International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:12, No:6, 2018

Development of Groundwater Management Model Using Groundwater Sustainability Index

S. S. Rwanga, J. M. Ndambuki, Y. Woyessa

***Abstract*—**Development of a groundwater management model is an important step in the exploitation and management of any groundwater aquifer as it assists in the long-term sustainable planning of the resource. The current study was conducted in Central Limpopo province of South Africa with the overall objective of determining how much water can be withdrawn from the aquifer without producing nonreversible impacts on the groundwater quantity, hence developing a model which can sustainably protect the aquifer. The development was done through the computation of Groundwater Sustainability Index (GSI). Values of GSI close to unity and above indicated overexploitation. In this study, an index of 0.8 was considered as overexploitation. The results indicated that there is potential for higher abstraction rates compared to the current abstraction rates. GSI approach can be used in the management of groundwater aquifer to sustainably develop the resource and also provides water managers and policy makers with fundamental information on where future water developments can be carried out.

***Keywords*—**Development, groundwater, groundwater sustainability index, model.

I. Introduction

GROUNDWATER management in many countries of the world has progressed from virtually nil to a more regulatory regime today. Management of groundwater needs a useful tool which can be able to maximize the economic and social welfare of the community while protecting the resource so that future generations can access it [1]. Management of groundwater resources requires that recharge to the groundwater be known on finer scales, therefore modelling is often the chosen method of estimating recharge [2]. Due to exploitation of groundwater resources, the world suffers most from lack of sustainability strategies as evidence by the negative environmental impacts (drying wetlands, seawater intrusion in coastal aquifers as well as lowering of water tables) witnessed, especially in areas of intensive groundwater exploitation. Although one may argue that by undertaking artificial recharge such aquifers can be restored, it is important to note that artificial replenishment of groundwater is only applicable within a small scale environment. Thus, sustainable management of the groundwater aquifer is very important [3].

According to [4], sustainability in water resource management means: “Water resource systems that are managed to satisfy the changing demands put on them, now and on into the future, without system degradation”. As further indicated by [4], an aquifer management plan can assist to achieve this by developing an understanding of how an aquifer works and answer questions such as: How much water is available? Are there any practices that could possibly pollute the aquifer? Is the aquifer being over pumped? What can be done to protect this resource?

Reference [5] defined a sustainable groundwater system as one in which pumping can carefully continue for an indefinite period. It was further suggested that if water managers adopt the definition safe yield as

> “the maximum long-lasting pumping such that all logistic, environmental, legal, social, economic, and physical constraints are met, then sustainable groundwater use solutions can be identified”.

GSI can be used as a tool to manage groundwater resources development and protection. Groundwater indicators are considered as important tools in instigating various aspects of water resource management. These tools underline the state of development, stress, and other aspects connected to condition of aquifers and help significantly in the struggle for sustainable water supply solutions. Groundwater indicator compares the amounts of the abstracted groundwater to total groundwater recharge. GSI reveals if groundwater is used in a sustainable way or if there is any indication of over abstraction. When abstraction is less than recharge, groundwater is considered sustainable [6].

Reference [7] indicated that GSI indicators are useful tools which can be used for policy making because of its simplicity and the scale at which these indicators can be applied (i.e. national and regional). However careful measures must be taken into consideration as oversimplification can misinform policy for example if the indicator is 100 percent nationally, that means abstraction is equal to recharge. This indicator does not translate into sustainable groundwater management nationally. Moreover, in the event of using GSI indicator, it is necessary to specify how the data on obstructions were collected (i.e. from users themselves by compulsory evidence or by estimates).

Reference [8] also points out that groundwater sustainable planning and management can be developed through the use of GSI. This is because GSI indicators provide simplified information about the current situation and future trends in the groundwater system. Different authors from different

S. S Rwanga (PhD student) is with the Tshwane University of Technology, and Lecturer at Vaal University of Technology, Department of Civil Engineering, Andries Potgieter, private bag X 021, Vanderbijlpark, SE7, 1900 South Africa, (corresponding author; phone: +27169509172; e-mail: sophia.rwanga@yahoo.com).

JM Ndambuki is a Professor of Civil Engineering, Department of Civil Engineering, Tshwane University Technology, Private Bag X680 Pretoria 0001, South Africa (phone: +27(0)123825225; e-mail: ndambukijm@yahoo.co.uk).

