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Investigation of Groundwater Resources Quality for Drinking Purposes Using GWQI and GIS: A Case Study of Ottawa City, Ontario, Canada †

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Abstract: Evaluating groundwater quality for certain purposes requires accurate quantitative and qualitative management, accessibility to the study area, and knowledge of the governing environmental processes. Groundwater resources are used as a supplementary for drinking water consumption alongside surface water in most countries. This study aims to investigate the quality of groundwater resources in the city of Ottawa located in Ontario, Canada, using the Schoeller diagram and the Canadian Groundwater Quality Index (GWQI) in fuzzy environment. To determine the water quality, the qualitative groundwater parameters including Ca, Mg, Na, Cl, SO_4, HCO_3, NO_3, F, pH, TDS, TH, K, EC, and Alkalinity were considered in the Schoeller diagram and GWQI. Each parameter's interpolated water quality Map layer is prepared using the Kriging method in GIS environment. The results of Schoeller's diagram indicated that the range of drinking water quality was non-potable to inappropriate in more than 22% of the investigated groundwater resources. Moreover, the obtained results of the groundwater quality interpolation map layer based on the GWQI revealed more than 70% of the groundwater resources were examined in the good and excellent range for drinking purposes. Finally, the obtained interpolated map layers of Schoeller diagram and GWQI were integrated using GIS. Accordingly, the results indicate that the interpolation values of an integrated layer in the study area are well within the permissible limits and the quality of the groundwater is suitable for drinking and other inhabitants' consumption.

Keywords: water quality; groundwater; Schoeller diagram; Groundwater Quality Index (GWQI); GIS

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1. Introduction

Water is one of the substantial requirements in planning, developing, protecting, and controlling water resources. Improper and inefficient assessment and management of surface and groundwater could provide essential risks in the fields of human health and wellbeing, food security, industrial development, and the life of ecosystems [1–4]. Groundwater is considered one of the most important resources worldwide in the drinking and agriculture sectors. During the last few years, urbanization and uncontrollable population growth have led to an increase in the use of groundwater resources. Therefore, water quality evaluation is one of the significant problems in groundwater studies [5]. Variation in the quality of water resources is a great danger in the usage of the agricultural, urban, and industrial sectors [6,7]. Several methods have been developed for the water quality determination. Among these key methods to evaluate and manage groundwater resources for drinking purposes, the Schoeller diagram and the Water Quality Index (WQI) methods are the most common. In this study, to assess the water quality of groundwater, combine the Schoeller diagram, Canadian Groundwater Quality Index (GWQI), and Geographic Information System (GIS). Schoeller's semi-logarithmic diagram is widely used to compare groundwater quality. This graph shows the concentration differences between water samples. It is classified based on several physio-chemical parameters to evaluate the quality of groundwater [8]. The GWQI method has high capability for groundwater quality assessment across the world. In the GWQI index based on GIS, several chemical parameters affecting quality of groundwater are integrated. GIS is used for the interpolation and classification of water quality parameters. For this purpose, kriging method is applied to interpolate each data layers of water quality parameters. Further, to reduce the uncertainties of the obtained results, interpolation map layers are converted to fuzzy set in GIS environment.

During recent years, multiple studies were presented to evaluate water quality for drinking uses by Schoeller diagram, Water quality indices, and GIS software in different parts of the world [9,10]. In another study, NickPeyman and Mohammadzadeh 2013 studied groundwater quality in Mashhad plain aquifer by estimating the GQI index [11]. Soleimani et al. 2013 conducted a study entitled Investigation of qualitative changes in water resources of east Koohsorkh using the GQI quality index in the GIS environment [12]. Sadat-Noori et al. 2014 used a combination of the Water Quality Index (WQI) and GIS to determine the groundwater quality of Saveh-Nobaran aquifer in Arak province, Iran. They used the kriging method in GIS for creating spatial distribution maps of pH, TDS, EC, TH, Cl, HCO, SO_4, Ca, Mg, Na and K [13]. In another studt, Alavi et al. 2016 assessed water quality of Dez eastern in Iran for drinking and agricultural uses by Schoeller and Wilcox diagrams and zoning water quality in GIS environment considering physical and chemical parameters. They used kriging interpolation method in GIS [14]. Farhan et al. 2020 investigated the Canadian Water Quality Index (CCME WQI) for drinking and domestic use in Mosul, Iraq. This research examined ten sampling sites along the river to collect samples from 2008 to 2014. The results showed that the water quality of the Tigris River was between 3.66 and 7.93, which is in the good and moderately good category [15]. Pourkhosravani et al. 2021 tried to evaluate groundwater resources' chemical quality for drinking and agricultural purposes using Schoeller and Wilcox diagrams in Sirjan Plain of Iran. Their classification map of each effective parameter prepared using IDW based GIS [16]. Given the fact that a comprehensive study on chemical parameter variations of the groundwater quality has not been done in the study area, this study aimed to investigate variation of groundwater quality parameters for drinking purpose in Ottawa city using the interpolation of GWQI and Schoeller diagram in GIS environment.

