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Groundwater quality assessment using GIS, the case of Omdurman area, central Sudan

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Abstract

Omdurman area, located west of the River Nile and White Nile is witnessing rapid urban expansion and land use change. Several axial irrigation schemes have developed accelerating the demand for water supply. This indeed, will place more pressure over the available groundwater resources. In order to measure any change of groundwater quality it is necessary to initially evaluate the background condition. This contribution employs a GIS- based Groundwater Quality Index (GQI) which synthesizes different variable water quality data (e.g. Cl^-, Na^+ and SO_4^{2+}) by indexing them numerically relative to the World Health Organization (WHO) standards in order evaluate the overall groundwater quality in the study area.

The GQI computed for Omdurman area indicated that the water quality is generally high (mean GQI = 90 out of 100) with respect to the WHO standards. Spatially the groundwater quality of the study area increased from the central area in the northeastern direction and decrease in the southeastern direction. This result was interpreted in terms of general groundwater flow, the recharge zone, geology and soil composition. Drilling at close distances and over pumping specially in the central region might create local variations of groundwater flow resulting in mixing of waters of different qualities deteriorating the quality of water in previously safe zones. This is expected due to the low hydraulic gradient (< 0.001) characterizing some parts of the study area as well as the minimum recharge far from the River Nile and the White Nile.

المستخلص

منطقة أمدرمان الواقعة غرب نهر النيل و النيل الابيض تشهد تمدد عمراني سريع و تغير في إستخدامات الارض. العديد من مشاريع الري المحوري نمت لتزيد في الطلب على المياه. الشيء الذي سيضع حتماً عباً إضافياً على المصادر المتوفرة للمياه. من الضروري تحديد نوعية المياه الاساسية لنتمكن من قياس التغير فيها. هذه الدراسة تستخدم مؤشر نوعية المياه الجوفية القائم على نظام المعلومات الجغرافية و الذي يعمل على تحليل و إختزال المتغيرات المختلفة لنوعية المياه عن طريق مقارنتها بالمعدلات القياسية لمنظمة الصحة العالمية وذلك لقياس نوعية المياه بصورة عامة في منطقة الدراسة.

مؤشر نوعية المياه الجوفية لمنطقة أمدرمان أوضح أن المياه الجوفية بالمنطقة عالية الجودة (متوسط قيمة المؤشر =90 من 100) بالنسبة لمقاييس منظمة الصحة العالمية. مكانياً تزداد جودة المياه الجوفية في إتجاه الشمال الشرقي من وسط منطقة الدراسة بينما تتناقص في إتجاه الجنوب الشرقي. هذه النتيجة فسرت على أساس الإتجاه العام لسريان المياه الجوفية، نطاق التغذية، جيولوجية المنطقة و نوعية التربة. الحفر على مسافات متقاربة و الضخ العالي خصوصاً في المنطقة الوسطى قد يتسبب في تغيرات محلية في سريان المياه الجوفية ينتج عنها إختلاط مياه جوفية بنوعيات متباينة مما يغير في جودة المياه في المناطق الآمنة اصلاً. هذا متوقع نسبة للميل الهايدروليكي المنخفض (أقل من 0.001) الذي يميز بعض المناطق بالإضافة للتغذية الضعيفة بعيداً عن نهر النيل و النيل الأبيض.

Key words: Groundwater quality, WHO standards, index modeling, GIS

1- Introduction

Groundwater is almost globally important for human consumption as well as for the support of habitat and for maintaining the quality of base flow to rivers. They are usually of excellent quality. Being naturally filtered in their passage through the ground, they are usually clear, colourless, and free from microbial contamination and require minimal treatment. It seems that we can no longer take high quality groundwater for granted. A threat is now posed by an ever-increasing number of soluble chemicals from urban, industrial and modern agricultural activities. Nevertheless, environmental processes such as climate change may also impact the quality of groundwater by directly affecting aquifer recharge and indirectly increasing demand and posing stress over available resources in some regions. The chemical composition of groundwater is a measure of its suitability as a source of water for human and animal consumption, irrigation and for industrial and other uses. The definition of water quality is therefore not objective but is socially defined depending on the desired use of water. The chemistry (quality) of groundwater reflects inputs from the atmosphere, from soil and water-rock reactions (weathering) as well as from previously mentioned pollution sources. Therefore monitoring the quality of groundwater is necessary to ensure sustainable safe water resources. Background groundwater quality condition is a prerequisite for an appropriate evaluation of its change over space and time. Describing the overall water quality condition is difficult due to the spatial variability of multiple contaminants and the wide range of indicators that can be measured.