Y Woyessa is associate Professor Civil Engineering, Department of Civil Engineering, Central University of Technology, South Africa (e -mail: woyes002@umn.edu).

countries use GSI for their studies, thus includes [9]-[11], [6]. These indicators were also applied for detecting groundwater quality [12], [13].

This paper aims at developing groundwater management model using GSI. The motive behind this paper was to examine how much water can be withdrawn from an aquifer without producing nonreversible impacts on groundwater quantity. This is because intensive extraction of groundwater from aquifers may affect groundwater levels, base-flow of streams and groundwater storage. Moreover, formulation of GSI indicator can facilitate sustainable development, management and conservation of groundwater quality. The approach used in this paper can be applied in other areas where conditions are similar to the case study presented in this work.

A. Study Area

The study area is situated in central Limpopo, South Africa. The area falls under latitude -23 0 31.09 S, 29 30 48.56 E and 24 2 48.30 S and 29 32 16.90 E (Geographic Lat/Lon WGS 84) with total area of 19188 km^2. Fig. 1 shows the location map of the study area. The study area is regarded as semi-arid subtropical with summer average temperature of between 32.2 °C and 27.3 °C and winter temperature varies from 9.2 °C to 4.3 °C. The mean annual rainfall of the study area amounts to 453 mm as recorded at five stations found in the area. South East parts of study area have maximum annual mean rainfall of 475 mm, while the northern part has annual mean rainfall of 205 mm.