2. Materials and Methods

2.1. Study Area

Ottawa city, with the area of 2790 km^2, is located in in the east of southern Ontario. This city is located at latitude 45°25′29″ N and longitude 75°41′42″ W, with an elevation of 70 m above sea-level. The climate is semi-continental, with a warm, humid summer and a very cold winter. The temperature typically varies from −14°C to 27°C, while the mean precipitation is 920 mm. Rainfalls throughout the year in Ottawa. The higher mean monthly rainfall in Ottawa is in July, with an average rainfall of 76 mm, while the least rainfall month is February, with an average rainfall of 12.7 mm. The study area involved different residential and industrial regions which supply the needed water from groundwater resources. Groundwater is one of the main sources of water in this area. There are lots of wells in the study area aquifers that have high potential a source of drinking water. The location of the study areas is illustrated in Figure 1.

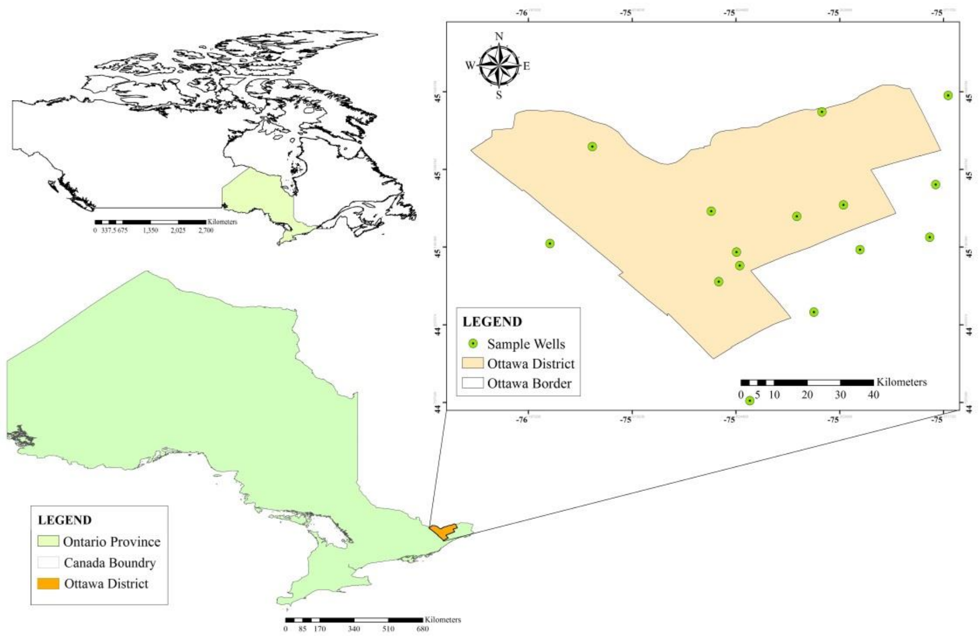

Figure 1. Location of the study area and the sampling wells.

2.2. Methodology

In this study, available groundwater level and chemistry data of 15 sample wells distributed across the Ottawa city were first collected and analyzed from the Provincial Groundwater Monitoring Network (PGMN) Program of Ontario Province in the Ministry of the Environment, Conservation and Parks website [17]. A long-term qualitative data was used during a 17-year statistical period from 2002-2019. In this phase, the important parameters were considered important parameters in this phase, such as Ca, Mg, Na, Cl, SO4, HCO3, NO3, F, pH, TDS, TH, K, EC, and Alkalinity of groundwater quality.

