Sciknow Publications Ltd.
Journal of Engineering Geology and Hydrogeology

JEGH 2014, 2(4):54-61
DOI: 10.12966/jegh.11.02.2014

Groundwater Resource Potential and Water Balance Components in Tokar Delta- Sudan

Elgaily M. Babiker[1,*], E. A. Elzein Mohammed[2]

[1]Faculty of Earth Sciences Red Sea University Portsudan P.O.Box 24, Sudan
[2]Faculty of Pure and Applied Sciences, International University of Africa, Khartoum, Sudan

*Corresponding author (Email: elgailymb@hormail.com)

Abstract - Hydro geological investigation including measurements of water level and pumping test were carried out during wet and dry seasons in Tokar Delta area. This in connection with the vertical electrical sounding measurements was used to evaluate the groundwater potentiality and to assess the various components of water balance in the study area. Water in storage and annual recharge were estimated. The area underwent annual water deficit of about 1.2 million cubic meters which appears to be taken from the groundwater storage. Using the concept of Groundwater Potential Index (GWPI), the study area was classified into three sub-areas to help in future groundwater development.

Keywords - Tokar Delta, Groundwater balance, Groundwater potential index

1. Introduction

Tokar Delta is located in the southern part of the Sudanese coastal plain. It extends between latitudes 18°00' and 18°45' N and longitudes 37°30' and 38°05' E covering an area of approximately 1450 square kilometer. The delta has been formed by Khor Baraka which is an intermittent stream originates in the higher lands of Eritrea and Sudan. It flows northeast across the area and terminates in a wide delta which starts from Shidden Rock and ends at the Red Sea (Fig.1). The river flows for a period of three months a year during or shortly after the rainy season with a mean annual discharge of $260X10^6$ cubic meter and average duration of flow between 61 and 124 days (Hobler et al., 1980; Babiker, 2008).The climate of the Red Sea littoral area is a typical semi desert climate where precipitation mainly occurs during the winter months from October to March with annual average of 100 mm. However, the replenishment of the aquifers occurs due to the flood waters rise from the summer (July through September) monsoon-type rains on the hills and the mountains (RRI, 1989). Tokar Delta is known to be one of the important agricultural areas of Sudan having the most fertile soil and the biggest cultivated area in the Red Sea State (RSS). Groundwater recharge measurement in semiarid and arid areas is particularly a controversial issue that inherits uncertainty, because aquifer recharge is generally low and variable (Simmers, 2000). Groundwater is known to be the sole source for drinking water and watering livestock in the study area. Moreover groundwater is used for complimentary irrigation after the flood season. Also there was a water loss via seepage to the sea and to the very coastal area of the delta (El Natiq, 1976; Babiker, 2008). Hence the estimation of groundwater potential is of great importance in these semiarid areas for future groundwater development projects. This study is aiming at evaluating the components of groundwater budget, estimating of groundwater in storage and subdividing the area according to its potentiality using the approach of groundwater potential index.

