Geospatial Distributions of Groundwater Quality in Gedaref State Using Geographic Information System (GIS) and Drinking Water Quality Index (DWQI)

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Abstract: The observation of groundwater quality elements is essential for understanding the classification and distribution of drinking water. Geographic Information System (GIS) and remote sensing (RS), are intensive tools for the performance and analysis of spatial datum associated with groundwater sources control. In this study, groundwater quality parameters were observed in three different aquifers including: sandstone, alluvium and basalt. These aquifers are the primary source of national drinking water and partly for agricultural activity in El Faw, El Raha (Fw-Rh), El Qalabat and El Quresha (Qa-Qu) localities in the southern part of Gedaref State in eastern Sudan. The aquifers have been overworked intensively as the main source of indigenous water supply in the study area. The interpolation methods were used to demonstrate the facies pattern and Drinking Water Quality Index (DWQI) of the groundwater in the research area. The GIS interpolation tool was used to obtain the spatial distribution of groundwater quality parameters and DWQI in the area. Forty samples were assembled and investigated for the analysis of major cations and anions. The groundwater in this research is controlled by sodium and bicarbonate ions that defined the composition of the water type to be Na HCO₃. However, from the plots of piper diagram; the samples result revealed (40%) Na-Mg-HCO₃ and (35%) Na-HCO₃ water types. The outcome of the analysis reveals that several groundwater samples have been found to be suitable for drinking purposes in Fa-Rh and Qa-Qu areas.

Keywords: aquifers; drinking water quality index DWQI; spatial distribution; piper diagram; interpolation methods

1. Introduction

Groundwater is a noble resource for water in arid and semiarid areas [1–6]. Accessibility to water is an important global goal whose effects are abundantly felt in developing countries. The benefit of
understanding groundwater geochemistry is to ensure its good quality for drinking [7–9]. In arid and semi-arid areas, the potential use of groundwater for drinking and agricultural projects is threatened by the decline of water quality due to physical and anthropogenic characteristics. Evaluation of the geochemical status of groundwater is required to competently plan and control the groundwater resources [10]. The interaction between water and rocks has usually been studied to provide an understanding of the physical and chemical procedures controlling water chemistry [11–13]. Several factors control the groundwater geochemistry such as the type of rock forming the aquifer, the residence time of water in the hosted aquifer, the origin of the groundwater and the flow directions of groundwater [14,15].

The estimation of quality and the use of groundwater for different purposes are becoming more significant [16]. Thus, probes related to an understanding of the hydro-chemical aspects of the groundwater, geochemical processes and its development under natural water flowing manners, not only aids in the practical utilization and protection of this expensive resource but also aid in visualizing the changes in the groundwater environment [17,18].

Statistical analysis methods such as the correlation matrix, bivariate, and Hierarchal component analysis; produce a reliable alternative procedure for understanding and explaining the complex system of water quality with the capability of analyzing large amounts of data [19].

GIS and RS, are intensive tools for performance and analysis of spatial datum associated with groundwater sources control. Remote sensing data are essential in many geo-resources, such as mineral research, hydrogeology, and other geologic fields [20]. It is important in hydrogeological reconnaissance for understanding structural, geomorphological, and lithological features. The acquired RS information improves our knowledge of the hydrogeological conditions. Satellite images are universally applied for qualitative estimation of groundwater resources by investigating geological structures, geomorphic features, and their hydrological characteristics [21–23]. The spatial distribution maps were designed and integrated within ArcGIS v.10.5 software.

Drinking water quality index (DWQI) presents a single number to reveal the overall water quality at a particular position and time, based on various water quality factors. It is interpreted as a number that indicates the combined impact of several water quality parameters [19,24–28]. DWQI has been popularly utilized in water quality evaluations for both surface and sub-surface water, and it has represented an increasingly significant function in the water resource environment and management [29–31].

Shortage of drinking water in East Central Sudan especially in the basaltic terrain is a common problem. Most of the rural community depends on groundwater sources in their daily life for drinking purposes. This research aims to generate groundwater distribution maps and to evaluate water quality for drinking purposes in Qa-Qu and Fw-Rh areas in the southern part of Gedaref State in eastern Sudan. The area consists of one of the essential agricultural fields of Gedaref State, the El Rahad project which was developed as a mechanized project in Sudan in 1978 [32].

In this work, forty samples were observed and monitored from selected boreholes. Hence, an attempt of statistical analysis methods such as correlation matrix and Hierarchal component analysis were applied to determine the variation in hydro-chemical facies and understand the development of hydro-chemical processes. Moreover, adopting Piper and Durov diagrams by use of Aqua Chem. v.2014.2 software, to classify the groundwater facies and water types in the area. The world health organization (WHO) [33] standard has been used for correlations with the results of sample analysis to examine the permissible amount of water for drinking.

The analytical results achieved from the samples when plotted on Piper’s plot, explained that the alkalis (Na⁺, K⁺), appear considerably over the alkaline elements (Ca²⁺, Mg²⁺), and the weak acidic (HCO₃⁻) appear considerably over strong acidic anions (Cl⁻ & SO₄²⁻). Moreover, the Piper diagram matched 40% of the samples, under Na-Mg-HCO₃ group and 35% under Na-HCO₃ type. According to the plotting from the Durov diagram, most of the elements of water plotted within the HCO₃·Na zone, except some other samples that fell in HCO₃ Cl-Na, SO₄ Cl·HCO₃-Na, or HCO₃ Cl-Na·Mg types.
DWQI was calculated by adopting weighted arithmetical index methods considering thirteen water quality parameters (pH, TDS, Ca$^{+2}$, Mg$^{+2}$, Na$^{+}$, K$^{+}$, Fe$^{+2}$, Cl$^{-}$, HCO$_3^{-}$, SO$_4$$^{2-}$, F$^{-}$, NO$_3$$^{-}$, and E.C) in order to assess the degree of groundwater contamination and suitability for drinking purposes.

