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Groundwater Quality Prediction Using Logistic Regression Model for Garissa County

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ABSTRACT

Groundwater quality modeling can reduce the cost of exploration and siting of boreholes considerably. The present study applies Logistic Regression Model to predict the probability of siting boreholes of fresh or saline water based on geospatial data such as altitude (m), longitudes, latitudes and depths (m), and geophysical data such as electrical resistivity from 45 exploration sites. The geology of the study area is represented by permeable water-bearing Tertiary-Quaternary sediments located within the Anza Rift. The water bearing zones, or water struck levels, range in depth between 50 and 150 m and the average yield of about 1 - 5 m^3 per hour, in the case of old wells done using percussion rigs in the period between 1960s to the 1990s. Recently, the discharge in the wells done using modern mud rotary equipment yields up to 30 m^3 per hour, with depths ranging between 200 to 250m below ground level. The modeling results show strong correlation between the dependent variables; depth, mean resistivity, longitudes, and latitudes on one hand, and salinity status of aquifers. It is, therefore, possible to know the water quality of a location in the study area before actual drilling is undertaken. Of all the runs made, 93% were predicted accurately while only 7% of the cases deviated from the predicted quality. These findings prove the usefulness of the LRM in predicting and identifying sites of high groundwater accumulation and groundwater salinity in arid region.

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1. Introduction

Groundwater is the main source of water supply in northern Kenya. However, the water quality has been deteriorating especially in towns such as Dadaab, Dertu, and Liboi due to unprecedented growth of refugee and host community population and steady rise in the number of boreholes being sunk in the area. The area lies on Lagh Dera that has three other refugee camps with more than 400,000 refugees [1]. Since 2015, Dadaab has had the largest solar-powered borehole in Africa, which is equipped with 278 solar panels and provides 16,000 residents of the complex with a daily average of about 280,000 m^3 of water per day [1]. The challenge has been that the groundwater has high salinity except along the Merti aquifer to which the depth and width of the aquifer is not well known [2]. The groundwater sometimes has been too brackish to be of any practical use to the community, livestock, irrigation, or domestic usage according to WHO standards [3]. Security issues also have hampered access to some borehole sites in the Dadaab sub county.

The objective of the present study is to apply Logistic Regression Model (LRM) to predict boreholes of acceptable water quality, based on secondary data obtained from the Northern Water Services Board (NWSB) which comprise these variables: longitudes (L) and latitudes (La), electrical conductivity (EC), Total Dissolved Solids (TDS), altitude (m) and depth (m). The algorithm helps determine the probability of a borehole being saline or fresh. The factors that determine groundwater quality are geology, climate, depth, and permeability. The study area is in north eastern region of Kenya covering Dadaab, Dertu, and Liboi within latitudes 2°05' south and 4°16' north and longitudes 38°40' and 41°52' east. The region has an altitude range of between 150m to 165m above mean sea level.

1.1. Climate

The region is in a semi-arid environment characterized by low rainfall that is bimodal distributed across the year [

Figure 1

Figure 1]. The region is represented by rainfall stations located at Garissa (gsaRain), Habaswein (habRain) and Wajir town (wajRain). The rainfall distribution shows two wet seasons, namely, from March to May and October to December. The months between June and September mark the driest period although the named wet seasons are fairly dry. Precipitation in this area is markedly erratic. Much rain falls as intense local convectional storms which may yield 50 to 60 mm in a single event.

The average annual potential evaporation (E_o) for Wajir is 205 mm (Figure 2). The spatial variability of E_o is considerably lower than the recorded differences in rainfall (P). In addition, seasonal variations are relatively small. Generally, the potential open water evaporation [*Figure 2*] is significantly higher than the actual evapotranspiration. The potential evapotranspiration is, therefore, a more accurate expression to apply in water balance evaluations, as it is based on a vegetated rather than water-logged surface [5]

Evidences abound of jointing and fracturing of the carbonate sediments on the surface, alluding to intense forces of fracturing, carbonation, and quaternary tectonic faulting. Much of the south westerly – north easterly directed stress fields helped sculpture the terrain into its present geological state. Owing to the relatively high fractions of clays in the beds, there is no sufficient time available for maximum catchment input infiltrations into the sub surface zones lying on the adjacent aquifer units in the proposed well sites.

