and 9% of the long term annual precipitation.

To apply the flownet computation method, transmissivity values and aerial distributions of groundwater levels are required. Transmissivities adopted for the Forest Sandstone aquifer range between 11 and 97 m^2/day and were determined from pumping tests carried out at 21 wells that are reasonably well distributed over the study area. The groundwater level measurements at the seven wells used for the water-table fluctuation method are part of a larger network of 41 groundwater level monitoring wells which showed that the levels range from a high of about 1,220 m above sea level in the southeast to a low on the order of 1,100 m above sea level in the northwest at Sawmills.

Figure 7 shows the groundwater level contour lines where flownet computations have been carried out using Eq. (4) for each individual stream tube. By summation of the flows obtained for each tube, the total flow through the Forest Sandstone aquifer at the selected contour line was obtained. Transmissivity values representative for each set of selected contour lines have been considered. The computations have been done for the dry and rainy seasons of the periods from 1997 to 1998 and from 2000 to 2001 which can be considered to represent an average and a wet year respectively. The average flow in the aquifer using the contour lines of 1,190 and 1,200 m above sea level has then been computed in the range of 1,600–2,100 m^3/day and for the lines 1,120 and 1,130 m above sea level, from 11,500–14,300 m^3/day.

Recharge values for the area of 960 km^2, in between the mentioned sets of contours, have been computed considering that this parameter is equal to the outflow at the downstream set of contour lines minus the inflow at the upstream set of lines plus the net groundwater abstractions and any transpiration losses by deep-rooted plants reaching the water table. The domestic abstractions in the area for the city of Bulawayo have been measured at 20,000 m^3/day and agricultural abstractions for irrigation schemes have been estimated at 25,000 and 12,000 m^3/day (Beasley 1983; Martinelli and Hubert 1996, respectively). For the whole study area, net agricultural abstractions of about 17,000 m^3/day have been considered taking into account a 10% return flow based on the position of flow monitoring points and the use of efficient sprinklers. Since some wells are located 'downstream' of the groundwater level contour lines used for the flownet computations, the actual net agricultural abstraction taken for recharge calculations amounted to 12,000 m^3/day. The abstraction values have further been confirmed in the modeling process.

Transpiration losses by deep-rooted plants is an issue that is also elaborated on in the modeling section, but for recharge computations using the flownet approach, cases whereby roots do not reach and do reach the water table have been considered. In the first case, the losses are not considered in the recharge computation. However, in the second case, deep-rooted vegetation may take water at a rate of 31,000 m^3/day (or 12 mm/year, Obakeng 2007) from the water table. This amount of water has been included in the recharge computations. Filling in the data and expressing the parameter as a yearly rate the average recharge over the periods from 1997 to 1998 and from 2000 to 2001 have been computed at 16.1 and 16.5 mm/year, respectively, for the case whereby the roots do not reach groundwater and from 27.9 to 28.2 mm/year for the