For the better understanding of geological units in this project, the thin sections of rock samples have been generated. With this ability, the rock mineral contents have been determined much better. This study has great importance; due to the plan for obtaining drinking water from the groundwater sources to Fw-Rh and Qa-Qu localities. However, this investigation is helpful in understanding groundwater environments and its suitability for human uses, especially in arid and semi-arid regions.

2. Materials and Methods

2.1. Geology

Geologically Figure 1; the lower Proterozoic rocks of the basement complex (Mainly Granitic Gneisses) [34], Syn-orogenic Granit and Syn-orogenic gabbro underlain the sandstone of Gedaref formation, Tertiary (Oligocene) basalt [35], Umm Rawaba formation, sand sheets and recent alluvium and wadi deposits. The groundwater of the area was tapped at the sandstone of Gedaref formation sequence, alluvium soil, and fractures of the Oligocene basalt aquifers with depths ranging from 14 to 64 m.

2.2. Hydrogeological Setting

The groundwater was studied by using the data collected from forty boreholes drilled in Fw-Rh and Qa-Qu area as seen in Table 1. The hydrogeological characteristics of rock units were investigated, and aquifer systems were determined depending on field investigations and previous studies. Therefore, the hydrogeological map of the Fw-Rh and Qa-Qu area was settled adopting ArcGIS v.10.5 software, based on characteristics of the lithological units Figure 2. According to these evaluations, the aquifer types were described as sandstone, alluvium, and fracture basalt.
Table 1. Hydrogeological data of forty wells drilled in the study area.

| Aquifer Type | Well Depth (m) | S.W.L (M) | Elevation (m) | Water Table (m) | Well Name |
|--------------|----------------|-----------|---------------|-----------------|-----------|
| Alluvium     | 23             | 16        | 425           | 409             | Ellewatah3 |
| Sandstone    | 27             | 16        | 424           | 408             | Abu Kalbo |
| Sandstone    | 64             | 37        | 423           | 386             | Um Rakuba |
| Sandstone    | 48             | 27        | 425           | 398             | Um Tireaza |
| Sandstone    | 21             | 11        | 444           | 432             | Um Tireaza 2 |
| Sandstone    | 60             | 13        | 554           | 505             | Macancana |
| Sandstone    | 48             | 11.94     | 426           | 414             | Wd Margi  |
| Sandstone    | 21             | 11        | 446           | 435             | Um Tireaza 2 |
| Alluvium     | 14             | 7         | 424           | 417             | Um Gazaz |
| Sandstone    | 64             | 12        | 425           | 413             | Wad Elkarar 1 |
| Alluvium     | 27             | 19        | 424           | 405             | Eldar Elbeida |
| Sandstone    | 42             | 13        | 655           | 634             | Ellewatah 2 |
| Alluvium     | 27             | 16        | 486           | 470             | Halayy5 |
| Alluvium     | 30             | 14        | 427           | 413             | Wad Elwosta |
| Alluvium     | 57             | 34        | 424           | 383             | Wad Elkarar 2 |
| Basaltic     | 42             | 24        | 423           | 410             | Hilat Ali |
| Alluvium     | 22.5           | 12        | 428           | 416             | Abu Saeed |
| Alluvium     | 28             | 13        | 427           | 414             | Elyas |
| Alluvium     | 26             | 12        | 648           | 634             | Elmeageerah |
| Sandstone    | 25             | 7         | 598           | 591             | Dora |

Well Code | Aquifer Type | S.W.L (M) | Elevation (m) | Water Table (m) |
|-----------|--------------|-----------|---------------|-----------------|
| Fw-Rh21   | Alluvium     | 34        | 14            | 447             | 433 |
| Fw-Rh22   | Alluvium     | 18        | 10            | 444             | 434 |
| Fw-Rh23   | Alluvium     | 57        | 41            | 433             | 399 |
| Fw-Rh24   | Alluvium     | 26        | 18            | 428             | 410 |
| Fw-Rh25   | Alluvium     | 21        | 14            | 422             | 411 |
| Fw-Rh26   | Basaltic     | 15        | 8             | 658             | 650 |
| Fw-Rh27   | Alluvium     | 24        | 10            | 428             | 418 |
| Fw-Rh28   | Alluvium     | 21        | 8             | 431             | 423 |
| Fw-Rh29   | Alluvium     | 23        | 16            | 425             | 409 |
| Qa-Qu01   | Sandstone    | 53        | 32            | 627             | 595 |
| Qa-Qu02   | Sandstone    | 60        | 49            | 426             | 413 |
| Qa-Qu03   | Alluvium     | 21        | 12            | 422             | 411 |
| Qa-Qu04   | Basaltic     | 42        | 21            | 631             | 607 |
| Qa-Qu05   | Basaltic     | 26        | 14            | 454             | 442 |
| Qa-Qu06   | Sandstone    | 43        | 35            | 500             | 465 |
| Qa-Qu07   | Alluvium     | 27        | 16            | 428             | 412 |
| Qa-Qu08   | Sandstone    | 21        | 11            | 431             | 417 |
| Qa-Qu09   | Sandstone    | 57        | 42            | 635             | 593 |
| Qa-Qu10   | Sandstone    | 31        | 21            | 447             | 426 |
| Qa-Qu11   | Basaltic     | 30        | 9             | 650             | 641 |

Figure 2. Hydrogeological map of the study area.
2.3. Spatial Interpolation and Groundwater Quality Mapping

Spatial interpolation is a procedure of predicting the value of attributes at unsampled sites from measurements made at point locations within the same area [36]. There are two main groupings of interpolation techniques: deterministic and geostatistical. Deterministic interpolation techniques create surfaces from measured points, based on either the extent of similarity (e.g., Inverse Distance Weighted) or the degree of smoothing (e.g., radial basis functions). Geostatistical interpolation techniques (e.g., kriging) utilize the statistical properties of the measured points.