In order to classify the water quality of groundwater and determine its type and characteristics, the GWQI index and Schoeller diagram method were used with the help of GIS software. Before that, Schoeller diagram, a highly recommended method, is applied to investigate the quality of drinking water considering eight parameters including TDS, TH, Na, Cl, SO_4, HCO_3, Mg, and Ca. This diagram shows the concentration differences between the sample wells. It is drawn in six classes including the good, acceptable, average, inappropriate, completely inappropriate, and non-potable based on several physio-chemical parameters to evaluate the quality of groundwater [8]. In the Schoeller diagram, an axis is considered separately for the parameters mentioned above, which determines drinking water quality [18]. Table 1 shows the classification of water quality using the Schoeller diagram method.

Table 1. The classification of water quality using the Schoeller diagram method (mg/L).

Water Classification	TDS	TH	Na	Cl	SO_4
Good	<500	<250	<115	<175	<145
Acceptable	500–1000	250–500	115–230	175–330	145–280
Average	1000–2000	500–1000	230–460	330–700	280–580
Inappropriate	200–4000	1000–2000	460–920	700–1400	580–1150
Completely Inappropriate	4000–8000	2000–4000	920–1840	1400–2800	1150–2240
Non-Potable	>8000	>4000	>1840	>2800	>2240

Next, The GWQI Index is utilized to determine the water quality of groundwater based on Ca, Mg, Na, Cl, SO_4, HCO_3, NO_3, F, pH, TDS, TH, K, EC, and Alkalinity parameters. After the definition of parameters, three factors to determine the GWQI must be calculated. The values of the three factors are calculated as follow [19]:

F_1: shows the percentage of failed parameters relative to all of the measured parameters:

$$F_1 = \left(\frac{Number\ \ of\ \ \ failed\ \ \ parameters}{Total\ \ number\ \ of\ \ \ parameters} \right) \times 100 \tag{1}$$

F_2: demonstrates the percentage of failed tests:

$$F_2 = \left(\frac{Number\ \ of\ \ \ failed\ \ tests}{Total\ \ number\ \ of\ \ \ parameters} \right) \times 100 \tag{2}$$

F_3: indicates a value that failed test values do not meet their guidelines. F_3 is calculated in three steps.

Step 1. The number of times an individual's concentration exceeds the guideline is called an "excursion" and is expressed as follows. When the test value should not exceed the guideline:

$$excursion_i = \left(\frac{Failed\ \ test\ \ value_i}{Objective_i} \right) - 1 \tag{3}$$

For cases where the test value should not be less than the guidelines:

$$excursion_i = \left(\frac{Objective_i}{Failed\ \ test\ \ value_i} \right) - 1 \tag{4}$$

Step 2. The cumulative amount by which individual tests are out of compliance is calculated by summing the excursions of individual tests from their guidelines and dividing by the total number of tests. This parameter, called the normalized sum of excursions or nse, is determined as follows:

$$nse = \frac{\sum_{i=1}^{n} excursion_i}{Number\ \ of\ \ tests} \tag{5}$$

Step. Then, F_3 is calculated by an asymptotic function that yields the normalized sum of excursions from instructions (nse) to a range between 0 and 100.

$$F_3 = \left(\frac{nse}{0.01nse + 0.01} \right) \tag{6}$$

Once the three factors are obtained, the index itself can be calculated by summing the three factors as a vector and using the Pythagorean theorem. Therefore, the sum of squares of each factor is equal to the square of GWQI.

$$CWQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right) \tag{7}$$

A divisor of 1.732 normalizes the resulting values to a range between 0 and 100, where 0 represents the worst water quality and 100 represent the best water quality.

Computed GWQIs are classified into five categories including excellent, good, fair, marginal, and poor for human consumption in Table 2 [19] The outcome of the index includes a number between 0 (worst water quality) and 100 (best water quality) [20,21].

Table 2. The classification of water quality using the GWQI [19].