Omdurman, representing part of the capital city Khartoum, extends on the western side of the River Nile and the White Nile. It represents one of the highly populated spots in Sudan (>200 per squire kilometer). Recently, the region is experiencing a rapid development of large agricultural investments based on axial irrigation from groundwater. This poses extra stress over the available groundwater resources. Multiple drilling at close distance and over pumping to meet the new demands will indeed affect the groundwater flow system causing mixing of water of different qualities and abating natural recharge capabilities of the aquifer. Thus, it is necessary to determine the background groundwater quality in the region to appropriately evaluate any change in time and space before initiating monitoring practices to support sustainable management and planning of these resources.

In this contribution the authors aim to use the groundwater quality index (GQI) proposed by Babiker et al. [1] which synthesizes different available quality data into easily understood format. This index provides a way to summarize overall water quality conditions in a manner that can be clearly communicated to different audiences, can help understanding whether quality of groundwater poses a potential threat to various uses of water, can validate and complement aquifer vulnerability assessments and can indicate success in protection and remediation efforts. Here, the capabilities of geographical information system (GIS), will be employed to implement the proposed index and perform a statistical procedure to select the optimum parameters to compute the GQI. GIS are designed to collect diverse spatial data to represent spatially variable phenomena by applying a series of overlay analysis of data that are in spatial register [2].

2- The study area

The study area, located between latitudes 15^o 26$^'$ 38$^"$ and 15^o 45$^'$ 47$^"$ and longitudes 32^o 18$^'$ 44$^"$ and 32^o 34$^'$ 5$^"$ (Fig. 1), represents part of the Nubian Sandstone aquifer that covers about 30% of the old united Sudan and provides 70% of water storage in the country. It is found overlying unconformably the basement complex rocks and consists of indurated sands and gravels of variable grain sizes [3] deposited in an alluvial environment during the Cretaceous [4]. The thickness of the aquifer ranges between 300~500 meters separated in some parts into two aquifers: upper and lower by lenses of clay with variable thickness. This indicates a semi-confined aquifer. In the southern part of the study area, the Nubian sandstone is cut by intrusive volcanic basalts introduced during the Cenozoic age causing thermal metamorphism of the sedimentary rocks. This thermal metamorphism resulted in a considerable decrease of permeability and porosity of the sandstone aquifer as well affected the quantity and quality of groundwater [5]. The River Nile and its tributary the White Nile are the main sources of recharge. The hydraulic conductivity and yield of the aquifer increase towards the recharge zone (the River Nile) with some local differences due variations in the grain size of sediments (heterogeneity), degree of consolidation and the presence of clay lenses. . Elkrail et al [6] made a serious attempt to hydrochemically evaluate the groundwater at Khartoum State. They delineated salinity zones (brackish water) in shallow groundwater attributed to the evaporation and evapotranspiration rates due to arid climate.