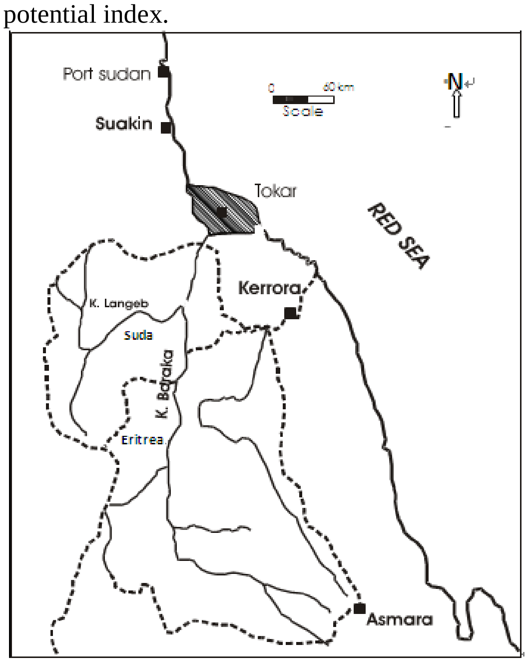

Fig. 1. Location map and catchment area of Khor Baraka

2. Geological Setting

Tokar Delta and its offshore continuation is a part of a NW-SE trending fault controlled sedimentary basin which developed during the Tertiary. The western boundary of the delta is marked by NNE trending faults (RRI and GRAS, 1995). Outcrops of the Basement rocks occur at the lower reaches of Khor Baraka, they comprises mainly of volcano- sedimentary sequences of high grade metamorphism. Tertiary formations overlie the basement rocks and only have been reported in boreholes drilled for oil exploration. Quaternary sediments include the alluvial fan sediments of Tokar Delta which consist mainly of gravels, sands and silts with some clayey layers, have a maximum thickness of about 500m in the middle part of the delta (Babiker, 2008). Quaternary Formations also include reef deposits, which represent the major features of the coastline of Tokar Delta (Whiteman, 1971), and lagoon deposits composed mainly of evaporites. Geological map of the study area is shown in (Fig.2).

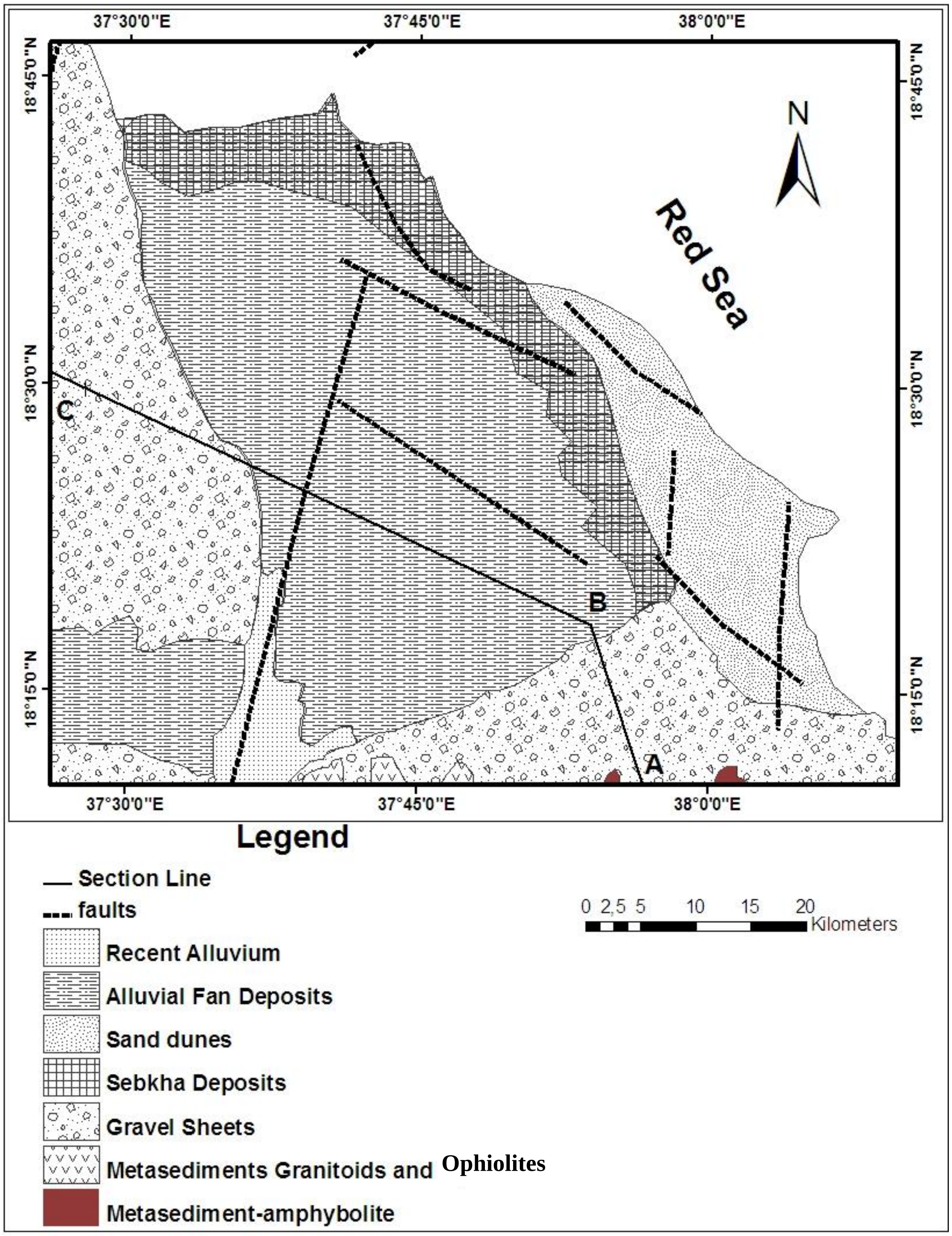

Fig. 2. Geological Map of Tokar Delta and adjacent area (modified after GRAS 2001)

