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# GIS based Vulnerability Model Assessment of The Alexandra Jukskei Catchment in South Africa

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***Abstract -*** This article sets out to detail an investigation of groundwater management in the Juksei Catchment of South Africa through spatial mapping of key hydrological relationships, interactions, and parameters in catchments. The Department of Water Affairs (DWA) noted gaps in the implementation of the South African National Water Act 1998: article 16, including the lack of appropriate models for dealing with water quantity parameters. For this reason, this research conducted a drastic GIS-based groundwater assessment to improve groundwater monitoring system in the Juksei River basin catchment of South Africa. The methodology employed was a mixed-methods approach/design that involved the use of DRASTIC analysis, questionnaire, literature review and observations to gather information on how to help people who use the Juskei River. GIS (geographical information system) mapping was carried out using a three-parameter DRASTIC (Depth to water, Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone, Hydraulic conductivity) vulnerability methodology. In addition, the developed vulnerability map was subjected to sensitivity analysis as a validation method. This approach included single-parameter sensitivity, sensitivity to map deletion, and correlation analysis of DRASTIC parameters. The findings were that approximately 5.7% (45km2) of the area in the northern part of the Juksei watershed is highly vulnerable. Approximately 53.6% (428.8 km^2) of the basin is also at high risk of groundwater contamination. This area is mainly located in the central, north-eastern, and western areas of the sub-basin. The medium and low vulnerability classes cover approximately 18.1% (144.8 km2) and 21.7% (168 km2) of the Jukskei River, respectively. The shallow groundwater of the Jukskei River belongs to a very vulnerable area. Sensitivity analysis indicated that water depth, water recharge, aquifer environment, soil, and topography were the main factors contributing to the vulnerability assessment. The conclusion is that the final vulnerability map indicates that the Juksei catchment is highly susceptible to pollution, and therefore, protective measures are needed for sustainable management of groundwater resources in the study area.

***Keywords:*** Contamination, DRASTIC, Groundwater, Model, Vulnerability

## 1. Introduction

The Department of Water and Sanitation Affairs (DWS) defines water as “inorganic, transparent, tasteless, and nearly colourless chemical substance, which is the main constituent of Earth's hydrosphere and the fluids of all known living organisms” [1]. It is vital for all known forms of life, even though it provides no calories or organic nutrients. Water has a density of 997kg/m3, a boiling point of 1000C and a melting point of 00C [2]. Water can be divided into three parts; ground water, climate water, and surface water [3]. Of all the Earth's water, only 3% is freshwater; the rest is saline (ocean) water [4]. Of all the freshwater on Earth, 68.7% is permanently stored in icecaps and glaciers, 30.1% is groundwater, 0.3% is surface water, and 0.9% is other minor storage [5]. Thus, groundwater is about one hundred times more plentiful than surface water [6]. However, while surface water is typically low in salt ions, groundwater, particularly that lying at great depths, may contain high concentrations of salt ions, effectively limiting its economic use [7]. Saline groundwater has concentrations of more than 1,000 parts per million (ppm) [8]. In the United States of America, the depth of saline groundwater varies from less than 500 ft (150 meters) to more than 1,000 ft (300 meters) [9]. The study aims to set out an investigation on groundwater management through spatial mapping of key hydrological relationships, interactions, and parameters in the Jukskei catchment in Alexandra. The study also aims to estimate groundwater vulnerability to contamination using the standard DRASTIC method to determine other modelling methods that have been used around South Africa to manage groundwater. Therefore, based on this background, the research objectives were to:

- To Estimate groundwater vulnerability to contamination using the standard DRASTIC method.
- To Establish the new DRASTIC index by integrating the standard DRASTIC

## 2. Literature review

The Department of Water and Sanitation Affairs in South Africa defines groundwater as the Earth’s water that percolates into the ground because of the Earth’s water cycle [10]. Groundwater is water that is stored beneath the earth’s surface, in soil and porous aquifers that accounts for about 30.1% of the total water withdrawals worldwide [11]. Precipitation is known as the source of all the groundwater, new and old [12]. The precipitation that does not form part of the surface runoff or remains on the land surface percolates into the ground [13]. Once there, it follows three distinct paths which are; remain in the unsaturated zone subject to capillary action or return to the atmosphere via evaporation and evapotranspiration or flow downwards until it reaches the water table at which time it joins the groundwater [14]. Then it is said that groundwater usually occurs when the water in the unsaturated part of the earth's surface moves downwards, until it reaches the water table [15].

