IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG)
e-ISSN: 2321–0990, p-ISSN: 2321–0982.Volume 9, Issue 6 Ser. II (Nov. – Dec. 2021), PP 01-15
www.iosrjournals.org

Estimating groundwater recharge for a carbonate aquifer: Case of WonderfonteinspruitCatchment (South Africa).

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Abstract :
Groundwater recharge is a key parameter needed for the calculation of water budgets, which are necessary for accurate sustainable groundwater management. In this context, the quantification of groundwater recharge in karst aquifers situated in the Wonderfonteinspruitcatchment (South Africa) is an important, yet not easy task to address. This catchment is divided into six groundwater compartments (Zuurbekom, Gemsbokfontein,Venterspost, Bank, Oberholzer and Boskop-Turffontein Compartments) by mostly north-south trending dykes. In reality, natural groundwater recharge of the study area has been intensely affected by a lack of precipitation. In this paper the recharge rateswere estimated for these compartments using various recharge methods including the Chloride Mass Balance method, Saturated Volume Fluctuation (SVF) method, Kessler method, APLIS method and Thornthwaite method. The results suggested that the SVF method is the most accurate method for showing the recharge rate ((12.1%)Zuurbekom Compartment, (14.24%)Gemsbokfontein Compartment, (15%)Venterpost Compartment, (19.66%) Bank Compartment, (11.80%) Oberholzer Compartment and (4.85%) Boskop-Turffontein Compartment).

Keywords: *Groundwater recharge,Chloride Mass Balance method, Saturated Volume Fluctuation method, Kessler method, APLIS method, Thornthwaite method, South Africa.*

Date of Submission: 04-12-2021 Date of Acceptance: 18-12-2021

I. Introduction:

Water is an important resource; however, several countries are strugglingdue to water crises. In many cases, problems arise from inefficient and unsustainable use of water.

South Africa is a country with diverse mineral deposits such as diamonds,gold, platinum, coal anduranium.The country has a rich biodiversity but is unfortunately also a country with insufficient water resources. This is due to high evaporation rates, unpredictable rainfall and low runoff rates. The water resources in South Africa are unevenly distributed due to the topography and the uneven spatial distribution of rainfall. The country has a semi-arid climate and an average rainfall of 450 mm per annum which is significantly lowerthan the world average of 860 mm per annum. The main rivers in the country are shared with neighbouring countries, namely Namibia, Botswana, Zimbabwe and Mozambique. Many of the water management areas in the country are facing a water shortage as water demands exceed the availability of water (SOER NW 2002).

The ever-increasingdemand for water in the country whether for agriculture, industry ormining directly impacts the volume of surface water available and the associated quality thereof. For this reason, groundwater has become an importantresource. The dolomites are documented as the highest-yielding water-bearing rock type in South Africa (Barnard 2000). These aquifers that occur in the West and Far West Rand are one are of the most significant aquifers in the country, with some of these aquifers draining into the Wonderfonteinspruit (WFS).

The WFS catchment is situated in a karst landscape. Mining related activities took place from 1912 (Swart et al. 2003a)and some are still active today. These mining activities change surface water and groundwater systems due to factors such as dewatering of the dolomites leading to adecline in the water table thereby drying up of streams and springs.This can also lead to the formation of sinkholes and water being contaminated(Swart et al. 2003a, b; Durand,2012). According to Brink (1979), approximately 38 people lost their lives following sudden sinkhole collapse. The construction of buildings and other structures on dolomites have been extremelychallenging.The WFScatchmentconsists of dolomitic compartments separated by semi-impervious dykes. Due to mining, some of these dykes have been breached. Flooding can therefore impact more than one compartment. The compartments as from east to the west as follows: The Zuurbekom, Gemsbokfontein,Venterspost, Bank, Oberholzer and Boskop-Turffontein Compartments.

Variable rainfall, wind speed, temperature, soil type, solar radiation, topography, irrigation, permeability, infiltration capacity, and groundwater levels can all have an impact when quantifying groundwater recharge (Andreo et al. 2008; Martos-Rosillo et al. 2015). It must also be noted that calculating groundwater recharge for karst aquifers is far more challenging than other South African aquifers due to variances in permeability and porosity(Andreo et al.2008). These factors also are also necessary for the determination of infiltration rates, discharge and flow within the unsaturated zone (Bakalowicz 2005; Kiraly 2003; Martos-Rosillo et al. 2015).

Existing information from previously published and unpublished reports as well as unpublished and published figures and maps will be acquired for a background summary of the study area.Many research efforts to date have been devoted to the dolomitic compartments' recharge characteristics using different methods (Bredenkamp 1993; Enslinand Kriel 1967; Fleisher 1981; Foster 1988; Wolmarans1984).

This paper aims to estimate recharge rates in the compartments within the dolomitic aquifers in the WFS catchment. Several methods will be used and associated results will be compared. These methods include empirical methods for example Thornthwaite 1948; Penman 1948; Turc 1954, Kessler 1967 chemical methods Schoeller 1962; Eriksson and Khunakasem1969. The APLIS1 method and Saturated Volume Fluctuation (SVF) method Van Tonder and Xu 2000 are also taken into consideration. These methods will be discussed in more detail in Section 5.

II. Study Area:

The WFS catchment covers a surface of roughly 1600 km^2.The WFS flows acrossone of South Africa's richest mining areas. The WFS'origin is close to Krugersdorp, it then crosses the Gauteng provincial boundary to the North-West Province, where it flows into the Mooi River, close to the town of Potchefstroom (Wade et al. 2004). The name "Wonderfonteinspruit" is an Afrikaans word meaning "Wonder-fountain-stream".

The flow in the WFS is controlled by the presence of dams, canals and pipelines(Figures 1c,d). These pipelines' purposeare mainly to transmit water to various dams/compartments and prevent the water from returning to aquifers below the WFS(Figure 1c). Coetzee et al. 2006; Opperman 2008; Winde and Stoch 2010provide detailed information regarding the above mentioned scheme.

The study area is located between longitude 27º0'0"- 28º0'0"east and latitude 26º0'0"- 26º40'0"south with the elevation ranging from1322 to 1839 meter (m) above sea level (a.s.l) (Figure 1).

The area experiences a warm mildly humid climate. The area falls within the summer rainfall region of the country, with rainfall occurring from November to March. The winters are cold and dry. The average annual rainfall varies from east to west from 500 mm to 800 mm. The total average evaporation for this area is 1560 mm/a (De Klerk 2018).

III. Geology

The geology of the WFS catchment has been described in numerous publications (De Kock 1964; Brink 1979; Engelbrecht 1986; McCarthy 2006). The Transvaal and Karoo Supergroups formthe surface and near surface geology. The study area is underlain by theMalmani Subgroup (Figure 2). This Subgroup is within theChunniespoortGroup of the Transvaal Supergroup, consisting of approximately 1300m thick dolomitic limestone which contains numerous bands of chert within its upper 200m (De Kock 1964). The rocks of the Transvaal system dip at a low angle of 5˚to 12˚to the south. These rocks overlie the older Ventersdorp Lava and the gold bearing conglomerates of the Witwatersrand Supergroup. The area is characterised by a number of fault planes.It is along these fault planes as well as along joints fissures and bedding planes that the collapse and slumping of dolomite occurs on a large scale, particularly along the major fault planes where geological "valleys" were formed. Deposits of the younger Karoo system were either deposited or slumped in these valleys (Pulles et al. 2005) (Figure 2, 3).