In this study, we found that the Kriging (Ordinary and Simple) interpolation method is the most suitable method. Thus, the histograms and normal QQplots were plotted to examine the normality distribution of the observed data for each water quality element in both Fw-Rh and Qa-Qu localities.

2.4. Drinking Water Quality Index DWQI

DWQI has been determined based on the standards of drinking water quality as counseled by WHO. Therefore, thirteen chemical parameters (pH, TDS, Ca, Mg, Na, K, Cl, HCO3, F, NO3, Fe, and E.C.) were used for the calculation. To apply DWQI in the current study, the study area was divided into two parts, Fw-Rh, and Qa-Qu localities. The water quality parts were generated by a weighting factor and then formerly aggregated by using the simple mean calculations. To estimate the water quality in this project, the quality rating (Qi) for all elements was estimated through the following equation;

\[ Q_i = \left\{ \frac{(V_a - V_i)}{V_s - V_i} \right\} \times 100 \]  

(1)

where, \( Q_i \) = Quality ranking of the element form a total number of water quality elements, \( V_a \) = Real amount of the water quality element taken from laboratory study, \( V_i \) = Ideal rate of the water quality element can be realized from the standard Tables. \( V_s \) for pH = 7 and for other elements it is equaling to zero. \( V_s \) standard = Value of WHO standard.

Then, the Relative weight (W_r) was studied from inversed proportional of recommended standard (S_i) for the corresponding parameter using the following expression;

\[ W_r = \frac{I}{S_i} \]  

(2)

Here \( W_r \) = Relative (unit) weight for specific element; \( S_i \) = Standard allowable amount for certain element; I = Proportionality constant.

Assuredly, the total DWQI was determined using the assemblage equations of the quality rating with the unit weight linearly as the following:

\[ DWQI = \frac{\sum Q_i W_r}{\sum W_r} \]  

(3)

where \( Q_i \) = Quality rating; \( W_r \) = Relative weight.

In general, DWQI is determined for particular and intended uses of water. In this work, the DWQI was estimated for human consumption, and the maximum DWQI value for the drinking purposes was regarded as 100 scores.

The methodology ideas in this work have been done through several steps Figure 3.
3. Results

Several factors may control the groundwater geochemistry such as the type of rock forming the aquifer, residence time of water in the hosted aquifer, the origin of the groundwater and the flow directions of groundwater. Hydro-chemical properties of the groundwater of the area are shown in Table 2. The water pH ranges between 7.5 and 8.9, indicate an alkaline chemical reaction in both sandstone and basaltic aquifers. The electrical conductivity (E.C) varies from 345 to 3342 μS/cm.

Table 2. Descriptive statistical analysis result of water samples (N = 40).

| Variable | WHO (mg/L) | Minimum | Maximum | Mean | Std. D. | Minimum | Maximum | Mean | Std. D. |
|----------|------------|---------|---------|------|---------|---------|---------|------|---------|
| pH       | 7.0–8.0    | 7.50    | 8.90    | 8.03 | 0.35    | 7.60    | 8.70    | 7.96 | 0.32    |
| TDS      | 242.00     | 601.72  | 399.60  | 163.00 | 2007.00 | 663.18  | 502.41 |
| Ca       | 75         | 130.00  | 3.74    | 10.44 | 53.00   | 118.60  | 930.00  | 355.40 | 247.40  |
| Mg       | 30         | 120.53  | 34.28   | 23.86 | 72.00   | 23.86   | 18.23   |
| Na       | 200        | 359.00  | 214.28  | 69.87 | 214.28  | 69.87   | 150.29  |
| K        | 15.00      | 70.00   | 41.72   | 13.40 | 115.00  | 33.36   | 28.68   |
| Cl       | 250        | 172.50  | 35.90   | 10.00 | 118.60  | 930.00  | 247.40  |
| HCO₃⁺     | 8.10       | 1450.00 | 311.78  | 118.60 | 930.00  | 355.40  | 247.40  |
| SO₄²⁻     | 50         | 15.00   | 3.88    | 1.50  | 11.10   | 5.05    | 3.11    |
| F         | 0.01       | 0.55    | 0.55    | 0.02  | 2.56    | 0.65    | 0.70    |
| E.C (μS/cm) | 345.00   | 3342.00 | 888.23  | 570.54 | 281.53 | 9692.00 | 1777.97 | 2721.19 |

(WHO)= The world health organization standard.

3.1. Interpolation and Elements Distribution Maps

The quality of interpolation is described by the difference of the interpolated value from the true value. Thus, the Anderson-Darling test, which is an ECDF (empirical cumulative distribution function) based test, tests the prospect that the value of a parameter falls within a particular range of values (confidence level 95%). The data points are relatively close to the fitted normal distribution line. The p-value is greater than the significance level of 0.05. Subsequently, the scientist fails to reject the null hypothesis that the data follow a normal distribution.
According to this test, in Fw-Rh area we found that the parameters (Na and K) showed a normal distribution when the other elements (Ca, Mg, HCO3, Cl, SO4 and TDS) showed a more or less abnormal distribution in Figures 4 and 5.

Figure 4. Graphical summary and probability plots of cations in Fw-Rh area.
The same test has been performed in (Qa-Qu) area, which showed that the (Mg and SO\textsubscript{4}) parameters reflected normal distribution while the other variables (Ca, K, Na, HCO\textsubscript{3}, Cl, and TDS) present non-normally distributions.