Rank	Water Quality Ranking System
Poor	0–44.9
Marginal	45–64.9
Fair	65–79.9
Good	80–94.9
Excellent	95–100

Afterward, a spatial classification map for each important parameter of the Schoeller diagram and GWQI Index method was prepared as a raster layer based on the kriging interpolation technique in GIS. It should be noted, in order to reduce the uncertainty of all the classified Raster parameters, each parameter layer is fuzzified based on the linear membership function in GIS [22–24]. Then the final interpolation layers of the two methods (Schoeller and GWQI) are created by integrating fuzzy Raster layers as effective parameters using the fuzzy overlay tool. Finally, the classification map of the groundwater quality of the study area is generated by integrating the Schoeller and GWQI classified maps based on the overlaying method.

3. Results and Discussion

In this study, the water quality parameters of sample wells in the city of Ottawa for the drinking sector have been studied using the Schoeller diagram and the GWQI Index. Therefore, based on Schoeller's classification, the amounts of cations such as calcium (Ca), magnesium (Mg), sodium (Na) and anions such as chloride (Cl), sulfate (So4), bicarbonate (HCO3) and two important parameters of total dissolved solids (TDS) and the total hardness (TH) were checked in the diagram, which is shown in Figures 2 and 3.

Regarding the discussion of limitations and practical implications in the current research, the groundwater quality in the urban area of Ottawa was explored. Using the approach implemented in this study, water quality could be analyzed concerning the environment, agriculture, and industry if more parameters were obtainable. However, due to the absence of pertinent environmental parameters, such as BOD, COD, and DO, and industrial and agricultural parameters, such as heavy metals including Fe, Cu, Zn, and As, and the time constraint involved in producing this article, only the drinking perspective was investigated concerning the quality of groundwater.

According to the diagrams (see Figures 2 and 3), the water quality of wells W_1, W_2, W_4, W_7, and W_{14} is in the good range and wells W_3, W_5, W_6, W_8, W_9, W_{10}, and W_{11} are in the acceptable range and the rest of the wells are in the lower quality range. In general, it is concluded that about 71% of the parameter values are in the good range and 29% of the rest parameters are in other quality classes.

