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A Modelling Framework for Groundwater Sustainability in the Upper Orange Catchment of South Africa

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ABSTRACT

Sustainability modelling of the C52 Upper Orange Catchment was done for 52 boreholes. This Modelling framework was developed because in arid and semi-arid areas of South Africa, farmers and communities only have a limited number of water provision points. This has put more pressure and increased the number of wells and boreholes being drilled where they can access groundwater which is needed for multiple purposes especially agriculture and drinking water provision. Excessive pumping can lead to groundwater depletion, where groundwater is extracted from an aquifer at a rate faster than it can be replenished. This will put undue pressure on aquifers and catchments such as the Upper Orange (Modder). The methodology involved a detailed understanding of the parameters and ranking of the physical processes affecting groundwater system of the upper orange river catchment for 51 boreholes such as the climatic factors, aquifer system, rights, and equity. This model assessed whether there is undue pressure on the Upper Orange Catchment. The result and findings have been presented in a sustainability index. The outcome was a sustainability map showing areas depicting the most to least sustainable aquifers in the catchment. The developed sustainability index and maps are useful tools for future groundwater management.

Key words: Groundwater, Orange River Catchment, Modelling, Water resources

1.0 INTRODUCTION

This research aims to model important parameters governing the sustainability of groundwater systems in C52 catchment of the Upper Orange River system of South Africa. The Upper Orange River is part of the broad Orange River System. Due to the adverse impact of climatic change and increased dependence on the groundwater systems in the catchment, there is a need for development of a framework for sustainable groundwater management by modelling hydrological and human induced factors affecting the sustainability of the groundwater system. The quantity of groundwater resources varies between areas over time. This is due to important hydrological factors such as low yields of groundwater, poor water quality, lack of hydrogeological understanding and increasing threats to water supply and use.

2.0 LITERATURE REVIEW

Groundwater is reported as the most extracted natural resources. It is estimated that 600–700 km^3/year is withdrawn globally [1]. There is a balance between space and time in the natural occurrence of ground water. It is also found increasingly that ground water development in most places happens without the understanding of this balance. How ground water is recharged and its impact on the environment is not understood [2]. As a result, groundwater is excessively pumped leading to depletion. Some of the effects of depletion of water levels in aquifers are decline in water tables and yield of water wells, land subsidence and salinity intrusion in coastal aquifers. These three things are a major concern globally [3].

The concept of aquifer sustainability is complex. This is because of the contributory impact of many human activities on groundwater resources. This has increased the need for greater understanding of ground water management [4]. According to World Commission for Environmental Development [5], the concept of groundwater sustainability is frequently discussed. Most debates are on the negative effects of human activity.

'Groundwater sustainability' is defined by the development and use of the resource to address all development needs and changes [6]. Groundwater sustainability shows an optimal state that is not constant or static. Studies have shown that ground water is time and space dependent [2]. It, therefore, needs to be studied so that its change in quantity over time and space is understood. Adequate attempts to quantify of groundwater or its state in terms of sustainability are not yet made despite its wide discussion in the scientific, academic and water management arena. Part of the reason is that sustainability is a complex concept [7] and is not purely scientific [8].

Most texts define groundwater sustainability concept in terms of the nature of resource, the management requirements and actions of abstraction related to groundwater withdrawal. Groundwater is a renewable resource if not over abstracted. Groundwater is dependent on rainfall so that is continually recharged. The rate of recharge is important for groundwater sustainability. It takes several years for the water table to be renewed. This knowledge must be at the forefront with regards to developments that depend on groundwater provision [6]. The wide variations and great lengths of time it takes groundwater to recharge make it imperative that over pumping of groundwater is prevented. This is because the net effects of ground water pumping are realised overtime and takes ages to manifest. Proven concepts in groundwater sustainability call for an approach that considers the aquifer system performance through time, long term view on groundwater management and balance of ground water abstraction [6].

Groundwater sustainability is often discussed through key hydrologic terms which are safe yield, groundwater mining and overdraft [5]. Safe yield refers to specific effects of pumping [5]. It considers water quality changes, water level decrease and low stream flow. Safe yield is important for groundwater sustainability because measuring it frequently prevents over abstraction of the aquifer system. Groundwater mining is also another key term in ground water sustainability. In heavily pumped aquifers it indicates extended and increasing decline in the amount of groundwater stored. This effect is typically in arid and semi-arid climatic zones. Overdraft is the last key groundwater sustainability term. Overdraft is severe in that it describes situations where abstraction of groundwater from an aquifer system for a development activity is much higher than the rate at which the aquifer is recharged. This is not a desirable situation [6].