Generally, most of the collected elements in both Fw-Rh and Qa-Qu localities were skewed. However, the transformations (Log & BoxCox), have been used to make the data normally distributed and satisfy the assumption of equal variability for the data.
For the maps prediction, several kinds of semivariogram models were examined for each water quality parameter to obtain the preferable one, as seen in Figure 6 as an example. Predictive performances of the fitted models were checked on the basis of cross-validation tests. The values of mean error (ME), mean square error (MSE), root mean error (RMSE), average standard error (ASR) and root mean square standardized error (RMSSE) were estimated to ascertain the performance of the developed models. After conducting the cross-validation procedure, maps of kriged estimates were created that provided a visual representation of the distribution of the groundwater quality parameters in the Fw-Rh and Qa-Gu areas.

| Area | Groundwater Parameters | Kriging Type | Transformation | Best Fitted Model | ME  | RMSE  | ASE  | MSE  | RMSSE |
|------|------------------------|--------------|----------------|-------------------|-----|-------|------|------|-------|
|      |                        |              |                |                   |     |       |      |      |       |
| Fw-Rh| Na                     | Simple       | None           | Spherical         | −   | 1.5985| 71.0051| −0.0226| 0.9816|
|      |                        | Ordinary     | None           | Spherical         | −   | 0.2818| 13.6108| −0.0207| 0.9817|
|      | Ca                     | Ordinary     | Log             | Circular          | 0.6579| 32.1486| 30.1062| 0.0155| 1.0624|
|      | Mg                     | Ordinary     | Log             | Gaussian          | 0.5210| 18.9853| 22.6372| −0.0224| 0.8808|
|      | HCO₃                   | Ordinary     | BoxCox          | Stable            | 19.5080| 328.5189| 367.5360| 0.0498| 0.9083|
|      | Cl                     | Ordinary     | Log             | Circular          | −   | 0.4151| 38.0299| −0.0077| 1.0432|
|      | SO₄                    | Ordinary     | BoxCox          | Stable            | 0.0593| 0.6693 | 0.6351 | 0.0892| 1.0814|
|      | TDS                    | Ordinary     | BoxCox          | Stable            | 12.4257| 434.6693| 453.4310| 0.0294| 1.0040|
|      |                        | Simple       | None            | Stable            | 10.9458| 143.4509| 156.6227| 0.0688| 0.8907|
|      |                        | Simple       | Log             | Spherical         | −   | 0.1683| 27.1142| −0.0102| 1.4215|
|      |                        | Simple       | BoxCox          | Stable            | −   | 0.3761| 14.1042| −0.0176| 1.1645|
|      |                        | Ordinary     | Log             | Circular          | 1.6593| 20.6180| 23.8640| −0.0615| 1.0218|
|      |                        | Ordinary     | BoxCox          | Stable            | 15.3778| 261.7170| 258.9817| 0.0556| 0.9939|
|      |                        | Ordinary     | Log             | Stable            | −   | 0.3736| 9.6335 | −0.1165| 1.2648|
|      |                        | Ordinary     | None            | Spherical         | 0.0251| 0.3209 | 0.3193 | 0.0654| 1.0026|
|      |                        | Simple       | BoxCox          | Gaussian          | 6.7649| 614.1923| 453.6139| −0.2829| 1.8464|

(ME)= Values of mean error, (RMSE)= Root mean error, (ASE)= Average standard error, (MSE)= Mean square error, (RMSSE)= Root mean square standardized error.

![Figure 6. An example of Cross Validation Comparison. (a) Ordinary Kriging Spherical and (b) ordinary Kriging-Circular for Na element.](image)

Kriging (Ordinary and Simple) interpolation method is the most suitable method in the studied areas. The value range of the better interpolation models were observed and reported in Table 3. If the RMSE is close to the ASE, the prediction errors were assessed correctly. If the RMSE is smaller than the ASE, then the variability of the predictions is overestimated; conversely, if the RMSE is greater than the ASE, then the variability of the predictions is underestimated. The same could be deduced from the RMSSE statistic. It should be close to one. If the RMSSE is greater than one, the variability of the predictions is underestimated; also, if it is minimal than one, the variability is overestimated. After generating the cross-validation procedure, estimated maps of kriging were created, which gives a visual representation of the distribution of the groundwater quality parameters.
The hydro-chemical of Fw-Rh area; the sodium concentration patterns in Figure 7a show similar trends to the potassium in Figure 7b with higher values in the northwest and southeast when decreasing in the central part. The distribution of calcium Figure 7c, ranges from 4.54 mg/L to 37.47 mg/L, it reflects relatively moderate values in the middle of Fw-Rh area. The distribution of magnesium Figure 7d, ranges from 11.66 mg/L to 34.28 mg/L. It also reflects the relatively moderate value in the middle of Fw-Rh area. The distribution of bicarbonate Figure 7e, varies from 78.9 mg/L to 20.61 mg/L, it reflects relatively moderate value in the middle of the area. The bicarbonate HCO₃⁻ concentration Figure 7e, varies from 78.9 mg/L to 1450.00 mg/L, when the concentration of chloride Figure 7f, ranges from 8.10 mg/L to 78.9 mg/L, it reflects relatively moderate values in the middle of Fw-Rh area. The existence of potassium and sodium associated to the kaolin’s rich alunite (K, Na)Al₃(SO₄)₂(OH)₆ [36]); (Thirteen thematic layers of water quality parameters were used in ArcGIS environment to acquire the output of drinking water quality index DWQI maps for Fw-Rh Figure 8a, and Qa-Qu Figure 8b, localities. The water quality index was reclassified into five classes in order to characterize the quality of groundwater in the studied localities.

