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Groundwater of the Modder River Catchment of South Africa: A Sustainability Prediction

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Abstract: This paper presents a spatial interpolation of the hydrological and socioeconomic processes impacting groundwater systems to predict the sustainability of the Modder river catchment of South Africa. These processes are grouped as climatic (factor A), aquifer sustainability (factor D), social-economic and land use (factor B), and the human-induced parameters of rights and equity (factor C). The parameters evaluated for factors A and D included climatic zones, precipitation, sunshine, evapotranspiration, slope, topography, recharge, yields, storativity, aquifer types, and lithology/rock types. Factors B and C included population in the catchment, use per capita, water uses, tariffs and duration of the permits, pump rate per year, number of issued permits per year in the catchment, and number of boreholes in the sub-catchment. This paper, therefore, looks at the impact of the average values of the chosen set of parameters within the given factors A, B, C and D on groundwater in the C52 catchment of the Modder River, as modelled in a sustainability index. C52 is an Upper Orange catchment in South Africa. The results are presented in sustainability maps predicting areas in the catchment with differing groundwater dynamics. The Modder River groundwater sustainability ranged between low and moderate sustainability. The sustainability maps were validated with actual field groundwater recharge and surface water, a comparison between storativity and licensed volume, and a comparison of sustainability scores and storativity. The key finding in this paper will assist groundwater managers and users to adequately plan groundwater resources, especially on licensing and over pumping.

Keywords: groundwater recharge; groundwater sustainability; hydrology models; Modder River; sustainability index

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1. Introduction

Groundwater typically forms through the concept of recharge. Surface water and rainfall form most of the groundwater recharge. Precipitation that infiltrates and percolates the earth's surface has three paths: (1) Capillary action forcing water into the vadose zone, (2) high temperature causing evapotranspiration, and (3) infiltration and percolation contributing to the water table [1]. In the arid and semi-arid areas of South Africa, farmers and communities have merely a limited number of water provision points [2]. This increases the pressure on groundwater and has increased the number of wells and boreholes being drilled to access the groundwater needed for multiple purposes, particularly for agriculture and drinking water [3]. The limited resources of water provision have put undue pressure on aquifers, such as those in the C52 Modder River catchment [4]. The Modder River catchment is part of the broader Orange River system termed the C5 secondary catchment. The sub-catchment (Modder River) is termed the C52 catchment [4], which has the following drainage regions: C52G, C52H, C52J, C52B, C52A, C52E and C52F. The Modder-Riet River catchment is a combined system. C51 is termed the Riet catchment while C52 is the

Modder River catchment. Both belong to the bigger Upper Orange catchment. The Orange catchment itself is further divided into the Upper and Lower Orange River system.

Groundwater sustainability is important because groundwater, as a global asset, is the world's most consumed natural resource. Globally, the withdrawal is estimated at 600–700 km^3/year [5]. This extraction affects the balance between space and time in its natural occurrence. It is further increasingly found that groundwater development (drilling, usage, quality, etc.) in most places takes place without understanding this balance. How groundwater is recharged and its impact on the environment are complex [1,4,6,7]. As a result, groundwater is excessively pumped, leading to depletion. Low water levels in aquifers are responsible for salinity intrusion in coastal aquifers, land subsidence, and the decline in the yield of water wells. This is a major global challenge [6–8].

The undue pressures in the catchment have led to excessive pumping and increased abstraction. The ability to supply water directly from groundwater aquifers to the farmers and other water users depends fundamentally on the rainfall, which is a major source of groundwater recharge [9]. With the low rainfall in South Africa, groundwater recharge is low [9]. High groundwater abstraction, also known as excessive pumping, has several negative effects. One of these effects is groundwater depletion, a result of fast-rate groundwater extraction from an aquifer. Fast-rate extraction does not allow for adequate recharge of the aquifer [1]. Other secondary effects of depletion are related to climate change, including surface albedo distortion, increased groundwater salinity, the high cost associated with pumping, poor operation and maintenance of the wells, and increased damage of built-up wells [1]. There have been changes, trends and threats that negatively affect water resources in the Modder River catchment [4]. These include increased population growth and increasing urbanisation. The population of the Modder River catchment increased from 618,566 in 2001 to an estimated 1,083,886 in 2016 [4]. This resulted in increasing water demands and excessive pumping. The Modder River catchment, particularly the Bloemfontein area, has the highest demand for water in the Upper Orange River (C5) catchment, at 351 million litres of the total local requirement. Other negative effects are the increased degradation of the environment, high levels of man-made climate change, and a high variability of the natural climate. The net effects have been the depletion of aquifers and prolonged periods of drought [4]. It is therefore necessary to develop groundwater sustainability models/indices to make informed decisions for improved groundwater management.

2. Materials and Methods

2.1. Study Area

The Modder River Basin (see Figure 1) is situated in the south western part of the Free State Province, South Africa, forming some portion of the Upper Orange Water Management Area (WMA) [10]. The Upper Orange WMA expands further into parts of the Eastern and Northern Cape areas [11]. The Modder River Basin is located from latitude 28°50″ to 29°40″ South and from longitude 24°40″ West to 27°00″ East, covering a total area of approximately 17,366 km^2. The altitude ranges from 1057 to 2106 m above sea level (m.a.s.l.) with the Riet and Modder River and its tributaries being the main drainage system [12]. The highest areas (Maluti Mountains), close to South Africa (Lesotho boundary around Dewetsdorp on the eastern end of the basin), are characterised by flat-topped hills. The lowest area lies to the southern side of Kimberley. The Modder River originates near Dewetsdorp and then flows to the North, thereafter heading west. After about 340 km, the river flows into the Riet River that joins the Oranje-Vaal River. The Modder River was generally, as most inland rivers in South Africa, a regular stream, yet because of the development of three critical dams, namely the Rustfontein, Mockes and Krugersdrift Dams, the waterway currently looks like a perennial river [13]. The dams' levels may drop to as low as 30% during the dry season. Water in the lower side stagnates in winter [14]. According to researchers [12], the savannah grassland is predominant in the eastern part of the catchment. The result is a Karoo shrubbery to the South and West of the catchment.

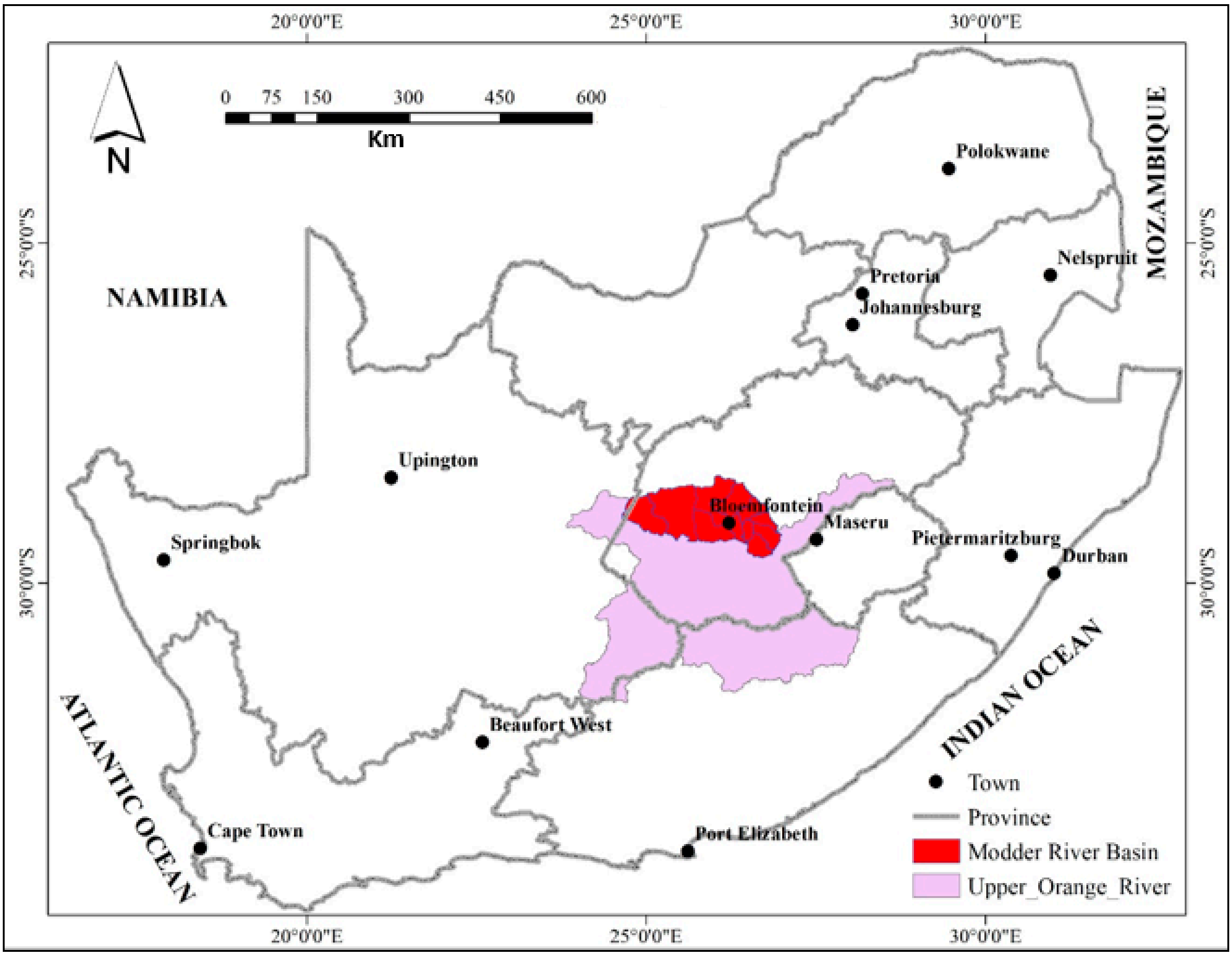


Figure 1. The location of the Modder River catchment showing boundaries within the Upper Orange River catchment and the Free State province of South Africa.

The Modder River catchment has both private boreholes and government monitoring boreholes. The study looked at the private boreholes whose owners gave consent. The private boreholes were of interest because the government is not in a position to monitor them. However, both private and government boreholes were used for the study. A monitoring system for all boreholes in the catchment is yet to be established [9]. The C52 catchment is further sub-divided into drainage regions: C52A to C52J. Figure 2 shows the boreholes available in the study area. The boreholes include both government monitoring boreholes (orange) and private boreholes (green).