Developments that rely on climate, ecosystems (e.g., the water cycle in figure 3) and natural resources are governed by system laws, physical laws and behavioural patterns based on challenges in the environment [9]. Through ecosystems, development paths, processes and human systems thrive [10]. In this case development is defined as the introduction of technical management practices over resources to attain a sustainable yield over a long period the continued harvesting and replenishment of a resource [5]. Development is constrained by physical limits of resources, energy, and dependence on the environment, space, and ecosystems viability. For this reason, safe yield, groundwater mining and overdraft are not enough in addressing groundwater sustainability.

Regarding increase in the body of knowledge of groundwater sustainability, some obstacles have been identified. These obstacles range from limited funding to ever increasing climate change variation [2]. There is need to increase policy and practice understanding of groundwater sustainability. Modelling can increase the improvements in groundwater resource understanding, sustainable groundwater management and conservation.

3.0 METHODOLOGY

The Modder River Basin is situated in the southwestern part of the Free State province in South Africa, forming some portion of the Upper Orange Water Management Area (WMA) (Figure 1). The Upper Orange WMA expands further into parts of the Eastern and Northern Cape provinces.

Figure 1: Map showing the study area C52 as marked. (Source: Water Affairs 2016).

The methodology (see figure 2) involved a detailed understanding of the parameters and ranking of the physical processes affecting groundwater system of the upper orange river catchment for 51 boreholes (see figure 3) such as the climatic factors (precipitation, evapotranspiration, sunshine, slope, topography, climatic zones), aquifer system (recharge, yields, storativity, aquifer types, lithology/rock types). Other important catchment factors and parameter rankings which are human induced are rights and equity (number of issued permits per year in the catchment, and duration of the permits.

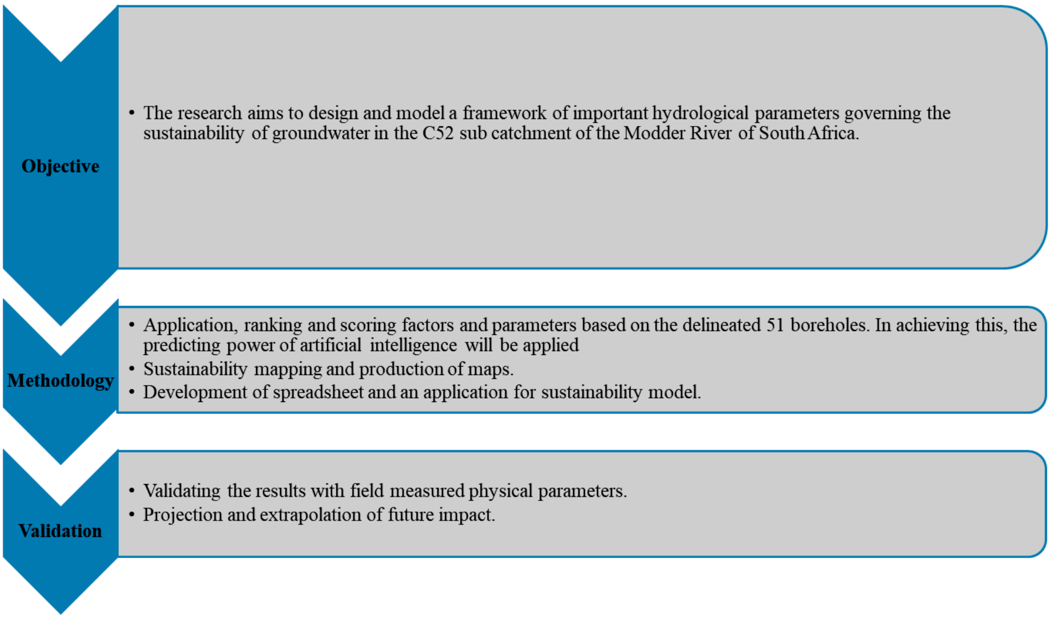


Figure 2: Approach/methodology flow chart. (Source: Author)