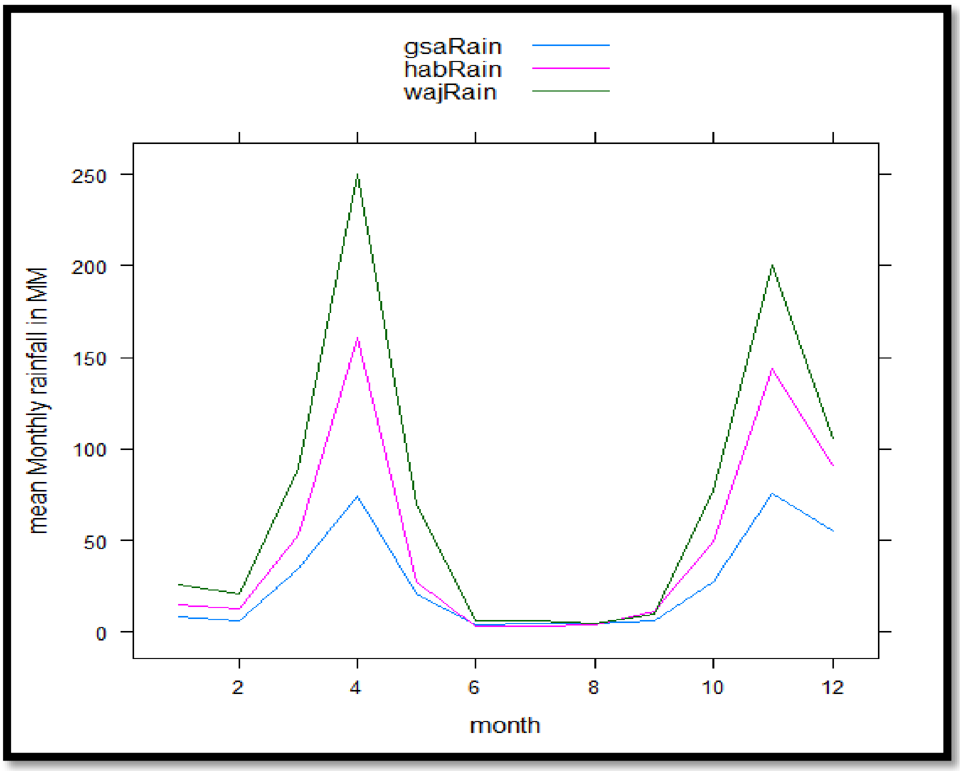


Figure 1: Mean Monthly Rainfall for Garissa, Habaswein and Wajir. Source: KMD 1990[4].

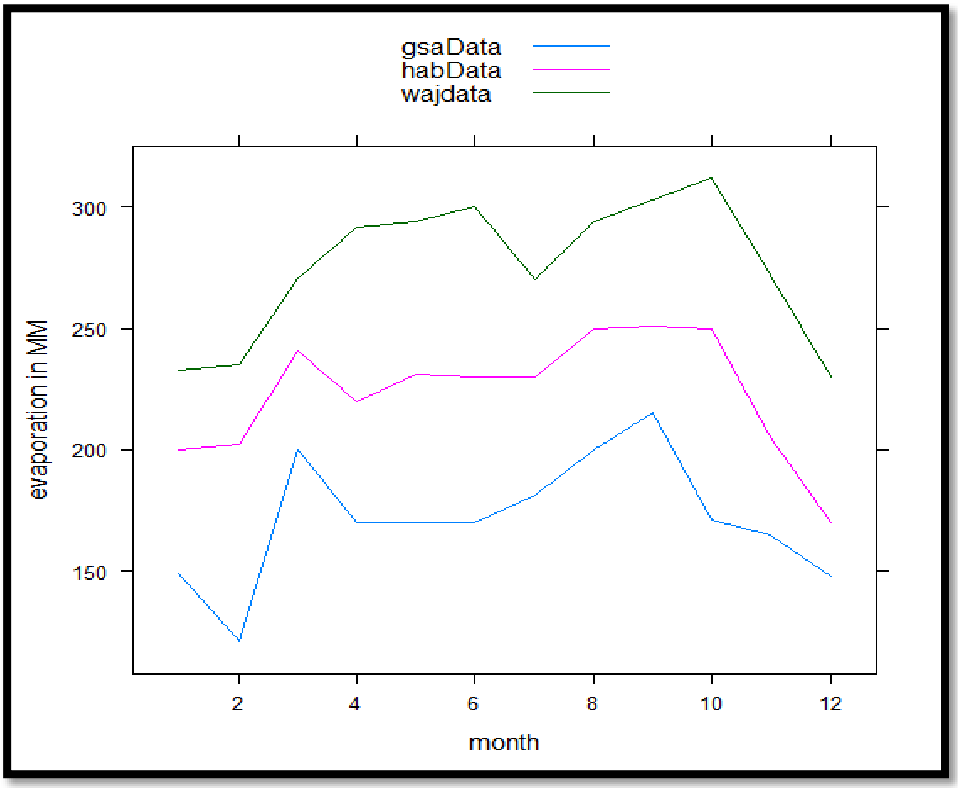


Figure 2: Mean Monthly Evaporation in various stations in Garissa/Wajir Areas. Source: KMD 1984 [4].

1.2. Regional and Structural Geology

The geological history of northern Kenya traces from the Basement Complex that represents an original sedimentary succession which by regional metamorphism during the Paleogene (65 to 25 million years) has been converted to a series of gneisses, schists, and quartzites [6, 7].