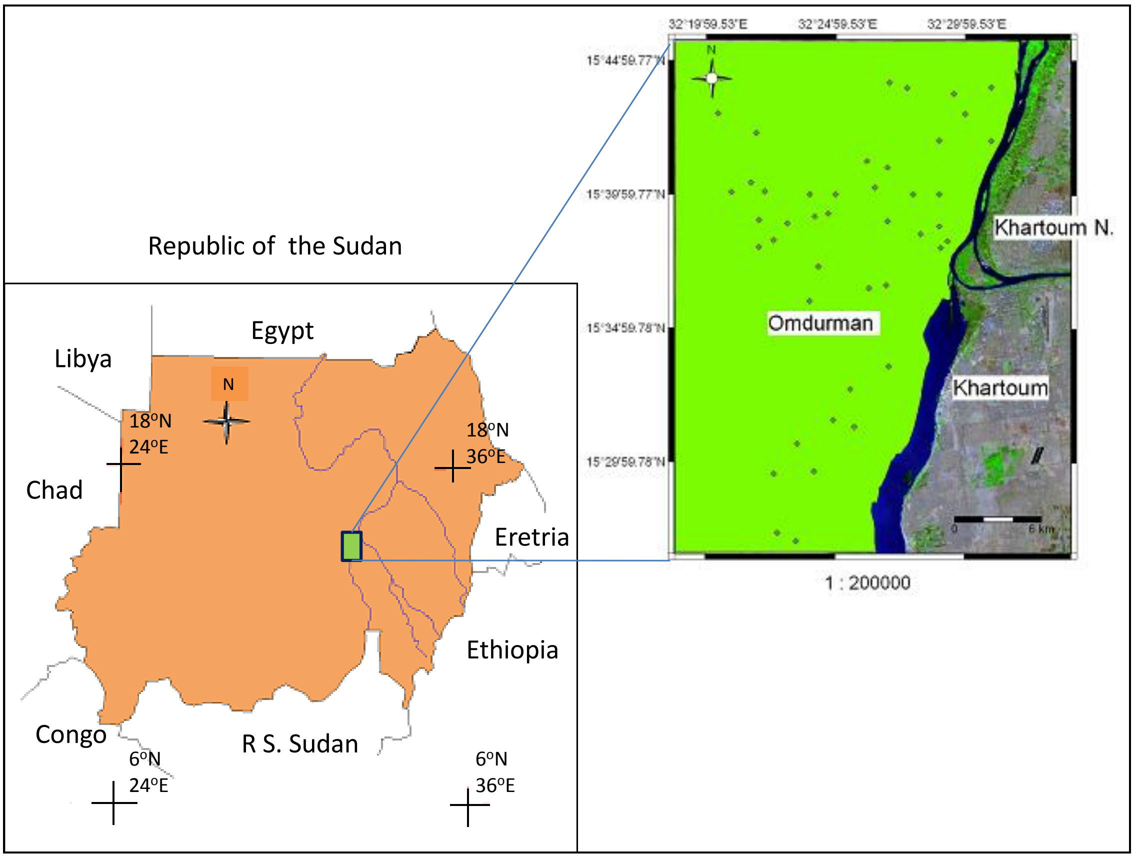

Fig 1 Location of the study area (Omdurman). The background is a Landsat colour composite (247) of the study area. The diamond shape indicates the location of water wells used in this study.

The study area is part of the arid semi-arid zone characterized by hot dry summer (March~June), moderately cold dry winter (November~February) and a rainy season between July and October. The annual rainfall ranges between 50~180 mm (average 157mm). Due to the scarse precipitation the main surface drainage is represented by the River Nile, the White Nile and seasonal wadies. Topographically, the area is flat plain where the surface elevation ranges between 380 and 400 m a.s.l. Elevated sedimentary hills (e.g, J. El Markhiat) are also encountered

3- Data and methods

3-1- Groundwater quality data

Water quality data for a number of 46 wells from the area west of the River Nile and White Nile were collected from several governmental agencies (Ministry of Agriculture and Irrigation: Groundwater and Wadies Directorate, Land use, Soil Conservation and Water Programming Administration and National Drilling and Investment Company) drilling companies (Islamic Development and Drilling Co. Ltd., Rawan Engineering Drilling Co. Ltd. and Darcy Co. Ltd.). These wells were chosen based on their location in the study area and completeness of data required to run the model.

Six parameters which are listed in the World Health and Organization (WHO) guidelines [7] for drinking water quality were selected from the data set to generate the GQI. Standards for drinking water were chosen since human health is taken as priority besides the high quality of drinking water makes it suitable for many other kinds of purposes. The six parameters (Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-} and Total Dissolved Solids (TDS)) fall under the category of chemically derived contaminants that could alter the water taste, odor or appearance and affect its “acceptability” by consumers [7]. Fixed guidelines have not been established for these chemical species, only thresholds for maximum desired concentrations were discussed. Parameters such as nitrate (NO_3^-) which are listed under the category of chemicals that might inflict "potential health risk" and are assigned a guideline value (50mg.l), were not available for all wells and were therefore, ignored when found (insufficient data). Table (1) displays the statistics of six groundwater quality parameters and their corresponding WHO threshold values.

Table 1 Statistics of seven groundwater quality parameters from Omdurman area and the corresponding maximum threshold values according to the WHO.