The study area consists of a wide valley flanked to the north by low rolling hills and to the south by the Gatsrante, in which numerous dolomitic caves and paleo-sinkholes are found(Figure 1b). These form the foothills of a more prominent range of hills of the Pretoria series with an elevation of approximately 180m above the valley. The hills to the north are formed by the Black Reef formation and underlying granite.

The development of hydraulic conductivity in the near surface zone of the Malmanidolomite is intimately related to karstification. Karstification is a major prolonged process in the disintegration of carbonate rocks. Soluble carbonate rocks are prone to dissolution by slightly acid, and therefore aggressive (Kiraly 2003). The development of karst involves a combination of closely related surface and subsurface features. Chemical dissolution associated with the creation of voids systems is confined principally to the saturated zone. It is in this zone that sub surface erosion is most active, calcium, magnesium and bicarbonate ions being removed in solution by circulating groundwater. The insoluble residual products such as silica, quartz, clay minerals, oxides, and hydroxides of iron and manganese (Wad) are left behind. The residual mass, when undisturbed, as in caves, is spongy, compressible, of low density and high void volume (Fleischer 1981). These as well as the fissures and cavities which normally occur at greater depths, form underground storage for dolomitic water. Where fault planes intercept dolomites and the older Ventersdorp and Witwatersrand formations, they act as conduits for water to seep into the mine workings(Figure 2, 3). In order for mining operations to continue,this water has to be pumped to the surface. All water pumped from the mines are from storage in overlying dolomite (Enslin 1967).

The Malmani Subgroup covers an area of approximately 140000 km^2 and is well known for its many perennial springs, which are the source of most rivers within the study area(Martini andKavalieris 1976).

The two geological features which have had the greatest influence on the dolomitic groundwater in this area are, firstly the post-dolomite syenitic dykes, and secondly the extensive crustal movements and faulting which occurred in pre-dolomite times, followed by further movements along these fault planes as well as along other planes in post-dolomite times(Figure 3).

Dolomite is for the most part a massive, compact and crystalline rock with practically no intergranular pores for storing water like other sedimentary rocks. Nevertheless, it is a well-known fact that carbonate rocks are among the best water storing rocks in the world. The reason is to be found in their chemical composition and that of the water penetrating them. Dolomite generally has bedding planes and often also a network of vertical as well as systems of transverse cracks. In cases where the rocks are tilted regionally, for example on the anticlinal axis north of the WFS catchment, these systems become accentuated. Rainwater that percolates through the surface layer finds its way into the cracks fissures and bedding planes (De Kock 1967).

The alkaline syenite- and dolerite dykes, which have subsequently intruded the stratigraphic succession have resulted in the compartmentalisation of the Malmanidolomite. The sizes of the dolomitic compartments vary from a few hectares to more than 100 square kilometres, depending mainly on the spacing of the dykes. The groundwater barriers which define the compartments are the dykes and the less pervious underlying Black Reef Series and overlying Pretoria Series (Enslin 1967).

The groundwater level in a particular compartment forms a fairly flat surface with a low gradient towards the lowest point of the barrier at the surface, where the dolomitic spring is located and all surplus water is discharged from the compartment. The water levels of adjoining compartments can differ appreciably, depending on the elevations of the overflowing springs and the sizes of the compartments.

Hydrogeology

Swart et al. 2003a, b, states that the WFS catchment, including dolomitic compartments were originally recharged by surface runoff and spring flow discharge before mining activities started. A number of syenite and diabase dykes of Bushveld age and dolerite dykes of Pilanesberg age, which cut the dolomite into six major groundwater compartments(Enslin 1967; Morgan and Brink 1984). These compartments in the WFS are referred to inSection 1 (Figure 1) and discussed in more detail below**.**

- **Zuurbekom compartment**

The Zuurbekom dolomitic compartment is located in the east of the WFScatchmentextending over an area of approximately 360 km^2. It is delimited on its western, southern and eastern flanks by three major dykes. The WFS crossesthe Zuurbekom compartment in a NE to SW direction and the Klip River runs parallel to the eastern boundary (Fleisher 1981)(Figure 1a). These two water courses are separated by an elongated topographic high. This compartment is not dewatered.

- **Gemsbokfontein compartment**

The Gemsbokfontein compartment has an approximate area of 138 km^2. The compartment borders the Zuurbekom compartment in the north and the dewatered Venterspost compartment to the west. This compartment is delineated by rather impermeable dykes, the Panvlakte dyke to the north (separating the Zuurbekom and the Gemsbokfontein Compartments), Gemsbokfontein dyke to the west (forming the boundary between the Venterspost and Gemsbokfontein compartments) and Klip River dyke to the east (Figure 1a). To the south the Pretoria Group overlie the dolomite, this is a confining layer. The WFS runs over the northern part of the compartment (Fleisher 1981). Upstream, Donaldson Dam, forms the boundary for the lower WFS. Natural discharge of groundwater is via springs (eyes) for example theGemsbokfontein eye. In June 1986 when dewatering started (Parsons et al. 1988), as a result the Gemsbokfontein spring dried up.

- **Venterspost compartment**

The extent of the Venterspost Compartment is approximately 77 km^2. It is delimited on the east and to the west by dykes which constitute hydrological boundaries. The Malmani dolomite dips in a southerly direction below the Pretoria Group. The flow direction of the WFS is from the east to the west of the compartment in its central section (Fleisher 1981). There are a number of sink holes this compartment, with 166 sinkholes developing between 1954 and 1984 (Wolmarans1984). The deepest sinkhole in this compartment had a depth of approximately 50 mbgl. The discharge of groundwater is via springs. According to many studies (Fleisher 1981;

Wolmarans 1984), in 1940 the Venterspost mine started dewatering the dolomite compartments and the Venterspost spring dried up 1947.

- **Bank compartment**

The Bank dolomite compartment extends over an area of 248 km^2. Syenite dykes striking north-south delimits the eastern and western boundaries. The Black Reef Formation's impervious rocks shape the boundary to the north of compartment.The dolomite dips below the impervious shales of Pretoria Group to the south of the compartment (Fleisher 1981). The WFS crosses the compartment following an east-west direction. The discharge is mainly via springs in the Bank compartment. The dewatering of this compartment was completed in the first months in 1969(Fleisher 1981).