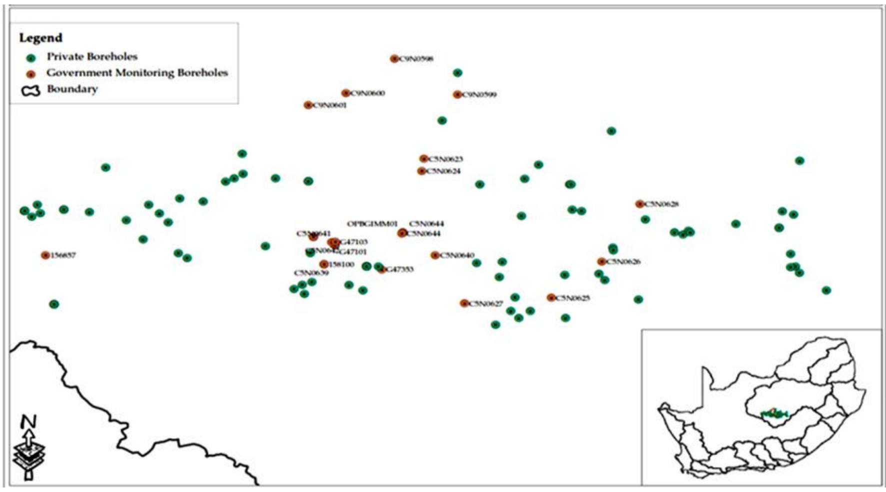


Figure 3: Map showing the location of study boreholes in the Upper Orange River Catchment. (Source: Water Affairs, 2016).

4.0 FINDINGS

The conceptual framework (figure 4) was developed based on the physical processes governing hydrological cycles in relation to groundwater sustainability in the Upper Orange catchment. It was found that some of these processes are surface to groundwater interactions, land use to groundwater interactions and land use and climate interactions. These processes were grouped as factors and includes climatic, socio-economic and land use, aquifer sustainability, right and equity of resources.

The developed framework (figure 5) was proposed in a sustainability index. The sustainability indices were ranked based on a scoring system from the highest score of 100 which implies highly sustainable system to the lowest score of 19 which suggest the least sustainable. It was found that the final groundwater sustainability index score of 19-35 means very low sustainability, 35-51 means low sustainability, 51-67 means moderate sustainability, 67-83 means high sustainability and 83-100 means very high sustainability.

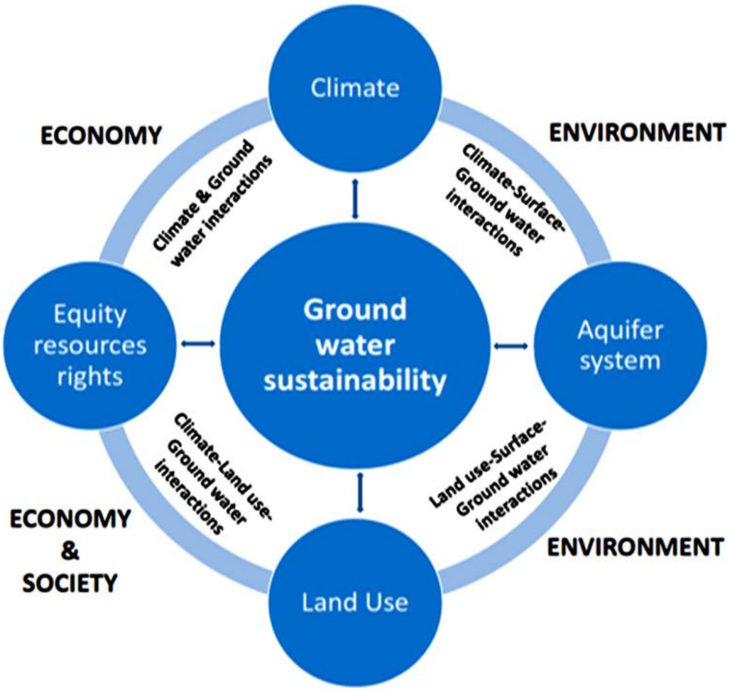


Figure 4: Designed conceptual framework. (Source: Author)