| Area  | Groundwater Parameters | Kriging Type | Transformation | Best Fitted Model | ME    | RMSE  | ASE  | MSE  | RMSSE |
|-------|------------------------|--------------|----------------|-------------------|-------|-------|------|------|-------|
| Fw-Rh | Na                     | Simple       | None           | Spherical         | −1.5985 | 71.0051 | 73.1880 | −0.0226 | 0.9816 |
|       | K                      | Ordinary     | None           | Spherical         | −0.2818 | 13.6108 | 14.0445 | −0.0207 | 0.9817 |
|       | Ca                     | Ordinary     | Log            | Circular          | 0.6579 | 32.1486 | 30.1062 | 0.0155  | 1.0624 |
|       | Mg                     | Ordinary     | Log            | Gaussian          | 0.5210 | 18.9853 | 22.6372 | −0.0224 | 0.8808 |
|       | HCO₃⁻                  | Ordinary     | BoxCox         | Stable            | 19.5080 | 328.5189 | 367.5360 | 0.0498  | 0.9883 |
|       | Cl                     | Ordinary     | Log            | Circular          | −0.4151 | 38.0299 | 37.4075 | −0.0077 | 1.0432 |
|       | SO₄²⁻                  | Ordinary     | BoxCox         | Stable            | 0.0593 | 0.6693  | 0.6351  | 0.0892  | 1.0814 |
|       | TDS                    | Ordinary     | BoxCox         | Stable            | 12.4257 | 434.6693 | 453.4310 | 0.0294  | 1.0040 |
|       | Na                     | Simple       | None           | Stable            | 10.9458 | 143.4509 | 156.6227 | 0.0888  | 0.8907 |
|       | K                      | Simple       | Log            | Spherical         | −0.1683 | 27.1142 | 19.2737 | −0.0102 | 1.4215 |
|       | Ca                     | Simple       | BoxCox         | Stable            | −0.3761 | 14.1042 | 11.5697 | −0.0176 | 1.1645 |
|       | Mg                     | Ordinary     | Log            | Circular          | 1.6593 | 20.6180 | 23.8640 | −0.0615 | 1.0218 |
|       | HCO₃⁻                  | Ordinary     | BoxCox         | Stable            | 15.3778 | 261.7170 | 258.9817 | 0.0556  | 0.9939 |
|       | Cl                     | Ordinary     | Log            | Stable            | −0.3736 | 9.6335  | 7.1223  | −0.1165 | 1.2648 |
|       | SO₄²⁻                  | Ordinary     | None           | Spherical         | 0.0251 | 0.3209  | 0.3193  | 0.0654  | 1.0026 |
|       | TDS                    | Simple       | BoxCox         | Gaussian          | 6.7649 | 614.1923 | 453.6139 | −0.2829 | 1.8464 |

(ME)= Values of mean error, (RMSE)= Root mean error, (ASE)= Average standard error, (MSE)= Mean square error, (RMSSE)= Root mean square standardized error.

![Figure 7](image-url)
random distribution values in the Qa-Qu area. The bicarbonate $\text{HCO}_3^-$ concentration Figure 9e, varies from 78.9 mg/L to 930.00 mg/L when the concentration of chloride Figure 9f, ranges from 10.00 mg/L to mg/L 45.00. The distribution of sulfate Figure 9g, ranges from 1.36 to 2.29, with the highest values in the southeast and lowest values in the southwest. The TDS in Figure 9h, ranges from 183.00 mg/L to 2007.00 mg/L, appears with low to medium values at the central part then, increases to the southeasterly direction. The Qa-Qa area represented the most of Gedaref Formation, which is superimposed and intercalated by basaltic rocks (Oligocene) and substantially covered by the clay soils. Thus, the origin of most of its cations could be from chemical weathering, hydro-chemical reactions and the solubility of minerals (See thirteen thematic layers of water quality parameters used in ArcGIS environment to acquire the output of drinking water quality index DWQI maps for Fw-Rh Figure 10a, and Qa-Qu Figure 10b, localities. The water quality index was reclassified into five classes in order to characterize the quality of groundwater in the studied localities.

Figure 9. (a) Na, (b) K, (c) Ca, (d) Mg, (e) $\text{HCO}_3^-$, (f) $\text{SO}_4^-$, (g) Cl, and, (h) TDS distributions in Qa-Qu area.
The project area describes three examples of groundwater aquifers; (1) sandstone aquifer, dominant at pH/Na negative correlation in (Qa-Qu) area, indicated as: Mg$^{+2}$ and Mg elements; Mg$^{+2}$ reflected strong correlations as: NO$^{3-}$ and Ca$^{+2}$ identified between Na found as (five boreholes) at Qa-Qu area. (Table 4); Fw-Rh; reveal a strong positive correlation can be dominant at Fw-Rh area; (12 Boreholes) and only one borehole at Qa-Qu area. (3) Basaltic aquifer Fw-Rh area; (11 Boreholes) and subdominant at Qa-Qu area; (5 Boreholes). (2) Alluvium aquifer, groundwater quality elements. These coefficients are applied to suppress the strength of the linear relationship between the variables. It has been used to estimate both positive and negative correlations. The project area describes three examples of groundwater aquifers; (1) sandstone aquifer, dominant at Fw-Rh area; (11 Boreholes) and subdominant at Qa-Qu area; (5 Boreholes). (2) Alluvium aquifer, dominant at Fw-Rh area; (12 Boreholes) and only one borehole at Qa-Qu area. (3) Basaltic aquifer found as (five boreholes) at Qa-Qu area. (Table 4); Fw-Rh; reveal a strong positive correlation can be identified between Na$^+$/K$^+$ (r = 0.99), TDS/E.C (r = 0.99), E.C/Mg$^{+2}$ (r = 0.55), TDS/Mg$^{+2}$ (r = 0.53), and Ca$^{2+}$/K$^+$ (r = 0.51). It is found that NO$_3^-$ in most of the groundwater samples in this locality reflected strong correlations as: NO$_3^-$ /TDS (r = 0.56), NO$_3^-$/E.C (r = 0.55), and NO$_3^-$ /Ca$^{2+}$ (r = 0.50).

### 3.2. Correlation Matrix

The correlation matrix provides the assessment of the correlation coefficients “r” between groundwater quality elements. These coefficients are applied to suppress the strength of the linear relationship between the variables. It has been used to estimate both positive and negative correlations. The project area describes three examples of groundwater aquifers; (1) sandstone aquifer, dominant at Fw-Rh area; (11 Boreholes) and subdominant at Qa-Qu area; (5 Boreholes). (2) Alluvium aquifer, dominant at Fw-Rh area; (12 Boreholes) and only one borehole at Qa-Qu area. (3) Basaltic aquifer found as (five boreholes) at Qa-Qu area. (Table 4); Fw-Rh; reveal a strong positive correlation can be identified between Na$^+$/K$^+$ (r = 0.99), TDS/E.C (r = 0.99), E.C/Mg$^{+2}$ (r = 0.55), TDS/Mg$^{+2}$ (r = 0.53), and Ca$^{2+}$/K$^+$ (r = 0.51). It is found that NO$_3^-$ in most of the groundwater samples in this locality reflected strong correlations as: NO$_3^-$ /TDS (r = 0.56), NO$_3^-$/E.C (r = 0.55), and NO$_3^-$ /Ca$^{2+}$ (r = 0.50).