Parameter	Statistics of groundwater quality data from Omdurman			WHO threshold value
	Minimum	Maximum	Mean	
Ca^{2+} (mg/l)	18	132	40.2	300 mg/l
Mg^{2+} (mg/l)	2.5	57.6	24.1	300 mg/l
Na^{+} (mg/l)	2	440	91.9	200 mg/l
SO_4^{2-} (mg/l)	3	700	96.7	250 mg/l
Cl^{-} (mg/l)	5.4	296	68.5	200 mg/l
TDS (mg/l)	120	2072	524	600 mg/l

3-2- Data input and preparation of GIS model

In order to capture the spatial variation of groundwater quality of Omdurman area, spatial analyses with GIS were conducted employing ILWIS, the GIS software of the International Institute for Geo-Information Science and Earth Observation (ITC).

First the collected well data was input to build up the spatial data base. The data base includes the well name, location (coordinates), the static water table level in addition to the concentration in mg/l of the six chemical parameters mentioned above. A sub-image of the Landsat false colour composite 247 was used as a base map to display the well distribution and surface drainage system.

The GIS used here adopts the raster model which represents the simplest way for storing spatial data. In this model the spatial data consists of cells or pixels (30 m in size)- organized in rows and columns- for which information is explicitly recorded. The raster model is suitable for the kind of overlay analysis performed in this study because it provides; a simple data structure, easy and efficient overlaying, sufficient representation of high spatial variability and unified grid cells for several attributes. However, some drawbacks might affect the analyses and results of raster model such as; the large computer storage, errors in perimeter, areas and shape of geographical entities, inefficient projection transformations, loss of information when using large cells and less accurate and beautiful maps.

3-3- Spatial autocorrelation and cross correlation of groundwater quality variables

Many variables that have discrete values measured at several locations (such as the concentration of chemical constituents in groundwater) can be considered as random process which processes a certain degree of correlation with itself in space. First, pattern analysis was used to examine the arrangement of the well data in space and to investigate whether they are randomly distributed. Second, the spatial autocorrelation analysis is used to show the correlation between parameter values for different shifts in space and to visualize the spatial variability of the phenomenon under study (groundwater quality). On the other hand, chemical constituents in groundwater are usually spatially correlated. Therefore the spatial autocorrelation can measure the level of interdependence between different variables and the nature and strength of the interdependence. This is critical for the construction of the GQI model and understanding its performance and sensitivity.

3-4- Development of the groundwater quality index, GQI

The following sub-sections describe the steps leading to the formulation of the GQI. The process involves the generation of representations for the spatial variability of the originally scattered measurements and the multiple transformations of groundwater quality data into a corresponding index rating value related to groundwater quality.

3-4-1- The primary map I

Concentration maps representing the "primary map I" was constructed for each parameter from the point data using Kriging interpolation. Unlike other point interpolation methods (nearest point or moving average) Kriging is built on a statistical method. It requires an input point map and returns a raster map (primary map I) with estimations (concentration value) for each cell, together with an error map. The Kriging method performs a weighted averaging on point values where the output estimates equal the sum of product of point values and weights divided by the sum of weights. The weight factors in Kriging are determined by using a user-defined semi-variogram model based on the output of a spatial correlation operation and the distribution of input points [8].

3-4-2- The primary map II

In order to relate the data to universal norm, the measured concentration, $X^{'}$, of every pixel in the "primary map I" was related to its desired WHO standard value, X, using a normalized difference index:

$$C = X^{'} - X / X^{'} + X \quad (1)$$

The resultant "primary map II" thus displays for each pixel a contamination index values ranging between -1 and 1. This is close to the contamination index approach which is calculated as the ratio between the measured concentration of contaminant and the prescribed maximum acceptable contaminant level [9, 10, 1]. However, the normalized difference index used here provides fixed upper and lower limits for the contamination level.

3-4-3- The rank map

The contamination index (primary map II) was then rated between 1 and 10 to generate the "rank map". The rate 1 indicates minimum impact on groundwater quality while the rate 10 indicates maximum impact. The minimum contamination index level (-1) was set equal to 1, the median level (0) was set equal to 5 and the maximum level (1) was set equal to 10. The following polynomial function can thus be used to rank the contamination level (C) of every pixel between 1 and 10:

$$r = 0.5*C^2 + 4.5*C + 5 \quad (2)$$

Where C stands for the contamination index value for each pixel and r stands for the corresponding rank value. An example of three step maps for a single parameter (TDS) is presented in Figure (2).