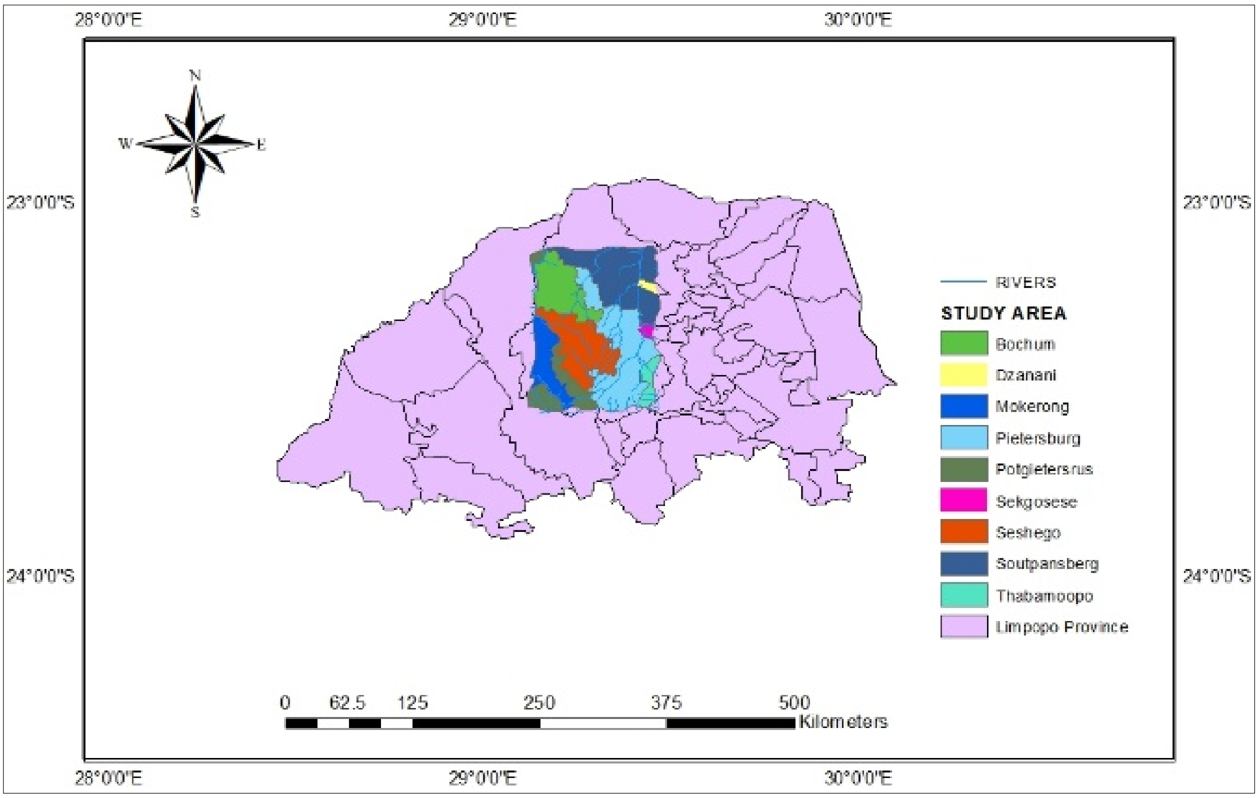

Fig. 1 Study area location map

1. Study Area Characteristics

Geology and Lithology of the Study Area

The presence of Geological structures in study area (Fig. 2) (faults, fractures and lithologic contacts) promotes greatly the movement and occurrence of groundwater. Dominant Geology and Lithology types found in the study area is presented in Table I.

Aquifer Characteristics

The characteristics of aquifers are very important in any groundwater studies. The study area is characterized by major and minor aquifers as described by [14]. 50.6% of study area is covered by major aquifer which is a good indication that water can be abstracted in large quantity for public supplies. On the other hand, 49.6% of study area is covered by minor aquifers. These aquifers do not have high permeability although water can be abstracted in limited amounts. The main aquifers in the study area are fractured and weathered aquifers in the Alma formation rocks and along the sill and dyke contact zones.

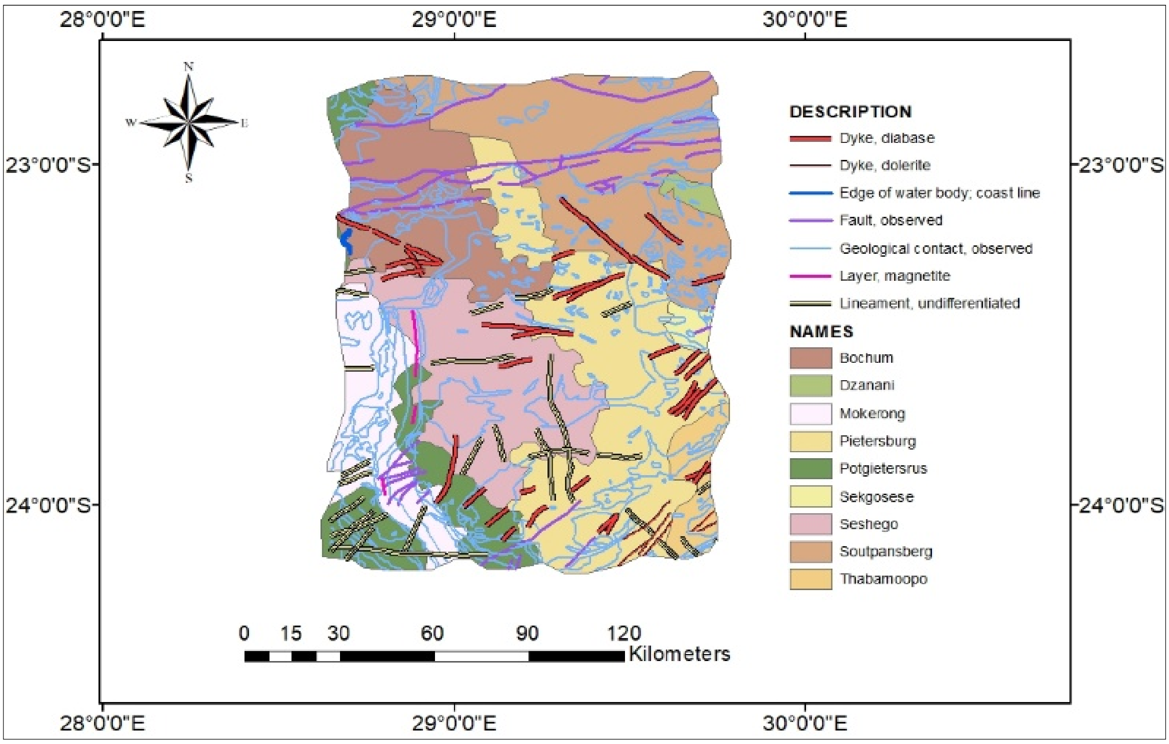

Fig. 2 Geological structures map.