- **Oberholzer compartment**

The total surface area of Oberholzer compartment is 293 km^2. This compartment is delineated by dykes' boundary on the east and to the west. To the south confining strata of Pretoria group overlie the dolomite. The WFS crosses the compartment in its central part. The discharge of groundwater is through springs like Oberholzer eye. The dewatering of the compartment was in the 1950s until 1959. As a result, the Oberholzer spring dried up (DWA 1960). In the Oberholzer section of the Lower WFS, sinkholes had formed (Wolmarans 1984). At Blyvooruitzicht area in this compartment, multiple houses were demolished soon afterwards (Swart et al. 2003a,b)

- **Boskop-Turffontein Compartments.**

The Boskop-Turffontein compartment covers approximately 293 km^2. The WFS runs through the central section of this compartment. The dolomite dips southwards where it is overlain by sediments of the Pretoria Group (Fleisher 1981). This compartment has not been dewatered.

In every compartment within the study area, groundwater is contained in channels, fissures and caves. The direction of the surface and groundwater water flow is from east to west. Dykes obstruct subsurface flow, daylighting as springs(De Klerk 2018).

Every compartments have its own water table elevation. There is a point of overflow in each compartment, which is situated at the lowest topographic point ofthe compartment.Dewatering of some compartments led to the formation of sinkholes and spring drying up(Usher and Scott 2001)(Figure 1b).

IV. Method:

A number of methods/approaches have been considered to determine and compare groundwater recharge values in WFS catchment. The most suitable methods were pre-selected. These methods are as follows:

Kessler method:

The empirical**Kessler method** was developed to calculate recharge values for karst aquifers located in in semi-arid/temperate areas (Penman 1948; Turc 1954). The method is based on hydrometeorological data (rainfall and temperature). The method forms a relation between the first four months rainfall of the year (January to April) and the last 4 months (September to December). This is based on the assumption that the most rainfall occurs during these periods.

The calculations are as follows:

$$R_d = R' x\ 100/R$$
$$X = R'' - R''_m$$
$$R''_m = \left(\sum R''\right)/n$$
$$R_c = R_d + K$$

Where

R_d: *is the determinative rainfall rate* ($mm\ year^{-1}$)
R': *represents the rainfall measured during January to April* (mm)
R: *refers to the total accumulated precipitation in the year* ($mm\ year^{-1}$)
X: *corresponds to the corrective precipitation rate* ($mm\ year^{-1}$)
R'': *the accumulated precipitation during September to December of theprevious year* (mm)
R''_m: *represents the perennial average precipitation* (mm)*recorded in these months*
n: *is the number of years defining the study period.*
R_c: *is referred to as the corrected rainfall* ($mm\ year^{-1}$)
K: *is the correcting constant* (*table found in Kessler* 1967)

Thornthwaite method:
Anotherempirical method, known as theThornthwaite method(1948)has been used to determine the effective rainfall calculation from monthly precipitation and air temperature. Thornthwaite (1948) proposed the following formula:

$$e = 16\ \times (10\ \times t/I)^{a}$$

e: $evapotranspiration\ of\ month\ (mm)$.
t: $average\ monthly\ temperature\ (°C)$.
I: $annual\ heat\ index$
a: $is\ an\ empirical\ third - order\ formula\ containing\ the\ I\ parameter$
The monthly, or daily, potential evapotranspiration (ETP) can be obtained multiplying e by a correction factor (K):

$$ETP = K \times e$$

APLIS method:
The GIS based APLIS method estimates the mean rate of annual recharge in carbonate aquifers.The results are expressed as a percentage of precipitation. The following parameters are taken into account, namely altitude, slope, lithology, preferential infiltration layers, soils, and a correction factor (Andreo et al. 2008). The correction factor is depending on the hydrogeologic characteristics of the materials outcropping on the surface (Marín 2009). The final recharge calculation is as follows:

$$R = \ [(A + P + 3\ \times\ L + 2\ \times I + S)/0.9]\ \times Fh$$

Where R means Recharge (expressed in percentage); A: Altitude; P: Slope; L: Lithology; I: Infiltration; S: Soil; Fh Correction factor.

Chloride mass balance (CMB) method:
The conservative tracer, chloride is utilised in the above-mentioned method. Chloride can provide an indication of evaporation(Schoeller 1962). This method is based onthe ratio of atmospheric chloride to the chloride in the subsurface. The resultant is the direct recharge flux. This method is calculated as follows(Schoeller 1962; Eriksson and Khunakasem, 1969):

$$R\ \times\ Cl_{gw} = P\ \times\ Cl_{p} \rightarrow R = \ \left(P\ \times\ Cl_{p}\right)/Cl_{gw}$$

Where
Clp: $mean\ chloride\ concentration\ in\ precipitation$
$Clgw$: $average\ chloride\ concentration\ in\ the\ groundwater\ of\ shallow\ aquifer,$
P: $mean\ of\ annual\ precipitation\ and$
R: $total\ recharge\ (mm/year)$.

Saturated Volume Fluctuation (SVF) method:
The SVF method is based on a lumped parameter groundwater balance approach. The parameters that are taken into account include: specific yield, groundwater levels, all groundwater inflows (including recharge) and outflows. The area of the aquifer is also taken into account in the calculation which is as follows: (Van Tonder and Xu 2000).

$$h_t = h_{t-1} + \frac{R_t}{S_y} + \frac{Q_{in} - Q_{out}}{A\ \times S_y}$$

Where,
t: $Current\ time\ step\ (T)$
Sy: $Specific\ Yield$
ht: $Head\ in\ current\ time\ step\ (L)$
A: $Aquifer\ surface\ area\ (L2)$
ht_{-1}: $Head\ in\ previous\ time\ step\ (L)$
Q_{in}: $Sum\ of\ all\ groundwater\ inflows\ (L3)$
R_t: $Recharge\ in\ current\ time\ step\ (L)$
Q_{out}: $Sum\ of\ all\ groundwater\ outflows\ \ (L^3)$

The SVF calculation is based on an enclosed area. Varying in and out flows between compartments(including stream flows) are taken into account by means of a conductance term to properly account for these head dependency.

V. Results and discussion

The rainfall map (Figure 4) ranging from 256 to 715 mm/year with an average of 450 mm/year.

The APLIS method allows the researcher to obtain a map with the spatial distribution of water infiltration rate in the WFS. This recharge map was generatedusing Arc GIS 10.6.1. The combination of the isohyets map period (2000-2013) and the obtained recharge percentage makes it possible to estimate the annual average volume of water infiltrating each compartment. This distribution isshown in Figure 5. The recharge map (Figure 5) of the WFS represents three classes, very low (2.1-20%), low (20-40%) and moderate (40-57%) with the dominance of the low recharge class. This low recharge area coincides with the Malmani dolomites. The results of mean annual recharge for each compartment are shown in Table 1. The maximum recharge rate calculated is for the Boskop-Turffontein compartment and is approximately 27%, 23 %.The minimum correspond to Zuurbekom compartment (15.5%) and Gemsbokfontein (15.6%) compartments. The values of19.9%, 21.32%, and 22.64% are calculated for the recharge rates for Oberholzer, Bank and Venterpost compartments respectively.