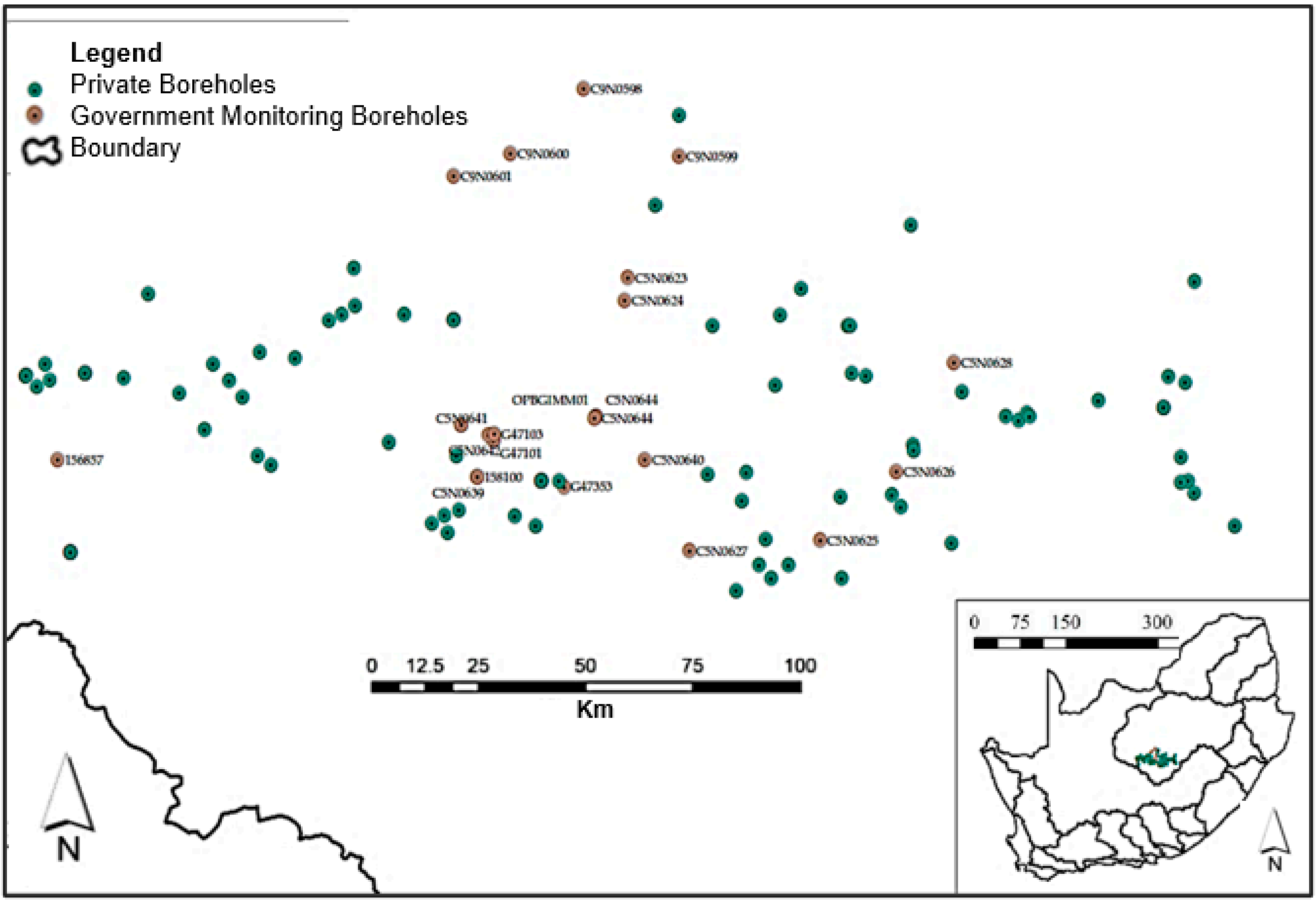


Figure 2. Map showing borehole distribution in the Modder River catchment.

2.2. *Geological Formation Present in the Modder River Catchment*

According to [15], the general geology of the Modder River catchment comprises mainly sedimentary rocks of the Karoo Super group, which were formed before the breakup of the Gondwana supercontinent. The Karoo Super group [16] covers around 66% of the present land surface of southern Africa. Its strata record a relatively endless glacio-marine to terrestrial succession. It started in the Permo-Carboniferous era (280 Ma) and ended 100 million years after the early Jurassic era. Its silt achieved an extreme combined thickness of up to 12 km in some places [17]. Overlying basaltic magmas, which denote the Lesotho area, are 1.4 km thick. These were collected in a retro-circular segmented basin [18], named "Karoo Basin." Along its southern fringe, the Karoo Basin is bordered by the Cape Fold Belt [19]. It was created amid a progression of compressional beats, beginning in the Late Carboniferous era and ending in the Late Triassic era [20]. The Late Palaeozoic advancement was started by plate assembly, subduction and growth along the palaeo-Pacific edge in the south western part of Gondwana [21]. The Cape Fold Belt comprises an E–W striking southern branch, with north-skirting folds and a N–S striking the western part of open folds, which converge into a 100 km-wide syntaxis zone. Its mountain ranges consist of siliciclastic silt, with an aggregate thickness of 8000 m, placing it within the Ordovician–Carboniferous Cape Supergroup.

As evidenced in Figure 3, the deposition of the Karoo Supergroup began after a rest at the Cape/Karoo Supergroup limit with the Dwyka Group. After glaciation, a broad sea remained facilitated by the melt water. Clays and muds of the Lower Ecca Group were aggregated. Deformation of the southern edge of the basin caused elevation and disintegration of the mountains towards the south. Quick down-warping of the basin was the result of thrust sheets in the nearby Cape Fold Belt [18]. The southwestern part of the

Karoo Basin was isolated by the Cape Fold Belt syntaxis into the Laingsburg and Tanqua sub-basins [22].

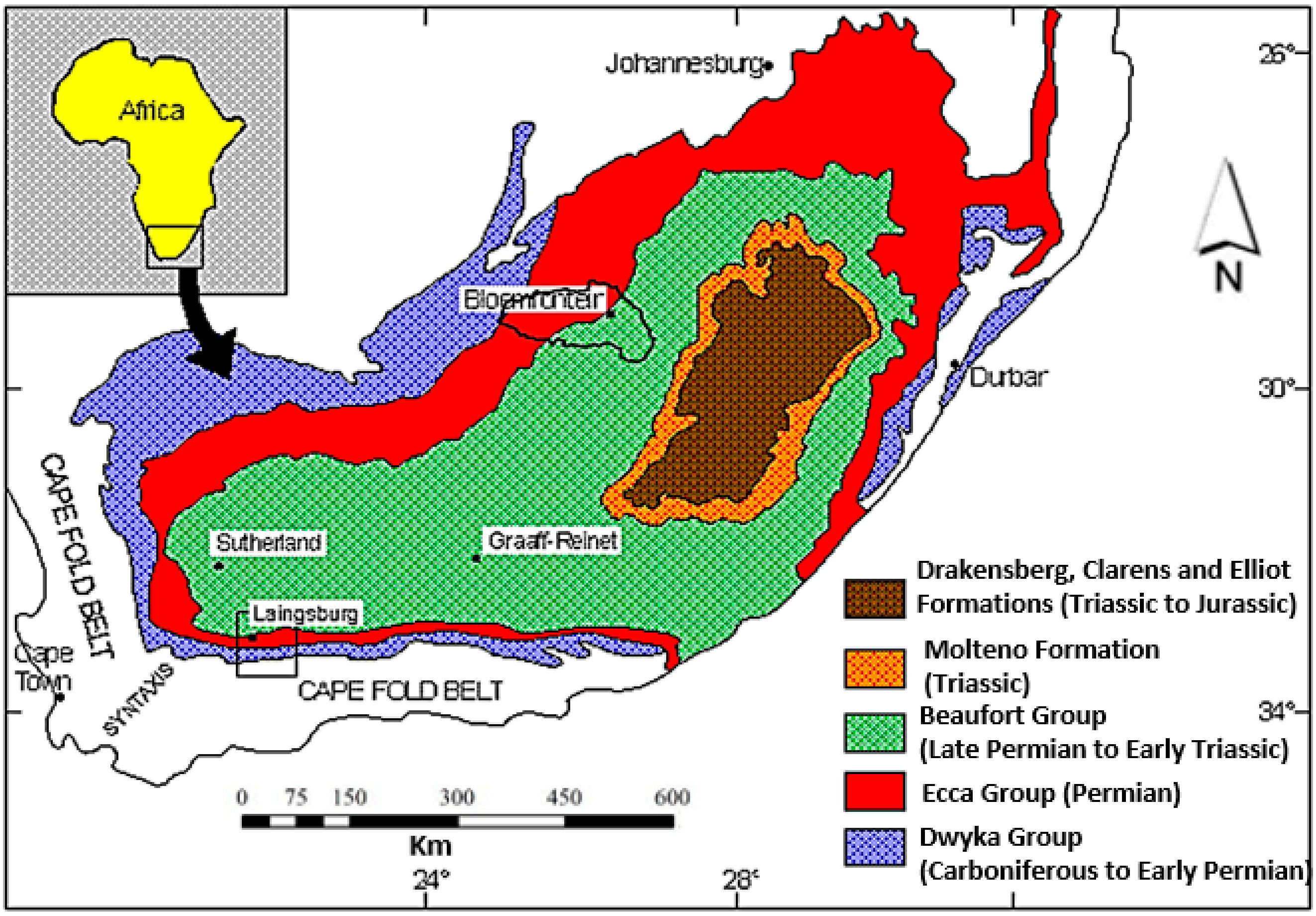


Figure 3. Regional geology of the Karoo Basin with inset of Modder River catchment location.