In terms of hydrological modelling, process-based models can obtain accurate results because they require a large input of data [15]. Behind this paper and its key methodology, the models of overlaying and index used are DRASTIC, COP, EPIC, and GOD [16]. Drastic model is one of the most widely used methods [17]. The term "Drastic" stands for seven parameters used in the model, which are; Depth to water, Net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, and Hydraulic Conductivity [18]. Drastic model is considered the best model because it allows for simplicity and flexibility in criteria structure to realise the estimation [19].

## 3. Methodology: Research Approach and Design

The mixed-methods approach was used in this research as it offers diversified tools of collecting data. This included both qualitative and quantitative research methods to provide drastic calculations. In the qualitative portion, the method of data collection involved informal interviews and the collection of secondary data [20]. Quantitative research method, on the other hand, is a method that includes the use of numerical calculations [21]. Observations were made to help the researchers describe the existing situation by using common knowledge and the previously recorded results [22]. This method can also hold ethical requirements since it involves fieldwork data collection, which requires active looking, improving memory, and encouraging endurance [23]. It has been said that observation is a participatory process which is described as process that allows researchers to learn about people's day-to-day activities, for example, water usage practices by residents of Alexandra [24].

### 3.1 Research Study Area

The Gauteng Province, particularly Alexandra township (see Fig. 1) was the most suitable area where an investigation can be placed, making data collection easier because respondents were accessible. The target population was the people who use the Jukskei River, Johannesburg Metropolitan Municipality officials who deal with water sanitation and serve the surrounding communities such as Alexandra, Bramley View, and Lombardi.

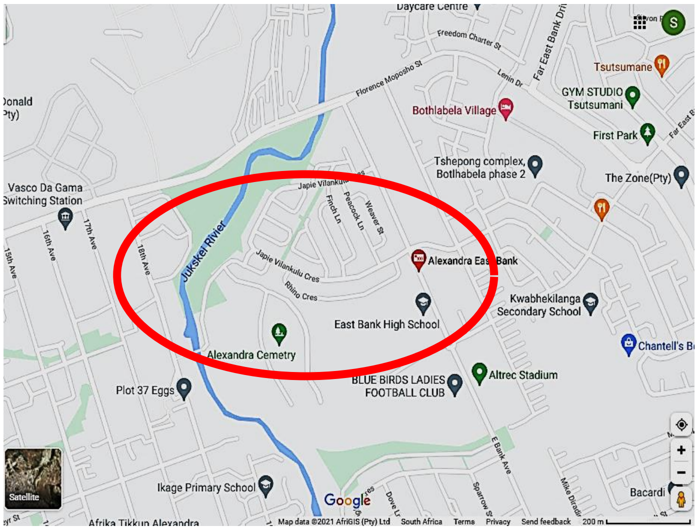

Fig. 1 The study area, Jukskei, Alexandra [Source: Google maps).

### 3.2 Sample Size

Sample size for this paper was defined as a portion of the population or the universe and not necessarily a number of people in the subject of the investigation [25]. Data collection in an investigation is much important and it enables a better understanding of the study aims of the research [26]. About 70 people who reside along the Jukskei River and 16 people from the surrounding areas such as Bramley View, Lombardi, and Alexandra were selected as participants in the investigation. The respondents were people who use the Jukskei catchment as an alternative during water shortages, and municipal officials who work within the water sanitation department. Out of the 70 selected, 52 people responded, which accounts for 74 % response rate.