### Table 4. Correlation matrix analysis result of the groundwater quality parameters in Fw-Rh area.

| Variables | pH   | TDS  | Ca   | Mg   | Na   | K    | Cl    | HCO$_3^-$ | SO$_4^{2-}$ | F    | NO$_3^-$ | Fe    | E.C  |
|-----------|------|------|------|------|------|------|-------|-----------|------------|------|--------|------|------|
| pH        | 1    |      |      |      |      |      |       |           |            |      |        |      |      |
| TDS       | 0.20 | 1    |      |      |      |      |       |           |            |      |        |      |      |
| Ca        | 0.11 | 0.26 | 1    |      |      |      |       |           |            |      |        |      |      |
| Mg        | 0.10 | 0.53 | 0.51 | 1    |      |      |       |           |            |      |        |      |      |
| Na        | -0.30 | 0.23 | 0.07 | 1    |       |       |      |           |            |      |        |      |      |
| K         | -0.31 | 0.23 | 0.08 | 0.99 | 1    |       |      |           |            |      |        |      |      |
| Cl        | -0.14 | 0.33 | 0.51 | 0.49 | 0.13 | 0.15 | 1    |           |            |      |        |      |      |
| HCO$_3^-$ | -0.11 | -0.16 | -0.07 | 0.10 | -0.01 | 0.00 | -0.10 | 1        |            |      |        |      |      |
| SO$_4^{2-}$ | 0.10 | 0.05 | -0.08 | 0.01 | -0.17 | -0.18 | 0.06 | -0.34 | 1        |      |        |      |      |
| F         | -0.26 | -0.17 | -0.35 | -0.21 | 0.14 | 0.13 | -0.18 | 0.09 | -0.26 | 1    |      |      |      |
| NO$_3^-$  | 0.25 | 0.56 | 0.49 | 0.32 | 0.24 | 0.24 | 0.16 | -0.19 | 0.03 | -0.21 | 1    |      |      |
| Fe        | -0.15 | -0.14 | -0.15 | -0.41 | -0.02 | -0.09 | -0.26 | -0.17 | 0.13 | -0.06 | 1    |      |      |
| E.C       | 0.19 | 0.99 | 0.24 | 0.55 | 0.00 | 0.00 | 0.34 | -0.16 | 0.05 | -0.16 | 0.55 | -0.15 | 1    |

Values in bold are different from 0 with a significance level alpha = 0.5.

(Qa-Qu); the magnesium has a strong positive correlation between most of the groundwater elements; Mg$^{+2}$/Ca$^{+2}$ (r = 0.75), Mg$^{+2}$/SO$_4^{2-}$ (r = 0.73), Mg$^{+2}$/HCO$_3^-$ (r = 0.54), Mg$^{+2}$/K$^+$ (r = 0.41), and Mg$^{+2}$/Na$^+$ (r = 0.40). Another positive correlation can be identified very strongly between; Na$^+$/K$^+$ (r = 0.99), HCO$_3^-$ /SO$_4^{2-}$ (r = 0.70), NO$_3^-$/Fe$^{2+}$ (r = 0.66), and pH/HCO$_3^-$ (r = 0.57). The strong negative correlation in (Qa-Qu) area, indicated as: Mg$^{+2}$/NO$_3^-$ (r = -0.54), Cl$^-$/Fe$^{2+}$ (r = -0.46) pH/Na$^+$ (r = -0.38), Mg$^{+2}$/K$^+$, (r = -0.38), and Ca$^{2+}$/F$^-$ (r = -0.35) (Table 5).
Table 5. Correlation matrix analysis result of the groundwater quality parameters in Qa-Qu area.

| Variables | pH | TDS  | Ca   | Mg   | Na   | K    | Cl   | HCO$_3$ | SO$_4$ | F    | NO$_3$ | Fe   | E.C   |
|-----------|----|------|------|------|------|------|------|---------|--------|------|--------|------|-------|
| pH        | 1  |      |      |      |      |      |      |         |        |      |        |      |       |
| TDS       | 0.09 | 1    |      |      |      |      |      |         |        |      |        |      |       |
| Ca        | 0.15 | 0.05 | 1    |      |      |      |      |         |        |      |        |      |       |
| Mg        | 0.13 | -0.09 | 0.75 | 1    |      |      |      |         |        |      |        |      |       |
| Na        | -0.38 | -0.09 | 0.04 | 0.40 | 1    |      |      |         |        |      |        |      |       |
| K         | -0.38 | -0.09 | 0.04 | 0.41 | 0.99 | 1    |      |         |        |      |        |      |       |
| Cl        | 0.33 | 0.45 | 0.29 | 0.06 | -0.19 | -0.19 | 1    |         |        |      |        |      |       |
| HCO$_3$   | 0.57 | -0.21 | 0.52 | 0.54 | 0.00 | 0.01 | -0.07 | 1    |        |      |        |      |       |
| SO$_4$    | 0.24 | -0.16 | 0.37 | 0.73 | 0.43 | 0.44 | -0.15 | 0.70 | 1    |      |        |      |       |
| F         | -0.27 | -0.22 | -0.35 | -0.18 | -0.09 | -0.09 | -0.16 | -0.42 | -0.30 | 1    |        |      |       |
| NO$_3$    | -0.26 | 0.06 | -0.19 | -0.54 | -0.15 | -0.15 | -0.34 | -0.08 | -0.50 | -0.16 | 1    |      |       |
| Fe        | 0.18 | -0.16 | -0.05 | -0.26 | -0.29 | -0.29 | -0.46 | 0.08 | -0.27 | -0.11 | 0.66 | 1    |      |
| E.C       | -0.13 | 0.24 | -0.16 | -0.04 | 0.14 | 0.16 | 0.13 | 0.34 | -0.27 | 0.15 | -0.23 | 1    |       |

Values in bold are different from 0 with a significance level alpha = 0.5.