3-4-4- The GQI

The GQI was calculated as follows:

$$GQI = 100-((r_1w_1+r_2w_2+....+r_nw_n)/N) \quad (3)$$

r, stands for the rate of the rank map (1～10); w, stands for the relative weight of the parameter which corresponds to the “mean” rating value (r) of each rank map (1～10) and to the “mean r + 2” (r ≤ 8) in the case of parameters that have potential health effects (e.g. nitrate); N is the total number of parameters used in the suitability analyses.

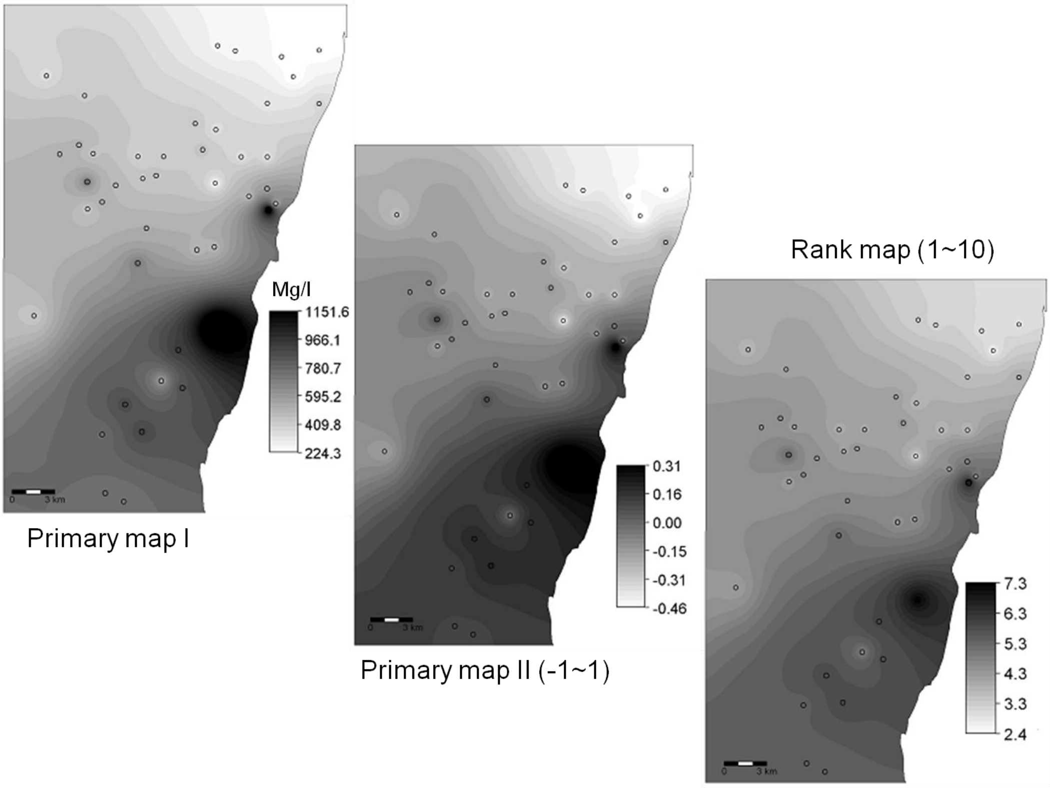

Fig 2 An example of three step maps (primary map I, primary map II and Rank map) for a single parameter (TDS). Refer to the text for the procedure of obtaining three maps.

The main part of the GQI represents an averaged linear combination of factors. The weight (w) assigned to each parameter indicating its relative importance to groundwater quality, corresponds to the mean rating value of its “rank map”. Parameters that inflict higher impact over groundwater quality (high mean rate) are assumed to be similarly more important in evaluating the overall groundwater quality. Particular emphasis was given to contaminants that posses potential risk to human health (w = mean r +2). This helps to avoid subjectivity associated with assigning weights of importance to the different parameters involved in the index computation. Dividing by the total number of parameters involved in the computation of the GQI averages the data and limits the index values between 1 and 100. In this way the impact of individual parameters is greatly reduced and the index computation is never limited to a certain number of chemical parameters. The “100” in the first part of the formula was incorporated to directly project the GQI value such that high index values close to 100 reflect high water quality and index values far below 100 (close to 1) indicate low water quality.

The index scores are presented based on the classification scheme introduced by Chung and results without imposing arbitrary thresholds, it is considered free of subjectivity and useful in comparing results from different areas.