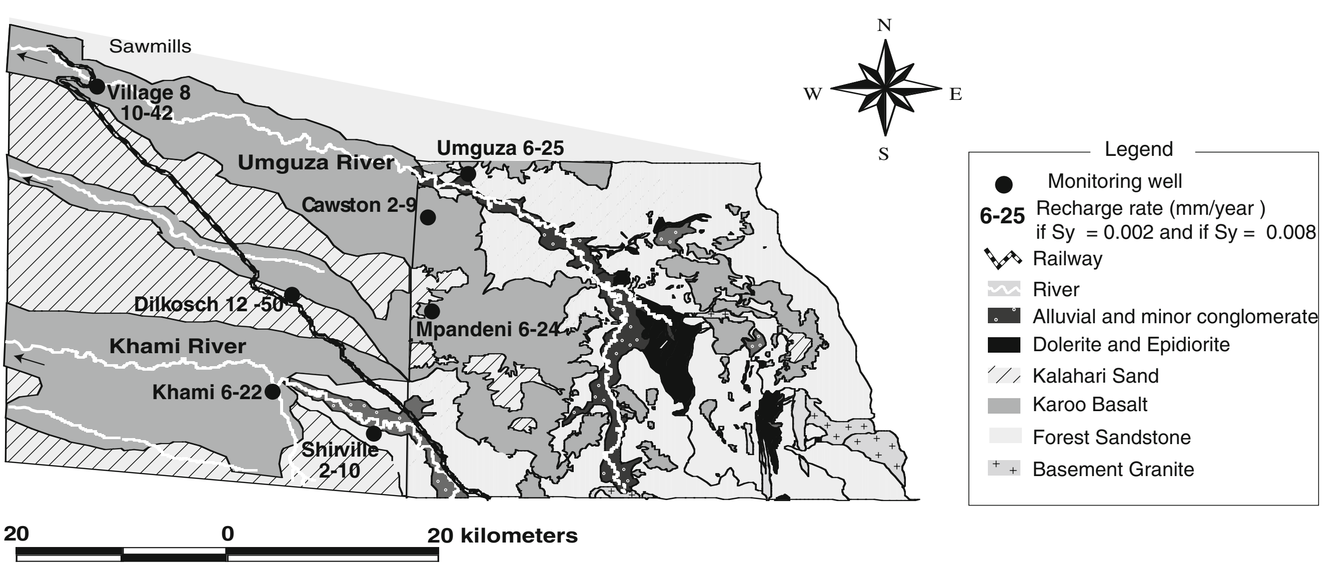

Fig. 6 Recharge determined with the water-table fluctuation method

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case where the deep roots tap the water table. These recharge estimates amount to 2.9 and 5% of the average annual precipitation, respectively.

The recharge values calculated are a combination of two components, recharge from precipitation and influent flow from river-bank infiltration. River-bank infiltration only occurs after heavy rains when the streams are flowing and, as explained in the hydrogeological conceptualization, contributions to the total recharge can be assumed to be small.

Groundwater dating using ^{14}C gives an average recharge rate of 25 mm/year. This corresponds to 4.5% of the long-term average annual rainfall of 555 mm/year. The estimation is based on samples taken in boreholes in the recharge areas. All ^{14}C ages were determined using equations for mean residence time computations described by Vogel (1970) and Mook (1989). The results show that recent groundwater is located in the central and eastern part of the study area, while older groundwater dominates in the west (Fig. 8). The mean residence time of the water is a function of the flow distance from the recharge area and the flow velocity in the aquifer. Groundwater ages increase with distance following the flow gradient indicating that the assumption of Darcian flow in the main Forest Sandstone aquifer is defendable.

Groundwater flow modeling

A numerical groundwater flow model of the Nyamandhlovu aquifer system was prepared to complement and confirm the findings of the estimations of the recharge rates using the four methods discussed in the previous sections. The modeling activities comprised the formulation of the conceptual model, the specification of the model code, grid and input data, and the model calibration.

Conceptual model

In the first place, the model conceptualization comprises the schematization of the model layers. Three distinct layers were considered for the groundwater model of the Nyamandhlovu area. These include the Kalahari Sand as the upper layer (layer 1), the Karoo Basalt as the middle layer (layer 2) and the Forest Sandstone as the bottom model layer (layer 3). The Basement Complex mainly consisting of impermeable granitic-gneissic and locally doleritic material acts as the impermeable bottom in the model. Layer 1 was modeled as unconfined while layers 2 and 3 were modeled as convertible between confined and unconfined.