TABLE I
GEOLOGY AND LITHOLOGY TYPES FOUND IN THE STUDY AREA

	Lithology_Type	Area (km^2)	% Covered by area
1	Goudplaats-hout river gneiss	12088.2	48.7
2	Letaba	2705.5	10.9
3	Matlabas	1635.3	6.6
4	Wyllie's poort	1087.7	4.4
5	Pietersburg	913	3.7
6	Malala drift gneiss	866.9	3.5

B. Materials and Methods

In order to accomplish the objective of developing the groundwater sustainability model, data on groundwater recharge as well as total abstraction rate were used. The tools used included GSI; used to develop a management model and Geographic information system (GIS) software used for data manipulation.

Groundwater Recharge

The recharge value used in this work was based on water budget analysis done through groundwater simulation model, MODFLOW. The results of recharge from MODFLOW were mapped using GIS. Four recharge zones were demarcated based on calibrated hydraulic conductivities zones. Table II shows the simulated recharge from MODFLOW for the four zones of the study area.

Groundwater Abstraction

Reference [13] defined total groundwater abstraction as the total withdrawal of water from a given aquifer or groundwater unit by means of boreholes, wells, springs and other abstraction ways for the purpose of public water supply, agricultural, industrial and other usage. In this study, the abstraction rates were calculated from dataset obtained from department of water affair. Only abstraction rates from functional boreholes were used for analysis. The amount of groundwater abstraction was obtained by summing all the pumping rates of a particular cell, and for all the cells in each of the demarcated four zones. Table III presents total pumping rates for the demarcated zones.

TABLE II
RECHARGE VALUES FOR THE FOUR ZONES

Zones	**Area [km^2]**	**Recharge [mm/year]**
Zone 1	8791.677	4.95
Zone 2	1366.934	192.76
Zone 3	3323.288	127.17
Zone 4	4018.728	101.52

TABLE III
PUMPING RATES VALUES FOR FOUR ZONES

Zones	Original Pumping rate (m^3/day)
ZONE 1	14218.85
ZONE 2	13150.94
ZONE 3	4740.768
ZONE 4	16536.96

GSI Analysis

The analysis started by randomly increasing the pumping rates from initial pumping rates (obtained from primary data) until calculated GSI reached the predetermined value of approximately 0.8. The GSI was calculated using (1).

$$GSI = \frac{GW_{ab}}{GW_{rech}} \quad (1)$$

where GSI is the Groundwater Sustainability Index, GW_{abs} is the Groundwater abstraction and GW_{rech} is the Groundwater recharge. Values of GSI close to unity and above indicate overexploitation (i.e. 0.8) [13].

C. Results and Discussions

Pumping Rate and Simulated Recharge

The aim of this investigation was to examine how much water is currently available in each zone, how much is extracted and if there is potential for further exploitation of the aquifer within the individual zones. Pumping rate of each zone was obtained by demarcating the wells falling in each zone (Fig. 3). By using ArcGIS (statistics tool), the total amount of pumping rate was obtained. Simulated recharge was obtained through numerical modelling (using MODFLOW Software). Thus, results from mass balance were used for analysis. Fig. 4 presents the amount of recharge in each zone, while Fig. 5 shows the relationship between pumping rate and recharge for each zone. Figs. 4 and 5 demonstrate that, there is still potential for further groundwater abstraction in the study area. This is because the amount of abstraction in relation to recharge is substantially minimal for zone 2, 3 and 4.

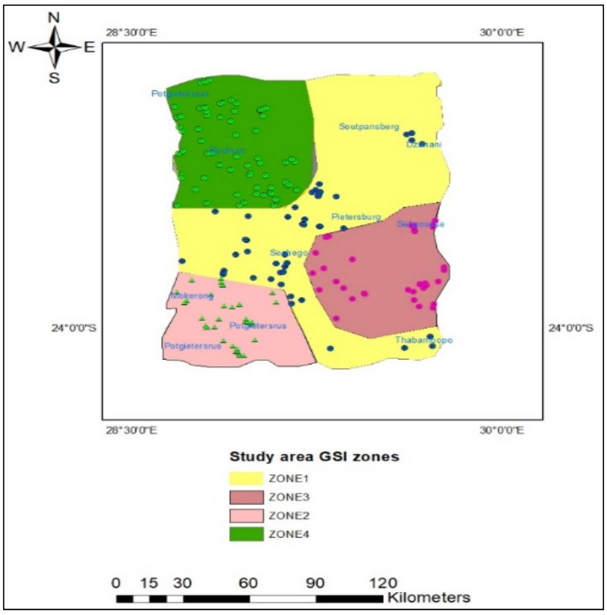

Fig. 3 Demarcation of GSI zones

GSI Results

Table IV and Fig. 6 show the results of GSI in relation to exploitation level for each zone (i.e., exploitation kicks in when GSI attains a value of 0.8 and above), while Table V presents the completed dataset wells used for analysis with respect to total area covered and their combined pumping rates. Zone 1 has 54 wells within an area of 8791.677 km^2 and total pumping rate of 14218.85 m^3/d. Through GSI analysis, this zone can tolerate pumping rate of up to 36.33 Mm^3/year an increase of about 14.3% from the current pumping rate.