The general strike and dip of the gneisses in the area is somewhat to the East. No outcrops are observed in the region since they are found at great depths. After a long period of uplift and erosion, a marine incursion took place in the early Jurassic (200-145 million years ago) which led to deposition of sandstones, shales, limestone and coarse to fine-grained sediments with calcite [8]. During this period, erosion largely removed the Jurassic rocks and further uplift and erosion followed, culminating in the maturation of the peneplain; a later cycle resulted in the deposition of marine and fluvial sediments on the sub-Miocene surface. Other exposures are to the South-East of the Yamicha Plateau and in the area north of the Eldera-Modogashe road. Their exposure is poor on the featureless plains that extend from Merti all the way to Habaswein and Dadaab, since they easily erode on account of their friable nature which leaves them covered by thick soils. The grits are however exposed along rivers notably at the Galana Gof [10].

The Merti aquifer, probably the best known groundwater aquifer in the area, is defined by permeable water-bearing layers located within the Anza Rift [10, 11]. The formation is of unknown thickness in this area although in the Garissa area it is believed to be at least 270 m thick [8]. The water is confined and found at depths between 110m and 180m below ground level (bgl).

The groundwater distribution is determined by the geological structures. The geology of the area is controlled by tectonic movements that led to the break-up of Gondwana in the Jurassic and by Cretaceous activity on the Anza Rift [6, 10]. The most significant fault lines are Lagh Boghol, Lagh Choichuff, Habaswein-Wajir Bor [12], and Hagardera-Liboi fractures many of which have been traced by laghas. There is also a lineament passing slightly North of Sericho town and trending in South West - North East direction. Lagh Choichuff intercepts another major fracture which cuts through Mount Marsabit and trends in the north-eastern direction. The Lagh Boghol lineament marks the north east boundary of a confirmed gravity and magnetic (geophysical) sedimentary basin. The western border of the study area has been indicated by geophysical data as not being a major fault zone but a combination of faulting and tilting [13], although several unsuccessful attempts have been made to define the extent of the aquifer with limited success [14].

The Merti aquifer is believed to extend from Habaswein in Kenya to Somalia at Liboi and beyond, bounded by the presence of adjacent saline water bodies. There is no comprehensive information that defines the aquifer's vertical extent.

A likelihood that salinity of the groundwater increases with depth and the extent of the freshwater aquifer is either limited by impervious layers and or the presence of saline groundwater is known [15]. The Merti Formation is underlain by a succession of Jurassic and Cretaceous rocks, which are in turn underlain by metamorphic rocks of the Basement Complex. Tertiary/ Jurassic marine clays, sands and conglomerates, the so-called Merti Beds cover the whole eastern area, extends also to Somali. Sands and conglomerates form extensive aquifers [16].

The Mid-Pleistocene to Holocene has been marked with rapid climatic fluctuations in the region. This is attributed to periods of intense weathering followed by erosion and deposition of the weathered material. Most of the colluvium and calcrete in the area is believed to have been deposited during that time. The Quaternary sediments are composed of lacustrine sediments with limestone, calcrete and superficial deposits belonging to both Pleistocene and Holocene periods. The texture of the lacustrine sediments is coarse to fine grained. The superficial deposits comprise alluvium which contains sand and silt along the river courses, and colluvium composed mainly of crudely stratified mixtures of clay, silt, and rock fragments along the slopes of large inselbergs. Groundwater quality reflects the influence of topography, geology, and climate.