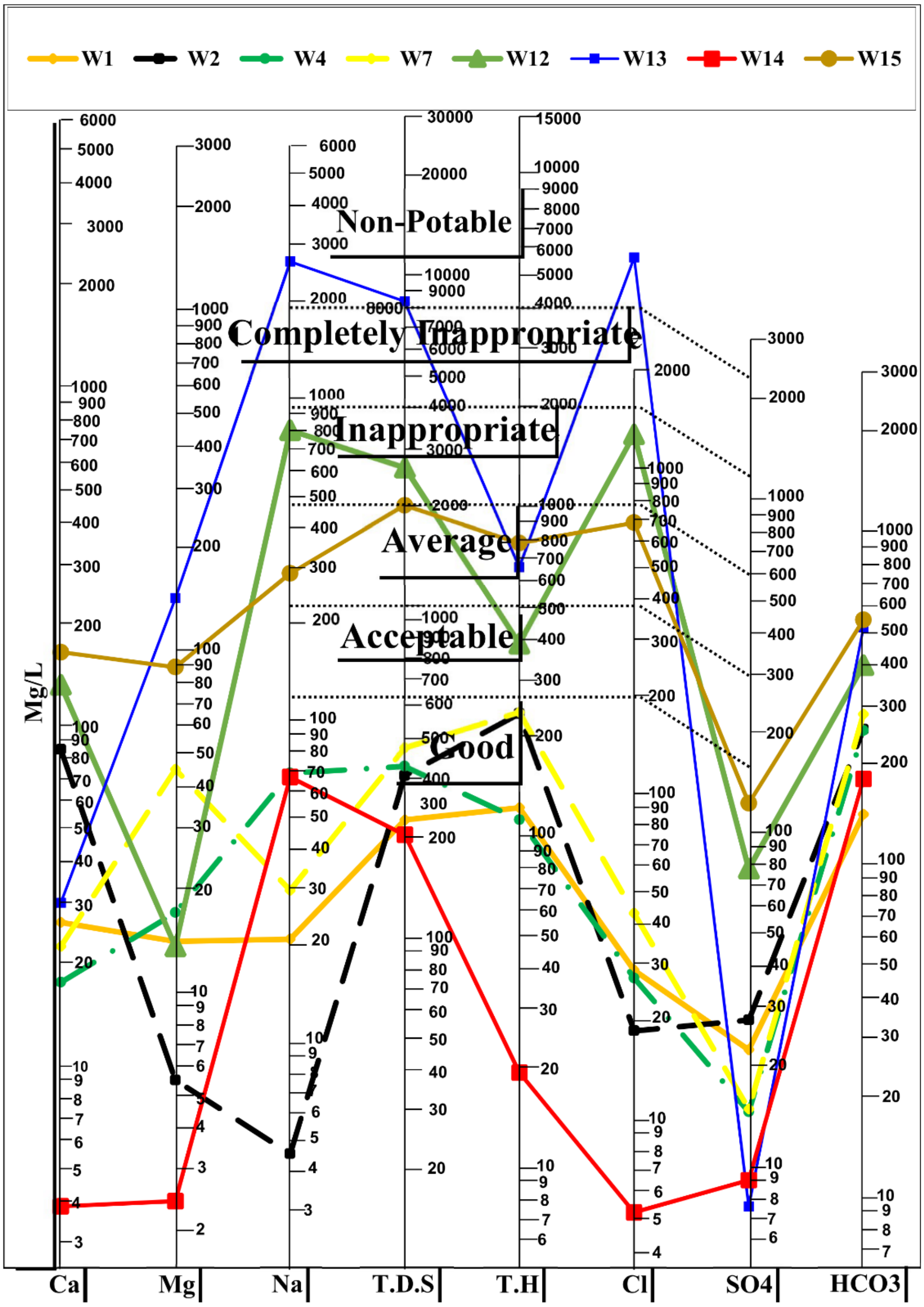

Figure 2. The Schoeller diagram of the studied wells.