Second, the conceptual model entails the formulation of a groundwater balance which can be formulated as follows for the Nyamandhlovu aquifer system:

$$\left[Q_{\text{prec}} + Q_{\text{surfin}}\right] - \left[Q_{\text{well}} + Q_{\text{lso}} + \text{ET}\right] = 0 \quad (6)$$

Q_{prec} (mm/year) is groundwater recharge into the Forest Sandstone, Karoo Basalt and Kalahari Sand complex originating from precipitation and Q_{surfin} (mm/year) is the recharge supplied from surface water. Q_{well} (mm/year) is the net abstraction at domestic and agricultural wells, mainly in the eastern and central part of the model area. Q_{lso} (mm/year) is the subsurface outflow which mainly takes place at the western margin of the model area, and ET (mm/year) is the transpiration of the deep-rooted vegetation possibly tapping water from deep water tables. Obakeng (2007) proves that deep-rooted vegetation in the Serowe area, about 300 km southeast of the study area, is taking up transpiration water from deeper layers in the unsaturated zone and possibly from the water table. The similarity between both areas from a meteorological, hydrogeological and land use (vegetation) point of view justifies the consideration of an ET component in the groundwater balance.

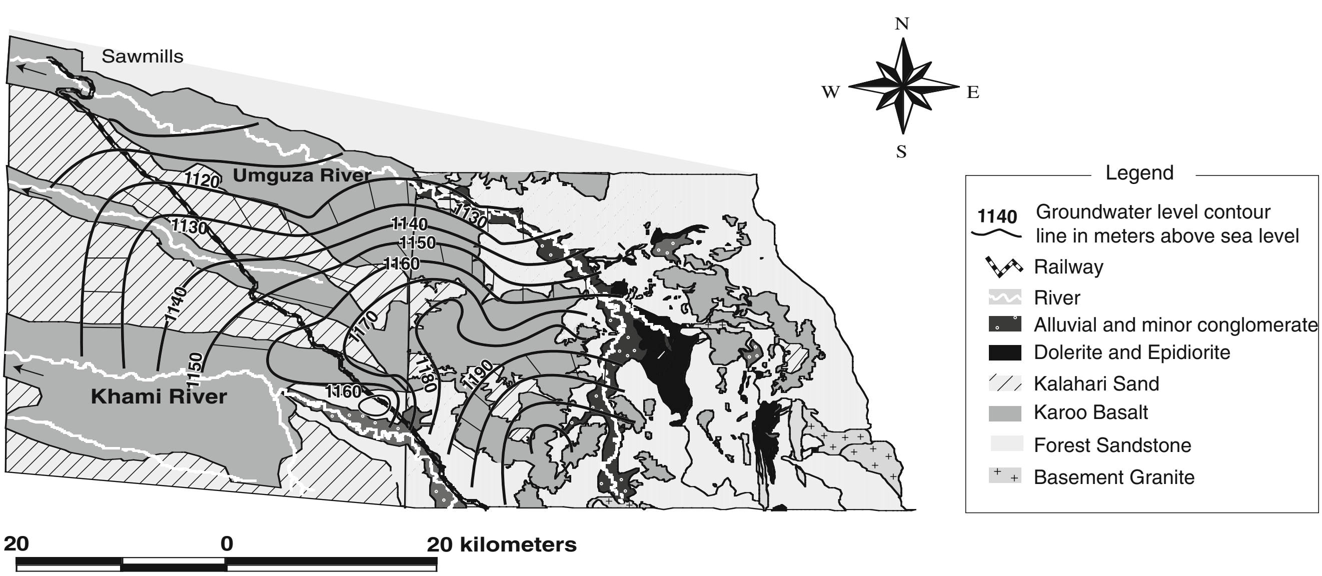

Fig. 7 Groundwater level contour map and flownet computation method

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Third, the model boundaries were defined. In the east the model boundary is roughly the contact between the Forest Sandstone and the impermeable Basement Complex. In the north and south, the model boundaries follow, in most places, groundwater flow lines north of the Umguza River and just south of the Khami River. The maps in Fig. 9, which cover the active model domain, demonstrate that flow lines roughly being perpendicular to the contour lines follow the model boundaries. Finally, in the west the boundary mainly follows groundwater level contour lines west of Sawmills.

Fourth, the groundwater flow condition was determined. Groundwater levels considered for the long-term modeling period from 1989 to 2004 showed a downward trend from 1989 to 1999 and levels were restored from 1999 onwards. For the overall period there is not a significant up- or downward trend and steady-state modeling was therefore performed.