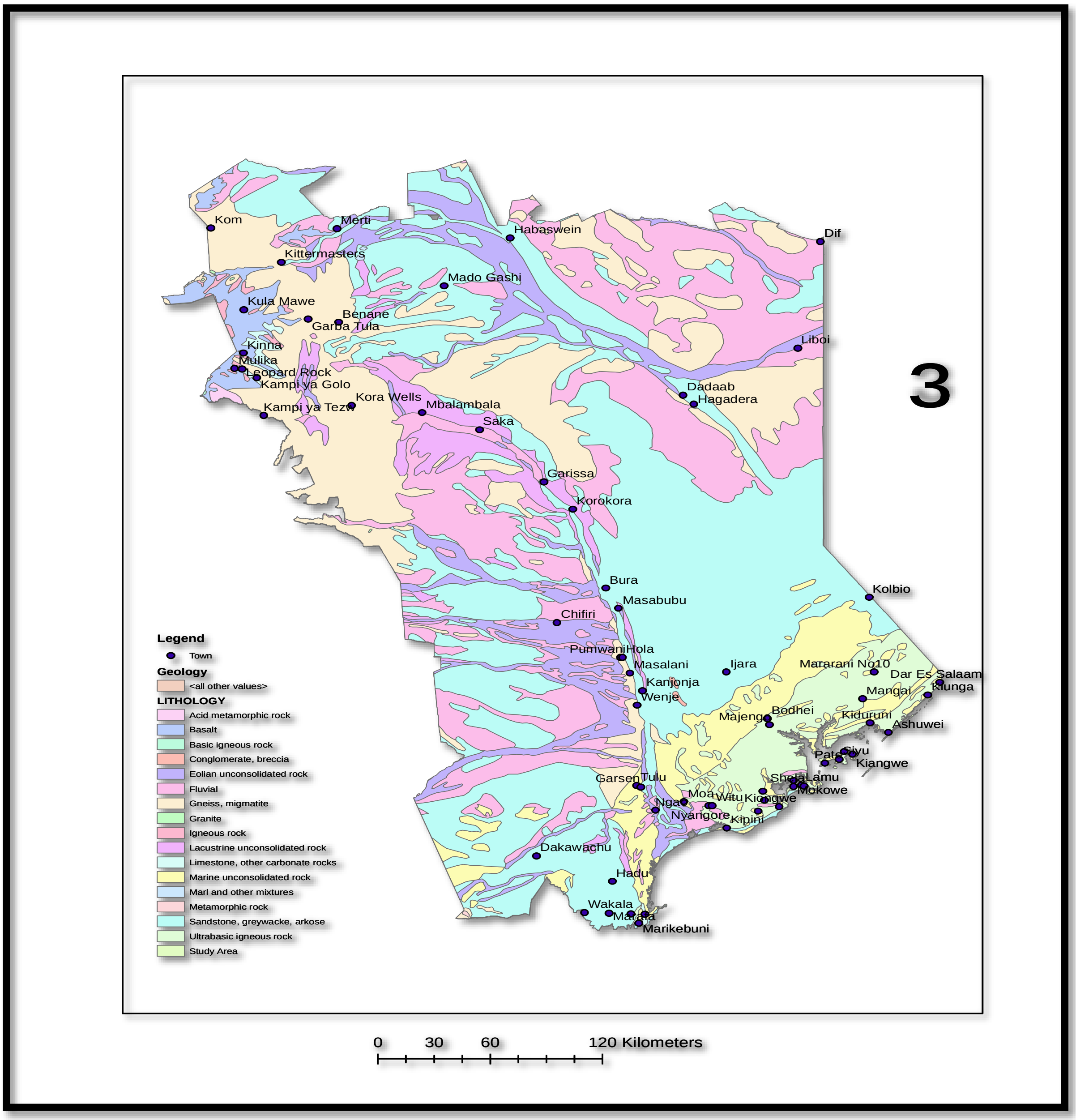


Figure 3: Lithology of the study area.

2. Materials and Methods

The present study collected unpublished geophysical and hydrological data from 55 exploration sites for the period taken between December 2015 and February 2016 within the study area. Additional data were obtained from Water Resources Management Authority (WRMA) sub regional office in Garissa as well as data from UNHCR Dadaab field office. The aim was to use the groundwater chemical analysis test results such as Electrical Conductivity (EC), and Total Dissolved Solids (TDS) and other borehole drilling information such as depth, longitudes, and latitudes to predict areas with fresh or saline water.

To achieve this, the data frame with secondary information was used. The columns are longitudes, latitudes, elevation, depth, resistivity, and water quality. Supposing the final row is Number 54, the field data vertical electrical sounding (VES) results are to be plotted in excel sheet, and the average resistivity taken for the zones known to harbor aquifers, so that this mean is inserted in the row number 55.

The final column value for this new site is NA, indicating that the water quality at the well that has not yet been drilled is unknown. The algorithm helps us predict this NA in the final row, and this gives us the water quality.