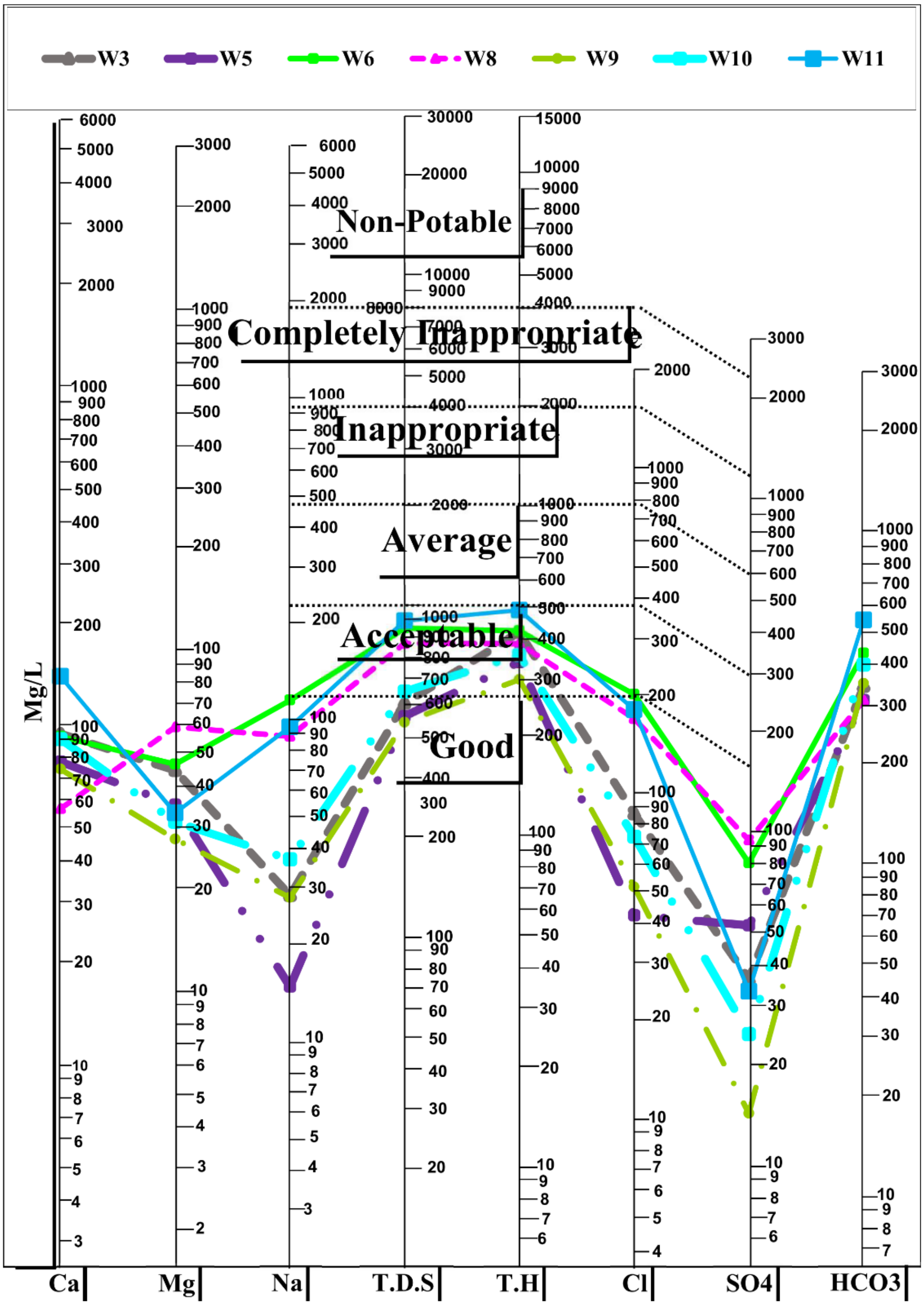

Figure 3. The Schoeller diagram of the studied wells (Continuous).

In the following, the values of each parameter of Schoeller's diagram were interpolated based on the six classes of Schoeller's classification in ArcGIS software using the kriging method, and finally, six classified maps were integrated with the Fuzzy Overlay tool in the form of water quality classification map of Ottawa city (see Figure 4).

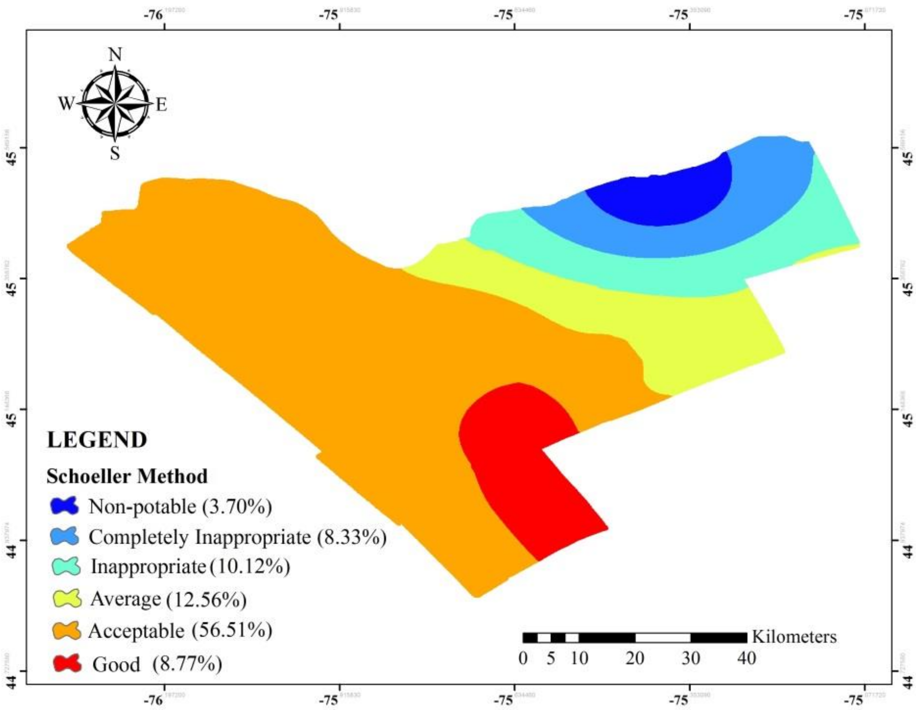

Figure 4. Water quality classification map of Ottawa city using Schoeller method.