Model code, grid and input of data

A numerical groundwater flow model was prepared using the MODFLOW-PMWIN code. A regular mesh and a block centered finite difference grid with 1-km^2 cell areas with a total of 50 rows and 90 columns was used. With a total grid area of 4,500 km^2, the active model area is 1,900 km^2. This area is considerably larger, mainly stretching out towards the west, than the middle and eastern part of the study area (960 km^2) for which the recharge estimation methods were mostly applied. Using the copying and field interpolator facilities of PMWIN, the data input could be conveniently accomplished.

Based on ample well information, the top and bottom elevations of the three model layers were inserted in the model. Permeabilities for the Forest Sandstone, ranging from 0.2 to 1.2 m/day and determined from pumping tests carried out at 21 wells, were distributed over the model area. Permeabilities for the Karoo Basalt and the Kalahari Sand were taken from literature and input into the model as single values for the whole unit.

Recharge rates, computed by the recharge estimation methods, have been considered as input for the model. Since none of the recharge estimation methods were able to show clear differences in recharge rate between the Forest Sandstone and the Karroo Basalt areas, the same recharge rates, mainly based on the flownet computations, have been applied for these two formations. The Kalahari Sands have been assigned slightly lower recharge rates than the sandstone and basalts (Fig. 10). Although the sands have a larger permeability than the rocks, the lower recharge rate is partly due to the absence of preferential flow and the abundant vegetation growing on this unit, giving rise to high transpiration rates (see also Martinelli and Hubert 1996).

The recharge rates based on the recharge estimation methods have been assigned to the middle and eastern part of the Nyamandhlovu model area. The other slightly smaller part, in the west, is expected to receive a low recharge and very low rates have been assigned to this part of the model area. The allocation of higher recharge rates in the middle and eastern part of the model area follows the hydrogeological conceptualization where the reduction in recharge towards the west was already suggested.

Net abstractions from wells, which are on the order of 37,000 m^3/day, have been assigned to the Forest Sandstone Formation represented by the third model layer. The value is based on abstractions of 20,000 m^3/day for domestic purposes and net withdrawals of 17,000 m^3/day for irrigation.

Model calibration

Similar to the approach adopted for the flownet computation, a case whereby the deep-rooted vegetation does not reach the water table and a case where the roots do reach this water table have been considered for model calibra-