The existing extraction rate of Zone 2 is 4.8 Mm^3/year. However, through GSI, this zone has a potential groundwater abstraction rate of 264 Mm^3/year. This zone is located on the southern part of the study area where the infiltration rate is high compared to the other zones. Current abstraction rate of zone 3 is 1.73 Mm^3/yr, while results of GSI analysis indicate that this zone has potential for groundwater abstraction of up to 346 Mm^3/yr. Moreover, Zone 4 which is located at the northwestern part of the study area can accommodate an increased pumping rate of approximately 80.68 Mm^3/y, which is far more than the current abstraction rate of 6.04 Mm^3/yr.

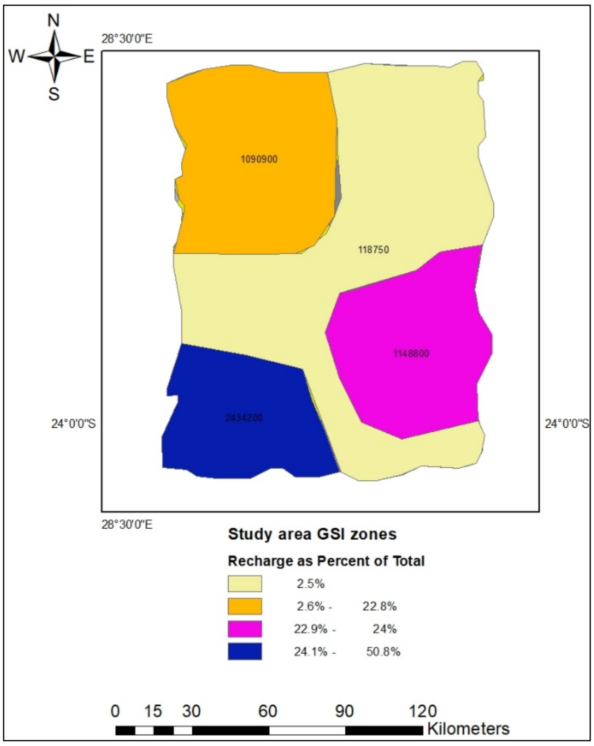

Fig. 4 Amount of recharge in percentage for four GSI zones

D. Comparisons of Findings with Previous Studies

The results were compared with recent studies done in the study area. The study by Limpopo Water Management Area North Reconciliation Strategy (LWMRS) [15] presents the finding of Limpopo Water Management Area (WMA). The results indicated that about 659 Mm^3/yr estimated by [15] is available for exploitation, while this study estimated a value of about 1138 Mm^3/yr using GSI and stochastic approach. This implies that there is an excess of 479 Mm^3/yr which was not captured on the previous study.

In general, all zones showed potential for higher abstraction rates compared to what is currently abstracted. Pumping wells available are very few compared to the size of the area. This implies that there is need to increase the number of pumping wells in the study area in order to accommodate increasing water supply demands from the communities living in the study area.