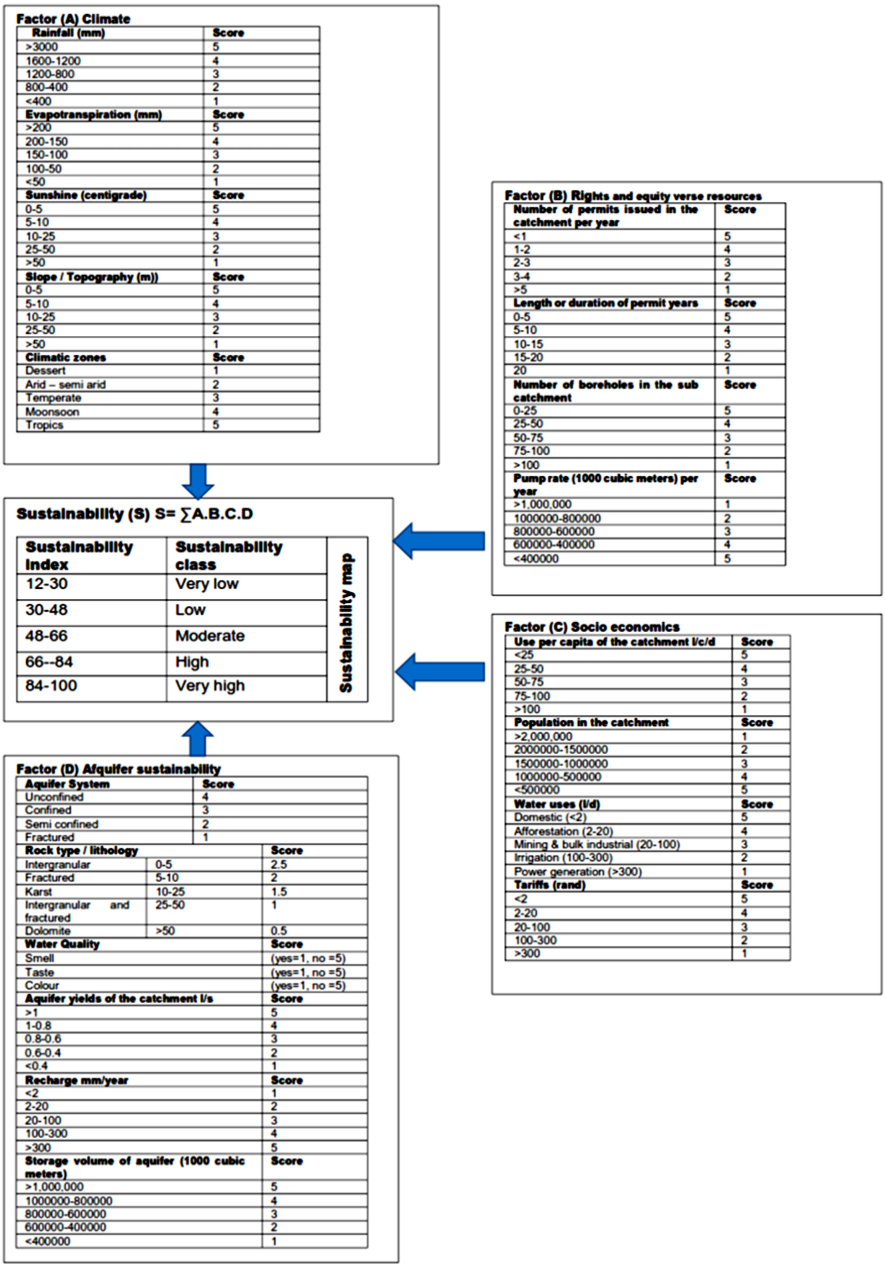


Figure 5: Sustainability index/model. (Source: Author).

The final sustainability map (Figure 6) was derived from the sustainability index calculations, which was computed, based on the principles behind sustainability by combining the factors of climatic conditions, rights and equity as related to the groundwater resources, socio-economics, and the aquifer system sustainability. All factors were given equal weighting prior to the addition as sustainability gives an equal weighting to factors considered with resource conservation issues. The final sustainability score was calculated as follows:

Sustainability $S = \sum A+B+C+D$ $\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathit{Equation}\ 16$

A = Climatic condition score;
B = Rights and equity score;
C = Socio-economic score;
D = Aquifer system score.

The final sustainability factors were added up because they all impacted the groundwater sustainability. Factor D and A elements (aquifer system and climatic conditions) were complex in the natural context and responsible for percolation and infiltration.

As stated earlier, all factors carried equal weights. For Factor A and D six parameters were considered for each of Factor A and Factor D, thereby carrying equal weights of 30. Aside from the higher parameters considered for these two factors, the sustainability method further assumes rainfall as the principle climatic condition for groundwater availability in the catchment, initiator of the infiltration and, later, percolation, which contributes to recharge and later becomes groundwater. The implication is that, if rainfall or another recharge mode is absent, there is no groundwater formation and sustainability is low. The impact of Factor B and C on groundwater sustainability may be higher or lower depending on whether human activity will deplete whatever groundwater is available and not replenish it. For this reason, equal parameters and weights were assigned and considered for these two factors.

