Estimation of groundwater recharge response from rainfall events in a semi-arid fractured aquifer: Case study of quaternary catchment A91H, Limpopo Province, South Africa

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Abstract: This study estimated groundwater recharge response from rainfall events in a semi-arid fractured aquifer. This is crucial as recharge response has an influence on available groundwater in an aquifer. Groundwater levels were modelled and used to evaluate the response of groundwater recharge from rainfall events using Extended model for Aquifer Recharge and soil moisture Transport through unsaturated Hard rock (EARTH) model. Chloride Mass Balance (CMB) method was also used to estimate groundwater recharge in quaternary catchment A91H. Calculated local recharge using CMB method was interpolated in ARCGIS to generate groundwater recharge distribution maps. Estimated local recharge using CMB method ranged from 0.24 to 8.8 mm/a (0.04–1.3% mean annual precipitation (MAP)). Estimated recharge using EARTH model ranged from 3 to 10.3% of 656 mm of MAP. The average recharge was 6.12% of the MAP, equivalent to 40.1 mm/a. EARTH model and CMB method yielded results which were found to be in the same ranges to those obtained from other studies. Rapid—intermediate recharge response mechanism was identified in the study. The results

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PUBLIC INTEREST STATEMENT

The response of groundwater levels to rainfall has an effect on available groundwater supplies. Determination of this is crucial in semi-arid fractured aquifers as most of communities in these areas are dependent on groundwater and sustainable management of groundwater is required. In addition, there is very little knowledge on response mechanism of groundwater recharge to rainfall in fracture aquifer systems characterized by complex geology. Therefore, this study plays a major role in contributing to groundwater management. The study also focused in estimating groundwater recharge using EARTH model and CMB method. The EARTH model has never been used to estimate recharge response at a local or regional scale in the study area, and its results were compared to those of CMB method to test their reliability. Recharge estimation will enable determination of future groundwater recharge rates and provide more knowledge on the aquifer system of the catchment. The study identified recharge response from rainfall as rapid—intermediate.
confirmed and expanded knowledge on the nature of groundwater recharge response from rainfall in fractured aquifers in semi-arid areas and the applicability of EARTH model and CMB method in recharge estimation.

Subjects: Earth Sciences; Geology—Earth Sciences; Hydrogeology & Groundwater

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1. Introduction

Groundwater recharge is an important process in replenishing groundwater resources. For the past decades, groundwater has continued to become more constrained as a result of increasing population, climate change, water scarcity, deterioration of surface water quality, and poor water service delivery particularly in the semi-arid rural regions. Since surface water is more susceptible to pollution than groundwater, this leaves groundwater as a more potentially reliable water resource. In order to sustain long-term groundwater use, make intelligent groundwater allocation decisions, and develop proper water and environmental management strategies in semi-arid regions, groundwater recharge rate is one of the most important components required.

Although there are factors making it difficult to estimate recharge, Nyagwambo (2006) and Adib, Khalili, Kamgar-Haghi, and Zand-Parsa (2015) mentioned that finding cost-effective, simple methods for estimating recharge at time periods that allow real-world water resource management decisions to be made is a major challenge for water resource managers. Although quantifying recharge is important in managing water resources worldwide, it is particularly very important for quaternary catchment A91H which is situated in arid to semi-arid region of South Africa where rainfall is highly seasonal and low with very little knowledge on groundwater recharge estimates, and insufficient historical data. In addition, knowledge on groundwater recharge response from rainfall events is crucial in understating the aquifer system of the catchment and its dynamics. Examples of some of the studies that have been done on groundwater recharge response to rainfall are highlighted below.

Hanell (2011) conducted groundwater recharge study for 10 boreholes in Kalaloch, Olympic Peninsula using groundwater response to rainfall approach. The study further showed that the response of groundwater levels to rainfall varied as a result of differences in hydrologic soil properties, borehole depth, slopes at which boreholes are located, vegetation and rainfall intensity at different locations. Lutz et al. (2014) estimated groundwater recharge in the northern region of Ghana in the Savelugu, Kadja, District Assembly and Kpatoribogu areas by assessing the response of groundwater levels from seasonal rainfall. The response of groundwater level ranged from 0.1 to 5.1 m in all the boreholes. Cai and Ofterdinger (2016) estimated groundwater recharge in the fractured Hardrock aquifer in Ireland using groundwater level response to rainfall approach in about 19 boreholes. The results showed that water level in the high elevation of hillslope had smooth and seasonal change of 4–5 m between recharge and recession. Boreholes situated at intermediate slope showed stable water level variation of less than 0.35 m, while boreholes situated at the foot of the hill showed annual variation of less than 0.6 m.