The application of the Thornthwaite method applied with monthly data for precipitation and temperature in the study area shows different values for the five selected stations weather, namely C2E007, C2E018, C2E009, C2E004, C2E015 (Table2). The calculated recharge rates in mm per year range between 9.84 (mm/year) in C2E004 station and 23.88 (mm/year) in C2E007 station. After using the kriging option with Arc GIS software, the mean recharge rates in percentage for each compartment, as seen in table1, 13.59% (Boskop-Turffontein), 15.72% (Oberholzer), 17.12% (Bank), 17.66% (Venterpost), 17.93 % (Gemsbokfontein) and 17.95% (Zuurbekom)along with the mean recharge rates calculated using the Kessler method in WFS valley for each compartment, from the five weather stations, namely C2E007, C2E004, C2E009, C2E015, C2E018. The attributed values for each station are respectively 66.43 %, 75%, 68.96%, 66% and 66%. For this case of the compartments (using the indicator kriging), the infiltration rate range from 64.86 (Oberholzer compartment) to 66.70% (Gemsbokfontein compartment) of the annual precipitation.

Based on the chloride map of groundwater and the rainfall map in the study area, the resulting recharge map from the Chloride method range between 3.4 to 40 mm/year with an average 21 mm/year(Figure 6). The estimation of the mean recharge rates in per cent (%) for each compartment, as seen in Table 1, in Zuurbekom compartment (11.60%), Gemsbokfontein compartment (18.96%), Venterpost compartment (19.14%), Bank compartment (31.62%), Oberholzer compartment (15.19%) and Boskop-Turffontein compartment (3.34%).

As the study area is characterized by impermeable dykes and the inflows from the adjacent compartments are known, it was able toapply the SVF model. The SVF model necessitates rainfall data as well as groundwater level data for the same time period. Figure 7 shows the position of piezometer chosen to be used in the SVF model. So, three piezometers have been chosen for the Bank compartment (2627BC00016, 2627BC00020, 2627BC00212), three piezometers for the Gemsbokfontein compartment (2627BC00010, 2627BC00092, 2627BC00102), Three piezometers for the Zuurbekom compartment (2627BA00023, 2627BB0001, 2627BB00036), also, two piezometers for the Boskop-Turffontein compartment (2627AC00171, 2627AC00002) two piezometers for the Venterpost compartment (2627BC00029, 2627BC00234) and finally two piezometers for the Oberholzer (2627AD00004, 2627BC00015). The SVF method wasprogrammed in an Excel spreadsheet to estimates the mean recharge for each compartment. Model calibration wasrealized by using the monthly rainfall as well as water level data and calibrating the model response to observed measurements by changing specific yield, recharge and outflow to obtain the best fit. The results of the SVF method are shown in Table 1 and Figure 8. The mean effective recharge percentage corresponds for each compartment (Table1) is estimated in Bank compartment (19.66%), Zuurbekom compartment (12.1%), Gemsbokfontein compartment (14.33%), Venterpost compartment (15%), Oberholzer compartment (11.8%) and Boskop-Turffontein compartment (4.85%).

The majority of these used methods showed that minimum recharge value is that of Boskop-Turffontein compartment and the maximum recharge is attributed toBank compartment.

Some earlier works (Enslin and Kriel 1967; Fleischer 1981;Wolmarans 1984; Foster 1988;Bredenkamp 1993)indicated that average groundwater recharge for each compartment (Table 4), is 14.7 % (Zuurbekom compartment), 13.1 % (Gemsbokfontein compartment), 27.5 % (Venterpost compartment), 16.2 % (Bank compartment), 11.6% (Oberholzer compartment) and 5.6 % (Boskop-Turffontein). Therefore, this amount of recharge has been held as a reference in the study area.

The estimated average recharge for each compartment using the Thornthwaite method shows variable values on the selected rain stations (Table 1 and 2). The results of the recharge obtained from C2E007 and C2E004 stations appears to be consequential with the hydrogeological and physiographic characteristics of the region. These two stations are the most representative compared the other station owing to their specific situation, where, C2E007 has the highest altitude (1755m) with the maximum of rainfall (624 mm), unlike C2E004 which has the lowest altitude (1350 m) with the minimum of rainfall (415 mm). Generally, the obtained results by the Thornthwaite method are not different from other results used and published for some compartments. The Thornthwaite method cannot be applied in the study area (carbonate aquifer) mainly becausethe evapotranspiration is not a relevant variable in the semi-arid region

The recharge rate calculated by Kessler's method showsthe highest mean infiltration coefficient, 75% for the C2E004 station (Table 2). The results of this method are very high compared to those obtained using other methods. Kessler's method does not take into consideration the particular hydrogeological characteristics of carbonate aquifers and does not allow the identification of the spatial distribution of the recharge. It is necessary in the case of karst or carbonate aquifers to integrate this information such as fracturation, altitude, infiltration zones, slope, soil type, lithology which is crucial for a better understanding of the infiltration process.

The APLIS method has been successfully used in the karst aquifer from many worldwide countries (Andreo 2008; Farfan et al. 2010;Gerner et al. 2012.). Moreover, the application of the APLIS method in WFS provides a map of the spatial distribution of recharge for each compartment. So, it possible to distinguish the low infiltration zone (20-40%), which coincides with the dolomite of the Malmani formation (Figure 5). The average infiltration coefficient obtained by APLIS method is likely more accurate than the Kessler and Thornthwaite methods because this method takes into account many physical and geographical variables like slope, lithology, karst feature, soil type, altitude and hydrogeological characteristics. With the APLIS method, similar values were found compared to other published values obtained by other methods (Table 4)for each compartment, just Boskop-Turffontein compartment indicated a high value (27.23%) compared to others (Table 1). Meanwhile, the CMB method is always a useful method for recharge estimations in the hydrogeological domain. The results were obtained using the chloride method that involves precipitation chloride and groundwater chloride data. However, the map (Figure 6) shows an indication of the principal recharge areas over the study area. The highest recharge rates indicate in the north part of Bank, Venterpost and Oberholzer compartments which coincide with areas of high elevation and many sinkholes. On the other hand, these highest rates coincide also with the major streams. Cook et al. (2003) stated that he was against the use of the CMB method in fractured aquifers like carbonate and karst aquifers due to the effects of the various types of porosities. Conversely, the same study showed that the method can give reliable estimates of recharge to fractured rock aquifers over other methods. The SVF method quantifies the recharge rate at different temporal scales. This method includes stocking of inputs in relation to outputs over a specific time period of the water balance. This is significant because one has to re-count the input to rainfall that occurred over the same period. The groundwater level fluctuation and rainfall were successfully used to estimate recharge rates. Water level data in different piezometers are usually disposable in most of the study area (Figure 8). Doubts with regard to the determination of storage coefficients and contributing zones to recharge in a fractured hard rock field remains a problem for hydrogeologists. The estimates used in the calculations with SVF method are the best estimates. In theWFS catchment, the SVF and CMB methods provide results that are in close agreement. Moreover, the estimation of recharge rate determined by the SVF and CMB methods shown in Zurrbekom, Boskop-Turfontein and Oberholzer compartments have similar results.