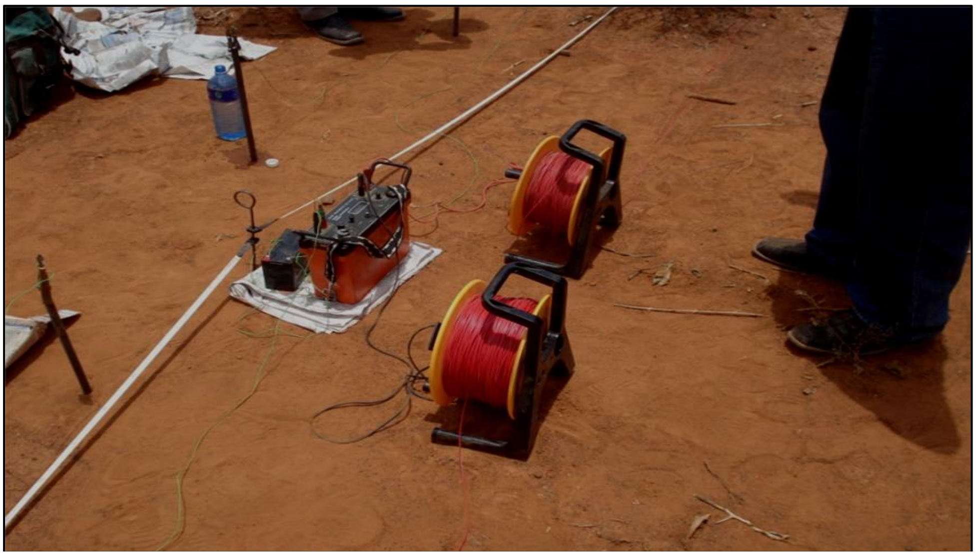
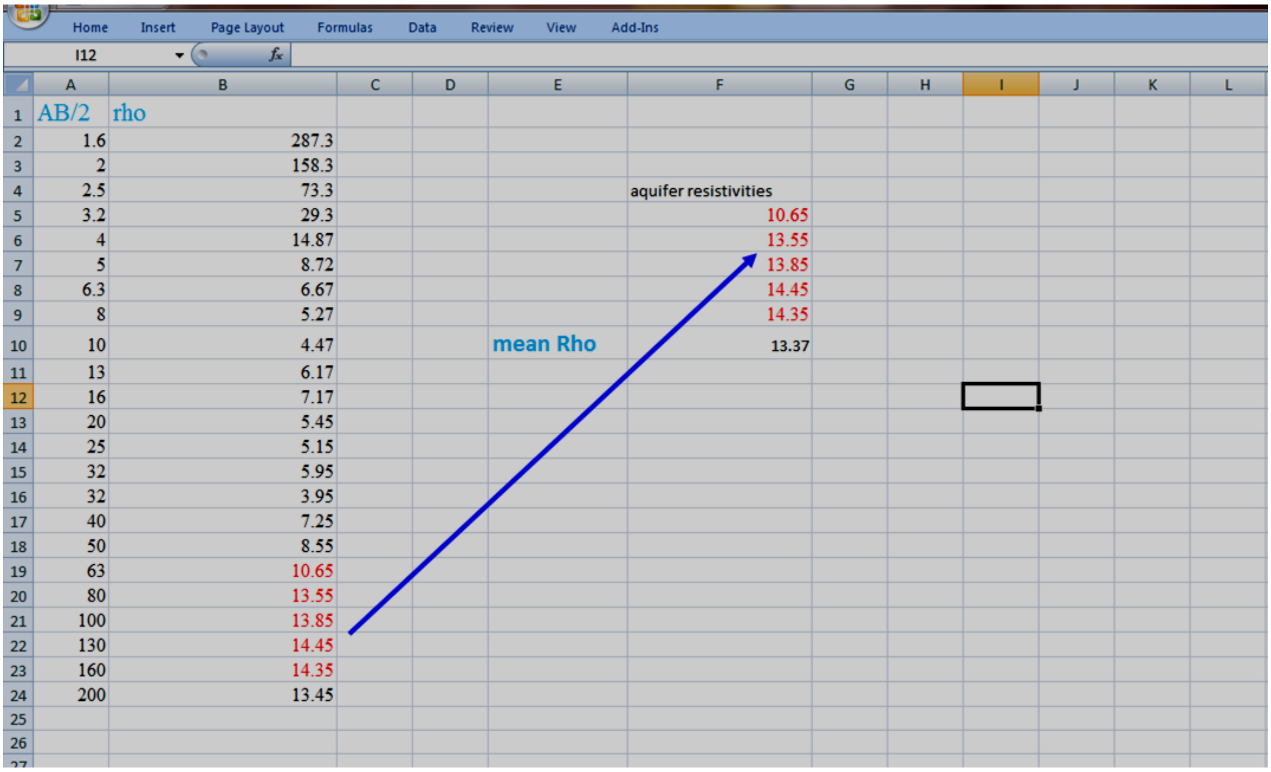


Figure 4:ABEM SAS 4000 Equipment Set Used For Geophysical Exploration along the Lower River Ewaso Ng'iro Catchment.

The equipment used in Northern Kenya in the 1980s was and still is the ABEM SAS Terrameter Model 300 [15] but model 4000 modern Lund Imaging System [**Error! Reference source not found.**] has been in use over the past ten years. The data were analyzed using both GEWIN and IPI2WIN. The results generated would display AB/2 (depth to aquifer) against Rho (resistivity). The depths range between from 63m to 250m bgl and the resistivity values at the depths known to bear aquifer in the area would be picked from the mean resistivity for use in modeling. The resistivity measurements at these depths were averaged, giving mean ρ **(***rho)* in the table [Figure 5] used for our research.