3. Methodology

Systematic geophysical and Hydro geological investigations were carried out in the area. The hydro geological investigation has included more than 70 wells and 15 boreholes. The distribution of these wells is largely controlled by rural settlement and farming activities. Repeat measurements of water level were carried out in the months of December 2003 and June 2004. Geoelectrical survey included 33 vertical electrical sounding (VES) points was conducted to delineate the areal extent and thickness of the aquifer. Former drilling works have given direct information as regard to the geological stratification, and the litho logy of the formations encountered. The locations of the borehole and the VES points are shown in Fig, 3.

4. Results and Discussion

Results obtained from hydro geological and geophysical investigation are revealed and discussed below to understand the hydro geological setting, flow regime and groundwater potentials in the study area.

4.1. Hydro geological Findings

The aquifer system in the study areais semi confined to semi unconfined and comprises of alluvial fan deposits of Toker delta. It is a uni-layered aquifer system consisting of gravel and sand with intercalations of fine sediment which become dominant in the north-eastern part of the delta near Tokar town because of the decreasing velocity of surface flow. On the other hand cobbles and boulders up to 30cm in diameter occur in the up-stream part of the aquifer near Dolabyai (Fig.3).The sediments are sub angular to sub rounded indicating that they were derived from the basement rocks of the catchment area. The elevation of the water level ranges between 36 m above mean sea level (amsl) in the southwest to 5 m (amsl) in the northeast. The general groundwater flow is from SW to NE parallel to the direction of the surface flow. The geoelectric investigation has shown that the freshwater in the aquifer overlies saline or brackish water. The freshwater-bearing aquifer has an area of 200 square kilometre representing about 14% of the total area of the delta and its thickness varies between less than 10 m to more than 80 m the latter is attained near and southwest of well No. 20 at Krimbit well field (Fig.3). The aquifer has reasonable hydraulic properties. The transmissivity and specific yield values obtained by pumping test methods and are summarized in (Table 1).