3-5- Potential GQI

This section addresses two concerns basically originating from the spatial distribution and association of the different groundwater quality indicators (parameters). First, many of the water quality parameters are spatially invariable which imply that they contribute little to the variation of the overall GQI in the study area. Second, most of major chemical constituents in groundwater are spatially correlated which involves duplication and increases the probability of misjudgment. Since the above mentioned data properties might affect the reliability of the computed index an objective method was introduced by Babiker et al. [1] in order to select the best combination of water quality parameters to generate a GQI that could best display the actual situation of groundwater quality in any area. The optimum Index factor (OIF) [8] is used to select the optimum combination of three rank maps with the highest amount of information (highest sum of standard deviations) and least amount of duplication (lowest correlation among map pairs).

$$OIF=SD_i+SD_j+SD_k/|Corr_{i.j}|+|Corr_{j.k}|+|Corr_{i.k}| \quad (4)$$

Where I, j and k; are any three rank maps, SD; standard deviation, corr; correlation. Thus the maximum OIF value indicates the best combination of rank maps.

4- Results and discussion

4-1- Aspects of spatial autocorrelation, spatial variability and cross correlation of groundwater quality variables.

The result of pattern analysis indicated that the point data (wells) are arranged in a complete spatial randomness. The probability of finding one, two, three, four, five and six other point(s) within the specified distance of any point showed an exponential growth with distance. The spatial autocorrelation analysis indicated all variables have either very weak positive or negative autocorrelation again indicating their typical randomness.

On the other hand correlation analysis reflects the significant spatial association between the six groundwater quality variables (Fig. 3). The Na^+ ion was more correlated to the SO_4^{2-} than to Cl^- which supports the assumption of their dissolution from soil salts (Na_2SO_4) that characterize the upper part of El Gezira and Omdurman formations. The stronger correlation of Ca^{2+} and Mg^{2+} with SO_4^{2-} (0.69 and 0.61, respectively) compared to their correlation with HCO_3^- (0.5 and 0.49, respectively) indicates a none-carbonate type of hardness in groundwater. The groundwater of the study area ranges from soft to moderately hard (20 ~ 190 mg/l).

Ca^{2+}					
Mg^{2+}	0.54				
Na^+	-----	0.37			
SO_4^{2-}	0.69	0.61	0.75		
Cl^-	0.46	0.67	0.72	0.70	
TDS	0.61	0.74	0.79	0.94	0.84
	Ca^{2+}	Mg^{2+}	Na^+	SO_4^{2-}	Cl^-

Fig 3 Correlation matrix of six groundwater quality parameters in Omdurman area. All correlations are significant at p=0.01.

4-2- Groundwater quality of Omdurman area

Figure (4) shows that the groundwater of the study area is generally high (mean GQI = 90.3, maximum quality =100). Seven groundwater quality classes were identified in the study area at a 10% interval. The classification scale reflects the same level of detail for the six lowest classes corresponding to 60% of the total area. The 40% of the study area of the best groundwater quality was considered less important and was assigned a one-class interval (>60%). The statistics (Table 2) of the six rank maps (parameters) used to compute the GQI, indicate that parameters such as TDS, Na^+, SO_4^{2-} and Cl^- dictate the spatial pattern of groundwater quality portrayed in Figure (3) due to their high mean rank value and spatial variability (standard deviations).

Table2: Statistical summary of the six rank maps used to generate the groundwater quality index for Omdurman area.

	Statistics of rank maps			
Parameter	Minimum	Maximum	Mean*	SD
Ca^{2+} (mg/l)	1.4	3.3	1.89	0.19
Mg^{2+} (mg/l)	1.2	2.2	1.54	0.12
Na^+ (mg/l)	1.2	6.6	3.42	0.94
SO_4^{2-} (mg/l)	1.1	7.2	3.03	0.95
Cl^- (mg/l)	1.3	5.9	2.99	0.71
TDS (mg/l)	2.4	7.3	4.73	0.83

SD, the standard deviation. The mean rank values are used as weighting factors for the corresponding parameter in the GQI formula.