### 3.3 Data collection

Data collection is defined as a process of gathering information from the targeted people, information that aims to answer the relevant research questions and achieve the study objectives [27]. Data was collected from the Jukskei catchment during observation, specifically observing how people in Alexandra can manage the groundwater

### 3.4 Data Analysis

Data that was collected using the observation method and the visual assessment were analysed and interpreted using the Excel spreadsheet. The results were shown using pictures, a histogram, and a dot plot chart. The data collected using the DRASTIC method was presented using calculations. The data analysis methods used were as follows:

### 3.4.1 The DRASTIC Model

Surface water and groundwater are both important sources for the provision of water in agricultural activities. Even though surface water is used mostly as a source of water supply due to its capacity and continuity, to date, groundwater is still the main source in several areas, especially in developing countries. Although several spatial models designed to assess groundwater sustainability and pollution hazard have been proposed, DRASTIC is arguably the model most widely used for such efforts [28]. A detailed account of the DRASTIC methodology, its evolution, and guidelines for applications is given. The model was designed to be a simple, nationally applicable tool for groundwater pollution hazard assessment [29]. The acronym, DRASTIC, is derived from the seven factors considered in the model:

- Depth to water table
- Recharge (net),
- Aquifer media (geologic characteristics),
- Soil media (texture),
- Topography (slope),

### 3.4.2 Sensitivity analysis

The sensitivity analyses are used to establish the relationship between the DRASTIC mapping parameters [30]. The DRASTIC method is characterised by using a high number of parameters, which is believed to limit the impact of errors and uncertainties in the individual parameters on the final outputs. The sensitivity analysis is divided into two, namely, the single parameters sensitivity and map removal sensitivity. The single sensitivity analysis aims to compare the subjectivity in assigning weight and score to the DRASTIC theoretical weight and the effective weight and is calculated as follows [31]:

$W = 100P_rP_w/V$ (1)

Where W refers to the effective weight of each of the parameter $P_r$ and $P_w$ are the weights of each of the parameter, respectively and V is the Overall vulnerability index.

### 3.6.3 The Map removal sensitivity

Removal sensitivity of the vulnerability towards removing one or more maps from the vulnerability analysis is computed as follows in equation 1:

$S = ((V/N - V/N)/V)*100$ (2)

### 3.6.4 Probability check

The probability was also used to determine the chances of a situation to happen. The probability is simply how likely something is to happen whenever we are not sure about a certain outcome, equation 2 was used:

P = (Event/Outcome) $p = (\frac{\text{event}}{\text{outcome}})$ (3)

Where: P− Probability

## 4. Findings and Discusion

This section focuses on the results that were attained from the questionnaires and the DRASTIC modelling carried out for the Jukskei River, Alexandra, South Africa. As previously mentioned, the targeted respondents were the people from Alexandra, water affairs, people who work at the municipality, and people from the surrounding communities such as Bramley View, Lombardi, and Riverside.

### 4.1 Groundwater vulnerability assessments

Vulnerability assessment is defined as a general planning instrument and a =decision-making tool. The main objective of the vulnerability assessment is to direct regulatory, monitoring, educational, and policy development efforts to those areas where they are most needed for the protection of groundwater quality 32]. The purpose of the groundwater vulnerability assessment is often to differentiate between areas that need protection from potential contaminating activities and areas where such activities constitute a minor threat to the groundwater and are capable to sustain more time than more vulnerable zones [30], therefore we can say the groundwater vulnerability is about the traditional efforts for protection. Two important laws regarding groundwater vulnerability were outlined for groundwater to be to some degree vulnerable; uncertainty is inherent in all vulnerability assessments [32].

The DRASTIC index is probably one of the simplest overlay methods that is used to assess groundwater vulnerability, the index assessed the intrinsic groundwater vulnerability based on the inherent hydrogeological characteristics of certain subsurface [31]. The acronym of DRASTIC is derived from the seven factors considered in the model [18]. Where Depth is to the water table, Recharge (net), Aquifer's media (Geologic, characteristics), Topography (slope), Impact of the vadose zone (unsaturated zone above the water table), and the Conductivity (hydraulic) of the aquifer [16]. In addition, Geographic Information Systems (GIS) is one of the common tools that are useful for assessing groundwater pollution hazards. During the past 10 years' groundwater quality became one of the most important environmental issues [11]. Although several spatial models designed to assess groundwater pollution hazards have been proposed, Drastic is arguably the model most widely used for such efforts [17]. This is because the protection of groundwater quality is an important problem confronting much of the world's populace [18].