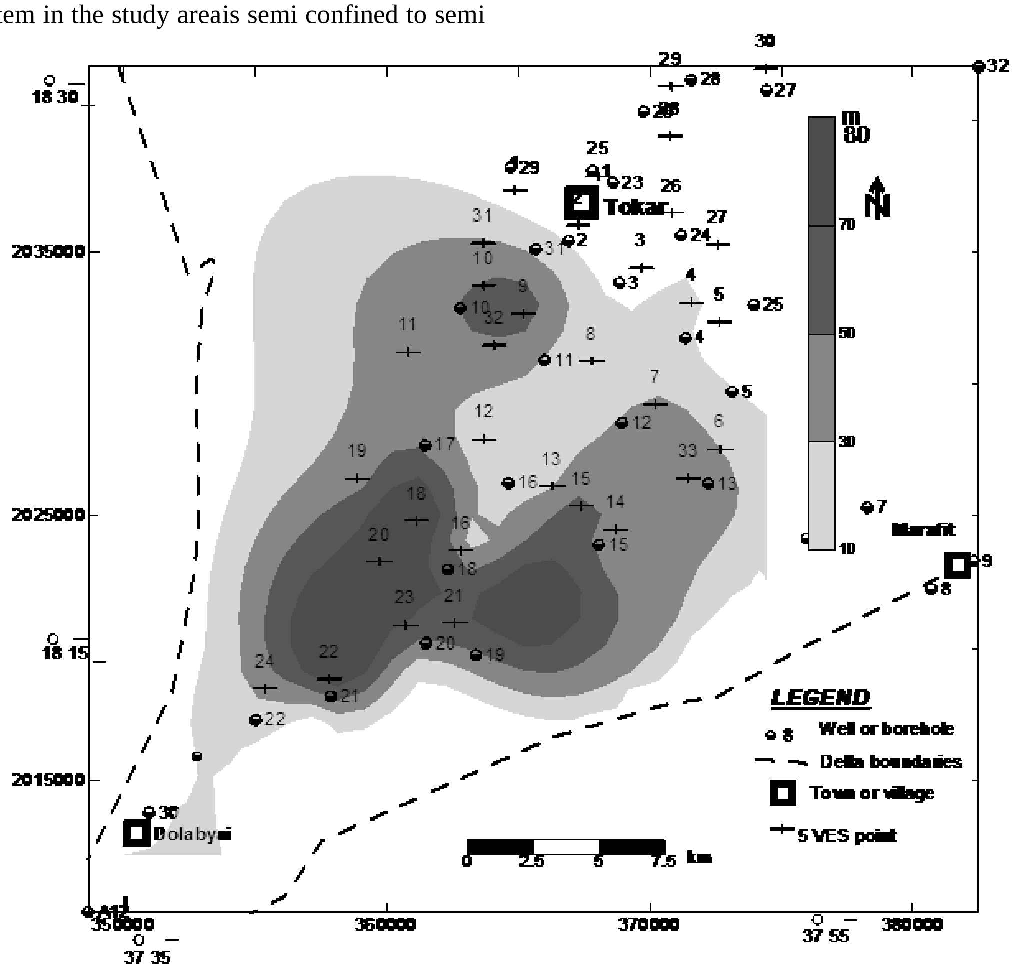

Fig. 3. Freshwater aquifer- thickness map determined by the geolelectric surveys and the borehole data

Table 1. Pumping test data analysis

Well no.	T in m2/d	Specific yield %
2 (bail test)	120	-
9	415	0.31
11 (bail test)	444	-
17 (bail test)	904	-
20	1030	0.04
22 (bail test)	830	-
31	577	0.03
A 12	1506	0.1
6730	4960	0.16

4.2. Groundwater in Storage

Evaluation of the amount of water in the aquifer is done on the basis of averaging the values obtained for the aquifer thickness (Fig.3), the specific yield (Table1) and the area of the freshwater body, using the formula:

$$S = h.\ S_{y.}\ A \quad (1)$$

Where:

S is the total water storage in the aquifer in cubic meter

h is the average saturated thickness of the aquifer in meter (30 m)

S_y is the average specific yield 0.13

A is the total area of the freshwater aquifer in meter square (200 x106m2). Hence water in storage is approximately equal to 642x106 m3.

4.3. Groundwater Recharge

Recharge of Tokar Delta aquifer comes almost entirely from the intermittent stream Baraka, where during the flood season large amounts of flood water enter the aquifer by infiltration. Infiltration rates of 40 – 100 mm/hour were determined for the overburden layers by Hobler et al (1980). Infiltration causes the water level to rise considerably with a mean value of seasonal fluctuation of 1.5m. The following methods are used to estimate the annual recharge in the study area.

1) Unsteady state method

Annual recharge is estimated on the basis of water level fluctuation. Two seasons could thus be identified to demonstrate the water table behavior during the wet and the dry seasons. Peak levels were recorded in December, whereas the minimum levels were recorded in June. The measured seasonal water level fluctuation during the period of the study ranges between 0.5 and 2 m.

The non steady state method was used applying the following formula:

$$R= S_{ya}.\ \Delta h_a.\ A \quad (2)$$

Where:

R is the annual recharge measured in cubic meter

S_{ya} is the average specific yield (0.13)

Δh_a is the net increase in the elevation of the water level in meters between the dry and the wet seasons (1.5m).

A is the surface area of the aquifer in square meter, which is estimated according to the aerial extent of the freshwater zone (200 $x10^6 m^2$). Accordingly the annual recharge is calculated as $31x10^6$ m^3/y.

2) Darcy's approach

Darcy's formula is applied to estimate the annual recharge by the subsurface inflow which takes place through the inlet of the aquifer. The subsurface inflow contributes to the total annual recharge that has already been calculated using the unsteady state method. The total volume of water entering the aquifer as subsurface inflow along the inlet can be calculated (Mandel and Shiftan, 1981) using Darcy's law:

$$Q = T.I.L \times 365 \quad (3)$$

Where:

Q, is the annual recharge in cubic meter

T is the average transmissivity of the aquifer (1500 m^2/d).