Unlike other methods (Kessler, Thornthwaite, APLIS and CMB) used for estimating recharge, the SVF method seems to be the best method of the ones used in this present work because of its parameters (Water level, specific yield, and Dolomite Storage) that are more realistic and its calculations that take the basin characteristics into account.

VI. Conclusions:

In the WFS catchment, groundwater stored is in dolomitic compartments (carbonate aquifers) is an important resource for farming activities. The recharge in this compartments can be estimated by multiple methods. Among such approaches is that the association of hydrometeorological methods (Kessler and Thornthwaite methods), method based on the use of chemical analysis (chloride mass balance), which is an important method used for estimating the recharge rates in carbonate aquifers and GIS approach method (APLIS method) intendedto establish the spatial distribution of the infiltration rate in aquifers, according to area characteristics such as (altitude, soil, lithology, slope and infiltration landforms). The CMB and APLIS methods lead to values that little closer than the references ones. Other is numerical (SVF method) where the recharge is considered to be one of the calibration parameters of the model. So, the most reliable methods in WFS catchmentis saturated volume fluctuation (SVF) because of its use of aquifer parameters such as specific yield.

Acknowledgements

The authors would like to thank Neil Kriel and Theuns van Wyk for theirassistance with data collection

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Figures

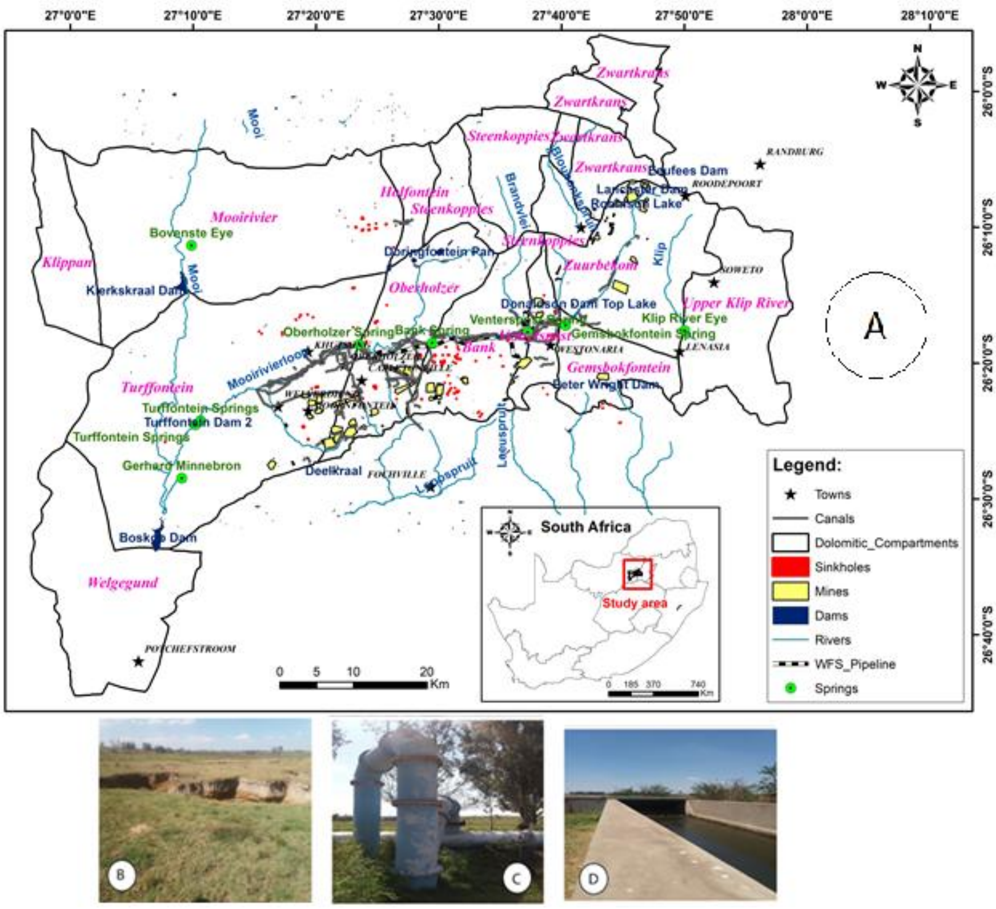


Fig 1: Map of the study area (b: sinkhole, c:pipeline, d:canal)

Supergroup	Group	Sub group	Formation	Lithology
Karoo	Ecca		Dwyka	Sandstone, Mudstone, cabonaceaous Shale, Coal, Diamitite
Transvaal	Pretoria		Hekpoort Andesite	Fain-grained clastic rocks
			Timeball Hill	
			Rooihoogte	
	Chuniespoort	Malmani	Eccles	Chert-rich Dolomite
			Lyttleton	Dark Chert-free Dolomite
			Monte Christo	Light Dolomite with abundant
			Oaktree	Dark Dolomite
		Black Reef		Carbonaceous Shale with Quartzite Conglomerate
Venters-dorp	Kliprivieres-berg	Andesitic lava with minor Tuffs		
Venterspost Conglomerate			Venterspost Contact Reef	
Witwaters-rand	Central Rand	Mainly Sandstone with minor Conglomerate		
	West Rand	Mainly Shale with minor Sandstone		
Base-ment	Granite and Gneiss and other matamorphic rocks			

Fig 2: Lithostratigraphic column in the study area (Els 1987,2000)