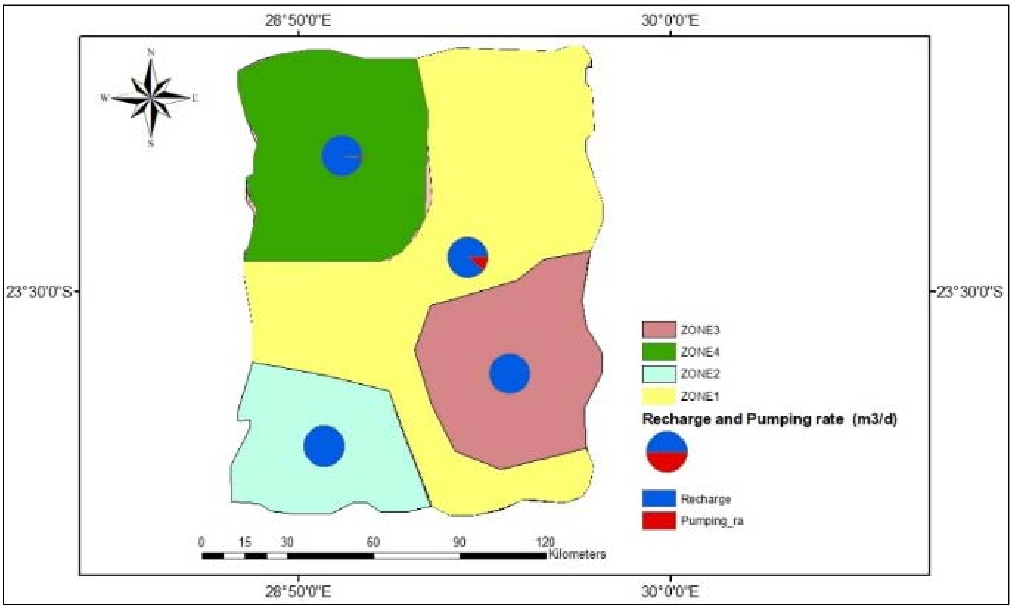

Fig. 5 Recharge and pumping rate for four GSI zones

TABLE IV
GSI RESULTS

Zones	Original Pumping rate (m^3/day)	Recharge (m^3/d)	GSI for Original	GSI after 7*Q	GSI after 55*Q	GSI after 160*Q	GSI after 200*Q
ZONE 1	14218.85	118750	0.1	0.8	6.6	19.2	23.9
ZONE 2	13150.94	2464200	0.0	0.0	0.3	0.8	1.1
ZONE 3	4740.768	1148800	0.0	0.0	0.2	0.7	0.8
ZONE 4	16536.96	1090900	0.0	0.1	0.8	2.4	3.0

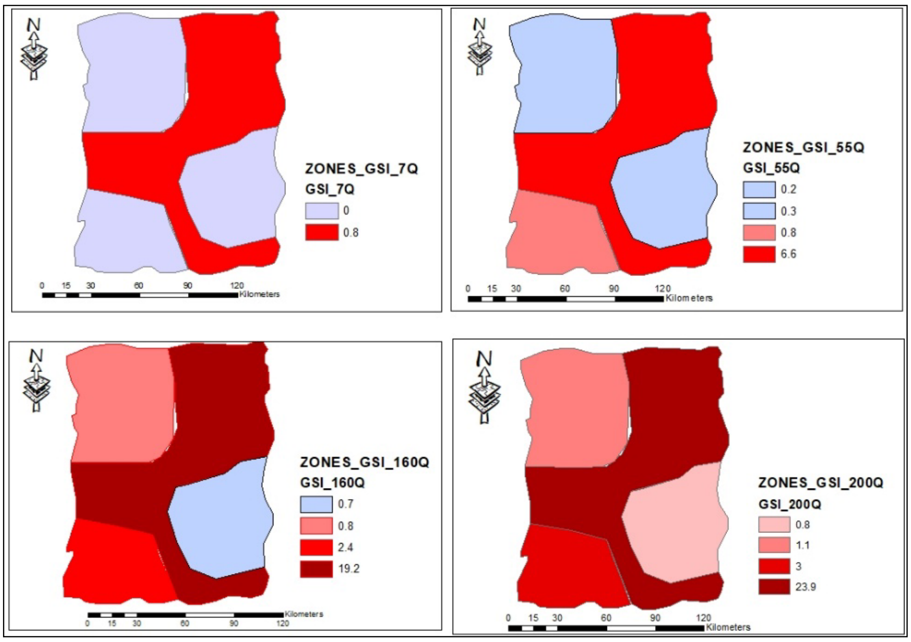

Fig. 6 GSI analysis for four zones

E. Conclusion

The availability of groundwater in the study area is very crucial for sustainable development of the region. This is because groundwater at Limpopo province especially in rural area is considered as a strategic water resource which accounts for almost 70% of rural domestic water supply. This research demonstrates that the resource is available throughout the study area in varying quantities depending on the hydrogeological properties of the underlying aquifer