Groundwater recharge estimation studies have been going on for more than four decades in South Africa (Xu & Beekman, 2003), but to a limited scale. It was only during the international groundwater recharge workshop held in Turkey in 1987 that an urgent need to develop new and improve on existing practical method for estimating recharge in arid and semi-arid areas was raised. Since then, there have been a number of groundwater recharge studies that have been carried out in Southern Africa including South Africa. To-date, a number of regional groundwater recharge studies have been conducted for South Africa, with only a few local studies.

Bredenkamp, Schutte, and Du Toit (1974) used tritium isotope to estimate groundwater recharge in dolomitic aquifers in the West Rand Basin yielding results of between 31 and 43 mm/a.
Verhagen, Smith, Mc George, and Dziembowski (1979) used radiocarbon and tritium isotopes to estimate recharge in the Northern Kalahari aquifer system yielding results between 5 and 18% of the mean annual rainfall. Gomo, Steyl, and van Tonder (2012) conducted a groundwater recharge study in Modder River catchment in Bloemfontein using groundwater level response approach. The study estimated recharge for 15 boreholes spatially distributed across the area and the recharge rates obtained varied from 37 mm/yr to 81 mm/yr.

A study by Tshelane, Ramoba, Mutheiwana, Tleane, and Seakamela (2014) estimated recharge in Limpopo region whereby groundwater levels trends were assessed based on rainfall. During the months of high rainfall for a longer period, groundwater level response was abnormally high at station A4Naboom-Vaal water. Groundwater level response at station A4Stockpoort which is located downstream in the discharge area showed slow long-term decreasing groundwater level response during wet season.

CMB has been successfully applied to estimate groundwater recharge in fractured rock aquifers in a number of studies including Sami and Hughes (1996), Cook, Leaney, and Jolly (2001) and Love, Cook, Harrington, and Simmons (2002). Regardless of its reservations, challenges, and difficulties, CMB remains the most reliable method for estimating recharge in fractured rock systems (Cook, 2003). EARTH model on the other hand makes use of long-term rainfall and groundwater level data to estimate recharge. However, limited studies have used EARTH model to estimate recharge in South Africa. A study by Holland (2011) estimated recharge (2.3% of MAP) in a nearby catchment at Thohoyandou using Cumulative Rainfall Departure (CRD) model; a model also built in the recharge excel spreadsheet developed by Xu and Van Tonder in 2000. Both CRD and EARTH model use long term rainfall, long-term groundwater levels, and specific yield data as model inputs. There are no historical local recharge estimates in the study area, which are very critical in developing proper groundwater management strategies. This creates a need to conduct groundwater recharge estimate at a local scale. Both CMB and EARTH model are point-source-based recharge estimation methods that estimate site-specific recharge. Due to their simplicity and reliability, CMB method and EARTH model have been applied with success.

This study was aimed at assessing the applicability of CMB method and EARTH model in estimating groundwater recharge rates in quaternary catchment A91H. This included determination of the relationship between rainfall and groundwater recharge in order to determine the response of groundwater recharge from rainfall events. Calibrating and validating EARTH model enable determination of future groundwater recharge rates and provide more knowledge on the aquifer systems of the catchment. This study applied CMB method and EARTH model for recharge estimation at a local scale. Studies at a local scale take into account local factors such as rainfall, climate, soil type and moisture, geology, fracturing, slope, amongst others, which improve the accuracy of recharge estimation. These factors are mostly not incorporated in regional scale studies. In addition to improving the accuracy of recharge estimation, the study also contribute to and expand existing groundwater knowledge on the physical nature of fractured rock aquifers in semi-arid areas. The study also contributes to good understanding and knowledge on the seasonal and inter-annual fluctuations of groundwater levels and recharge processes in fractured rock aquifer systems. The knowledge is of great importance as most communities residing in fractured rock aquifer systems are dependent on groundwater as their potable source of water supply.