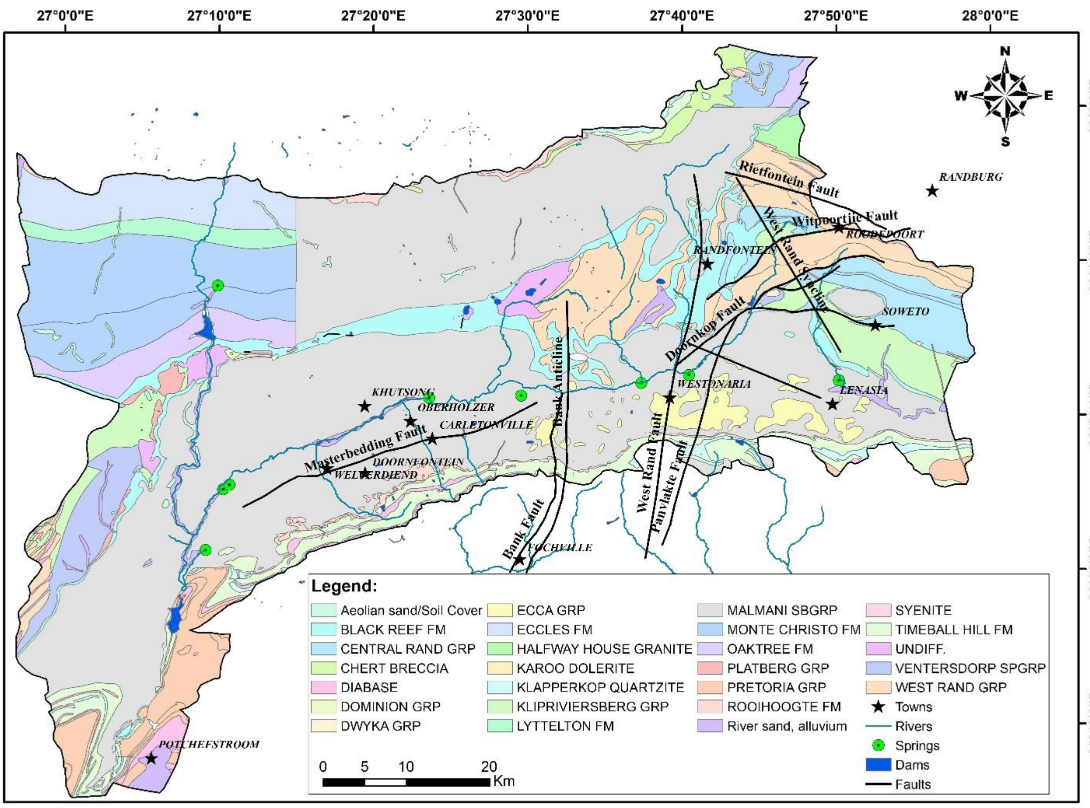


Fig 3: Geology map of study area

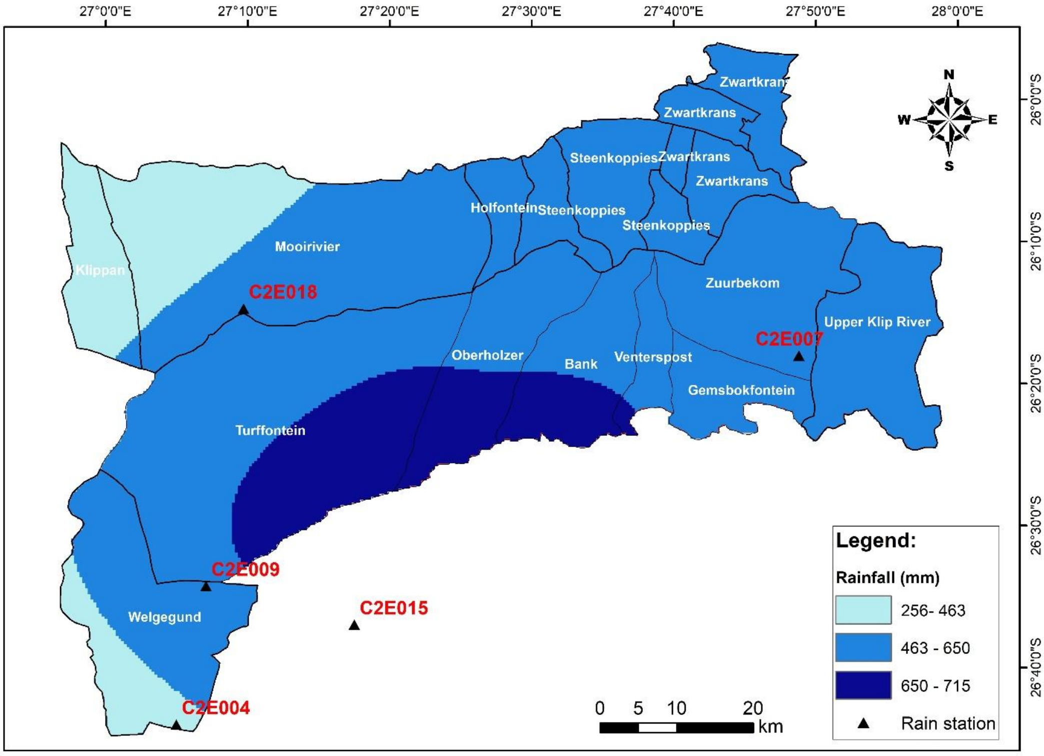


Fig 4: Rainfall map

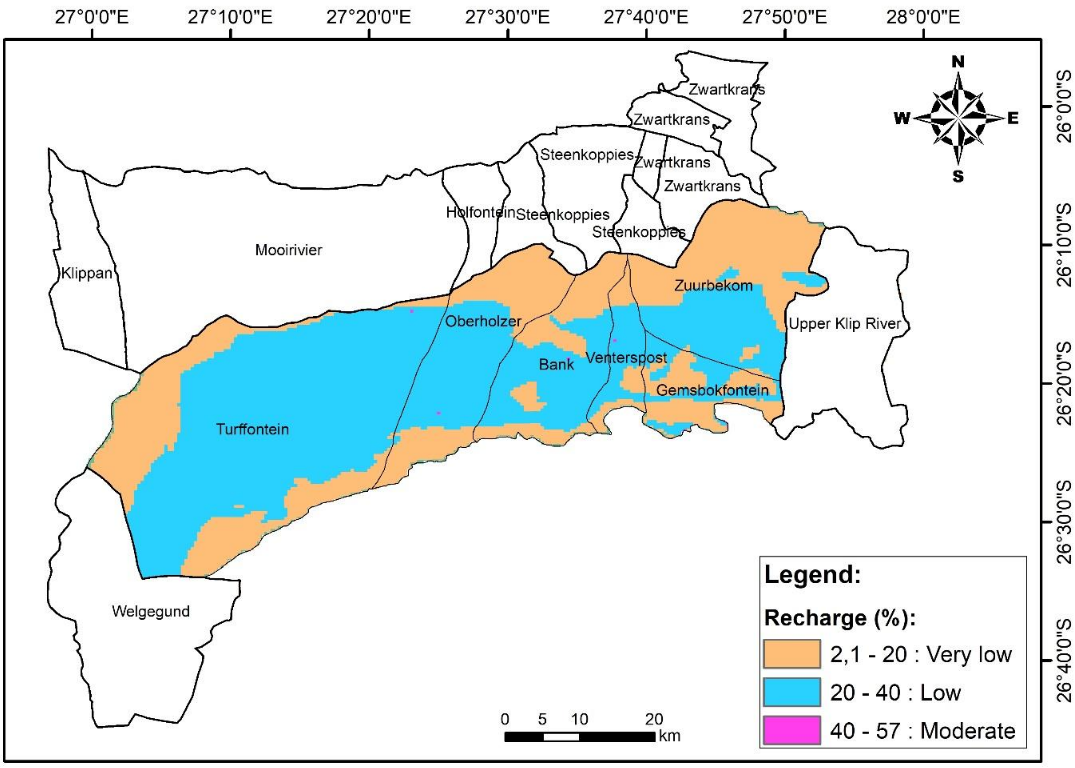


Fig 5: Recharge calculation based using APLIS method.