Deltaic progradation involved the filling of the sub-basins by a thick submarine fan and deltaic silt of the Upper Ecca Group [23]. Progressive shallowing of the fore took place within the Late Permian timeframe because of the rate of sedimentation surpassing the rate of subsidence [24]. The expansive scale backward succession protected the formation of the fluvial-lacustrine Beaufort Group. The Early Triassic lifted the Cape Fold Belt deposition in wide regions of the Karoo Basin [25]. In the focal piece of the Karoo Basin, the fluvial, alluvial, and aeolian residue of the Triassic Molteno, Elliot, and Clarens Formations were stored [26]. Regionally, the study area lies beneath the Beaufort Group on the east, the Ecca Group in the centre and the Dwyka Group on the western side [27]. The Main Karoo Basin becomes thinner from the south to the north [28].

Locally, according to GeoScience South Africa, the 1:1 million freely available geological information pieces, covering the Modder River catchment, five Karoo-aged rocks and Transvaal rocks are found in the catchment area. The Karoo-aged rocks are the Beaufort (Adelaide, Tarkastad), Dwyka, and Ecca Groups, as well as dolerite intrusive rocks [29]. The Karoo mafic intrusive rocks (dykes, sills) are scattered throughout [30]. The intrusive rocks are most pronounced on the northeastern side of Bloemfontein and areas surrounding Kimberley [31]. The Dwyka Group sediments, which are recorded to be stratified in a few places, are known to consist of diamictite (tillite) [32]. The Ecca Group (Tierberg) consists of undifferentiated shales, with interbedded siltstone [33]. Between Bloemfontein and Kimberley, Transvaal calcareous (limestone and calcarenite) rocks are exposed [34]. A small exposure of Transvaal Ventersdorp lava is found south of Kimberley [35].

2.3. Hydrogeology of the Modder River Catchment

The Modder River catchment is situated between the Ecca and Beaufort aquifer system, which will be discussed later. The underlying geology of the Modder River catchment is mainly sedimentary rocks intruded by the massive dolerite's dykes [36]. These numerous intrusive rocks reduce the pore spaces of the host rocks, thereby reducing the aquifer potential of the rocks. Therefore, the fractures are the only sources and target for abstracting large amounts of groundwater [37]. This suggests that the recharge rates and sustainable yields are relatively low in the catchment area in general even though some towns are using the small amount for rural water supply [38,39]. As a result of the rock type and minimal polluting surface activities, the quality of groundwater in the Modder River catchment is naturally satisfactory [40]. The eastern parts of the catchment have high rainfall with acceptable quality regarding taste, smell and colour [41]. The drier parts of the catchment, as well as areas with salt pan occurrence, are highly mineralised with brackish water [42].

The Ecca Group aquifers are mapped as combined fractured, as well as fractured and intergranular (Figure 4), with yields ranging between 0.5 and 2 L/s [43]. Burger [44] further concluded that the chances of obtaining an appreciable amount of water are where there are interlayered coal layers in the sediments than where there are solely sandstone and ordinary shale layers (Figure 3). It has been reported that the yield decreases as boreholes drilled closer to the dolerites dykes contact in the Ecca Group [45], which has been ascribed to small potential water-bearing fractures filled up with secondary materials, as well as baking of the contacts surrounding rocks with the dolerites intrusive rock [46]. This was observed in dry riverbeds where the various layers are exposed [47] and reported to be the best hydrogeological target for groundwater with good water quality [48,49].

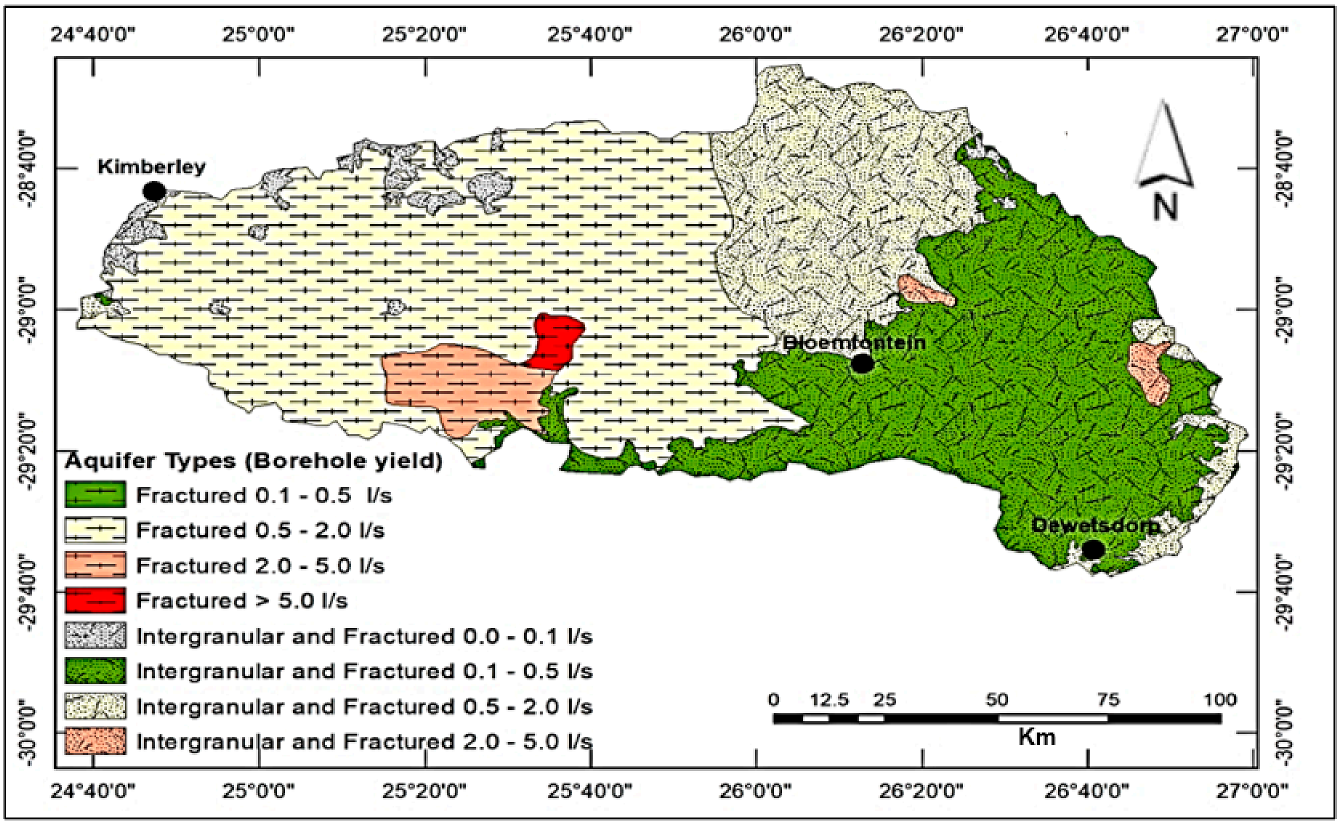


Figure 4. Aquifer types found within the C52 catchment area.

Beaufort Group aquifers are multi-layered, as well as multi-porous, with different thicknesses, owing to the complex geology of the formations of the Beaufort Group [50]. The contact plane between two different sedimentary layers will cause a discontinuity in the hydraulic properties of the composite aquifer [51]. This complex behaviour of aquifers in the Beaufort Group is further complicated by the fact that many of the coarser and thus more permeable sedimentary bodies are lens-shaped. The lifespan of a high-yielding borehole in the Beaufort Group may therefore be limited, if the aquifer is not recharged frequently [10,50].

Dolerite intrusions occur predominantly as sills and dykes throughout the Karoo sequence, with typical borehole yields of less than 2 L/s [12]. If the contact (side of the sill) is targeted, the factors to consider will be the same as when targeting a dyke (i.e., dip, recharge potential, static water level, the type of host rock and the distance to drill from the contact zone) [51]. When a source needs to be developed on a sill, three main targets should be investigated, namely, the upper weathered and fractured zone, the upper contact zone and the lower contact zone [52]. A number of factors has been stated to influence the success rate of boreholes on a sill [53].

2.4. Factors Affecting Groundwater Sustainability in Modder River Catchment

In reference to [54], three types of rainfall are mentioned: Orographic, cyclonic and conventional. The rainfall type determines the extent of the infiltration and percolation of rainwater to recharge the groundwater system [55]. Rainfall is an important groundwater sustainability factor because it is key to assessing any rainfall-runoff models [56]. The availability of precipitation data, its intensity and its duration are vital for hydrologic analysis during the design and management of water resources systems [57].

Topography defines the formation of the land surface. This includes its relief and the position of its natural and man-made features [56,58]. Topographic maps are usually used to show areas of different elevations. The elevations of mountains and valleys, steepness of slopes, and the direction of stream flow can be determined by studying topographic maps [56,59].

Topography is a key factor in groundwater sustainability because hydrologists use topographic and soil maps to understand an area [56,60,61]. In groundwater sustainability, topography dictates the direction of groundwater flow. Topography as reported by researchers [56,58] affects groundwater recharge and discharge. The impact of topography on rainfall distribution can be linked to different mechanisms, such as wind-driven effects and the small-scale topographic effects [56]. Topography is known to contribute to the base flow after the water table of groundwater in an aquifer has been satisfied.

Larger slopes generate more speed than smaller slopes. This can create faster runoff. Smaller slopes balance the rainfall input and the runoff rate that gets stored temporally over the area. With time, it can drain out gradually. This is an important consideration for groundwater sustainability. It is stated that a rise in surface slope showed a rise in surface runoff [56,62–64]. More runoff means less accumulation of groundwater in aquifers.

Land cover refers to natural vegetation cover and the human impact through several activities that are directly related to land occupation. Human activities make use of land resources and interferes in the ecological process that determines the functioning of land cover [56,65]. Land cover and therefore land use is one of the key parameters in the sustainable use of groundwater, particularly in the hydrologic cycle [56,66]. The effect of land use, land cover change and urbanisation on the hydrologic modalities and processes in catchments was studied in terms of vegetation conversion during the 1980s and 1990s [56,66]. In an investigation carried out by [67], it was found that urbanisation led to a 2.9% rise in the peak flow. In addition, a decrease of 14% on peak flows due to increased afforestation was also reported by [67]. A 5–12% increase in runoff was due to urbanisation [68]. Urbanisation causes an increase in storm flows in relation to the increased amount of surface runoff [69].