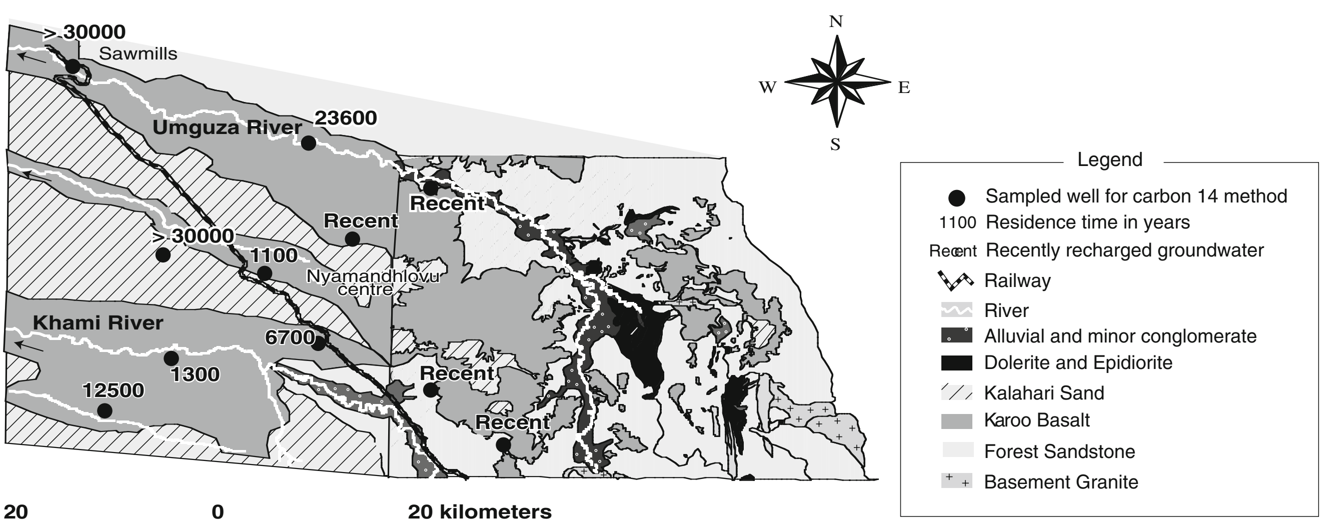

Fig. 8 Groundwater ages determined with the ^{14}C method

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tion. In the latter case, it has been assumed that all the transpiration water at a rate of 12 mm/year (Obakeng 2007) is taken from the water table and not from other deeper layers in the unsaturated zone.

Model calibration was accomplished by varying a set of parameter values that produce simulated groundwater levels that match field observations. In many cases, permeabilities and recharges are considered as parameters that should be selected for calibration and this selection often leads to non-unique modeling results (Scanlon et al. 2002). Due to the large number and reasonable distribution of pumping tests carried out in the Nyamandhlovu aquifer, it has been assumed that its permeabilities are rather accurate and recharge has been the main parameter considered for adjustment. In addition, some minor and local adjustment of abstraction rates was implemented without changing the total amount.

For the Nyamandhlovu model area, with a total difference in groundwater level on the order of 120 m, a maximum of 5 m difference between observed and calculated groundwater levels was thought to be an acceptable calibration target. After calibration, the groundwater level patterns of observed and computed groundwater levels were quite similar (see Fig. 9) and 95% of the level observations taken from a total of 24 wells were within 5 m of the computed values. The other 5% of the level observations were within 10 m of the model computed values.

Calibrated recharge rates for the middle and eastern part of the modeled Nyamandhlovu aquifer for the case whereby the deep-rooted vegetation does not tap the water table were found to be 14 mm/year for the Forest Sandstone and Karoo Basalt area and 10.5 mm/year for the higher strips with Kalahari Sand. Recharge rates for the western model area are low and on the order of 1.9–2.5 mm/year. For the case where the deep-rooted vegetation takes its transpiration water from the water table in the recharge area (approximately 12 mm/year), this component is simulated as an outflow component of the model's water balance leading to higher calibrated recharge values. For the middle and eastern part of the model area these recharge rates are 26 and 22.5 mm/year, respectively for the Forest Sandstone and Karoo Basalt, and Kalahari Sand areas.

Discussion

Comparison of results

Four basic methods and groundwater modeling to estimate groundwater recharge from precipitation in the Nyamandhlovu aquifer showed results that do not differ that much from each other. Table 2 summarizes the recharge rates obtained through the different methods applied in the study area. Despite the similarity there are differences in the results that can be explained as follows. The chloride mass balance method which is often recommended in semi-arid regions may over-estimate