Based on to the classified map of Schoeller, the water quality in classification for the Ottawa city area is in 6 categories from good to non-potable. So that in the south, west, and north-west areas towards the center, the water quality is good and fair for drinking purposes, and from the central area towards the east and northeast, the water quality has decreased. Based on the location of the two wells W_{12} and W_{13}, it can be pointed out that saltwater infiltrates the groundwater resources of these areas considering the high amount of Na and Cl ions and also the proximity of these two wells to the Ottawa River. According to Schoeller's classification map, some water samples may have good drinking quality, while those ones can contain other harmful and toxic substances; therefore, to solve this problem more parameters were used in the GWQI Index. Hence, those parameters such as Electrical Conductivity (EC), pH, Alkalinity (mg/L $CaCO_3$), Calcium (Ca), Sodium (Na), Magnesium (Mg), Potassium (K), Sulphate (SO_4), Chloride (Cl), Fluoride (F), Nitrate (NO_3) were evaluated for the GWQI classification map.

Considering Equations (1)–(7), the annual average values of GWQI considering Table 2 are calculated in the range of values 33 to 100. Therefore, the water quality in most wells for drinking purposes has been rated in the range of excellent and good. The GWQI values were interpolated in the ArcGIS environment using the kriging method shown in Figure 5. According to Figure 5, the southwest, west, and northwest regions towards the center of the study area have excellent and good drinking water quality, and from the central region toward the southeast, east, and northeast, the water quality is decreased due to the increase of NaCl ions.

Finally, after preparing Shuler and GWQI classification maps, these two classified maps overlapped with the Fuzzy Overlay tool in ArcGIS. And, the overlaid map was categorized into five classes from Excellent to Poor (see Figure 6). Furthermore, by investigating the integrated classification map, it was found that the values of groundwater quality are in the excellent and good class range for the area of Ottawa city in the south, west, and the northwest regions towards the center, and also the water quality range has decreased in the east and northeast regions.

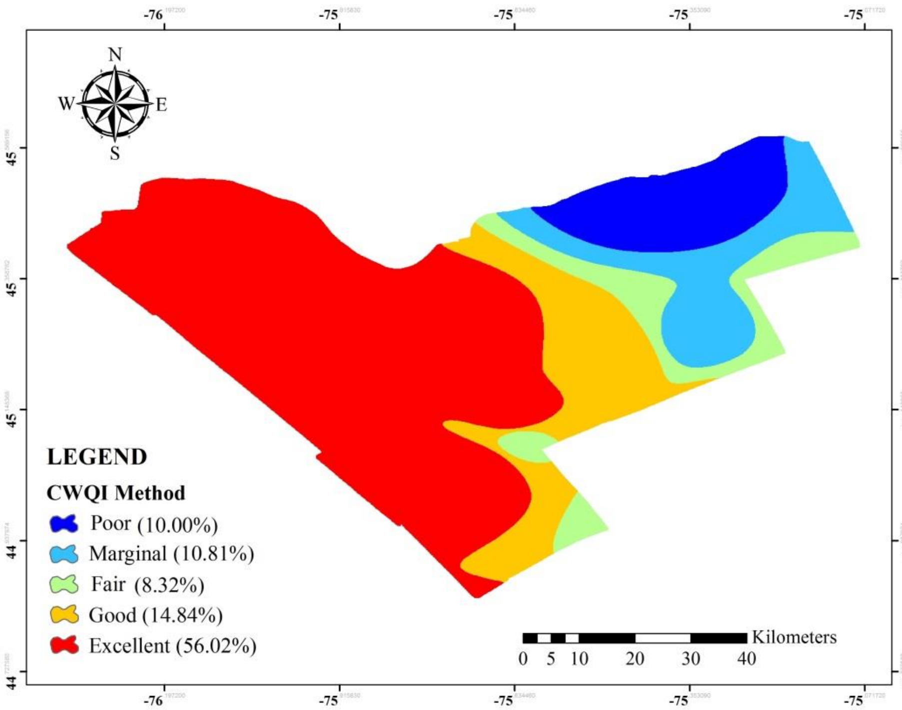

Figure 5. Water quality classification map of Ottawa city using GWQI Index.