The assessment into the negative effects of farming on hydrological processes are very important for groundwater sustainability modelling. Most assessments conclude that high grazing pressure lowers infiltration rates, increases run-off from the ground surface as it lowers vegetation cover, and increases soil/ground compaction [56,70]. The changes in the land use and cover result in changes in the distribution of surface runoff within the catchment affecting groundwater infiltration rates [71]. Furthermore, the effects of land use on runoff generation by taking infiltration measurements on different land use categories were studied [72]. The results were that surface runoff was generated in varying magnitudes for different land-use types, with farmland being highest. High run-off coefficients were reported for different uses of farmland: 8.40% for cropland, 7.16% for pastureland, 2.61% for shrubland, 5.46% for woodland and 3.91% for grassland [73].

Soil is an important factor for ground water sustainability. The texture of a soil says a lot about its hydraulic conductivity and its grain-size distribution [56,74,75]. Soil texture and its structural content are two important properties for groundwater recharge and discharge and sustainability. This is because it affects water flow through the soil. In addition, it also sets out the amount of water retained in the soil, contributing to the water table of the aquifer in a catchment [56,76]. Different soil types affect runoff characteristics and generation. In an analysis of Trinidadian soils, [77] reported mean runoff values of 22.2, 22.9 and 40.9 mm for the loamy sandy, loamy clay and clay soils, respectively. Therefore, clay soil has the highest value compared to sandy soil.

The permit/licence system is a vital part of the whole groundwater sustainability system. Permits are set to guard the quality of groundwater resources and monitor the duration of groundwater extractions. The permits also ensure that the distribution rates and sizes/magnitudes work within limits which are politically acceptable, socially and environmentally viable and technically feasible. The importance of permits regarding groundwater sustainability includes economic instruments, demarcating groundwater rights and groundwater licensing. Groundwater restrictions and rights enable effective groundwater management [78]. Groundwater licensing guarantees groundwater abstraction with water management plans. Permits from an economic standpoint are important as they conserve groundwater and its quality, and control groundwater extraction. Various methods have been used to lessen abstraction. These include enabling water right trading, subsidies, and taxation. Caution is advised when taking water licensing measures. These measures must consider the intrinsic value of groundwater for all sectors of the economy [78,79].

The National Water Act of South Africa (1998) [80] gives the country and government ownership of water resources. The country links groundwater directly to land surface. As such, whoever owns the land has rights to the ground water below it. To date, arrangements and provision for trading groundwater rights do not exist. This is important to note regarding groundwater sustainability because the National Water Act (NWA) promotes efficiency, equity, and sustainability as paramount to water resources development management in South Africa. However, equity has not received the desired attention according to [79], resulting in inequitable water allocation. Equity has been deemed by the government as necessary for promoting sustainable economic growth and eradicating poverty.

2.5. Theory/Calculation

2.5.1. Sustainability Concepts and Index

Through the conceptual framework for sustainable groundwater in catchment management, there are several physical processes governing hydrological cycles in relation to groundwater sustainability in an aquifer. Some of these processes are land use-to-groundwater interactions, land use and climate interactions, and surface-to-groundwater interactions. A conceptual framework helps to represent these processes as factors. For this paper, the factors were grouped as: climatic, aquifer sustainability, right/equity of resources and socioeconomics (Figure 5). This is set within the context of the environment, economy and society, which are all at play in the catchment.

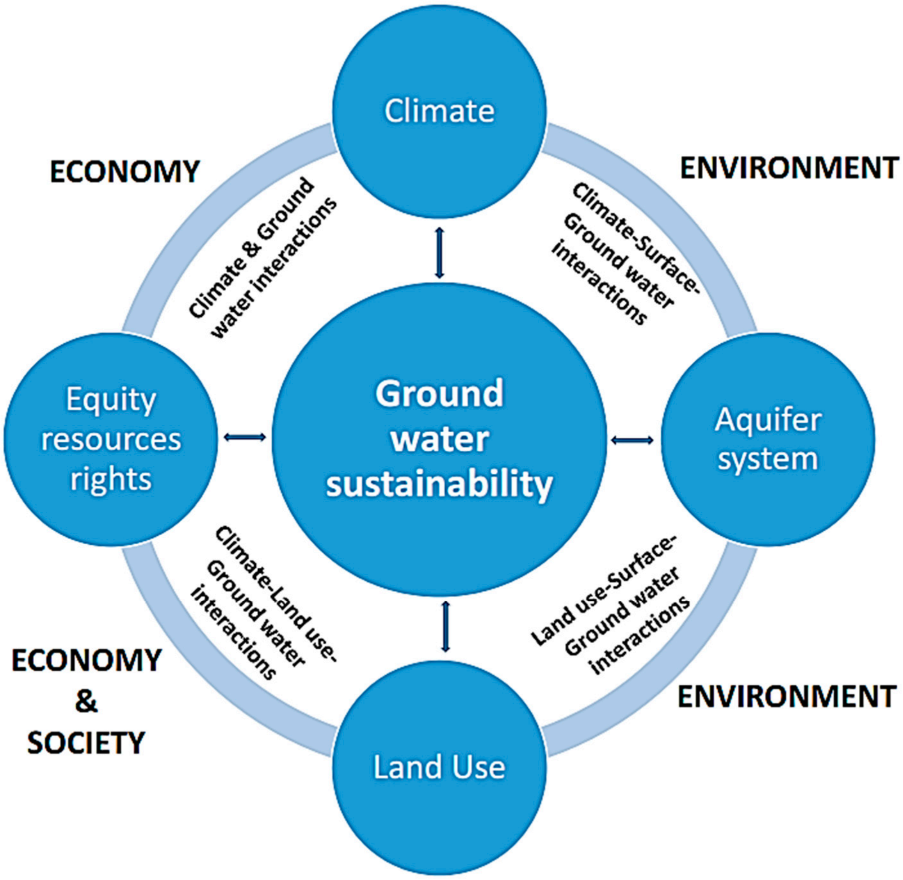


Figure 5. Supporting conceptual framework of predicting aquifer sustainability of Modder River catchment.

Sustainability in this context is a summative outcome of the link between the hydrological interactions. Water is extracted from an aquifer through well pumping, which is because of land use activity. Ownership and rights effectively shortcut the natural processes of recharge as the land is used. The amount of groundwater recharge and discharge in an aquifer is important to groundwater sustainability within this conceptual framework.

The conceptual framework was designed to trace the major relationships and interactions within the groundwater system in an aquifer that serves a catchment. This conceptual framework supports the making of inductions, deriving concepts from the data. It is also linked to the making of deductions directed at hypothesising the relationships between processes governing groundwater within the framework.

2.5.2. Rating of Hydrological Parameters

To achieve the sustainability prediction, important hydrological factors were rated. These ratings involve the assignment of values to the overall elements in factors A, B, C and D as follows:

2.5.3. Factor (A) Climate

Rainfall is assumed as critical in the catchment hydrological processes. Rainfall supports aquifer recharge, making it an important parameter in the overall sustainability prediction. A maximum score value of five is assigned to areas exceeding 3000 mm, and the lowest score of one is assigned to areas receiving less than 400 mm of rainfall. A similar approach is taken to assigning the maximum and minimum scores to evapotranspiration, sunshine, slope, vegetation and climate zones. Data used for these parameters were sourced from the South Africa Meteorological Centre office in Bloemfontein South Africa. In regions where the amount of rainfall is annually very low (< 400 mm/year), the lowest score value will be assigned. In general, when the rainfall rate is higher than the infiltration rate (intensity), the rainwater is likely to run off rather than infiltrate to recharge in aquifer, thus being stored as groundwater. This will also depend on the nature of the surface topography. The limitation of using rainfall in the sustainability design is that it does not consider a rating for rainfall intensity and the number of rainy days. This has all been captured by the annual volume an aquifer receives.

For factor A, the slope/topography is derived from the differences in contour values. Based on the slopes, scores were assigned as shown in Table 1. Lowest scores of 1 correspond to areas with the highest slopes greater than 50 m. These areas will encourage run-off and lower infiltration, while the lowest slopes of zero to 5 m correspond to areas with contours equal to those of water bodies, which encourage ponding. This means more infiltration and a high score of 5 assigned.

Slope/topography is derived from the difference between the highest topographic points to the lowest topographic point of an area. Run-off, infiltration, and recharge are influenced by the areal slope. Areas of low slope encourage ponding and retain water for a longer period, thereby increasing the possibility of percolation and infiltration and increase the potential for contaminated water migration. More runoffs occur in areas with steep slopes. This reduces the possibility of groundwater contamination. Flat slopes are prone to flooding and groundwater contamination because ponded surface water will readily infiltrate to groundwater. In summary, the equation that represents the evaluation of factor A is:

$$\mathrm{A} = \sum_{\mathrm{k}=0}^{\mathrm{n}} \mathrm{k}(\mathrm{R} + \mathrm{E} + \mathrm{S} + \mathrm{T} + \mathrm{V} + \mathrm{C}) \tag{1}$$

where:

A is the total score of all the parameters considered under Factor A;
K is the sum of the score of all the parameters considered under Factor A;
R is the rainfall;
E is the evapotranspiration;
S is the sunshine;
T is the topography;
V is the prevailing vegetation type;
C is the climatic zones assessed.

2.5.4. Factor (B) Rights and Equity versus Resources

Rights and equity to resources define the characteristics in an aquifer. The number of permits issued in the catchment per year is assumed to be important because it represents the abstraction activity in the catchment. Scores are within one and five. The maximum score value of five is assigned to areas receiving permits less than one, while the lowest score of one is assigned to areas receiving more than five permits. The same is considered in the assignment of scores for the duration of the permits, number of boreholes and pump rate. Based on global reports and databases, the values and score were assigned with the lowest scores corresponding to poor practices and the highest score of 5 to mean good practices. During analysis and the application of factors on the Modder catchment, the figures used were obtained from the Department of Water and Sanitation Affairs databases. In summary, the equation that represents the evaluation of factor B is:

$$\mathrm{B} = \sum_{\mathrm{k}=0}^{\mathrm{n}} \mathrm{k}(\mathrm{N} + \mathrm{L} + \mathrm{B} + \mathrm{P}) \tag{2}$$

where:

B is the total score of all the parameters considered under Factor B;
K is the score of all the parameters considered under Factor B;
N is the number of the permit;
L is the length or duration of permit years;

B is the number of boreholes in the sub-catchment;
P is the pumping rate.