### 4.2 Characteristics of the selected DRASTIC parameters the Jukskei River catchment in Alexandra

The individual Geographical Information System maps were created based on each set of criteria, indicating the relative groundwater vulnerability. The criteria that the DRASTIC method focuses on are the depth of the water table, recharge, aquifer, soil type, topography, impact on vadose zone, and hydraulic conductivity (table I).

Table I: Physical characteristics of the Alexandra Jukskei River catchment. (Source: Authors).

| Location | |
|---|---|
| Country | South Africa |
| Province | Johannesburg |
| Physical characteristics | |
| Source | Natural spring |
| Location | Alexandra, Johannesburg, South Africa |
| Coordinates | |
| Elevation | 0.374m |
| Recharge | |
| Drainage Depth | 0.374m |
| Average | $120m^3/s$ |
| Aquifer Media | |
| Soil Media | Sandy loam soil |
| Hydraulic conductivity | Basalt, dark-coloured, fine-grained, ingenious rock |
| Coordinates | |

### 4.3 Groundwater vulnerability assessments for the Alexandra Jukskei River catchment

### Depth of water table (denoted D)

The depth of water table (D) at Jukskskei River is relatively low; therefore, less exposed to pollution and has higher D values are not prone or exposed to pollution. The D values were given a range between 1 and 10 (see Table II), the Jukskei River has a depth of 0.374m, hence the factor of the water depth in the Jukskei River was given a rating of 10, which also verifies that it is exposed to pollution, see Fig. 6.

Table II: Depth range and rates. (Source: Authors).

| Depth range (m) | Rate | Area coverage (%) |
|---|---|---|
| 0-5 | 10 | 2 |
| 5-15 | 7 | 56 |
| 15-30 | 3 | 40 |
| 30 | 1 | 2 |

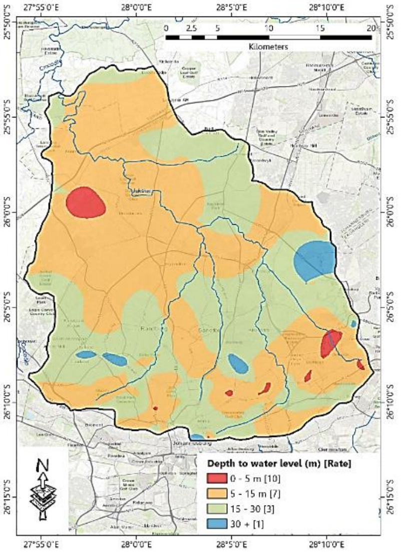

Fig. 6 Jukskei River water depth, (Source: The authors).

### K. Soil (denoted S)

Two types of soils are identified around the Jukskei River; namely, sandy loam, sandy clay loam, and loam. Almost 92% of the sub-catchment is covered with sandy loam, whereas about 8% of the area is covered with sandy clay loam. Since coarser textured soils have better permeability and infiltration, the sandy loam texture of most of the sub-catchment promotes recharge. Based on Table III, a rating has been assigned to soil texture classes [13]. The higher rating of 6 is assigned to sandy loam soils, and the lower rating of 5 is assigned to sandy clay loam soils, with a weight of 2. Since it is the most immediate recipient of rainfall and surface pollutants, the soil has a significant impact on both water flow and contaminant transport. The texture and size of soil particles influence how quickly water and contaminants percolate downward through the soil. The profile of the soil coarse-textured soils (e.g., sandy, or thin soils) allows contaminants to travel faster through open spaces and easily reach the water table. The fine-textured soils (e.g., clay and silt material) have low permeability, and restrict the downward movement of contaminants, and have a higher attenuation process, resulting in less potential for contamination. The visual /spatial outcome is shown in Fig.7. In this study area, the rating is 5 because it consists mainly of sandy clay loam and loam soil.