	A	B	C	D	E	F
1	AB/2	rho				
2	1.6	287.3				
3	2	158.3				
4	2.5	73.3				aquifer resistivities
5	3.2	29.3				10.65
6	4	14.87				13.55
7	5	8.72				13.85
8	6.3	6.67				14.45
9	8	5.27				14.35
10	10	4.47			mean Rho	13.37
11	13	6.17				
12	16	7.17				
13	20	5.45				
14	25	5.15				
15	32	5.95				
16	32	3.95				
17	40	7.25				
18	50	8.55				
19	63	10.65				
20	80	13.55				
21	100	13.85				
22	130	14.45				
23	160	14.35				
24	200	13.45				

Figure 5: Sample Geophysics Data Analyzed for Aquifer resistivity mean.

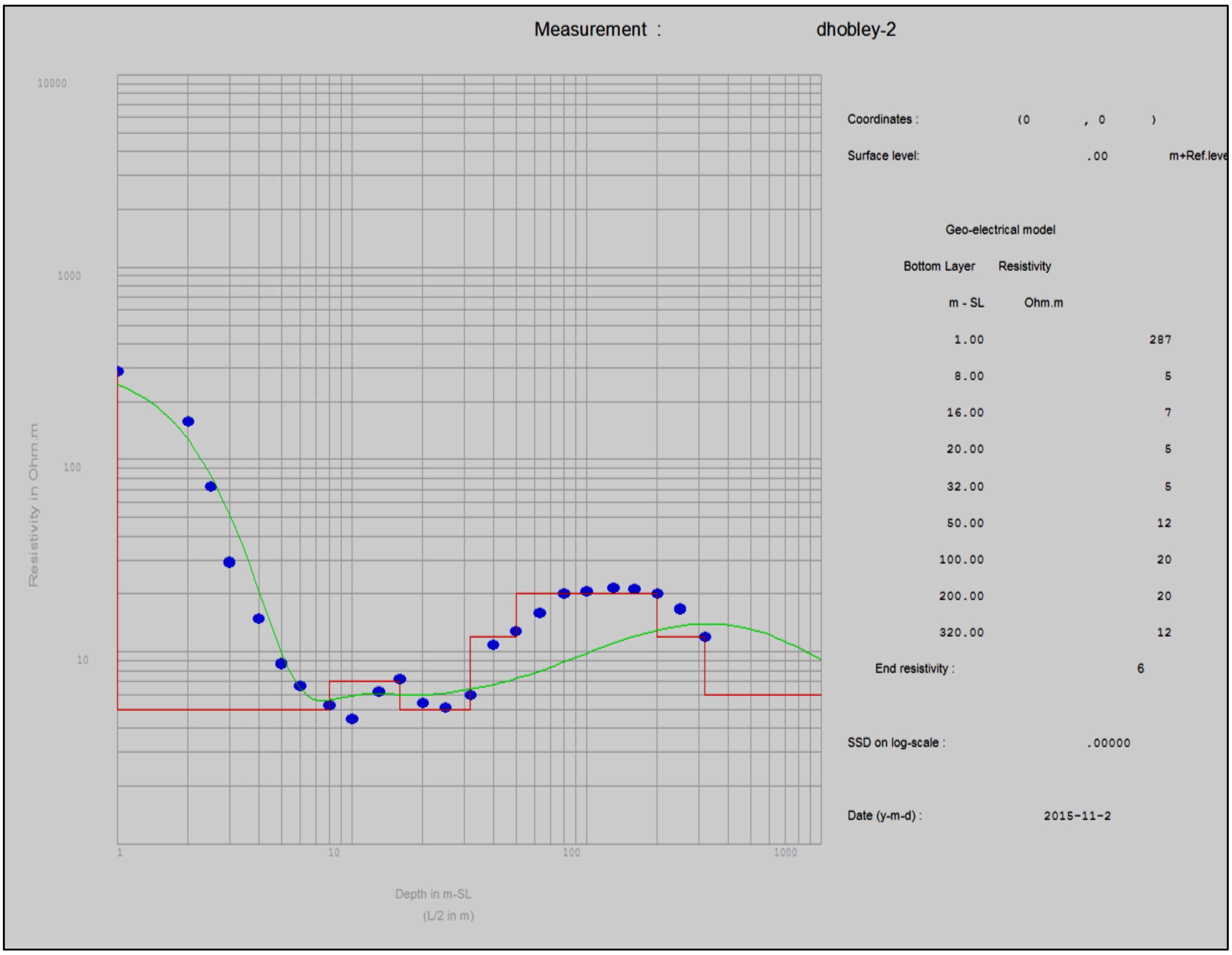


Figure 6: Curve fitting of electrical resistivity at VES R-002/2015 sited within the Merti aquifer zones

Figure 6 is the site that was recommended for drilling of a borehole.

2.1. Theoretical Framework

A Logistic Regression Model (LRM) can used to estimate the probability of the presence of an event, given information about predictors that can potentially influence the outcome [18]. As a class of generalized linear models, LRMs are distinguished from ordinary linear regression models by the range of their predicted values, the assumption of the variance of the predicted response and the distribution of the prediction errors [19].