2.5.5. Factor (C) Socioeconomics

Human activity affects an aquifer's sustainability through their use per capita. The use per capital of the catchment was assigned the maximum score of five to a use of less than 25 litres/capita/day, which is good practice for using little water. A per capita use of more than 100 is assigned a score of less than 1. This is the lowest score, and it indicates over-abstracting or using too much water. The scoring for the population in the catchment, water uses and tariffs takes the same trend as per capita use. These values/figures are from global reports and databases. However, in terms of the analysis of Modder catchment, the values assigned are derived from the Department of Water and Sanitation Affairs databases. Based on these data, scores were assigned with the lowest scores of 1, corresponding to poor practices, and the highest score of 5, denoting an acceptable practice. In summary, the equation that represents the evaluation of factor C is:

$$\mathrm{C} = \sum_{\mathrm{k}=0}^{\mathrm{n}} \mathrm{k}(\mathrm{U} + \mathrm{P} + \mathrm{W} + \mathrm{T}) \tag{3}$$

where:

C is the total score of all the parameters considered under Factor C;
k is the score of all the parameters considered under Factor C;
U is the use per capital of the catchment;
P is the population present in the catchment;
W is the water uses;
T is the tariffs.

2.5.6. Factor (D) Aquifer Sustainability

The pattern of groundwater recharges is found to be upstream supported by the discharge downstream. Most of the recharge areas correspond to mountain peaks where rainfall is higher; it is also at these points that higher recharge occurs as compared to low-laying plains. Aquifers are defined by their rock types. The extent to which rock type affects groundwater sustainability is dependent on hydraulic conductivity and permeability. Unfractured basement rock has little sustainability. The sustainability of fractured basement rock depends on the frequency variation, and the distribution and range of widths of the fractures. A score of five was assigned to intergranular rocks due to the expected longer time it will take for water to infiltrate into the groundwater. Water percolating through dense consolidated rocks is assumed to flow as surface run-off or subsurface horizontal flow, rather than as vertical infiltration flow, irrespective of the permeability of the topsoil. The dolerite dykes represent the lowest percolation in all geological rocks, and the low infiltration is due to the small pore spaces and lower permeability present in most of them. The dolerite formation is given a low score of 0.5 to a maximum score of 1. The water quality scoring will depend on the state of the water. If the water smells, tastes bad and is coloured, it is not fit for use and will frequently be wasted; therefore, a score of one was assigned; however, if the water is good in taste with no smell and colour, it is good and sustainable. A high-recharge aquifer (above 300 mm) is regarded as a sustainable aquifer and was assigned a high score, while a recharge of below 2 mm per year is unsustainable and was assigned a low score. During analysis of the Modder catchment, the values that are applied were obtained from databases from the Department of Water and Sanitation Affairs. In summary, the equation that represents the evaluation of factor D is:

$$\mathrm{D} = \sum_{\mathrm{k}=0}^{\mathrm{n}} \mathrm{k}(\mathrm{A} + \mathrm{R} + \mathrm{W} + \mathrm{Y} + \mathrm{R} + \mathrm{S}) \ldots \tag{4}$$

where:

D is the total score of all the parameters considered under factor D;
k is the score of the parameter.
A is the aquifer system in place;
R is the rock type present;
W is the water quality;
Y is the aquifer yield;
R is the recharge condition;
S is the storage volume of the aquifer.

2.5.7. Sustainability Index

The index comprises climatic conditions, aquifer sustainability/system, rights/resources and socioeconomics (Figure 6). The overall objective of the index is to assess the sustainability of groundwater management in an aquifer in a catchment through analysis of a hydrological model, using predetermined parameters. It is therefore a major decision support system in the development of sustainability analysis methods. It considers the availability of input data for the hydrogeological system under consideration. The developed sustainability method targets the assessment of resources locally, regionally and globally.

The methodology requires an in depth understanding of the parameters and ranking of the physical processes affecting the groundwater system of the Modder catchment. These include the climatic factors (precipitation, evapotranspiration, sunshine, slope, topography and climatic zones) and aquifer system (recharge, yields, storativity, aquifer types and lithology/rock types). The methodology looks at how these factors work together and relate to give a picture of the status of sustainability in a catchment.

The formula includes human-induced parameters such as rights and equity. These human factors include the number of issued permits per year in the catchment, duration of the permits, number of boreholes in the sub-catchment, pump rate per year, socioeconomic and land use, use per capita, population in the catchment, water uses and tariffs.

$$\text{Sustainability S} = \sum A + B + C + D \tag{5}$$

where:

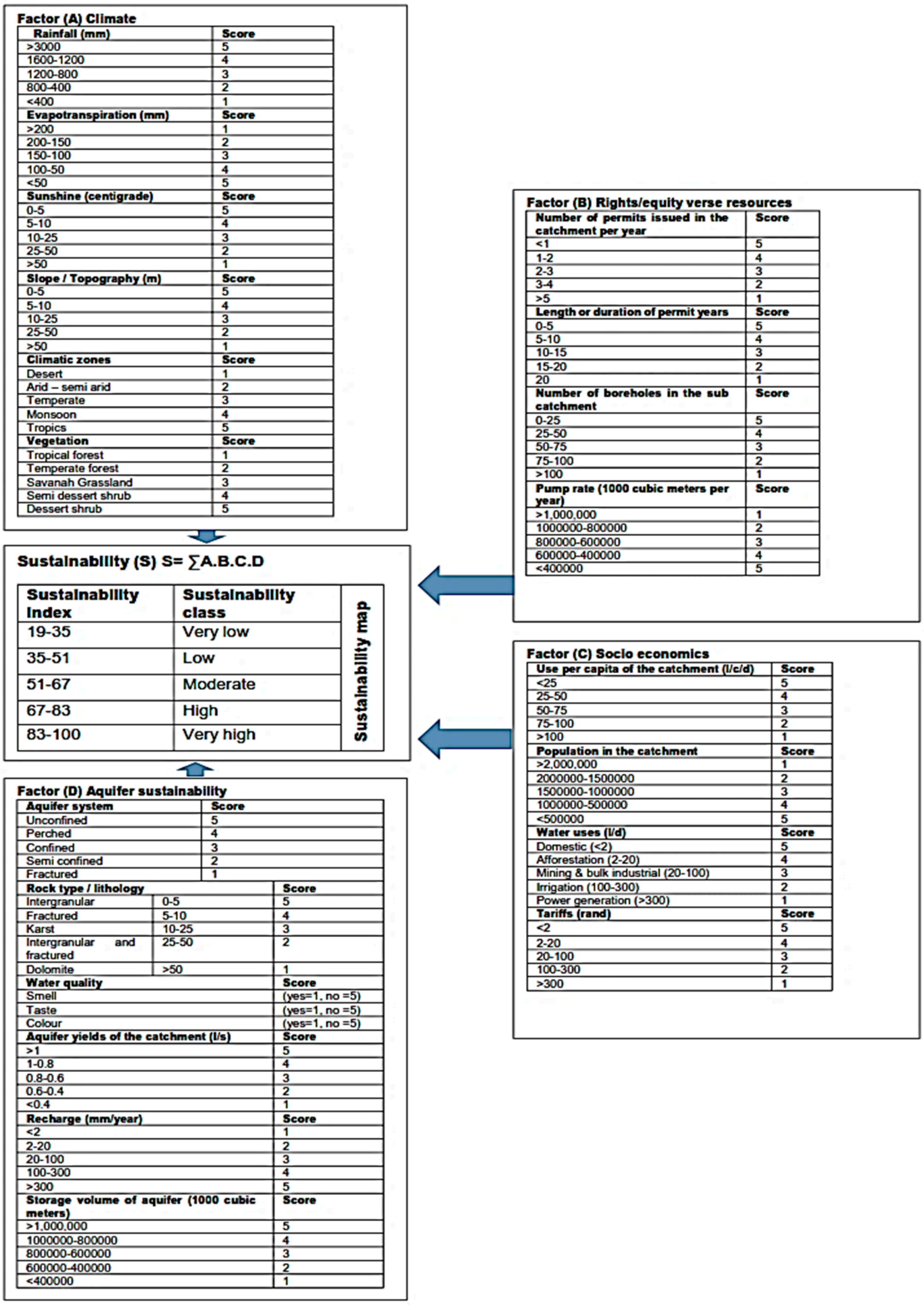
- A = Total score of the climatic condition factor (Factor A)
- B = Total score of the rights/equity factor (Factor B)
- C = Total score of the socioeconomic factor (Factor C)
- D = Total score of the aquifer sustainability factor (Factor D)

A and D have a scoring of 30 each, while B and C have a scoring of 20 each.

The final sustainability factors were added up because they all impact groundwater and therefore aquifer sustainability.

A and D factors (aquifer sustainability and climatic conditions) are complex in the natural context and, therefore, responsible for percolation and infiltration. As with the previously discussed principles of sustainability analysis, all factors have equal weighting. A carries an equal score to D because the sustainability methods assume rainfall evapotranspiration, sunshine and slope: As the principal climatic condition and initiator of the infiltration and subsequent percolation process which contributes to recharge and later becomes groundwater. The implication is that if rainfall is absent, there is no groundwater formation. The impact of B and C on groundwater sustainability may be higher on analysis as human activity will deplete whatever groundwater is available and not replenish it. For this reason, the scores of the two are the same.

The sustainability index was grouped into five classes. The classes and sustainability values are presented in Figure 6. A final groundwater sustainability index class score of 19–35 means a class of very low sustainability, 35–51 means a class of low sustainability, 51–67 means a class of moderate sustainability, 67–83 means a class of high sustainability and 83–100 means very high sustainability (Figure 7). The sustainability index acronym is derived from the initial letters of the factors used in ABC and D. The sustainability index method is designed to calculate the sustainability impact on groundwater.