2. Study area
Quaternary Catchment A91H is situated in the northern part of Limpopo Province in South Africa, between latitude of 22°38’ 0” and 22°52’ 0” S and longitude of 30°58’ 0” and 30°42’ 03.4” E and covers an approximate area of 449.9 km². Rainfall is highly seasonal and strongly influenced by the topography, with 95% occurring between October and April (M’marete, 2003). The catchment receives an approximate annual rainfall of 656 mm. Daily temperatures vary from about 25°C–40°C in summer and between 22°C and 26°C in winter (Mcezewa, Misi, & van Rensburg, 2010). The study area is situated in the severely faulted Soutpansberg Group. Dolerite intrusions that have
created secondary fractures, faults and joints in contact with the host rocks are found in the study area, resulting in fractured and intergranular and fractured aquifer types.

2.1. Geology
The study area is situated in the severely faulted Soutpansberg Group. Dolerite intrusions also created secondary fractures, faults and joints (Figure 2) in contact with the host rocks in the area. At a regional scale, the area consists of numerous geological structures. Fractures, faults, and joins are normally associated with groundwater occurrence that may be sufficient for domestic purposes. Fractured dolerite dykes normally form good aquifer systems. Groundwater recharge may also occur via faults, fractures and joints, which act as preferential path ways of water. Geological structures are generally associated with groundwater occurrence.

2.2. Geohydrology
In terms of geohydrology, the Messina Hydrological Map reveals that Quaternary Catchment A91H is entirely predominated by fractured and intergranular and fractured rock aquifers (Du Toit, Du Toit, & Jonck, 2002). Fractured rock aquifers are normally formed as a result of tectonic forces causing a network of fractures, fissures, and/or joints to be formed, mainly in the quartzite rocks formations. In the fractured rock aquifers, fractures normally act as conduits for groundwater flow whereas the surrounding matrix acts as storage reservoirs. Fractures may be continuous or discontinuous depending on their nature and may vary from centimeters to kilometers. Most parts of the study area are covered by fractured aquifer system (Figure 3).

The intergranular and fractured aquifer system only covers a small portion of the study area. The tectonic forces together with the subsequent processes of weathering, created two different hydraulically interconnected zones that occur in a vertical profile (DWA, n.d.), namely:

- A shallow weathered zone, where the original rock structure has been changed to a mass of more or less loose rock fragments, in a matrix of fine products of weathering, particularly sand, silt, and clay.
- A fractured zone, down to a depth where the rock is becoming solid and fresh in appearance. The transition to this deeper zone in generally gradual. The lateral movement of groundwater in the top zone is very slow and boreholes intersecting in are weak.

3. Methods

3.1. Groundwater recharge estimation
Groundwater recharge was estimated using CMB method and EARTH model. Recharge estimation using the CMB method was based on the premise that a known fraction of chloride in precipitation and dry-atmospheric deposition is transported to the water table by the downward flow of water (Sumioka & Bauer, 2004). Recharge estimates were obtained by incorporating the ratio of average chloride content in precipitation (wet and dry deposition) to that of groundwater in the entire study area using:

$$R_T = \frac{(P \times Cl_p)}{Cl_{gw}}$$

Where: $R_T$ total recharge (mm/a), $P$ is average annual precipitation (mm/a), $Cl_p$ Chlorine concentration in precipitation (mg/l), and $Cl_{gw}$ is Harmonic mean of chlorine concentration in groundwater below root zone (mg/l). The mean annual precipitation value of 656 mm/a within the study area was acquired from Groundwater Resource Direct Measures software generated by DWA (2010). Chloride data of about 77 boreholes for the period 1994–2010 was obtained from the Department of Water and Sanitation (DWS) and Global Project Management (GPM) consultants. The main reason for using data which cover a wide time span was to evaluate variation in groundwater chloride over prolonged duration. In addition to the data acquired from DWS and GPM consultants, 12 groundwater samples
were collected to fill-in identified gaps and were taken for chloride analysis at the Council for Geoscience laboratory. Rainfall samples collected during dry and wet season at Khubvi station were taken to the laboratory for chloride concentration analysis. Six rainfall samples were collected using wide-open containers, kept in sampling bottles and sent to the Council for Geoscience laboratory for analysis of chloride. An average value of the chloride concentration in dry and wet season was used in conjunction with chloride concentration in groundwater to estimate regional recharge. The results were then mapped using kriging method within 3D Analyst Tool of ArcGIS 10.2 software to generate recharge distribution maps for the entire area.