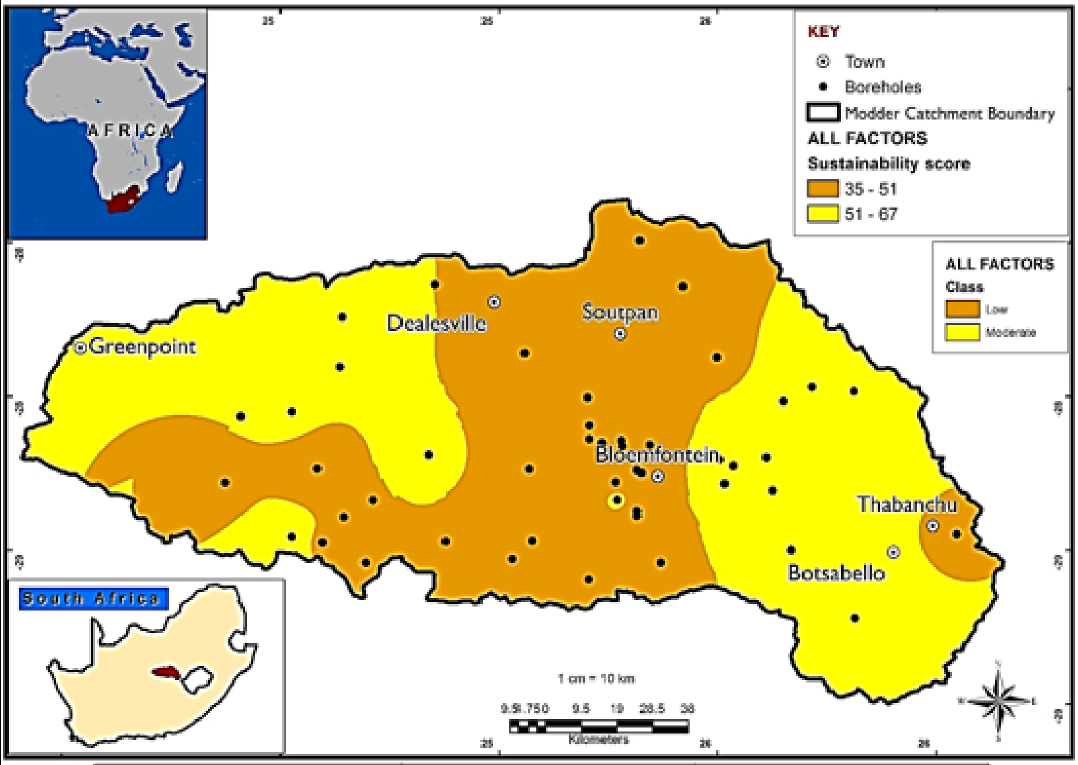
The sustainability index was grouped into five classes. The classes and sustainability values are presented in Figure 5.5. The final groundwater sustainability index class score of 19−35 meant a class of very low sustainability, 35−51 meant a class of low sustainability, 51−67 meant a class of moderate sustainability, 67−83 meant a class of high sustainability and 83−100 meant very high sustainability.

The rankings were based on a scoring system (see Table 1) from the highest score of 100, which implies a highly sustainable system to the lowest score of 19, which suggest the least sustainable system. The high and very high sustainability classes correspond to areas with favourable climatic conditions, and favourable groundwater interaction and processes (a fast rate aquifer system, especially recharge). They further have less abstraction and socio-economic activity. The moderate to low classes represent areas that are opposite to the favourable scenario, suggesting too much abstraction activity, unfavourable climatic conditions and slow to little groundwater processes and interactions (high or steep slopes and low rainfall).

Table 1: Combined sustainability score for all factors: A, B, C & D. Source: Author