Factor (A) Climate

Rainfall (mm)	Score
>3000	5
1600-1200	4
1200-800	3
800-400	2
<400	1
Evapotranspiration (mm)	**Score**
>200	1
200-150	2
150-100	3
100-50	4
<50	5
Sunshine (centigrade)	**Score**
0-5	5
5-10	4
10-25	3
25-50	2
>50	1
Slope / Topography (m)	**Score**
0-5	5
5-10	4
10-25	3
25-50	2
>50	1
Climatic zones	**Score**
Desert	1
Arid – semi arid	2
Temperate	3
Monsoon	4
Tropics	5
Vegetation	**Score**
Tropical forest	1
Temperate forest	2
Savanah Grassland	3
Semi dessert shrub	4
Dessert shrub	5

Factor (B) Rights/equity verse resources

Number of permits issued in the catchment per year	Score
<1	5
1-2	4
2-3	3
3-4	2
>5	1
Length or duration of permit years	**Score**
0-5	5
5-10	4
10-15	3
15-20	2
20	1
Number of boreholes in the sub catchment	**Score**
0-25	5
25-50	4
50-75	3
75-100	2
>100	1
Pump rate (1000 cubic meters per year)	**Score**
>1,000,000	1
1000000-800000	2
800000-600000	3
600000-400000	4
<400000	5

Sustainability (S) S= ∑A.B.C.D

Sustainability index	Sustainability class	Sustainability map
19-35	Very low	
35-51	Low	
51-67	Moderate	
67-83	High	
83-100	Very high	

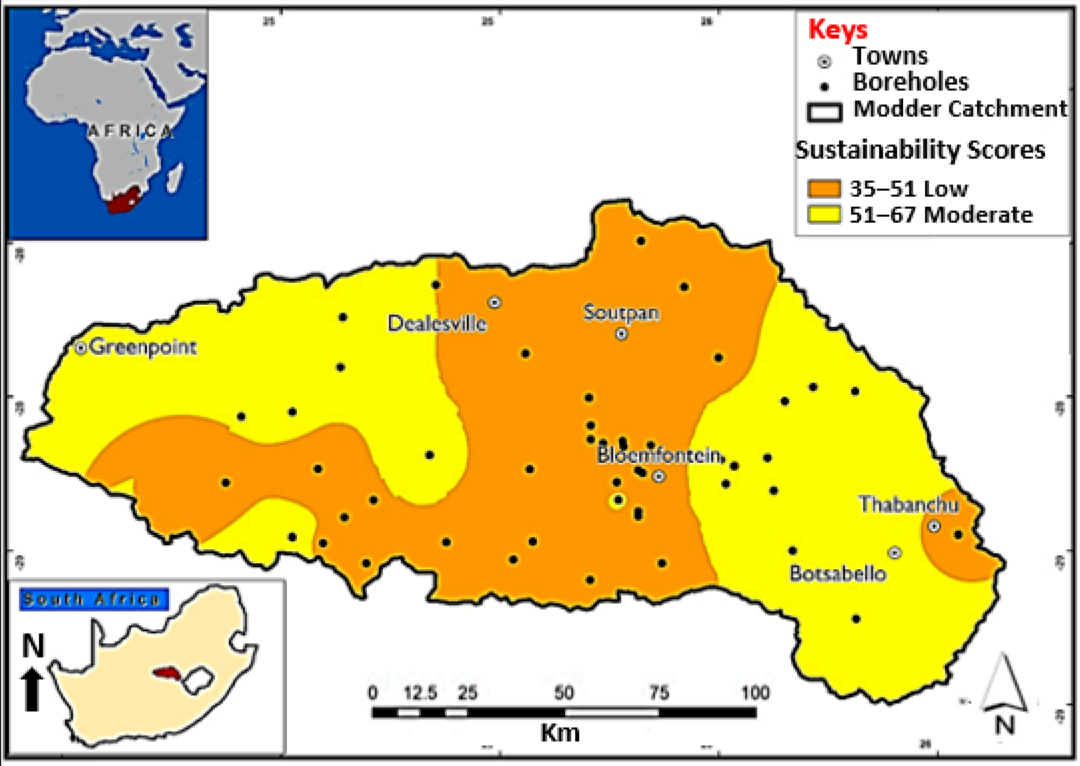
Factor (C) Socio economics

Use per capita of the catchment (l/c/d)	Score
<25	5
25-50	4
50-75	3
75-100	2
>100	1
Population in the catchment	**Score**
>2,000,000	1
2000000-1500000	2
1500000-1000000	3
1000000-500000	4
<500000	5
Water uses (l/d)	**Score**
Domestic (<2)	5
Afforestation (2-20)	4
Mining & bulk industrial (20-100)	3
Irrigation (100-300)	2
Power generation (>300)	1
Tariffs (rand)	**Score**
<2	5
2-20	4
20-100	3
100-300	2
>300	1

Factor (D) Aquifer sustainability

Aquifer system		Score
Unconfined		5
Perched		4
Confined		3
Semi confined		2
Fractured		1
Rock type / lithology		**Score**
Intergranular	0-5	5
Fractured	5-10	4
Karst	10-25	3
Intergranular and fractured	25-50	2
Dolomite	>50	1
Water quality		**Score**
Smell		(yes=1, no =5)
Taste		(yes=1, no =5)
Colour		(yes=1, no =5)
Aquifer yields of the catchment (l/s)		**Score**
>1		5
1-0.8		4
0.8-0.6		3
0.6-0.4		2
<0.4		1
Recharge (mm/year)		**Score**
<2		1
2-20		2
20-100		3
100-300		4
>300		5
Storage volume of aquifer (1000 cubic meters)		**Score**
>1,000,000		5
1000000-800000		4
800000-600000		3
600000-400000		2
<400000		1

Figure 6. Idealised illustration of the sustainability index/model.



Score	Class of sustainability	Colour code
19–35	Very low	Red
35–51	Low	Orange
51–67	Moderate	Yellow
67–83	High	Green
83–100	Very high	Blue

Figure 7. Groundwater sustainability map of the Modder River catchment.

There are challenges when using the most established data to assess areas. As such, the developed sustainability method has been designed to use a few climate-based hydrogeological parameters and fuzzy logic parameters such as rights and social-economic data to the assess groundwater sustainability of a delineated catchment like the Modder River. The delineation exercise caters for inflows and outflows from the catchments and caters for other processes that affect the characteristics of a sub-catchment. This allows for the identification of a unit of analysis such as the Modder River that is representative of the rest of the larger catchment such as the Upper Orange.

2.5.8. Groundwater Recharge Calculation of Modder Catchment

The Department of Water and Sanitation conducted a study to generate a groundwater recharge map for South Africa, with a 1 km by 1 km grid cell size [81,82]. The method used to produce the recharge map is GIS-based, while Quaternary catchments were used as the unit of measure [83]. The recharge method essentially comprises four main components [84]:

- Chloride mass balance (CMB) approach
- Empirical rainfall/recharge relationships
- Layer model (GIS based) approach
- Cross-calibration of the results with field measurements and detailed catchment studies.

The results obtained from the recharge study by the Department of Water and Sanitation (DWS) agreed with the results obtained from earlier recharge studies [81]. Though the approach did not differentiate between the preferred path and matrix diffusion recharge, it is GIS-based, making it sufficiently flexible to include updates and new datasets. Part of Figure 8C shows the recharge map of the study area, as extracted from the countrywide recharge map of South Africa. In the study area, high recharge areas (over 19 mm) are found in the eastern and south-eastern parts of the study area. The central and western parts of the study area are marked by lower recharge values (below 19 mm).