The built in excel spreadsheet of the EARTH model developed by Xu and Van Tonder in 2000 was used in this study. The part of the EARTH model used for recharge estimation in this study is the Saturated Flow (SATFLOW) model, which computes groundwater level with the estimated recharge from the percolation zone and rainfall. According to Rashid (2014), SATFLOW (Figure 2) is the last reservoir of the EARTH model. It is a simple independent one-dimensional parametric groundwater module, where parameters have a semi-physical meaning. SATFLOW calculates the groundwater level using the estimated recharge from the percolation zone and rainfall (Rashid, 2014). According to Van der Lee and Genres (1990) and Rashid (2014) the module is described using first order differential equation as:

\[
\frac{dh}{dt} = \frac{R}{STO} - \frac{h}{RC}
\]

Where: STO = storage coefficient [-]

R = recharge [L T^{-1}]

h = groundwater level [L] above local drainage base

RC = saturated recession coefficient [-]

In Figure 2, \( P_g \) is gross precipitation, \( E_o \) is evaporation from open body, \( \text{MAXIL} \) is maximum interception loss, SOMOS is soil moisture storage, \( ET_a \) is actual evapotranspiration, \( R_p \) is flux below root zone, \( Q_s \) is surface runoff, SUST is surface storage, LINES is linear reservoir, \( R_g \) is percolation zone transfer function, and \( R_d \) = outflow (drainage). Detailed description of EARTH model is provided in Gebreyohannes (2008). A challenge with EARTH method is that specific yield is poorly known and quite difficult to obtain. When there are enough boreholes in the area, specific yield can be estimated by means of conducting a pumping test, and can be calculated using the following equation (Neuman, 1986)

\[
S_y = \frac{V_w}{V_c}
\]

Where: \( S_y \) is the specific yield

\( V_w \) is the cumulative volume of discharge from the pumping well, and

\( V_c \) is the volume of the observed cone of depression from a water table.

The data required to estimate groundwater recharge using EARTH model includes long-term rainfall, groundwater levels and specific yield as shown in Figure 4. Three boreholes (BH) were drilled in the study area in the year 2010 with the aim of monitoring daily groundwater levels while additional groundwater levels data for two monitoring boreholes were requested from the Department of Water and Sanitation. These monitoring boreholes are shown in Figure 1. Daily rainfall data from 2005 to 2014 for Punda Maria weather station was obtained from South Africa Weather Service. In absence of pumping test data, soil types were used to determine the specific
yield values associated with that particular soil type based on Table 1. Soil samples for textural analysis to identify different soil types were collected at five sites (Figure 5) where monitoring boreholes are located. Each soil sample was collected using a hand auger at 1.5 m depth. Thien (1979) outlined textural analyses procedure to classify different soil types and this procedure was adopted in this study. The specific yield value for loamy soil is not available in Johnson (1967). It was therefore estimated based on the following:
Loam soil composition (40%-40%-20% concentrations of sand-silt-clay, respectively) as documented by Kaufmann and Cleveland (2008), specific yield values of sand, silt, and clay from Johnson (1967); and the following general equation that relate the specific yield of loam to those of materials that make up its composition.

\[ S_{Y,\text{Loam}} = (R_{\text{sand}} \times S_{Y,\text{sand}}) + (R_{\text{silt}} \times S_{Y,\text{silt}}) + (R_{\text{clay}} \times S_{Y,\text{clay}}) \]
Where $S_y_{Loam}$ is specific yield of loam soil, $R_{sand}$ is sand soil ratio, $S_y_{Sand}$ is specific yield of sand soil, $R_{silt}$ is silt sand ratio, $S_y_{Silt}$ is specific yield of silt soil, $R_{Clay}$ is clay soil ratio, and $S_y_{Clay}$ is specific yield of clay soil.

Calibration of EARTH model was done in order to minimize the errors and to acquire the best fit between the observed and simulated groundwater levels. Thus, the objective function of the model was to minimize the Root Mean Square Error (RMSE). Model calibration also assists with the evaluation of model performance and checking if the model gives an acceptable image in the real world. The steps followed during model calibration are similar to those used by Gebreyohannes (2008). Model validation was also done in order to check if the model performs in the same manner under parameters used for model calibration. Sixty percent of the groundwater levels data for the five boreholes was used for EARTH model calibration while the remaining 40% was used for validation (Table 2). The quantitative model performance evaluation was done using coefficient of determination ($R^2$), RMSE, and Mean square error (MSE).