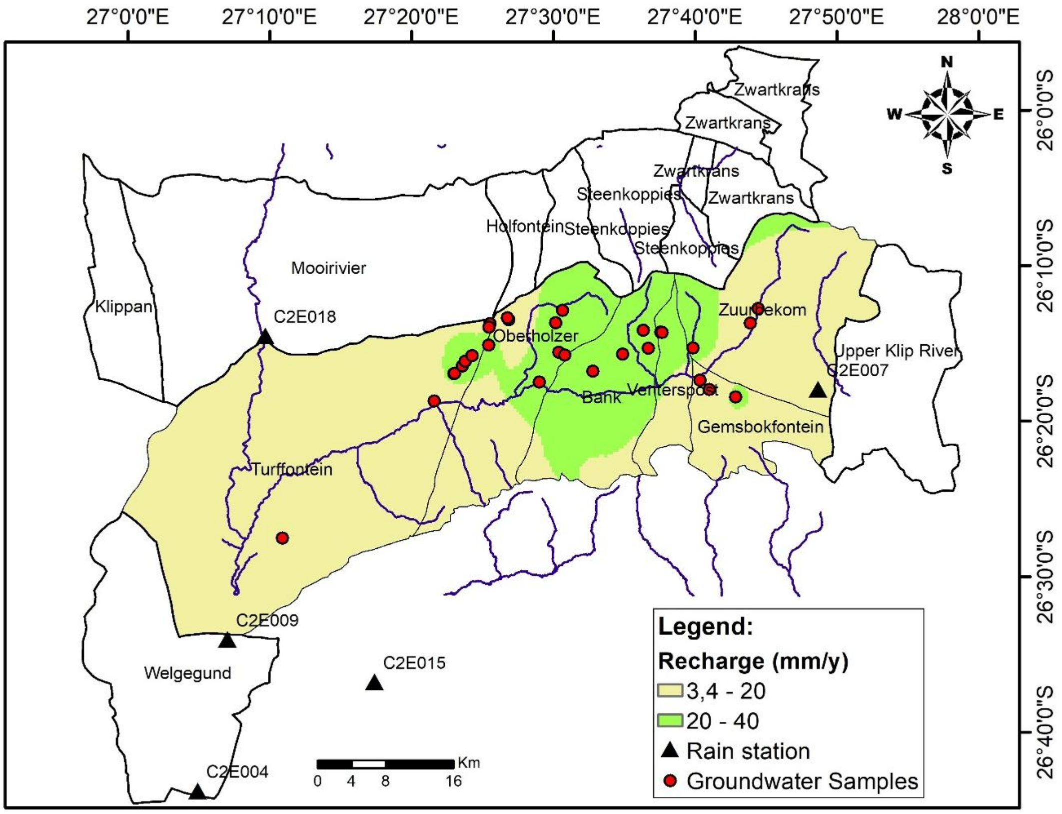


Fig 6: Recharge calculation based using Chloride method.

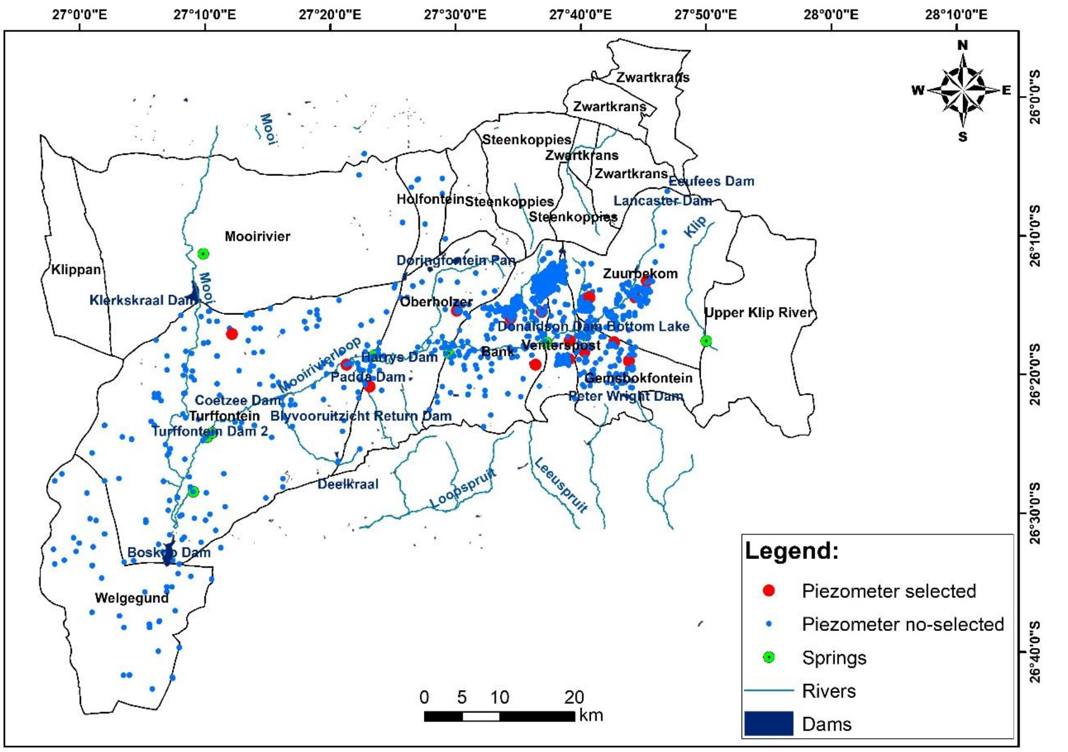
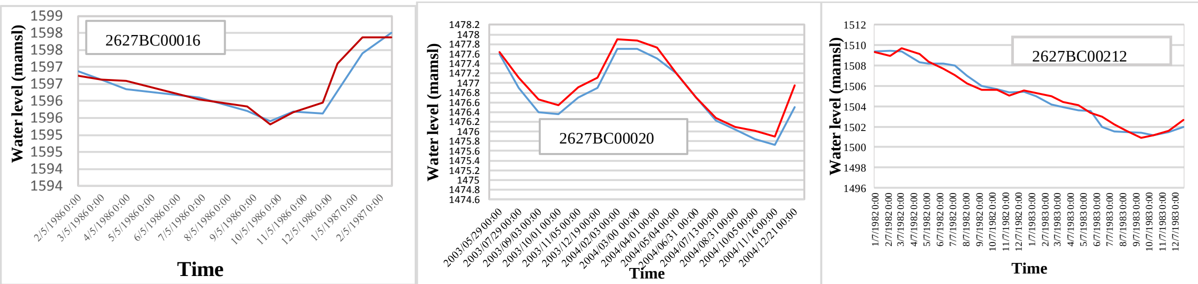
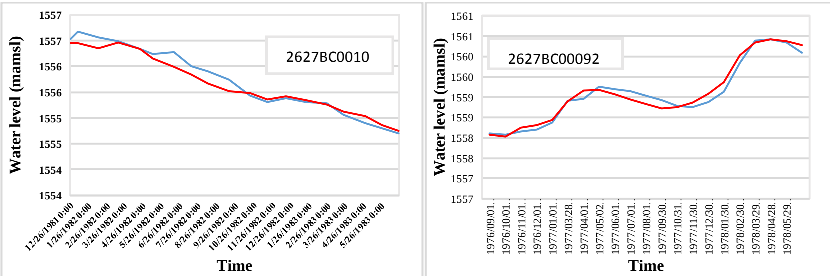