The GQI map shows a central zone of moderate quality increasing in the northeastern direction but decreasing in the southeastern direction. The first gradient is in harmony with the groundwater flow direction from the northeast (recharge zone, River Nile) to the southwest which imply an increase of ions concentrations in the groundwater due to dissolution of rock minerals along the flow direction. The second gradient however, may be attributed to the mineralization associated with the intrusion of Cenozoic basalts in the southern part of the study area (J. Toria outcrops in the area). The intrusion of basalt in the area may have caused thermal metamorphism of the Nubian sandstone [5] resulting in the decrease of its porosity and permeability as well as increase in mineral dissolution due to slow water movement. Another reason for the low groundwater quality in the southern part of the study area particularly close to the White Nile River banks could be attributed to the dissolution of soil salt (mainly, Na_2SO_4) that characterize the upper part of El Gezira and Omdurman formations [6]. This assumption was also supported by the cross-correlation analysis discussed in the previous section.

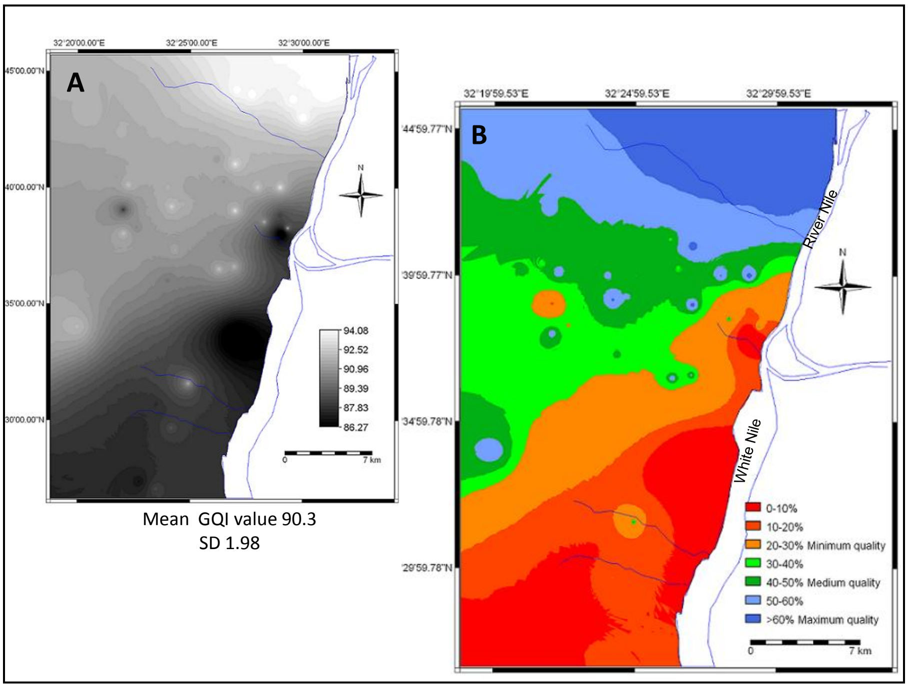

Fig 4 The groundwater quality of Omdurman area. A: the GQI (using all six parameters) (0~100), B: the GQI classified according to [10], SD: standard deviation.

The potential GQI computed using three parameters selected based on the OIF method; Na^{+}, Cl^{-} and SO_4^{2-} reveals a similar pattern of spatial variability of groundwater quality in the study area however - as expected - displayed a slightly lower mean index value (90) and more spatial variability (Fig. 5). This suggests that the GQI index is suitable for relative assessment of groundwater quality rather than absolute assessment [1]. Generally, the OIF method enabled to choose the best data set to represent groundwater quality avoiding duplication in an objective manner.

In general, the globally important groundwater resources have become under great risk due to the drastic increases in population, modern land use applications and demands for water supply, that endanger both water quantity and quality. Omdurman area in particular and the region west of the River Nile and the White Nile is not an exception. It is witnessing an accelerating development and change of land cover/land use associated with the emergence of several axial irrigation schemes for mechanized modern agricultural production. This indeed, will place more pressure over the available groundwater resources. In this contribution the GQI model of Babiker et al. [1] enabled to evaluate the overall groundwater quality of the study area. This index provided way to summarize overall water quality condition using commonly measured variables of water quality in a manner that can be clearly communicated to different audiences, can help to understand whether overall groundwater aquifer poses a potential threat to various uses of water and to indicate success in protection and remediation efforts. Obviously, the groundwater of Omdurman area is generally high with respect to the WHO standards. Spatially, it increases from the central area in the northeastern direction and decrease in the southeastern direction. Regions of low groundwater quality can then be targeted for more detailed investigations and tight monitoring programs. Drilling at close distances and over pumping specially in the central region might create local variations of groundwater flow resulting in mixing of waters of different qualities deteriorating the quality of water in previously safe areas. This is expected due to the low hydraulic gradient (< 0.001) characterizing some parts of the study area as well as the small amount of recharge far from the River Nile and White Nile.