Table III: Soil characteristics and rate. (Source: Authors).

| Soil range | Rate | Area coverage (%) |
|---|---|---|
| Sandy loam | 6 | 93 |
| Sandy clay loam and loam | 5 | 7 |

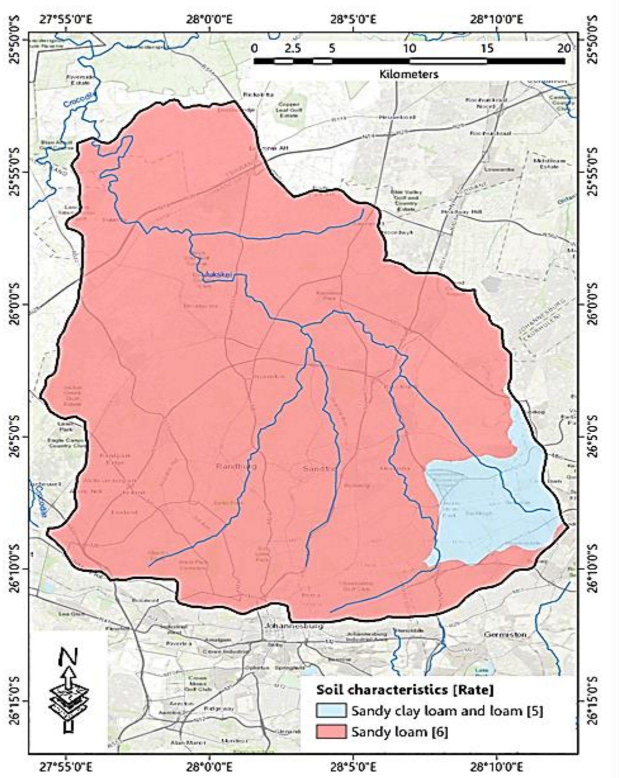

Fig. 7 Soil characteristics in Jukskei River, (Source: The authors).

## Hydraulic Conductivity (denoted C)

Hydraulic conductivity is a physical characteristic that assesses a material's capacity to transport the fluid through pores and cracks when a hydraulic gradient is being applied [17]. It can also be described as an aquifer formation's capacity to transfer water through pores or cracks under the influence of the hydraulic gradient [18]. This physical property determines the rate of contaminants' travel, residence time, and attenuation potential [19]. The hydraulic conductivity normally depends on the aquifer (rock material) and the properties of water, such as the relative density, kinematic, and viscosity [17]. The coarse grains normally have a higher hydraulic conductivity than the fine-grained materials, such as silt and clay [18]. The hydraulic conductivity is usually reduced due to compaction and intrusion of impermeable layers' (cementation) activities. In the Jukskei River, the aquifer was the intergranular alluvial covered zones and it is fine-grained. In hard fractured rocks, such as genesis, granites, etc. the hydraulic conductivity depends on the size, density, and interconnection of fractures [19]. Rocks with higher conductivity permit water and contaminants to move and spread quickly into groundwater, resulting in increased groundwater vulnerability (GWV). The measured values for the C were not available in the study area. Hence, the approximate hydraulic conductivity values for various rocks were extracted from hydrogeological literature, such as Domenico & Schwartz 1998 and Younger 2009. These values were further divided into five classes (see Fig. 8). The values have been rated, a higher rating is given to higher conductivity, while lower ratings to lower conductivity. The C of the dolomitic aquifer is assigned the highest rating (10) since such aquifers have high permeability due to their karstic formations [10]. These aquifers cover a tiny portion of the area, and they are in the north end of the sub-catchment. The Witwatersrand lithological formation was given a rating of 6, whereas the Vetersdrop formation was rated 4. The lowest rating (3) was assigned to basalt, which covers most of the Jukskei catchment area. The overall weighting of 3 was assigned to the C, based on Aller and Lynch recommendations [41];[52].