TABLE V
PUMPING WELLS, TOTAL AREA AND ABSTRACTION RATE

Zone	Number of wells	Pumping rate total (m^3/d)	Zone Area, km^2
1	54	14218.85	8791.677
2	38	13150.94	1366.934
3	42	4740.768	3323.288
4	69	16536.96	4018.728

Additionally, development of the groundwater management model was achieved through GSI approach. GSI values close to unity (i.e. 0.8) and above indicate overexploitation. Using this approach, results indicated that the potential for higher abstraction rates compared to the current abstraction rates is real. Further the research showed that an additional combined volume of 479 Mm^3/year can be abstracted from study area. Moreover, this paper has demonstrated that the groundwater resource is available throughout the study area in varying quantities that can be exploited for bulk-water supply.

REFERENCES

[1] X, Mao; P, Enot; D. A, Barry; L, Li and A, Binley; D. S, Jeng. Tidal influence on behaviour of a coastal aquifer adjacent to a low relief estuary. *Journal of Hydrology*. 2005, 327(110 - 127). DOI: https://doi.org/10.1016/j.jhydrol.2005.11.030.
[2] R. S, Crosbie; I. D, Jolly; F. D, Leaney and C, Petheram. Can the dataset of field based recharge estimates in Australia be used to predict recharge in data-poor areas? *Hydrology Earth System Science*. 2010, (14):2023–2038. DOI: https://doi.org/10.5194/hess-14-2023-2010
[3] H. A, Loaiciga. Climate change and groundwater. *Annals of the Association of American Geographers.* 2003, Volume 93: 30–41. DOI: 10.1111/1467-8306.93103.
[4] D. P, Loucks. Sustainable Water Resources Management. *Water International. 2000,* 25 (1): 3-10. https://doi.org/10.1080/02508060008686793.
[5] S. M. Gorelick and C, Zheng. Global change and the groundwater management challenge, Water Resource. 2015, 51, 3031–3051, DOI: 10.1002/2014WR016825.
[6] M, Lavapuro; A, Lipponen; A, Artimo and T, S, Katko. Groundwater Sustainability indicators: testing with Finnish data. Boreal Environmental Research. 2008, 13: 381-402.
[7] E, Ostrom. Crafting Institutions for Self-governing Irrigation System, 1992. ICS Press, San Francisco.
[8] S, A. Jothibase. Groundwater Sustainability Indicators in Parts of Tiruppur and Coimbatore Districts, Tamil Nadu. Journal Geological Society of India, Volume. 87, February 2016, pp.161-168. DOI: https://doi.org/10.1007/s12594-016-0384-y.
[9] J, Girman. Implementation of groundwater indicators in the Republic of South Africa. *In:* J. Vrba and A. Lipponen (Eds.), Groundwater resources sustainability indicators. IHP Groundwater Series 14, UNESCO, Paris, 2007, pp.85-98.
[10] R, Hirata; A. V, Suhogusof and A, Fernandes. Groundwater resources in the State of Sao Paulo, Brazil. *In:* J. Vrba andA. Lipponen (Eds.), Groundwater resources sustainability indicators, IHP Groundwater Series 14, *UNESCO, Paris*. 2007, pp, 73-84. http://dx.doi.org/10.1590/S0001-37652007000100016.
[11] J, Pernía and L, Lambán. Groundwater indicators in Sierra de Estepa (Seville, Spain). *In:* A. Lipponen (Ed.), Groundwater resources sustainability indicators. IHP Groundwater series, 14. UNESCO, Paris, 2007, pp 44-51.
[12] A, Melloul and L, Goldenberg. Early-indicator signals of groundwater contamination: the case of seawater encroachment. Environmental Geology. 1998, 33: 279. DOI: http://doi.org/10.1007/s002540050247.
[13] J, Vrba and A, Lipponen. Groundwater resources sustainability indicators, IHP Groundwater series 14, UNESCO, Paris. WHO (2004) Guidelines for drinking-water quality, recommendations. WHO, Geneva, Switzerland. 2007, volume 1, 3rd edition, pp.145–220.
[14] R. P, Parsons. A South African aquifer system management classification. Prepared for Water Research Commission and Department of Water Affairs and Forestry. 1995, WRC Report No. 77/95, *Water Research Commission*, Pretoria.
[15] Limpopo Water Management Area North Reconciliation Strategy. 2015. PWMA. Groundwater Assessment and Utilization Report, 01/000/00/02914/6.