| Material       | Number of determination | Specific yield |       |
|----------------|-------------------------|----------------|-------|
|                |                         | Maximum | Minimum | Average |
| Clay           | 15                      | 5       | 0       | 2       |
| Silt           | 16                      | 19      | 3       | 8       |
| Sandy clay     | 12                      | 12      | 3       | 7       |
| Fine sand      | 17                      | 28      | 10      | 21      |
| Medium sand    | 17                      | 32      | 15      | 26      |
| Coarse sand    | 17                      | 35      | 20      | 27      |
| Gravelly sand  | 15                      | 35      | 20      | 25      |
| Fine sand      | 17                      | 35      | 21      | 25      |
| Medium sand    | 14                      | 26      | 13      | 23      |
| Coarse gravel  | 14                      | 26      | 12      | 22      |
3.2. Response of groundwater level to rainfall events

Groundwater recharge response from rainfall events was evaluated based on hydrographs obtained from EARTH model. Gomo et al. (2012) stated that EARTH model assumes that the increase in groundwater level is only due to recharge. Meaning that, any increase in groundwater level indicates that recharge has reached the aquifer after rainfall event. In addition, van Wyk, van Tonder, and Vermeulen (2012) noted that the rising water table response, due to effective rainfall-groundwater interaction, presents the physical evidence of groundwater recharge events. The same assumption was adopted in this study. The behaviour of groundwater levels during rainfall events for all boreholes was assessed and further used to distinguish the recharge mechanism across the study area; either as rapid, intermediate or slow response. Since the recharge estimates from EARTH and CMB models are single values of groundwater recharge, they could not be used to evaluate the groundwater recharge response to rainfall events. As such groundwater levels were used to establish groundwater recharge response from rainfall since the study assumed that any increase in groundwater level was due to groundwater recharge.

4. Results and discussion

4.1. Soil textural analysis and specific yield

Soil samples were randomly collected at selected sites and were analyzed for textures, and a table outlined by Johnson (1967) for specific yields for different soil textures was used to assign specific yield values for identified soils in the study area. The identified soil types are provided in Table 3. Kruseman and de Radder (2000) defined specific yield as the volume of water that an unconfined aquifer system releases from storage per unit surface area of aquifer per unit decline of the water table, and normally ranges from 0.01 to 0.30 (1–30%). An aquifer with sandy material normally has higher specific yield, meaning that it has a higher potential to yield groundwater, while aquifers with clay material have low specific yields, meaning that their potential to yield groundwater is low. Based on the above facts the specific yield values (Table 3) for the study area show that the aquifer in most parts of the area has high potential to yield groundwater.

4.2. Groundwater recharge estimates

4.2.1. CMB model

Groundwater recharge rates of the area were calculated at both regional and local scales using rainfall and groundwater chloride concentration together with average annual rainfall of the area.

### Table 2. Classification of data used for model calibration and validation

| Borehole ID. | Calibration            | Validation             |
|--------------|------------------------|------------------------|
| Univen 1     | December 2010-April 2013 | May 2013-November 2014 |
| Univen 2     | December 2010-April 2013 | May 2013-November 2014 |
| Univen 3     | October 2010-March 2013 | April 2013-November 2014 |
| A9N0011      | January 2011-April 2013 | May 2013-November 2014 |
| A9N0015      | January 2005-November 2010 | December 2010-November 2014 |

### Table 3. Results of soil types and specific yield at selected sites

| Site name           | Soil type   | Specific yield (%) |
|---------------------|-------------|--------------------|
| Xikundu             | Sandy clay  | 0.03–0.12          |
| Tshifudi            | Clay loam   | 0.0–19.8           |
| Mahagala            |             |                    |
| Ha-LambaniNzwanwe   | Sandy loam  | 5.2–0.28           |
The average chloride concentration calculated from rain water samples collected in the area was 0.1 mg/L and was used to calculate the groundwater recharge.

Regional groundwater recharge using chloride concentration of 0.1 mg/L was calculated as 3.3 mm/a. The results show that only 0.5% of the mean annual precipitation of 656 mm contributes to the regional groundwater recharge of the area. The highest calculated local recharge was 8.8 mm/a, while the lowest calculated local recharge was 0.24 mm/a. Figure 5 shows the groundwater recharge distribution across the study area. From calculated results, recharge value of 4.4 mm/a was considered as a cut-off value. All recharge values below 2.2 mm/a were categorized as low recharge rates. Low recharge mostly occurs in eastern parts of the study area and to some extent in the northern and southern parts of the study area. Recharge values between 2.2 and 4.4 mm/a were classified as intermediate recharge and this is experienced predominantly in the central, north-western, north-eastern, and southern parts of the study area. Values above 8.8 mm/a were classified as high recharge rate. High recharge is experienced towards the mountainous parts (high elevation) of the area, mainly within and around Goba-Tshaulu-Lukalo-Ha-Lambani-Mavunde areas (Figure 6). Figure 7 shows the distribution of villages and boreholes across the surface elevation slope in the study area.