I is the hydraulic gradient (0.0015)

L is the length of the cross section (8000m).

The recharge from the subsurface inflow is calculated as $6.6x10^6$ m^3/year. This value represents only about 21% of the total annual recharge obtained by unsteady-state method. This indicates that most of the annual recharge comes mainly from direct infiltration of flood water over the inundated area after the inlet. Therefore the amount of recharge is directly related to the amount of flood water, the area flooded, and duration of the flooding period and the rate of infiltration.

4.4. Groundwater Discharge

The groundwater losses have to be accounted for to quantify the available exploitable surplus. The various means of groundwater discharge in the study area include evapotranspiration, groundwater withdrawal from dug wells and boreholes for domestic and irrigation purposes and the subsurface outflow from the basin outlet.

1) Evapotranspiration

Monthly potential evapotranspiration (PET) in the study area was determined by Hobler et al. (1980) using Thornthwaite's formula as 2045mm/y. It is recognized that the values obtained by this empirical formula are much higher than those measured by meteorological equipment in the region (Elsheikh, 2002). Evapotranspiration is particularly very significant in the area covered by the natural vegetation, which mainly consists of the mesquite trees (*Prosopischilensis)* forming dense and multi-aged forests in the lower delta and the upper delta. The total annual evapotranspiration of mesquite trees species and other vegetation types related to annual evaporation from open-water surfaces values per unit land area are revealed in (Table2), evapotranspiration is reported per unit land area occupied by each vegetation type, which includes the total water used by the vegetation including groundwater and surface water sources.

Table 2. Total annual evapotranspiration of specific vegetation types and open-water evaporation per unit land area(Leenhouts et al., 2005).

Vegetation type	Water use in mm/y
Mesquite wood land	670
Mesquite shrub land	565
Cotton wood	484
Open-water evaporation	1156

The factor relating open-water evaporation (E_o), and (PET) for specific crop is termed crop coefficient. It can be used to estimate (PET) as the product of (E_o) and the crop coefficient (FAO, 1979). Average value of 1200 mm/y for (E_o) was determined by Hobler et al. (1980), crop coefficient value of (0.4) is adopted in this study, as assigned by van Enk et al. (1984), who determined this value for moderately dense forests of phreatophytes in Kassala-Gash Basin. This gives rise to the actual evapotranspiration of 480 mm/y in the study area. The surface area of the freshwater aquifer which is covered by mesquite forests is about 45 km^2. Mesquite uses a combination of surface water, groundwater and deep vadose-zone sources (1 to 10 meters) depending on the availability of each source throughout the season (Lite, 2003). So that for simplicity and to get reliable estimates of the water volume extracted by evapotranspiration process, it is assumed that mesquite transpire excessive volume of water from the groundwater sources during the dry season, because the effects of the other sources are absent. Hence a total volume of groundwater discharged from the freshwater aquifer due to evapotranspiration is estimated to be 21.8 x106 m3/y.

2) Subsurface outflow

Groundwater leaves the aquifer under the effect of hydraulic gradient towards the sea through the aquifer outlet in the lower parts of the delta, where groundwater discharges into the coastal lagoons and/or into the sea. The cross section across which the subsurface outflow occurs has a length (L) of (25km), and the aquifer thickness (b) is about (20 m), the hydraulic conductivity K is (30m/d) and the hydraulic gradient (I) is (0.001). The subsurface flow (Q) is calculated according to the following equation:

$$Q=K.b.I.L \tag{4}$$

The volume of groundwater discharged annually as subsurface outflow is $8.2x10^6 m^3$.

3) Groundwater Withdrawal

The total volume of water discharged from the aquifer can hardly be estimated due to the inconsistency of water discharge, and complete absence of records. It is particularly difficult to estimate the water volume extracted by the shallow dug wells, because the discharge rate and the working period for the various wells are greatly variable. From field observation and personal contacts with the beneficiaries, the mean discharge rate for the shallow dug wells is estimated as 15 m^3lday and the annual working period is 270 day (October-June). So that the total extracted volume of water from 60 dug wells is estimated to be $0.24x10^6 m^3$. Withdrawal by 5 boreholes located in Krimbit and Dolabiai well field amounts to $1.3x10^6 m^3$. Water withdrawal from 10 boreholes is calculated as 0.7x $10^6 m^3$/y. Table 3 summarizes the groundwater volumes withdrawn from the aquifer by the present wells for domestic and irrigation uses. A summary of the volumes of the groundwater discharges by the different mechanisms are summarized in (Table4).