Bore-h	Latitude	Longitude	Score A	Score B	Score C	Score D	Sustainability	Sustainability	Colour
1	-28.867897	26.302778	11	11	12	10,5	44,5	Low	Orange
2	-29.567891	26.072222	11	10	12	10,5	43,5	Low	Orange
3	-29.098889	26.058333	11	11	12	10,5	44,5	Low	Orange
4	-29.014567	26.144565	11	11	12	10,5	44,5	Low	Orange
5	-29.012578	26.075565	11	9	12	10,5	42,5	Low	Orange
6	-29.005556	26.025898	11	9	12	10,5	42,5	Low	Orange
7	-29.292361	26.166667	11	10	12	10,5	43,5	Low	Orange
8	-29.076946	26.120568	11	11	12	10,5	44,5	Low	Orange
9	-28.995833	25.995833	11	11	12	10,5	44,5	Low	Orange
10	-29.168446	26.112233	11	14	11	10,5	46,5	Low	Orange
11	-29.075321	26.113345	11	11	12	13,5	47,5	Low	Orange
12	-29.067528	25.850528	11	11	12	10,5	44,5	Low	Orange
13	-29.182341	26.110765	11	11	11	10,5	43,5	Low	Orange
14	-29.239611	25.857694	11	8	12	10,5	42,5	Low	Orange
15	-29.283324	25.811056	11	9	12	10,5	42,5	Low	Orange
16	-29.332056	25.994028	11	9	12	10,5	42,5	Low	Orange
17	-28.519876	26.116667	11	11	12	10,5	44,5	Low	Orange
18	-28.896223	25.991389	11	11	12	10,5	44,5	Low	Orange
19	-29.007389	25.905608	11	8	12	10,5	41,5	Low	Orange
20	-28.791234	25.849082	11	12	10	10,5	44,5	Low	Orange
21	-29.066667	25.341667	11	8	12	10,5	42,5	Low	Orange
22	-28.962778	25.995833	11	8	12	10,5	42,5	Low	Orange
23	-28.633241	26.220044	11	12	10	10,5	43,5	Low	Orange
24	-29.223557	26.878324	11	12	10	12,5	45,5	Low	Orange
25	-29.141083	26.062083	11	9	13	16,5	49,5	Low	Orange
26	-29.425139	26.632917	11	9	10	16,5	46,5	Low	Orange

Bore-h	Latitude	Longitude	Score A	Score B	Score C	Score D	Sustainability	Sustainability	Colour
27	-29.262148	26.480619	11	10	14	16,5	51,5	Moderate	Yellow
28	-28.973456	28.978757	11	10	11	15,5	47,5	Low	Yellow
29	-28.904639	26.462567	11	9	13	15,5	48,5	Low	Orange
30	-28.880806	26.630833	11	9	7	15,5	42,5	Low	Orange
31	-28.876754	26.535642	11	12	13	16,5	52,5	Moderate	Yellow
32	-29.046543	26.425678	11	12	13	16,5	52,5	Moderate	Yellow
33	-29.044944	26.308056	11	12	13	16,5	52,5	Moderate	Yellow
34	-29.063256	26.345673	11	13	11	16,5	51,5	Moderate	Yellow
35	-29.103864	29.103089	11	8	7	14,5	40,5	Low	Orange
36	-29.102778	26.320278	11	9	11	14,5	46,5	Low	Orange
37	-29.118826	26.434841	11	12	14	14,5	51,5	Moderate	Yellow
38	-28.551254	25.373452	11	11	13	16,5	51,5	Moderate	Yellow
39	-28.625321	25.625765	11	9	13	14,5	47,5	Low	Orange
40	-29.243806	25.354222	11	8	8	14,5	41,5	Low	Orange
41	-28.941111	25.157778	11	9	7	14,5	41,5	Low	Orange
42	-29.233333	25.284567	11	9	11	14,5	45,5	Low	Orange
43	-29.122222	25.120872	11	10	14	16,5	51,5	Moderate	Yellow
44	-28.702785	25.401392	11	9	11	14,5	45,5	Low	Orange
45	-29.182972	25.405139	11	11	13	16,5	51,5	Moderate	Yellow
46	-28.822567	25.395757	11	9	8	14,5	48,5	Low	Orange
47	-29.291972	25.457528	11	8	7	14,5	46,5	Low	Orange
48	-29.141667	25.475567	11	9	7	14,5	47,5	Low	Orange
49	-29.241667	25.654352	11	9	7	14,5	47,5	Low	Orange
50	-29.033861	25.609833	11	13	11	16,5	51,5	Moderate	Yellow
51	-28.936565	25.283421	11	11	7	14,5	49,5	Low	Orange



Sustainability index	Sustainability class	Colour code
19-35	Very low	Red
35-51	Low	Orange
51-67	Moderate	Yellow
67--83	High	Green
84-100	Very high	Blue

Figure 6: The final groundwater sustainability map of the Modder River catchment. Source: Author

5.0 CONCLUSION

In Conclusion, the developed sustainability index was applied to the 51 boreholes mapped in the C52 tertiary catchment of the Upper Orange River Catchment. The outcome was a sustainability map showing areas depicting the most to least sustainable aquifers in the catchment. The developed sustainability index and maps are useful tools for future groundwater management.

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