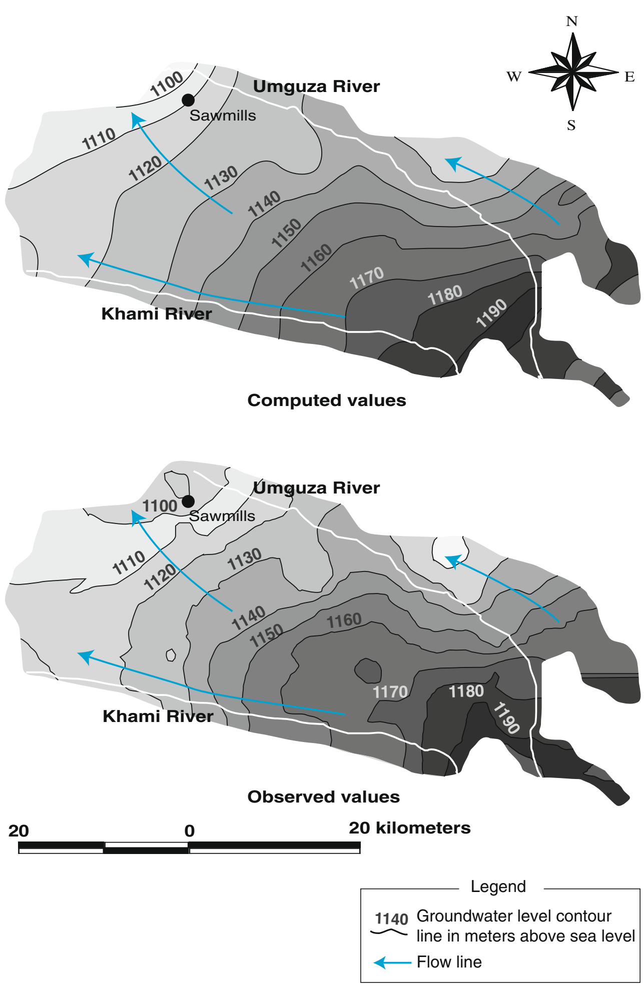

Fig. 9 Groundwater levels for the Forest Sandstone aquifer

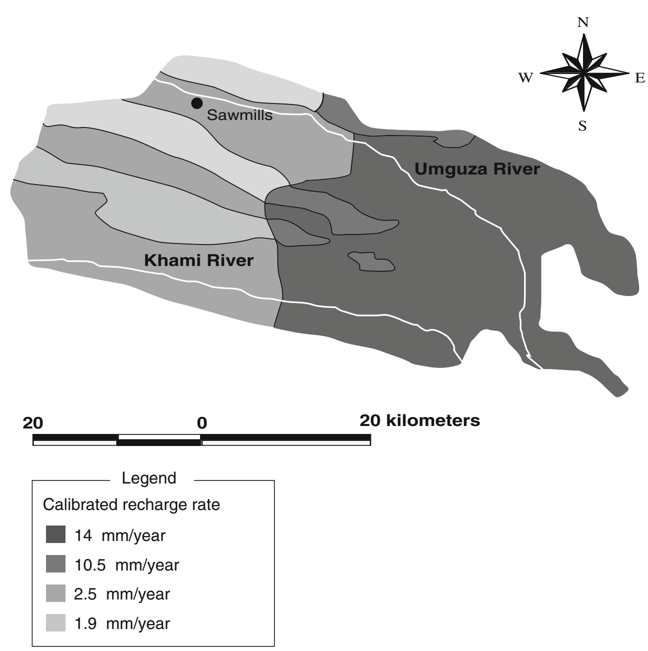

Fig. 10 Calibrated recharge rates; case with no transpiration from the groundwater system

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recharge rates in fractured rock areas. The method determines point recharge which is supposed to be diffuse recharge originating from weathered and fractured parts of the rock at or 'upstream' of an observation well where chloride samples have been taken. In these areas, the recharge estimation is correct, but the estimation can not be extended to areas where the rock is not weathered and aquifers are overlain by impermeable layers. Such areas are present in parts of the Nyamandhlovu study area. Therefore, the computed recharge range from 19 to 62 mm/year and the average rate of 37 mm/year are too high to be considered as averages for the typical recharge area covering the middle and eastern part of the Nyamandhlovu study area.

The water-table fluctuation method also determines point recharge. The highly variable specific yield in the study area, determined at only two locations, also has resulted in a very broad range of recharge values ranging from 2 to 50 mm/year. The application of the water table rise method in Nyamandhlovu does not allow the estimation of useful aerial recharge rates for the study area, but is useful in the sense that it provides wide limits to the recharge values which can be compared with the results of other methods.

The flownet computational method is not a method whereby point recharge is determined, but it integrates recharge over a larger area. Large variations and lack of information regarding transmissivity values and groundwater level contour lines may limit the application of this method, but for the Nyamandhlovu area, these parameters fall within fairly well-defined ranges allowing the estimation of recharge rates on the order of 16–28 mm/year. Being an integrating method, the computed rates provide an idea on the average recharge for the middle and eastern part of the model area.