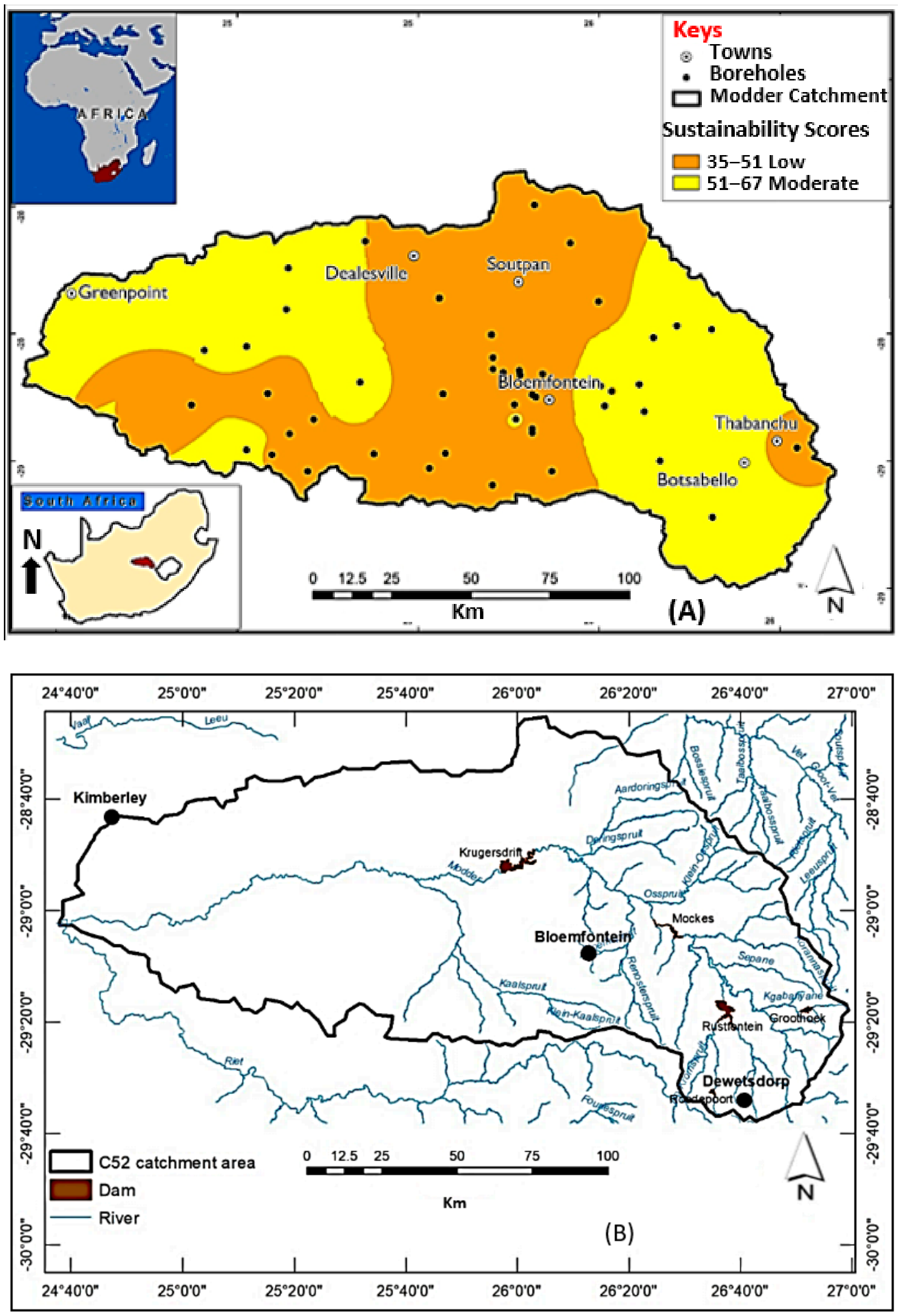


Figure 8. *Cont.*

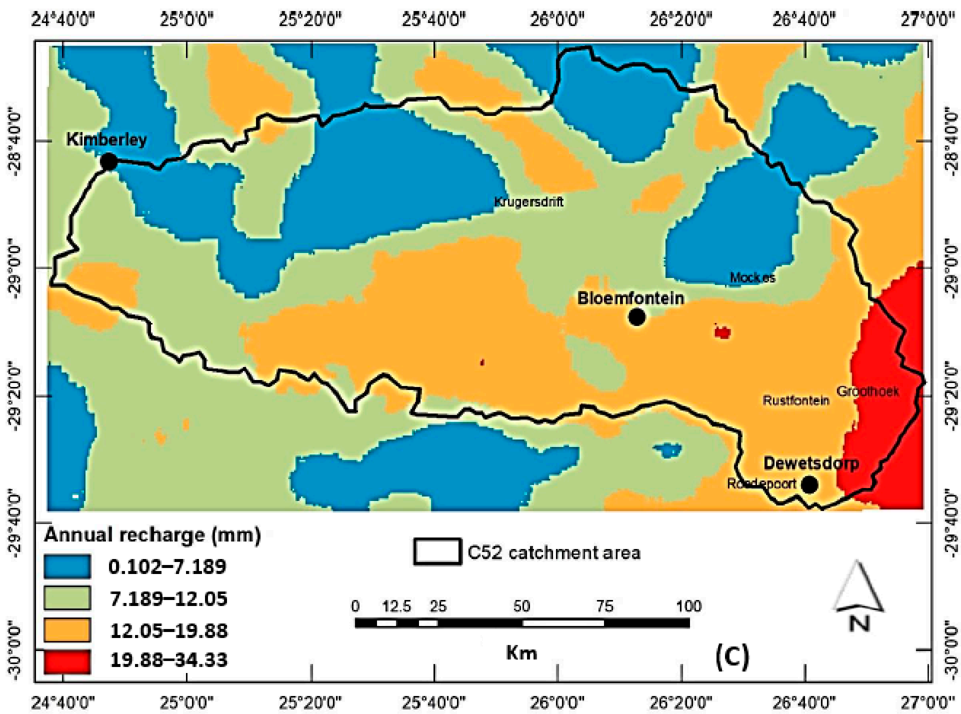


Figure 8. Final sustainability map (**A**), the river network map (**B**) and recharge map (**C**) of the Modder River catchment.

The chloride mass balance method was applied to the Modder River catchment. According to [81], it takes more than two years to measure the variability of recharge. This method uses chloride routing, as shown in Figure 5. This routing is the basis of the estimate of the net recharge of the catchment. For the Modder River, this is a collection from the slopes and channels without the losses through base flow discharged from the catchment. When applying the chloride model, Equation (6) is used. This equation calculates the net groundwater recharge volume denoted as R. It assumes a given number of years of rainfall in the catchment for which discharge takes place.

$$R = \frac{(P)(Cl_p) - (Q)(Cl_q)}{Cl_r} \tag{6}$$

In this equation:

- P is rainfall;
- Cl_p is the catchment's chloride concentration of rainfall;
- Cl_r is the measured groundwater chloride concentration of the catchment;
- Q is the total discharge from the catchment;
- Cl_q is the average chloride concentration in the stream discharge, i.e., the Modder River.

The application of this equation requires that the catchment's chloride concentrations for groundwater account for the evapotranspiration effects.

3. Results

3.1. Sustainability Map

Figure 7 represents the results from the application of the designed framework on the C52 catchment. The high-and very high-sustainability classes correspond to areas with favourable climatic conditions and favourable groundwater interaction and processes (fast recharge). It is also expected to have less abstraction and socioeconomic activity. The moderate to low classes suggest areas with the opposite of the previous scenario: Too much abstraction activity, unfavourable climatic conditions and slow or little groundwater recharge processes and interactions (high or steep slopes and low rainfall). Areas around Bainsvile west of Bloemfontein, South Africa (Figure 7) were declared as stressed; likewise, many boreholes in ThabaNchu, South Africa were declared stressed in 2015 during the last drought period.

3.2. Comparison of Recharge and Sustainability Map

The sustainability map was compared with the drainage map and groundwater recharge map for validation purposes. Figure 8 shows the final sustainability map (Figure 8A), the river network map (Figure 8B) and the chloride mass balance recharge map (Figure 8C) of the study area, as extracted from the countrywide recharge map of South Africa. The results obtained from the recharge study by the DWS correlated with the results obtained from the final sustainability map. In the study area, high recharge areas (over 20 mm) are found in the eastern and southeastern parts of the Modder River, which has high surface water and river tributaries. This suggests that the groundwater of the southeastern part of the Modder River is possibly recharged through base flow interactions. This assertion requires further investigations.

The central and western parts of the study area are marked by lower recharge values (below 7 mm). This is consistent with the final sustainability index maps and no river presence. There is a high correlation between the sustainability index (Figure 8A), the drainage basin (Figure 8B) and the recharge map (Figure 8C). The orange shaded areas in the sustainability map (Figure 8A) indicate low recharge. In relation to the river network maps (Figure 8B), surface water concentration suggests that the boreholes in the yellow zones are abstracting shallow river water that has percolated in the soil, especially along the streams and river levees, and the source of the deeply percolated water in boreholes. Therefore, there could be an interchange of groundwater–surface water exchanges. The groundwater recharge map (Figure 8C) shows red zones, which have slightly higher groundwater recharge. This is consistent with the yellow zones in the sustainability map (Figure 8A) that are consistent with moderate sustainability. The implications are that the Modder catchment has low ground water sustainability in the densely populated area of Bloemfontein. New developments relying on groundwater will not be viable in the low-sustainability zones.

4. Discussion

4.1. How Sustainable Will Groundwater Be in the Catchment?

It is important to explore the aquifer system sustainability in the catchment separately because of the possibility of some aquifers sustaining themselves, irrespective of the socioeconomic activities that the aquifer supports. Aquifers are recharged through several processes, including rainfall, infiltration and percolation and through recharge mechanisms and other hydrological processes (base flow, artificial recharge) that affect groundwater sustainability. The higher the population number in a catchment, the higher the socioeconomic activities (agriculture, mining, industrial and domestic); the higher their demands for groundwater, the more permits issued, which put the aquifers in vulnerable and less sustainable conditions.

The sustainability index scores of the study area (Table 1) consist of aspects such as the issuing of groundwater abstraction permits in the Modder River catchment, which therefore, serves as a measure of knowing the abstraction activity in the aquifer. This permit is issued by the regulatory agencies at Water Affairs in the Free State. The sustainability index scores in one of its parameters consider the rights and equity of the water users relating to the groundwater resources of the catchment. These comprise the number of borehole permits issued per year, duration or length of the borehole permit issued, number of actual boreholes drilled and pump rate per year currently in the Upper Orange River. These indicators are monitored and available at the Department of Water and Sanitation (DWS). The sustainability index, therefore, represents the groundwater abstraction rate in the aquifer. In addition to the DWS regulating the right of the water users to exploit the groundwater resources, it further issues permits and keeps records of the groundwater yields. Table 1 shows that most of the boreholes have low sustainability index scores and a corresponding low storativity. A few boreholes with higher storativity record high moderate sustainability index scores (boreholes 26, 27, 31, 32, 33, 37, 42, 44, 50). It should be noted that a borehole might have a higher storativity value but low sustainability scores because of over-abstraction taking place in the borehole.

Table 1. Calculated sustainability scores and classes linked to boreholes and storativity.

Drainage Region	Storativity (in 1000 cm^3/year)	Borehole	Sustainability Index	Sustainability Class
C52G	74,320.5	1	44.5	Low
C52G	74,320.5	2	43.5	Low
C52G	74,320.5	3	44.5	Low
C52H	160.51	4	44.5	Low
C52H	160.51	5	42.5	Low
C52H	160.51	6	42.5	Low
C52J	22,668.67	7	43.5	Low
C52H	160.51	8	44.5	Low
C52H	160.51	9	44.5	Low
C52H	160.51	10	46.5	Low
C52H	160.51	11	47.5	Low
C52H	160.51	12	44.5	Low
C52J	22,668.67	13	43.5	Low
C52J	22,668.67	14	42.5	Low
C52H	160.51	15	42.5	Low
C52H	160.51	16	42.5	Low
C52H	160.51	17	44.5	Low
C52H	160.51	18	44.5	Low
C52J	22,668.67	19	41.5	Low
C52J	22,668.67	20	44.5	Low
C52J	22,668.67	21	42.5	Low
C52J	22,668.67	22	42.5	Low
C52H	160.51	23	43.5	Low
C52B	62.58	24	45.5	Low
C52A	73,4547.6	25	49.5	Low
C52A	73,4547.6	26	52.5	Moderate
C52A	73,4547.6	27	51.5	Moderate
C52E	52,7202.8	28	46.5	Low
C52E	52,7202.8	29	48.5	Low
C52E	52,7202.8	30	48.5	Low
C52E	52,7202.8	31	52.5	Moderate
C52E	52,7202.8	32	52.5	Moderate
C52F	36,8407.7	33	52.5	Moderate
C52F	36,8407.7	34	46.5	Low
C52F	36,8407.7	35	46.5	Low
C52F	36,8407.7	36	51.5	Moderate
C52F	36,8407.7	37	51.5	Moderate
C52F	36,8407.7	38	47.5	Low
C52F	36,8407.7	39	47.5	Low
C52F	36,8407.7	40	46.5	Low
C52F	36,8407.7	41	47.5	Low
C52F	36,8407.7	42	51.5	Moderate
C52F	36,8407.7	43	46.5	Low
C52F	36,8407.7	44	51.5	Moderate
C52F	36,8407.7	45	46.5	Low
C52F	36,8407.7	46	48.5	Low
C52F	36,8407.7	47	46.5	Low
C52F	36,8407.7	48	47.5	Low
C52F	36,8407.7	49	47.5	Low
C52F	36,8407.7	50	51.5	Moderate
C52F	36,8407.7	51	49.5	Low

In addition, the sustainability index, as explained earlier, also reflects tariffs and the commercial use of water in the Modder River catchment, which therefore, represents the abstraction activity in the aquifer that supports economic growth. The sustainability index scores sum up the socioeconomic activities of the catchment, as related to their impact on the groundwater resources. The indicators considered in the sustainability index consist of the per capita use of the catchment, where boreholes are located, the population of the Modder River catchment, tariffs paid based on the use, the economic activities of the users, and the purpose of the groundwater use (mining, agriculture, and domestic and energy development). The sustainability index represents the potential use of the water, the economic growth that relies on the groundwater abstracted and the activities that impact the groundwater abstraction. Generally, these indicators represent the main activities that influence the groundwater sustainability of the Modder River catchment. These indicators are monitored and available at the DWS, as stated in methodology section. This makes the plot of sustainability index scores versus pump rate of great significance.