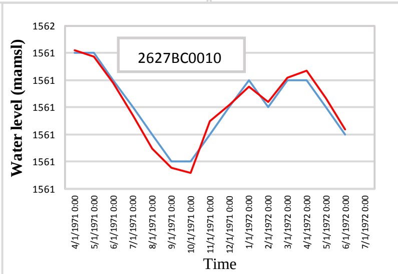
Fig 7:Distribution map of piezometers

Bank

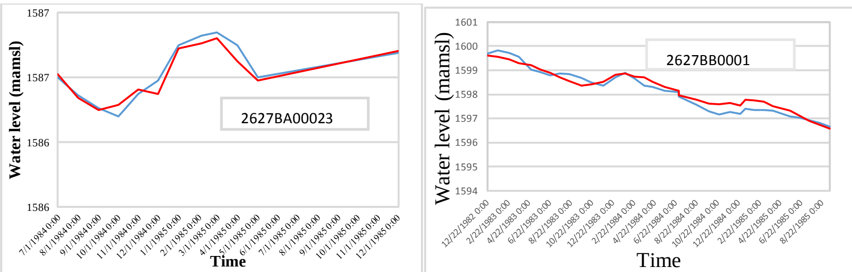


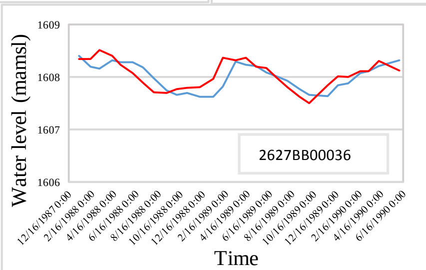
Gemsbokfontein



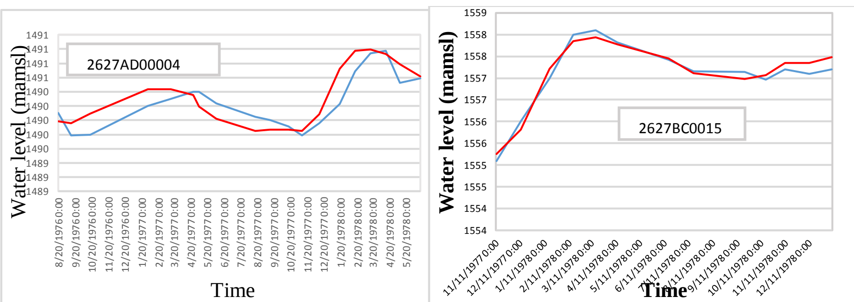


Zuurbekom





Oberholzer



Venterspost

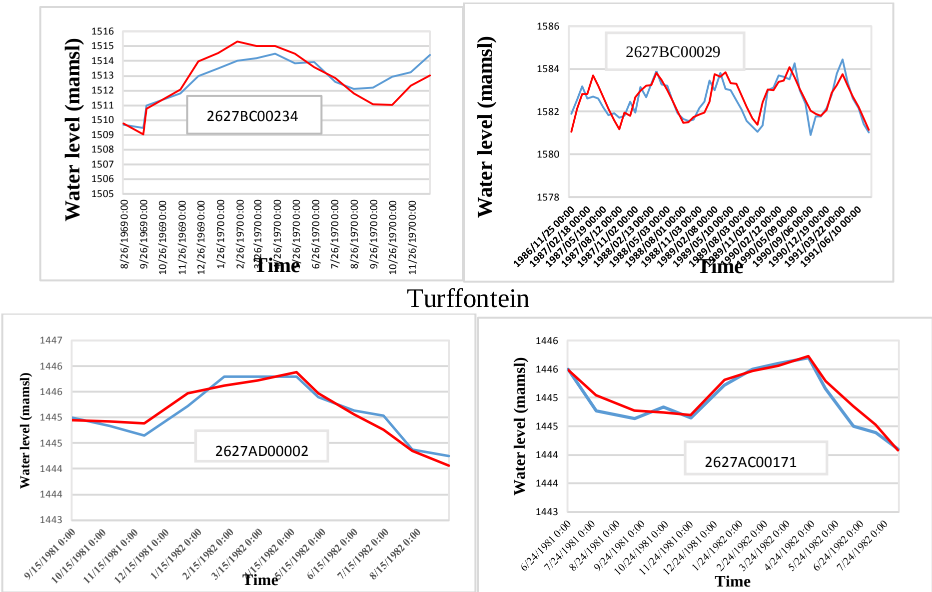


Fig 8: SVF model fit for selected piezometers

Tables

Table 1:Map of mean recharge (%) for each compartment

Compartment	**Chloride**	**APLIS**	**Thornthwaite**	**Kessler**	**SVF**
Zuurbekom	11,60	15,5	17,95	66,34	12,1
Gemsbokfontein	18,96	15,6	17,93	66,70	14,33
Venterpost	19,14	22,64	17,66	66,49	15
Bank	31,62	21,32	17,12	65,70	19,66
Oberholzer	15,19	19,9	15,72	64,86	11,80
Boskop-Turffontein	3,34	27,23	13,59	66,04	4.85

Table 2: Values of recharge obtained with Kessler and Thornthwaite methods

Weather station	Average rainfall (mm)	Thornthwaite	Kessler
C2E007	624	23.88	66.43
C2E004	415	9.84	75
C2E009	609	18.22	68.96
C2E015	676	23.54	66
C2E018	520	11.43	66

Table 3: SVF fitting parameters

	Study Area km2	Specific Yield	Effevtive Recharge (%)	Dolomite Storage (Ml/d)
Zurbekom Compartment				
2627BA00023		0.047	13.1	85
2627BB00001	360.056	0.04	11.2	102
2627BB00036		0.04	12	89
Average		0.042	12.1	92
Bank Compartment				
2627BC00016		0.02	20	93
2627BC00020	248.5234	0.02	18	87
2627BC00212		0.02	21	130
Average		0.02	19.66	103.33
Gemsbokfontein Compartment				

2627BC00010	138.059	0.07	14.4	58
2627BC00092		0.053	14.4	29
2627BC00102		0.075	14.2	42
Average		0.066	14.333	43
Oberholzer Compartment				
2627AD00004	293.553	0.037	11.6	62
2627BC00015		0.02	12	66
Average		0.0285	11.8	64
Venterspost Compartment				
2627BC00029	77.7544	0.015	14	21
2627BC00234		0.007	16	19
Average		0.011	15	20
Boskop-Turffontein compartment				
2627AC00171	972.729	0.006	5	86
2627AD00002		0.006	4.7	80
Average		0.006	4.85	83

Table 4: Mean recharge % (Map)

Compartment	Recharge (%)						
	Enslin et Kriel 1967	Fleischer (1981)	Wolmarans (1984)	Foster (1988)	Bredenkamp (1993)	Vegter (s.a)	Average
Zuurbekom	13	16.8	15	-	15.8	13.1	14.7
Gemsbokfontein	7.5	12.8	5.3	-	27	12.8	13.1
Venterspost	8.5	27	20	54.6	-	15.1-16.0	27.5
Bank	5.8	24	16.3	27.3	-	7.4	16.2
Oberholzer	3.6	-	18.3	12.9	-	-	11.6
Boskop-Turffontein	-	-	5.6	-		-	5.6