4.2.2. EARTH model
The final parameters obtained during EARTH model calibration are presented in Table 4 together with the default parameters. Specific yield and resistance were found to be the most-sensitive parameters during model calibration and validation.

The model performance during calibration and validation was evaluated and the computed results for $R^2$, RMSE and MSE ranged from 0.5 to 0.88, 0.05 to 0.34, 0.16 to 3.16, and 0.50 to 0.79, 0.07 to 0.68, 0.15 to 8.78 for calibration and validation, respectively (Table 5). The results show reasonable and acceptable model performance, except for MSE at borehole A9N0011 which was relatively high. This anomaly is due to the deviation between observed and estimated groundwater levels which could be due to model parameters being unable to accurately represent the complex hydrogeologic environment. Some performance measures values were averaged for the

Figure 6. Groundwater recharge distribution map of the study area.
current study due to delayed response of groundwater level to rainfall, resulting in a generally fair relationship between observed and estimated groundwater levels.

The estimated recharge rates from EARTH model ranged from 3 to 10.3% of 656 mm MAP. The average estimated recharge rate was calculated as 6.12% of the MAP which is equivalent to 40.1 mm/a. Groundwater recharge values estimated for A9N0015 is 3 mm/a. The results of calibrated and validated models are presented in Nemaxwi (2016). Figures 8 and 9 show comparison of observed groundwater level (OGWL) and estimated groundwater level (EGWL) for both calibration and validation runs.
| Performance measure          | Univen 1 | Univen 2 | Univen 3 | A9N0011 | A9N0015 | Acceptable values |
|-----------------------------|----------|----------|----------|----------|----------|------------------|
| Coefficient of determination ($R^2$) | 0.70 0.53 | 0.69 0.79 | 0.73 0.79 | 0.88 0.77 | 0.5 0.5 | $>$0.5- acceptable<sup>a</sup> |
| RMSE                        | 0.09 0.1 | 0.18 0.16 | 0.08 0.08 | 0.34 0.68 | 0.05 0.07 | 0 = Perfect<sup>b</sup> |
| MSE                         | 0.28 0.21 | 0.9 0.5  | 0.22 0.15 | 3.16 8.78 | 0.16 0.21 |                  |

<sup>a</sup>Shamsudin and Hashim (2002)

<sup>b</sup>Elshamy (2008)
The graphs for boreholes Univen 1, 2, and 3 show a continued reasonable and similar trend for both model calibration and validation. Graphs for borehole A9N0011 show noticeable deviation between OGWL and EGWL in the year 2013 wet season for model calibration period while the deviation during model validation was noticed in the year 2014 wet season. In the year 2006/2007 wet season, borehole A9N0015 graph (for model calibration) showed a noticeable deviation between OGWL and EGWL, while that for validation was noticed in the 2014 wet season. The model estimates groundwater level based on rainfall input, while observed groundwater levels may take time to respond during and/or after rainfall seasons. This creates a lag time between occurrence of rainfall and recharge, which is taken into account in the EARTH model by the lag time factor. This normally results in a model overestimating or underestimating the groundwater levels, which in-turn results in a mismatching relationship between OGWL and EGWL graphs.

The OGWL graph decreased while EGWL increased during the period December 2010 to August 2011 at borehole A9N0015. This may have been as a result of the initial conditions at the beginning of the simulations which were not accounted for by the model since it has a semi-physical nature. Initial conditions such as states of precipitation, surface storage, and runoff at the beginning of the simulation are known to impact on model outputs (Seck, Welty, & Maxwell, 2015). The fact that this was only prevalent in the validation run of A9N0015 would require further knowledge including detailed lithological characteristics at this borehole as this also affects groundwater recharge.
4.3. Response of groundwater recharge to rainfall events