Table 3. The volume of groundwater withdrawals by dug wells and boreholes

Wells	Annual Discharge in $10^6 m^3$
Hand-dug wells (60 wells)	0.2
Krimbit and Dolabiai Boreholes (5 boreholes)	1.3
Boreholes for irrigation (10 boreholes)	0.7
Total	2.2

Table 4. Volumes of groundwater discharged by the various mechanisms

Mechanism of discharge	Volume of water in $10^6 m^3$/y	*Percentage*
Evapotranspiration	21.8	*79*
Subsurface outflow	8.2	*14*
Artificial withdrawal for domestic and irrigation uses	2.2	*7*
Total	*32.2*	*100*

Evapotranspiration is the most important disposal item, which represents 79 % of the total groundwater discharge.

4.5. Groundwater Balance

Groundwater balance of the study area is done by comparing recharge to discharge volumes. This balance is obtained by subtracting the total discharges from the water-recharge volume, it shows a water deficit of 1.2 $x10^6 m^3/y$ (Table 5). Water losses due to the natural processes are much greater than the water volume extracted by artificial withdrawal, which represents the least percentage 7%. Excluding water losses due to evapotranspiration, the volume of water extracted by wells for different purposes, is still far below the potential of the aquifer.

Table 5. Groundwater balance in terms of estimated recharge and discharge

Item	Volume of water in 10^6 m^3ly
Total calculated recharge	31
Total estimated discharge	32.2
Difference	-1.2

4.6. Site Evaluation

Based on the results obtained the study area can be evaluated depending on the estimates of the groundwater potential index (GWPI). The GWPI indicates the potential parts of the study area according to the assessment of certain parameters. This method of evaluation classifies parameters which influence the aquifer potentiality. Each parameter has a weighting coefficient which has been determined with qualitative criteria according to its significance, and assigning the rating by analyzing the existing data for each parameter. This leads to a score which designates the GWPI (U.S. EPA, 1993; Panagopoulos et al., 2006). Five parameters controlling the availability and suitability of groundwater are considered, they include: the saturated thickness, water quality (salinity), hydraulic conductivity, specific yield and the lithology of the vadose zone. These parameters are imported in a simple linear equation after they have been reduced from the physical range scale in order to eliminate the large figures. The estimates of the rating scale can be accomplished by using the mean of every class of the parameters. (Table 6) shows the parameter classes as well as the corresponding rating of each class. The GWPI is calculated as the sum of the products of the weighting factors and ratings as follows:

$$GPWI = D_w.D_R+Q_w.Q_R+K_w.K_R+ S_{yw}.S_{yR} +Vw.V_R \qquad (5)$$

Where:

D is the saturated thickness

Q is the water quality expressed as the electrical conductivity

K is the hydraulic conductivity, S_y is the specific yield

V is the lithology of the vadose zone. The subscripts W and R indicate weight and rating.

To apply the above formula, the study area is subdivided into three sub areas according to the saturated thickness of the freshwater body and the groundwater salinity (Fig. 4). Then the GWPI is calculated in each sub area. The results are revealed in (Table 7), which show a maximum GWPI computed value of 50 in sub area II in the upper central part of the delta, and a minimum value of 22 in sub area I in the northeastern part of the delta. Therefore it is recommended to drill wells for future groundwater development in sub area II and the adjacent part of sub area III downstream to Dolabyiai. Considering the water mass balance of the study area in addition to the assessment of groundwater availability and suitability by using the above GWPI values, it is proposed that well fields can be established in these parts of Tokar Delta to extract about 20000 cubic meters per day (ca 7 million cubic meters per year) for various uses.