The logistic regression can be understood simply as finding the **β** parameters that best fit:

$$y = \{\beta o + \beta.1x + E\} > 0 \tag{1}$$

Where is an error distributed by the standard logistic distribution. The associated latent variable

$$y' = \beta 0 + \beta 1x + E \tag{2}$$

The error term **E** is not observed, hence termed "latent". Instead they are to be found by an iterative search process, usually implemented using R software. The general LRM formulation for predicting, for instance, the probability of striking fresh water in Dadaab, based on the geospatial and geophysical/hydrochemical parameters (namely, longitudes, L: latitudes, La, depths, d, and resistivity would take the form:

The probability, P(x),

$$\boldsymbol{P(x) = \frac{e^{\beta0+\beta1*L+\beta2*La+\beta3*d}}{1+e^{\beta0+\beta1*L+\beta2*La+\beta3*d}}} \tag{3}$$

Where:

βo, β1, β2, β3 are logistic regression coefficients

L is Longitude

La is latitude

d is depth (m)

Assume that:

$$\boldsymbol{y = e^{\beta0+\beta1*L+\beta2*La+\beta3*d}} \tag{4}$$

Then:

$$\boldsymbol{P(x) = \frac{y}{1+y}} \tag{5}$$

Assume that depth is the sole determinant of water quality, then the probability of saline borehole shall be:

$$\boldsymbol{P(x) = e^{\frac{(\beta0+\beta1*d)}{1+(e(\beta0+\beta1*d))}}} \tag{6}$$

If ***P(x)***≥ 0.5, then its chances of occurring is 0 meaning the water is saline and if ***P(x)*** ≤ 0.5, then its chances of occurring is 1 and the water is fresh. The r-value has only two choices, saline or fresh water, 0 and 1.

To obtain the coefficients βo, β1, β2... βn, a statistical summary of the tabulated dataset in R will be generated. Then the probability (Eq.6) is simplified, and applying to Eq. 3 one obtains:

$$\boldsymbol{P(x) = \left(\frac{e^y}{1+e^y}\right)} \tag{7}$$

First, the conditional distribution **y**= {1 β} in which β is a Bernoulli distribution because the dependent variable is binary. Second, the predicted values are probabilities and are therefore restricted to (0,1). The cases are independent and the variables are not linear combinations of each other.

Water-bearing and/or weathered rocks have lower resistivity than unsaturated (dry) and/or fresh rocks. The higher the porosity of the saturated rock, the lower its resistivity, and the higher the salinity (or electrical conductivity (EC) of the saturating fluids, the lower the resistivity. In the presence of clays and conductive minerals the resistivity of the rock is also reduced. The relation between the formation resistivity (ρ) and the salinity is given by the "Formation Factor" (**F**):

$$\boldsymbol{\rho_w = \frac{F_x 10000}{E}} \tag{8}$$

where:

Fx = Formation Factor

ρ_w = Resistivity of water

E = Electrical resistivity (µS/cm)

In sediments or unconsolidated layers produced by weathering, the formation factor varies between 1 (for sandy clays) and 7 (for coarse sands). Clayey formations with fresh water will respond similarly to deposits with brackish or saline water: the fact that the same resistivity can be obtained for completely different hydrogeological units is known as the “equivalence-problem”. Fresh and dry Basement rocks are marked by very high resistivity, with a common range from 1,000 to 10,000 Ωm. Moderately to slightly weathered but dry layers are less resistive, and usually show values between 100 and 500Ωm., depending on the portion of clays, the degree of weathering and the water content. The resistivity further decreases if the deposits are water-bearing, to 20 to 200 Ωm. The resistivity of impermeable clay layers (alluvial or produced by intensive weathering of clay-forming minerals) usually varies between 2 and 10 Ωm, while similar figures are recorded for aquifers with brackish to saline water.

Despite the problems of suppression attributed to the large Resistivity contrast between fresh and weathered basement (point *d*), this is also a favorable attribute. Because of the large difference, the depth of weathering can be measured quite accurately. Considering that aquifers often occur towards the boundary of the weathered zone and the bedrock, the drilling depth can be determined, even if the actual aquifer does not show up as distinct geophysical layer. Salinity of electrolytes, such as NaCl in water, affects resistivity in nearly inversely linear manner [20].

At T=O·C we have:

$$\boldsymbol{P = 9.545C^{-0.937} = \frac{L0}{C}} \tag{9}$$

Where C (g/l) is the concentration of NaCl.