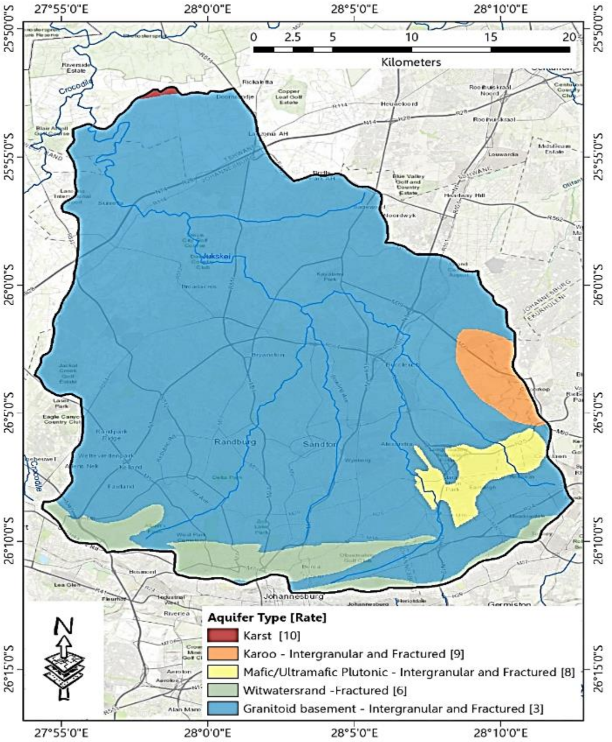

Fig. 8 Hydraulic conductivity, (Source: The authors).

### M. Net Recharge

The entire catchment area is characterised by a recharge rate between 100 and 150 m/s, which is commonly described as a lower net recharge area (see Fig. 9). Recharge is the main source of groundwater replenishment of natural and artificial origins. It is described as the volume of available water that infiltrates via the unsaturated zone and reaches the groundwater table [13]. Recharge plays a critical role in leaching and transporting contaminants from the ground surface to the aquifer [24]. The quantity of recharge also affects the dilution and dispersal of pollutants in the unsaturated and saturated zones. As recharge to the aquifer is higher, the potential of groundwater to pollution is also higher (higher vulnerability) because higher recharge promotes higher downward movement of contaminants. The study area falls within South Africa's summer rainfall region, with rain potentially occurring from October through to April, although December and January are the months when peak rainfall occurs. The study area's average mean annual precipitation (MAP) is 800mm, although extremes do occur in certain years with a low recorded of only 400mm and at the other end of the spectrum, a high of 1600mm [25].

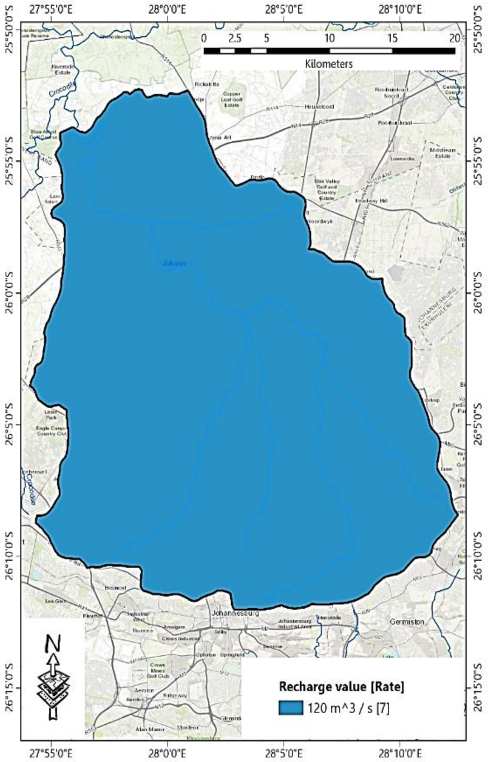

Fig. 9 Recharge, (Source: The authors).

### 4.4 The DRASTIC vulnerability summary ratings

From the summary below (Table IV), the depth of the water table along the Jukskei River was 0.374m going down from the surface, this data was collected from the Geo-request, and the Average recharge was 120m^3/s, the soil media type was sandy loam, and the hydraulic conductivity was the basalt, dark-coloured, with fine-grained and ingenious rock.

Table IV: Summary of the DRASTIC factors around the Jukskei River. (Source: The authors).

| | | |
|---|---|---|
| Drainage Depth | 0.374m | 10 |
| Average | 120 m/s | |
| Soil Media | Sandy loam soil | 5 |
| Hydraulic conductivity | Basalt, dark coloured, fine grained, ingenious rock | 3 |

### 4.5 Resultant vulnerability index for the Alexandra Jukskei River catchment

The resultant DRASTIC modelling below has employed four parameters (see Fig. 10) to assess the vulnerability of groundwater at the Jukskei River. The DRASTIC index model suggested that the minimum vulnerability value is 52 and the maximum is 112. When dividing this class into four equal sections one gets a class that ranges between 52-67, which is a very low or no risk class, , 67-76 is said to be a low class, 76-84 is a moderate class, and 84-112, is the high vulnerability risk. In the Jukskei River map, the results of the DRASTIC vulnerability index falls between the first class, i.e. between 80-156, which ranges from a very low to a very high vulnerability risk.