Table 6. Parameters Classes and ratings

S.Th.	R	WaterQualityEcin µS/cm	R	KIn m/d	R	Sy (%)	R	Vadoselithology	R
< 20	1	<1000	5	20-50	3.5	10-20	1.5	gravel-sand	4
20-40	3	1000-2000	3	50-70	6	20-30	2.5	Sand-silt	3
40-60	5	2000-3000	1.5	70-80	8	30-40	3.5	Silt-clay	2
>60	7	>3000	1	>80	9	>40	4.5	clay	1

S,Th= saturated thickness, R= Rating Sy= specific yield K= hydraulic conductivity

Table 7. Computation of GWPI for sub areas (I,II and III)

Parameter	Weighting factor	Rating x WeightingFactor		
		Sub area I	Sub area II	Sub area III
Saturated. Thickness	4	4	20	12
Water quality	3	6	12	9
Hydraulic conductivity	2	7	12	12
Specific yield	2	3	3	3
Lithology of vadose zone	1	2	3	3
Groundwater potential index		22	50	39

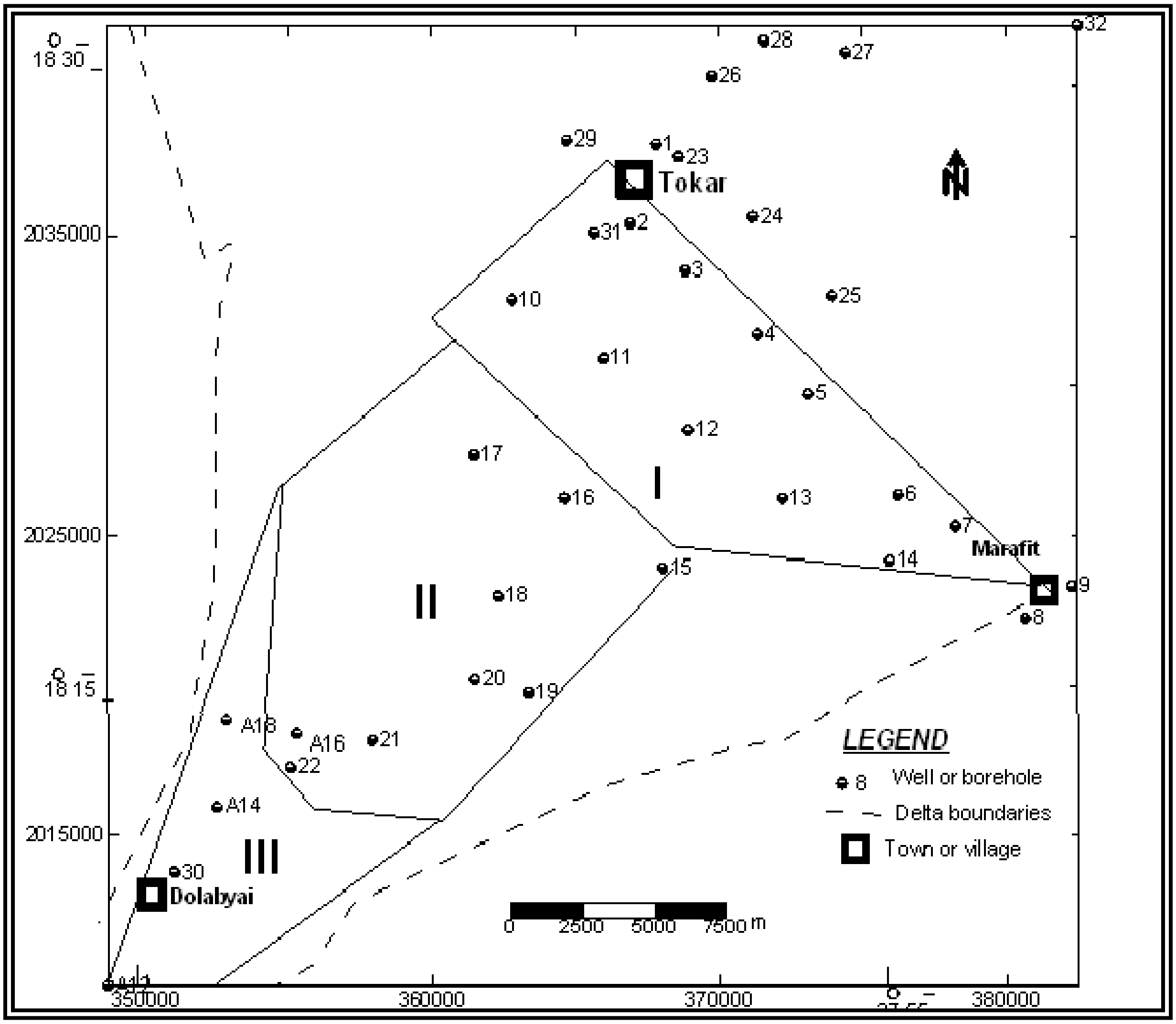

Fig. 4. Sub areas of the different GWPI values, indicating sub area II is the appropriate section for the future groundwater development.