3.3. Groundwater Facies

Groundwater facies were defined by applying a Piper plot and Durov diagrams as seen in Figures 11 and 12. The descriptions reveal that the area consists of eight groups of groundwater types Table 6, Na-Mg-HCO$_3$, Na-HCO$_3$, Na-Ca-HCO$_3$, Na-Ca-Mg-HCO$_3$, Mg-Na-Ca-Cl, Mg-Na-HCO$_3$, Na-Ca-Mg-HCO$_3$-Cl, and Na-Mg-Ca-HCO$_3$. The analytical results achieved from the samples when plotted on Piper’s plot, explained that the alkalis (Na$^+$, K$^+$), appear considerably over the alkaline elements (Ca$^{2+}$, Mg$^{2+}$), and the weak acidic (HCO$_3^-$) appear considerably over strong acidic anions (Cl$^-$ & SO$_4^{2-}$). Moreover, Piper diagram matched 40% of the samples, under Na-Mg-HCO$_3$ group and 35% under Na-HCO$_3$ type.

![Figure 11](image-url) (a) Piper and (b) Durov diagrams of Fw-Rh area.
Moreover, Piper diagram matched 40% of the samples, under Na-Mg-HCO$_3$ group and 35% under Na-HCO$_3$ type.

According to the plotting from the Durov diagram, most of the elements of water plotted within the HCO$_3$·Na zone, except some other samples that were fell in HCO$_3$ Cl–Na, SO$_4$·Cl·HCO$_3$–Na, or HCO$_3$·Cl–Na·Mg types.

### 3.4. Drinking Water Quality Index (DWQI)

To gain a comprehensive representation of the quality of the drinking groundwater, drinking water quality index (DWQI) is one of the useful tools. It supplies a single amount to a state’s overall water quality at a specific location and time, based on a number of water quality parameters. DWQI in Table 7, was calculated by adopting weighted arithmetical index method considering thirteen water quality parameters (pH, TDS, Ca$^{2+}$, Mg$^{2+}$, Na$^+$, K$^+$, Fe$^{2+}$, Cl$^-$, HCO$_3^-$, SO$_4^{2-}$, F$^-$, NO$_3^-$, and E.C) in order to assess the degree of groundwater contamination and suitability.

| DWQI Value | Rating of Water Quality | Percent % | Fw-Rh Area | Qa-Qu Area |
|------------|-------------------------|-----------|------------|------------|
| 0–25       | Excellent               | 8 (20%)   | 5          | 3          |
| 25–50      | Good                    | 20 (50%)  | 17         | 3          |
| 51–100     | Poor                    | 6 (15%)   | 3          | 3          |
| 101–200    | Very Poor               | 3 (7.5%)  | 2          | 1          |
| >>200      | Unsuitable for drinking | 3 (7.5%)  | 2          | 1          |

Thirteen thematic layers of water quality parameters were used in the ArcGIS environment to acquire the output of drinking water quality index DWQI maps for Fw-Rh Figure 13a, and Qa-Qu.
4. Discussion

In this study, most of the boreholes were recently drilled (2015–2017), no other boreholes were available. Due to the few observation points, limited previous investigations and few hydrogeological data, using geospatial distributions, GIS and DWQI provide support in groundwater studies. As far as we know, no other study was conducted using the techniques in Fw-Rh and Qa-Qu areas.

The chemical composition and elements concentration of groundwater, are related to the rocks lithology and time residence of the water in the aquifers. To identify the effects of the reaction between the groundwater and the (geological units) aquifer, the bivariate diagrams were applied to explain the chemical changes in ionic concentrations in the host rocks and groundwater. The reaction between water and the surrounding surface/soil from agricultural fields can change groundwater chemistry. The bivariate diagram of NO$_3$ vs. TDS and E.C, Figure 14a,b, records that six samples of alluvium aquifer and two samples of sandstone aquifer, plots along the 1:1 aquiline, show the highest correlation among TDS/NO$_3$. The appearance of NO$_3$ associated with the fertilizers activities in the agricultural farms [37–39]. The elements Na$^+$ versus K$^+$ Figure 14c, at both sandstone and alluvium aquifers, reflects a linear relationship at ($r = 0.99$) suggesting the reactions of water with sodium feldspar (Albite) and potassium feldspar (Orthoclase) in equations five and six respectively. The Mg$^{2+}$ strongly correlated with Ca$^{2+}$ and SO$_4^{2-}$ Figure 14d,e, especially in the basaltic aquifer and some other boreholes in the alluvium locations, show a high response of water with a group of minerals (i.e., Pyroxene, Olivine and Biotite) in equations seven, eight, and nine respectively. For the better understanding of geological units in research areas, the thin sections of rock samples have been generated and studied to identify the main mineral composition for each rock sample, as seen in Figure 15. With this ability, the rock mineral contents have been determined much better.
Conclusions

The hydrogeochemical evaluation outcomes and distribution of groundwater cations (Na+, Ca+2, K+, Mg +2) and anions (HCO3−, Cl−) have been studied in different aquifers. The main mechanism for the dissolution of rock minerals that releases the element such as: (Ca, Mg, Na, K and HCO3) into the groundwater, have been indicated in the following reactions:

(1) 
\[ \text{Ca(OH)}_2 + \text{H}_2\text{O} \rightarrow \text{Ca}^{2+} + 2\text{OH}^- \]

(2) 
\[ \text{Mg(OH)}_2 + \text{H}_2\text{O} \rightarrow \text{Mg}^{2+} + 2\text{OH}^- \]

(3) 
\[ \text{NaOH} + \text{H}_2\text{O} \rightarrow \text{Na}^+ + \text{OH}^- \]

(4) 
\[ \text{KOH} + \text{H}_2\text{O} \rightarrow \text{K}^+ + \text{OH}^- \]

(5) 
\[ \text{Na}_2\text{CO}_3 + \text{H}_2\text{O} \rightarrow \text{Na}^+ + \text{CO}_3^{2-} + \text{H}_2\text{O} \]

Figure 14. Bivariate diagrams of ionic relations in groundwater of different aquifers.