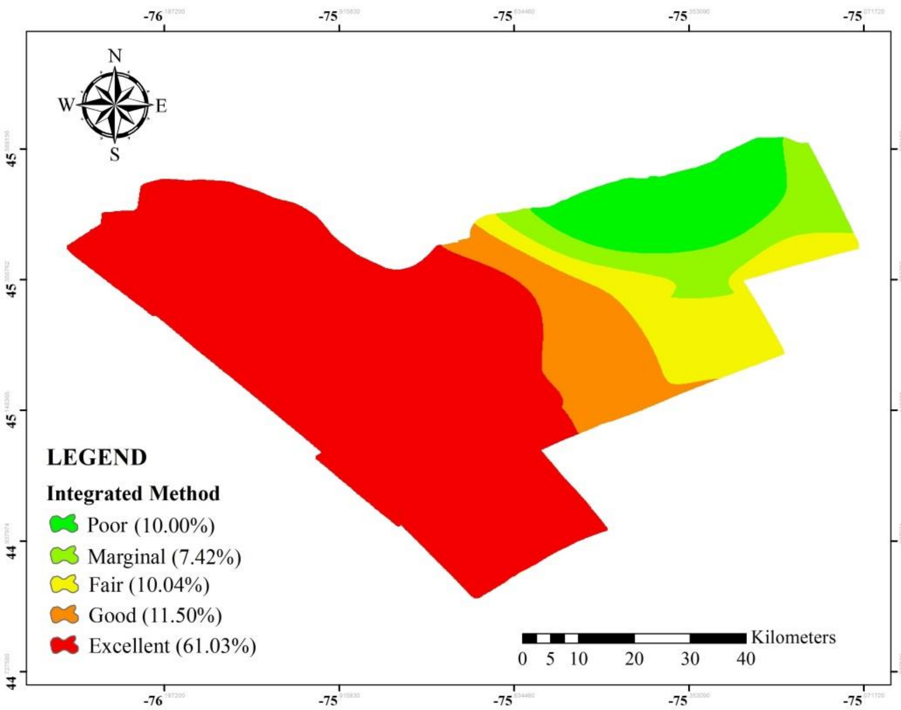

Figure 6. Integrated water quality classification map of Ottawa city.

4. Conclusions

In this study, the main aim is to investigate groundwater quality by the combination of the Schoeller diagram, Canadian Groundwater Quality Index (GWQI). This study tried to evaluate and analyze the water quality in Ottawa city in Ontario, Canada based on a long-term qualitative data from 15 sample wells between 2002 and 2019. The classified water quality Maps of each chemical parameter is prepared using the kriging method based on fuzzy set in GIS environment. The obtained results showed that based on the Schoeller diagram, most of the studied wells were located in good to acceptable quality regarding drinking purposes. According to the Schoeller classification map of groundwater resources, the acceptable class with 56.51% of the aquifer area and the non-potable class, with 3.70% of the aquifer area make the highest and lowest portions of the aquifer, respectively. Moreover, according to the GWQI water quality classification map results, 79.18% of the wells are in the fair to excellent range, and 10% are in the poor range. Finally, the results of assessing the integrated Schoeller and GWQI water quality classification map used for drinking purposes show that based on the values of these two methods, the water quality in the central areas and near-west areas are categorized into excellent and good classes, and from the central regions to the east, the water quality has gradually decreased. As well as, the transferability of the proposed method and results can be discussed in light of the obtained outcomes. Our approach integrates the GWQI index, Schoeller diagram, and GIS to develop a model that can be utilized for agricultural, industrial, and environmental purposes by including several chemical parameters. The GWQI index enables us to expand the model to encompass other water quality diagrams, such as Wilcox and Piper. Moreover, our study's reliability and transparency provide significant insights for researchers and decision-makers to analyze and make informed decisions about the quality of drinking water. These results show that the proposed method is transferable to more extensive case studies, providing valuable insights for various water quality applications.

Author Contributions: Conceptualization: A.N., F.R. and H.B.; methodology: A.N. and F.R.; software: A.N.; validation, F.R.; formal analysis, H.B. and A.N.; data curation, A.N. and F.R., writing—original draft preparation, A.N. and H.B.; writing—review and editing, H.B.; visualization, A.N., F.R. and H.B.; supervision: H.B. All authors have read and agreed to the published version of the manuscript.

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