A further step in this plot involves a comparison of the calculated indices with the measured physical values such as storativity. An analysis of the actual end users' validation was carried out to assess the ability of the sustainability index, to calculate values that are a close reflection of the physical system (sustainability index scores vs. storativity). Figure 9 shows a plot of the final sustainability index value against a measurable parameter (storativity). There is a high correlation between the storativity and the sustainability index.

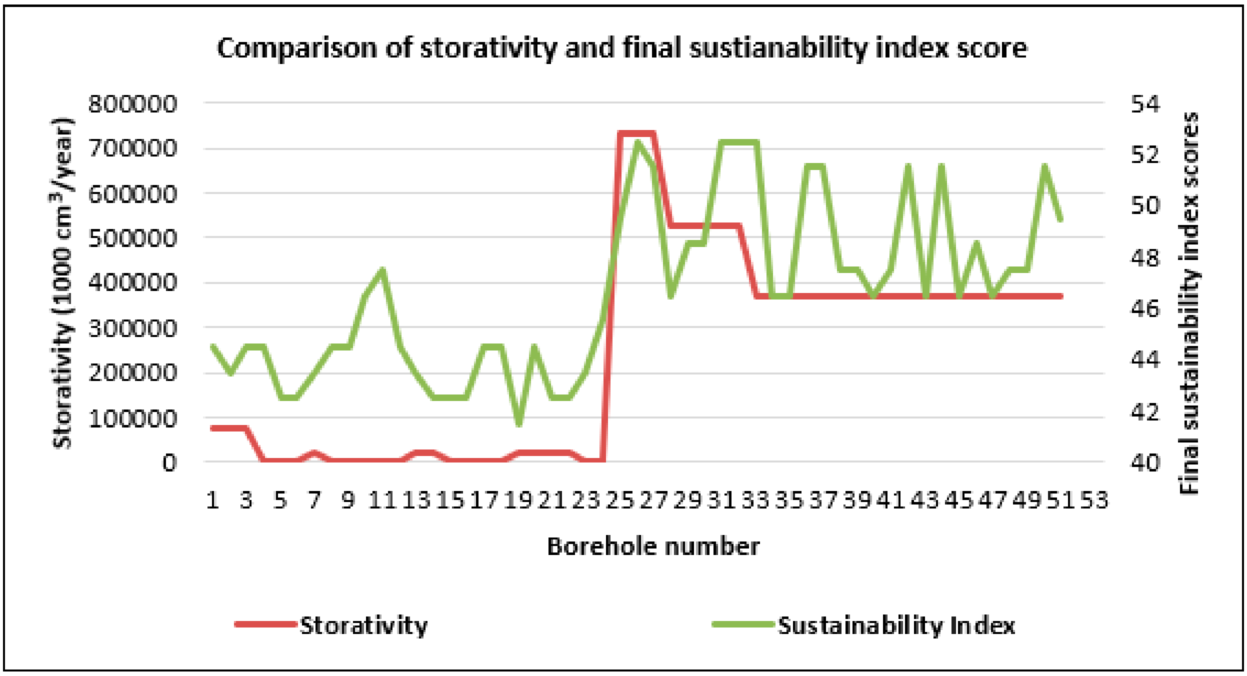


Figure 9. Plot of final sustainability scores against the storativity value of the catchment.

4.2. Groundwater Use versus Availability

A further validation tool is a critical look at the groundwater sustainability of the catchment as viewed through the socioeconomic activities of the catchment. This includes aspects such as the tariffs and commercial use of water in the Modder River catchment, which therefore, represents the abstraction activity in the aquifer that supports economic growth. This is of significance and considered part of validating the sustainability prediction. Figure 10 details the socioeconomic activities of the catchment as related to their impact on the groundwater resources. As explained earlier, these socioeconomics includes the per capita use of the catchment where boreholes are located, the population of the C52 catchment that relies on groundwater, the tariffs paid based on the use, the economic activities of the users and the purpose of the groundwater/land use (mining, agriculture, domestic use and energy development). Furthermore, this plot represents the potential use of the water, the economic growth that relies on the groundwater abstracted, and the activities that impact the groundwater abstraction. Generally, these are the main activities that influence the groundwater sustainability of the catchment.

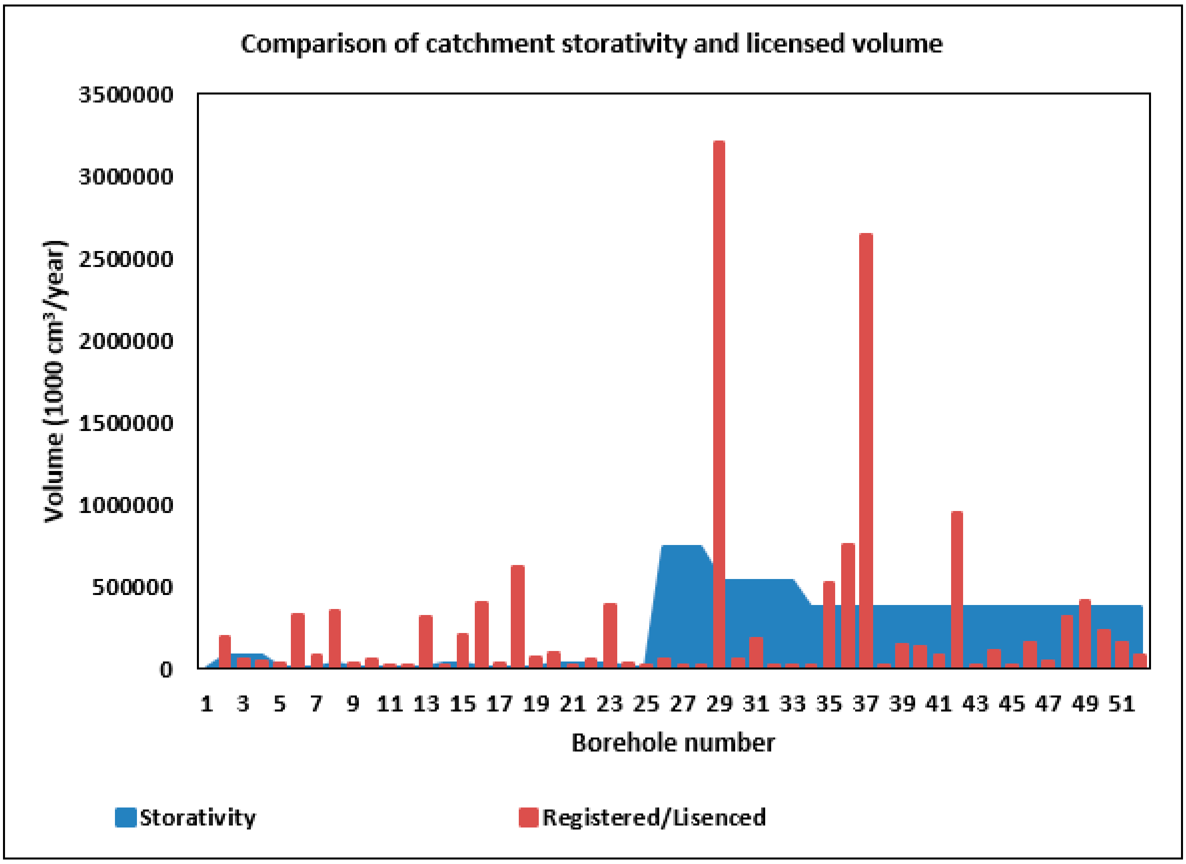


Figure 10. Relationship between storativity and licensed volume.

The graph of storativity versus licensed volume (Figure 10) shows that higher volumes are licensed as compared to the storage volume of the aquifer. The findings on the final sustainability map further correlate with this. There is no correlation between the pump rate/licensed volume and the storativity of Modder River catchment.

5. Conclusions

The sustainability method discussed in this paper was used to assess the sustainability of groundwater in the Modder River catchment. The sustainability class in the Modder River ranges from low sustainability to moderate sustainability. The moderate-to-low sustainability class is typical of areas with extensive dolerite, low slopes and low recharge.

The created sustainability index was applied to 52 boreholes in the Modder River catchment of South Africa. ArcView GIS (version 8, Esri, Redlands, CA, USA) was used in demonstrating the results for each of the 52 boreholes towards the groundwater sustainability concept. The results show that 9 boreholes are sustainable, implying that they are reasonably maintainable, while 43 boreholes have low sustainability scores, which indicates that they are not viable.

The sustainability method employed in this paper is designed from general techniques of indexing and rating, and the sustainability concept is simplified based on groundwater interactions with land and climate. The sustainability index method makes use of both the subjective and physically based techniques. The sustainability method and its evaluation are easy to collate, calculate and apply. Its successful application to the Modder River catchment shows that it can be further extended to groundwater in the Upper Orange River Basin and other similar catchments, particularly those in South Africa and also globally.

Author Contributions: S.A.O. and R.A. designed the conceptual framework and modelling framework. R.A. designed the sustainability index with contribution from S.A.O., R.A. and S.A.O. prepared the manuscript. Both authors have read and agreed to the published version of the manuscript.

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