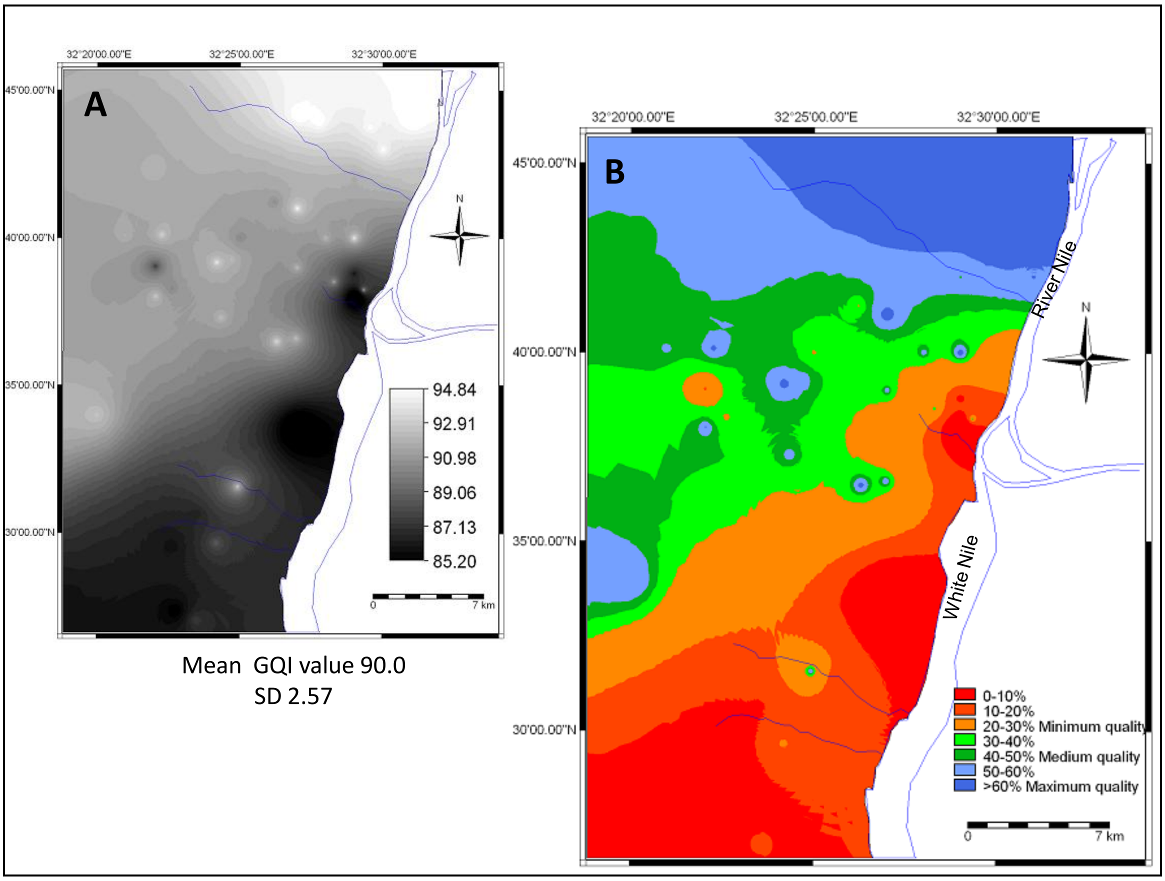

Fig 5 The groundwater quality of Omdurman. A: the potential GQI (using three parameters; Cl^-, Na^+ and SO_4^{2+}) (0~100), B: the potential GQI classified according to [10], SD: standard deviation.

The statistical investigations of the quality variables used in the GQI model indicated several degrees of interdependence and variability. Together with their relative values they all dictate the spatial pattern of groundwater quality in the study area. Generally, the GQI provides a relative assessment of the variability of water quality based on commonly available groundwater quality indicators (major ions). However, specifically important water quality indicators (e.g. Dioxin, Nitrate, bacteria count,…) for the local environment can always be incorporated to address the problem of groundwater quality in any area.

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