The groundwater dating method to estimate recharge also determines point recharge. The rough estimate on the porosity (0.1) of the Forest Sandstone aquifer required for the recharge estimation with this method could lead to errors. However, the recharge rate estimations on the order of 23–28 mm/year are close to the results of the other methods. The only two recharge estimates determined with the groundwater dating method are just locally valid in terrain characterized by flow through weathered and fractured rock.

Groundwater modeling is usually engaged to provide a check on the other recharge estimation methods, but can also be considered as an additional method by itself. A groundwater model provides recharge estimates for the various hydrogeological units. Model calibration for the study area resulted in recharge estimates on the order of 10.5–26 mm/year for the typical recharge area in the middle and eastern parts of the modeled study area. A reasonable set of data was available for the model and in particular the good set of permeability values gives confidence in the estimation of the model estimated recharge values.

Evaluation of methods

The confidence in recharge estimation improves when applying several methods and this point of view was also reported by other authors (e.g. Beekman et al. 1996; De Vries and Simmers 2002). Nevertheless, the different methods to estimate point recharge can be rated in terms of accuracy, ease and costs following a method introduced by Bredenkamp et al. (1995). The ratings are based on the presented results and studies carried out in Southern Africa.

Table 2 also summarizes the ratings following the suggested method. The chloride mass balance method rates high, as it is considered as one of the best point recharge estimation methods in terms of ease of application and costs (Bredenkamp et al. 1995). The water-table fluctuation method also rates high and also for this method the simple application and low costs are strong points. The applied groundwater dating method is the least accurate, most difficult to apply and the most expensive method to estimate recharge. Isotope data required for the groundwater dating method are often not readily available and the cost involved in the acquisition of the data is high. For example, analyzing one carbon-14 sample costs about several hundreds of Euros, and the time involved in sampling and analyzing the samples is enormous.

Table 2 Recharge estimations and rating of different point recharge methods

Method	Recharge rate (mm/year)	Limitations	Rating		
			Accuracy[a]	Ease[b]	Cost[c]
Chloride mass balance	19–62	Long-term atmospheric chloride deposition unknown.	2	1	1
Water-table fluctuation	2–50	Specific yield (S_y) difficult to determine	2	1	1
Darcian flownet computations	16–28	Poorly known transmissivities and contour lines	–	–	–
Groundwater dating	23–28	Poorly known porosity and correction of dead carbon contribution	3	2–3	3
Groundwater modeling	11–26	Lack of data	–	–	–

[a] Accuracy rating: *2* difference from true value within a factor of 5; *3* within a factor of 10 or more

[b] Ease of application: *1* easy to use; *2* not so easy to use; *3* difficult to use

[c] Cost: *1* inexpensive; *3* expensive

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Table 3 Model groundwater balance for the Nyamandhlovu aquifer

Groundwater inflows (m^3/year)		Groundwater outflows (m^3/year)	
Case 1: no deep root transpiration from water table			
Recharge from precipitation	15.9×10^6	Well abstraction	13.5×10^6
Recharge from streams	0.8×10^6	Net lateral sub surface outflow	3.2×10^6
		Transpiration	0
Total	16.7×10^6		16.7×10^6
Case 2: with deep root transpiration from water table in recharge area			
Recharge from precipitation	28.2×10^6	Well abstraction	13.5×10^6
Recharge from streams	0.8×10^6	Net lateral subsurface outflow	3.3×10^6
		Transpiration	12.2×10^6
Total	29.0×10^6		29.0×10^6

Conclusions

The hydrogeological conceptualization with regard to recharge is confirmed by the results of the recharge estimation methods. Recharge in the Nyamandhlovu aquifer is dominated by direct and localized percolation from precipitation during the rainy season whereas the influent flow from rivers and irrigated fields is small.

Where Forest Sandstone is exposed at the surface revealing unconfined conditions, recharge from precipitation takes place directly into this unit, which can be considered the main aquifer of the area. In the places where weathered and fractured Karoo Basalt crops out, overlying the Forest Sandstone, recharge also takes place into the basalt and subsequently the water is transferred to the sandstone. Finally, recharge may be accommodated through the Kalahari Sands and is also transmitted to the Forest Sandstone where the Karoo Basalt is permeable.