5. Conclusion

The aquifer system in the study area is semi confined to semi unconfined consisting of alluvial sediments. Lenticular Freshwater body is found floating on brackish to saline water. Annual groundwater recharge is equal to 31 million cubic meters and the total discharge is 32.2 million cubic meter. The water deficit is about 1.2 million cubic meters which appears to be taken from the groundwater storage. The total volume of fresh groundwater in storage is 600 million cubic meter. Evapotranspiration estimated as 21.8 million cubic meter per year is the major component of the groundwater discharge. Large part of the natural groundwater outflow (8 million cubic meters) discharges annually into the lower parts of the delta and ultimately to the sea. GWPI is calculated using weighting and rating method and accordingly an area of high groundwater potentiality which is located in the central and the upper part of Tokar Delta has been selected for drilling of new water supply wells.

References

Hobler, M. Bornhorst, K. A., Jacobi, K., & Fielitz, K., (compilers) (1980). Reconnaissance of groundwater and surface water, German Exploration Project.(Unpubl) Report. Berlin.

Babiker, E. M. (2008). Characteristics, assessment and management of groundwater resources of the coastal aquifer in Tokar Delta, Eastern Sudan. (Unpubl.) Ph.D Thesis. Khartoum Univer. Sudan. Pp 174.

Rhin- Rhur- Ingenieur- Gesellschaft MBH.(RRI). (1989). Water supply of Portsudan, review and pre-design study. Techn. Report submitted to Minstry of Finance and Economic Planning, Khartoum, Sudan. (Unpubl. report).

Simmers, I. (2000). Groundwater recharge principles, problems and developments. In: IHP., 2000. Hydrogeological research and water resources management strategies in arid and semi-arid zones. Techn. documents in hydrology, Bull.32. UNESCO, Paris. p 33-47.

El Natiq, S. (1976). *The hydrogeology of Tokar Delta.* M.Sc. Thesis, Univer. of London, UK. (Unpubl.).

Geological Research Authority of the Sudan (GRAS) and Robertson Research International, ltd. (RRI)(1995). Accompanying geological notes to the 1: 10,000,000 scale atlas of the Republic of the Sudan, Bull. 40. Khartoum Univer. Press.

Whiteman, A. J. (1971). *The Geology of the Sudan Republic.* Clarendon Press: Oxford.

Mandel, S., & Shiftan, Z. L.(1981). *Groundwater resources investigation and development*, Academic press, New York, London, 269 pp.

Elsheikh, A. E. (2002). Water resources development and management - Red Sea State, Sudan, Ph.D. Thesis, Al NeelainUniver. Khartoum, Sudan. Pp.133.

Leenhouts, J. M.,Stromberg, J. C., & Scott, R. I. (2005). Hydrologic requirement of and evapotranspiration by riparian vegetation along the San Perdo River, Arizona, U.S. Geological Survey Sientific Investigation Report, 154, 2005-5163.

FAO. (1979). Yield response to water, FAO irrigation and drainage paper 33, Rome.

Van Enk, D. C., & Mukhtar, A. (1984). Land and water resources of the Kassala Gash Basin, Sudan. Techn. Bull. 84-01. National Water Corporation, Khartoum. (unpubl.rep.).

Lite, S. J. (2003). San Perdo River riparian vegetation across water availability and flood disturbance gradients. Ph.D. dissertation. Tempe, Arizona State Univer. pp.166.

U.S. Environmental Protection Agency (E.P.A). (1993). A review of methods for assessing aquifer sensitivity and groundwater vulnerability to pesticides contamination. U.S EPA/813/R-93/002, EPA, Washington, DC

Panagopoulos, G. P., Antonakos, A. K., & Lambrakis, N. J. (2006). Optimization of the DRASTIC method for groundwater vulnerability assessment via the use of simple statistical methods and GIS. *J. Hydrol. 14*, 894-911.