Periodic fluctuation of groundwater recharge in response to rainfall is clearly noted during and/or just after a wet season (between December and March of each year) in all boreholes (Figures 10 and 11). Peak groundwater levels were noted in some boreholes (Univen 1, January 2012 and December 2013), Univen 2 (December 2012, December 2013), Univen 3 (February 2011, March 2012 and May 2013), A9N0011 (February 2011 and March 2014), and A9N0015 (March 2006, January 2008 and January 2009, January 2013 and March 2014) a few months after high rainfall, while in the same boreholes but different years (Univen 1 and Univen 3) (in the year 2014) and A9N0011 (in the year 2014) groundwater recharge increase can take up to 4 months or more to respond after rainfall event. This is likely to have been caused by the preferential pathways that groundwater follows within the subsurface or low rainfall in 2014 compared to that received in 2013. Rapid rise in groundwater level is normally associated with extreme single rainfall. All boreholes showed noticeable decrease in groundwater recharge between the years 2011 and 2012 due to low rainfall experienced during those years. Univen boreholes showed this decline in recharge in part of 2011 but DWS boreholes showed this in 2011 and 2012. Based on groundwater level response to rainfall events, recharge mechanism in the area can be classified under rapid–intermediate response.
It is often very critical to have a clear understanding in terms of geology of the area as it plays a major role in groundwater recharge. The study area is situated in the severely faulted Soutpansberg Group. The dolerite intrusions also created secondary fractures, faults and joints which are in contact with the host rocks in the area. These geological structures act as groundwater preferential pathways during recharge processes. Different rock matrices have different hydraulic conductivity and porosities and or fracture connectivity which also plays a role during groundwater recharge. Hydraulic properties between fractures and rock matrix may differ, and this may result in difference in the rate at which groundwater flows from fractures to the rock matrix or from the rock matrix to the fractures. This normally causes equilibrium between water within fractures and rock matrix to take long to be established after or during rainfall, which in turn causes a delay or lag in the response of groundwater level from rainfall events.

5. Conclusion
This study estimated groundwater recharge response from rainfall events in a semi-arid fractured aquifer. The groundwater chloride concentration ranged from 7.5 mg/l to 270.7 mg/l. Rainfall chloride concentration for both dry and wet seasons was 0.1 mg/l. Groundwater recharge rates estimated using CMB method varied from one place to another due to variation in chloride

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Figure 10. Rainfall and observed groundwater levels for Univen 1 and Univen 2.
concentrations across the study area. No sources of surface chloride to groundwater were identified in the vicinity of boreholes with high chloride concentrations. Boreholes with low measured chloride concentrations resulted in higher recharge rates while those with high measured chloride concentrations resulted in lower recharge rates.
concentrations resulted in low recharge rates. The estimated local recharge rates using CMB ranged from 0.24 to 8.78 mm/a (0.04–1.3% MAP) from chloride concentration of 0.1 mg/L, while regional recharge was calculated as 4.6% of MAP.

The specific yield values associated with soil types ranged from 0.0 to 0.198%, 0.052 to 0.28%, and 0.03 to 0.12% for clay loam, sandy loam and sandy clay soils, respectively for three identified soil types in the study area. These were used as inputs in EARTH model. The EARTH model has never been applied for recharge estimation in the study area, however, recharge rates ranging from 3 to 10.3% obtained were found to be comparable with those calculated at a regional scale of 4.6% obtained using CMB method. These results from the two methods were found to fall within similar ranges obtained in related studies. Groundwater levels data for five boreholes across the study area were used to evaluate the response of groundwater recharge from rainfall events using EARTH model. The hydrographs showed that groundwater levels response to rainfall events resulted in recharge mechanism within the study area to be classified under rapid–intermediate response.

The EARTH model performance during calibration and validation was evaluated and the computed results for $R^2$, RMSE, and MSE ranged from 0.5 to 0.88, 0.05 to 0.34, 0.16 to 3.16, and 0.50 to 0.79, 0.07 to 0.68, 0.15 to 8.78 for calibration and validation, respectively. The results showed reasonable and acceptable model performance except for MSE at borehole A9N0011 which was relatively high. This could have been caused by the delayed response of groundwater level during rainfall. The results obtained from both methods showed similar and low recharge values. The findings of this study are of great significance since they also give recharge rates at a local scale, which has never been estimated in the area before. Based on the above results, CMB method and EARTH model can be applied for recharge estimation in fractured rock aquifers with some level of certainty. This shows that it is possible to determine good groundwater recharge estimates using unsaturated hydrological models such as CMB and EARTH.

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