The study has revealed that the main contribution of recharge to the Nyamandhlovu aquifer occurs in the middle and eastern parts of the study area. The increasing thickness of the basalt towards the west indicates a reduction in recharge in this direction. However, the results of groundwater dating showing the virtual absence of recently infiltrated water into the Forest Sandstone aquifer in the western part of the study area and the outcome of the model calibration confirms the very low recharge rates in these areas.

This study has also shown that each of the different recharge estimation methods has its own individual merit. The chloride mass balance method, the water-table fluctuation method and the groundwater dating method are well suited to identify the existence of recharge and enable one to determine good estimates of point recharge values. Especially in fractured rock terrain, however, the extension of the point recharge values determined with these methods to a whole study area tends to over-estimate the aerial recharge. Because the methods integrate the recharge over selected areas, the flownet computation method and groundwater modeling provide better estimates of aerial recharge.

For the middle and eastern parts of the studied Nyamandhlovu aquifer, the estimates for recharge from precipitation using the flownet computation method and the groundwater modeling approach range from respectively 16–28 and from 10.5 to 26 mm/year. Since the transmissivity values and groundwater level contour lines used for the flownet method are less accurate than generated in groundwater modeling, the results of the modeling approach should be considered more reliable. The lower ends of the recharge ranges apply to the case whereby there is no uptake of water from the water table by deep-rooted vegetation and the upper ends relate to the case whereby all transpiration water obtained from deeper layers is obtained from the water table. Both cases are believed to apply for the Nyamandhlovu aquifer system. In the areas with shallow water tables on the order of 5–10 m below surface near the streams, and where the rock is soft, the direct uptake of water from the water table may prevail and in the higher areas where the water table is 30–40 m deep, and the rock becomes hard, the roots may take the majority of the deep transpiration water from the unsaturated zone. It is reasonable to assume for the recharge area covering the middle and eastern part of Nyamandhlovu, aerial recharge rates in the range of 15–20 mm/year representing 2.7–3.6% of the long-term average annual rainfall of 555 mm/year.

The range of recharge rates obtained in this study mostly agrees with the findings of similar studies in the region. Larsen et al. (2002) predicted for adjoining areas in the Mid Zambezi basin recharge rates on the order of 20–25 mm/year, Obakeng (2007) found for its similar region in northeast Botswana a recharge rate of 15 mm/year, and Beekman et al. (1996) adopted recharge values for Botswana in the range of 10–25 mm/year. Comparing with previous recharge studies carried out in the Nyamandhlovu area, it can be concluded that the computed recharge rates under this study are not far off from the estimates by Martinelli and Hubert (1996) ranging from 14 to 28 mm/year. The estimate of 125 mm/year adopted by Beasley (1983) is clearly too high and also does not fit into the predictions of the other researchers.

With the groundwater flow model, total recharges, including some inflow from streams, of 16.7×10^6 m^3/year and 29.0×10^6 m^3/year, respectively for the cases without and with the uptake of deep transpiration water from the water table in the recharge area, have been computed for the modeled Nyamandhlovu aquifer (Table 3). For the second case, the uptake of deep transpiration water amounted to 12.2×10^6 m^3/year. Assuming (again) that

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both cases of water uptake by deep-rooted system are applicable in the area, then a total recharge in the range of 20×10^6–25×10^6 m^3/year could be realistic for the study area. If at all possible, it seems unwise to use these estimated quantities of recharge all for domestic and agricultural abstractions in view of the ecological damage that will be done to the deep-rooted vegetation. The optimum groundwater availability for abstractions in the area is the quoted 16.7×10^6 m^3/year. This means that any substantial extension of the abstractions would not be possible in view of the existing abstractions. This availability assessment will be a crucial input for the "Catchment Outline Plan" for the Gwayi catchment.

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