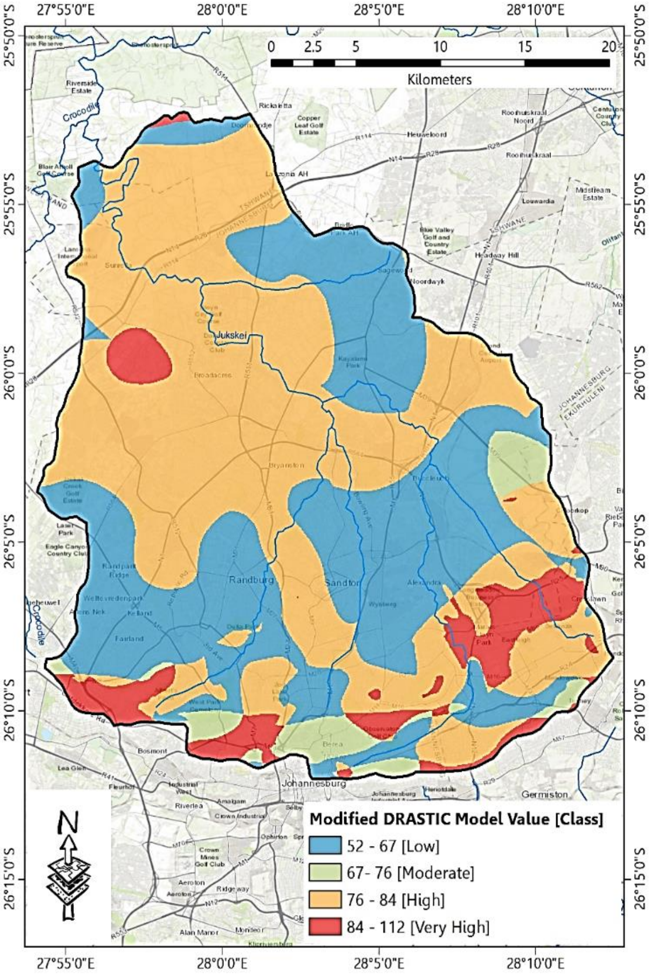

Fig. 10: The Resultant vulnerability index map, (Source: The authors).

Based on Table V, the results show that about 5.7% (45km2) of the area in the northern sub of the catchment, has high vulnerability. About 53.6% (428.8km2) of the catchment area also exhibited a high risk of groundwater contamination. This is mostly located in central areas, north-eastern, and western parts of the sub-catchment. Medium and low vulnerability classes cover about 4% (32km2) and 36% (288km2) of the Jukskei River, which is the study area, respectively.

Table V: Results of the vulnerability classes. (Source: Authors).

| Index range | Vulnerability class | Area (%) | Area (km2) |
|---|---|---|---|
| 52-67 | Low | 36 | 288 |
| 67-76 | Medium | 4 | 32 |
| 76-84 | High | 52 | 416 |
| 84-112 | Very high | 8 | 63 |

## 5. Conclusions

The DRASTIC vulnerability model was used to represent the unique vulnerability characteristics of the aquifer in the event of pollution. DRASTIC used three parameters to map and evaluate the vulnerability. This study divided the shallow groundwater of the Jukskei basin into areas of high, moderate, low, or very low vulnerability and associated risks when endangered groundwater in the basin is unprotected. Areas that have been shown to be more vulnerable to pollution require special attention and legislation to regulate land use activities. Other more vulnerable areas can be landfills and sites of groundwater pollution activity. The effects of depth and permeability have proven to be relevant and important parameters that users of the DRASTIC method must consider. It is important to consider the effects of hydraulic conductivity and aeration parameters as they represent the greatest risk for assessing shallow groundwater using the DRASTIC method.

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