Figure 15. Selective rock thin sections: (a) Granite, (b) Migmatite gneiss, (c) Quartz Syenite, and Oligocene basalt (Qtz = quartz, Pl = plagioclase, Bi = Biotite, Orl = orthoclase, Px = pyroxene, & Oli = olivine).
The main mechanism for the dissolution of rock minerals that releases the element such as: (Ca, Mg, Na, K and HCO₃); into the groundwater, have been indicated in the following reactions:

(Pl) Anorthite : \( \text{CaAl}_2\text{Si}_2\text{O}_3 + 2\text{CO}_3 + \text{H}_2\text{O} \rightarrow \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 + \text{Ca}^2+ + 2\text{HCO}_3^- (4) \)

(Pl) Albite : \( 2\text{NaAl}_3\text{O}_8 + 9\text{H}_2\text{O} + 2\text{H}^+ \rightarrow \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 + 4\text{H}_2\text{SiO}_4 + 2\text{Na}^+ (5) \)

(Orl) Orthoclase : \( 2\text{KAlSi}_3\text{O}_8 + 11\text{H}_2\text{O} \rightarrow \text{Si}_2\text{O}_5\text{Al}_2(\text{OH})_4 + 2\text{K}^+ + 2\text{OH}^- (6) \)

(Px) Pyroxene : \( \text{CaMg(Si}_2\text{O}_6) + 4\text{CO}_2 + 6\text{H}_2\text{O} \rightarrow \text{Ca}^{2+} + \text{Mg}^{2+} + 4\text{HCO}_3^- + 2\text{Si}(\text{OH})_4 (7) \)

(Oli) Olivine \( (\text{Fe, Mg}^{2+})\text{SiO}_4 + 4\text{H}_2\text{CO}_3 \rightarrow 2(\text{Fe, Mg}^{2+}) + \text{H}_4\text{SiO}_4 + 4\text{HCO}_3^- (8) \)

(Bi) Biotite : \( \text{K(Mg, Fe)}_3(\text{AlSi}_3\text{O}_10)(\text{F, OH})_2 + 5\text{H}_2\text{O} + 4\text{CO}_2 \rightarrow 2\text{K} + \text{Mg} + \text{Fe(OH)}_3 + 4\text{HCO}_3^- + \text{H} + 2\text{F} (9) \)

5. Conclusions

This study explains the geospatial distribution, adopting statistical methods with GIS to characteristics and mapped the groundwater quality in the different hydrogeological units such as sandstone, alluvium, and basaltic aquifers, which are located in eastern Sudan (the southwestern part of Gedaref State). Forty water boreholes samples from different locations were collected, analyzed and estimated.

Aqua Chem v.2014.2 software has been used for groundwater quality elements analysis, while ArcGIS software was chosen for the interpretation and spatial mapping, so that groundwater quality estimation studies have been completed successfully. This study envisions the significance of graphical illustrations, i.e., Piper, Bivariate, Dendrogram, and Durov diagrams plot, to determine variation in hydro-chemical facies and to understand the evolution of hydro-chemical processes in Qa-Qu and Fw-Rh areas.

The hydrogeochemical evaluation outcomes and distribution of groundwater cations (Na⁺, Ca²⁺, K⁺, Mg²⁺) and anions (HCO₃⁻, Cl⁻, SO₄²⁻, F⁻) in both the Qa-Qu and Fw-Rh areas, shows that the groundwater is chemically affected by aquifer lithology. According to the plotting from the Durov diagram, most of the elements of water plotted within the HCO₃-Na zone, except some other samples that fell in HCO₃-Cl-Na, SO₄-Cl-HCO₃-Cl, or HCO₃-Cl-Na Mg types. With the exclusion of a few elements, the quality of groundwater is mostly suitable for drinking purposes and other domestic uses. The groundwater in this project is controlled by sodium and bicarbonate ions, which define the composition of the water type to be Na HCO₃. According to this investigation, three potential aquifers (sandstone, alluvium, and basalt); have been identified in the research areas.

The DWQI was used to determine the groundwater quality and its suitability for drinking purposes. According to this investigation, 20% of groundwater samples represent “excellent water”, 50% indicate “good water”, 15% represent “poor water”, 7.5% shows “very poor water”, and 7.5% appear as “unsuitable for drinking”. The drinking water quality index that was produced for this study reveals that the northwest and southeast parts of Fw-Rh and the southwest part of Qa-Qu locations has the poorest water quality, which is classified as “unsuitable for drinking”.

It should be noted, that the actual variations in spatial interpolations, can considerably diverge from the values predicted by spatial interpolation, it may lead to probable limitations of Kriging especially when data is scarce and unequally distributed. Thus, it is essential to know the number of data locations and the geographical extent of the region containing those data locations. In this case, one of the crucial steps is estimating the variogram model, which is more difficult with a small number of data locations. In this study, the transformations (Log & BoxCox), have been used to make the data normally distributed and satisfy the assumption of equal variability for the data. Several types of semivariogram models were tested in Table 3, for all water quality parameters to achieve more reliable results.
Author Contributions: T.H., B.A.E. & J.Z. had the initial idea for the research project and writing of the article, M.M.B., W.A. & B.A.E. accomplished fieldwork, data acquisition and implemented the research experiments, K.M.E. & E.H.A. helping in data analysis and maps layout, H.T. supervise the plan and evaluate the conclusion of the manuscript.

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