2.2. Data manipulation and model application

The software R is an open source statistical software and has several packages for performing different analytical tasks. In the present study, we used the nnet package to predict the probabilities required using the data given. Logistic regression models were performed using the R software. The excel datasheet were entered into R, and the data analyzed.

so that:

$$\boldsymbol{x = e^{\beta0+\beta1*L+\beta2*La+\beta3*alt+\beta4*0.0886+\beta5*\rho}} \tag{10}$$

$$\boldsymbol{y = 1 + e^{\beta0+\beta1*L+\beta2*La+\beta3*alt+\beta4*0.0886+\beta5*\rho}} \tag{11}$$

Equations [10 & 11] were predicted from results of dataset rows used in this research. Using the codes 1 for fresh and 0 for saline water the probability for salinity is expressed in the form x/y.

Table 1: Coefficients of Logistic Regression with the independent variables

e	βo	β1	β2	β3	β4	β5
2.7183	0.2458	4.117	-6.433	0.1788	0.08806	7.083

3. Water Quality Characteristics of the Study Area

Results of our field assignments in the area coupled with secondary data that were obtained from partners give insight on the groundwater chemistry in the area. The distribution of Fluoride (mg/l), Electrical conductivity (µS/cm) and Total Dissolved Solids (mg/l) in the study area has been analysed to assemble maps that would be used to test the LRM.

Although the data was collected by different partners the instruments used for measurement and the procedure for data collection were fairly similar. This gave us the assurance that the results of their measurements may be compared.

The water samples were collected after borehole completion report had been completed either from privately-owned or community wells. The sampled water from source was allowed to stabilize before measurements were taken. Fluoride, EC and TDS content in the groundwater samples were determined directly after dilution. All the experiments were carried out by qualified laboratory technicians.

Figure 7 shows Fluoride districbution around Garissa town. Towards the middle the map eastwards lies the Merti Aquifer which has demonstrated good water quality. The water quality becomes variable and fluoride content progressively diminishes as one traverses towards Dadaab.

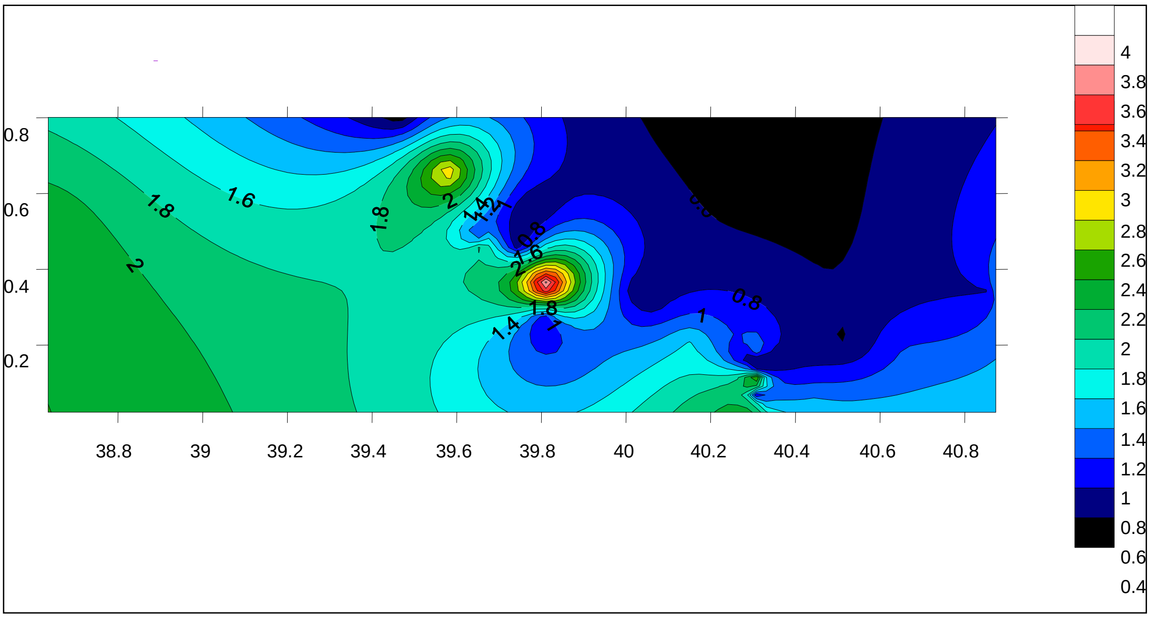


Figure 7: Fluoride distribution in groundwater (mg/l) within Garissa County.

The lowest/most favorable aquifers for groundwater development are found in areas with lowest fluoride levels in the area. In some areas the groundwater samples the concentration of fluoride was found to be moderately to very high, when compared to the NEMA or WHO standard for drinking water, which may lead to associated health risks in urban population, if the groundwater is being used without proper treatment.

Figure 8 shows Fluoride distribution in towns within Garissa County. Although there are few localised areas of Fluoride concentration, the pattern is consistent with results shown in Figure 7. The EC is a function of the drainage and the geology. The areas near River Tana and those near the Laghdera streams are having fairly good water quality [21] and hence the exceptionally low EC values in bluish are areas around River Tana in Garissa Township [9].

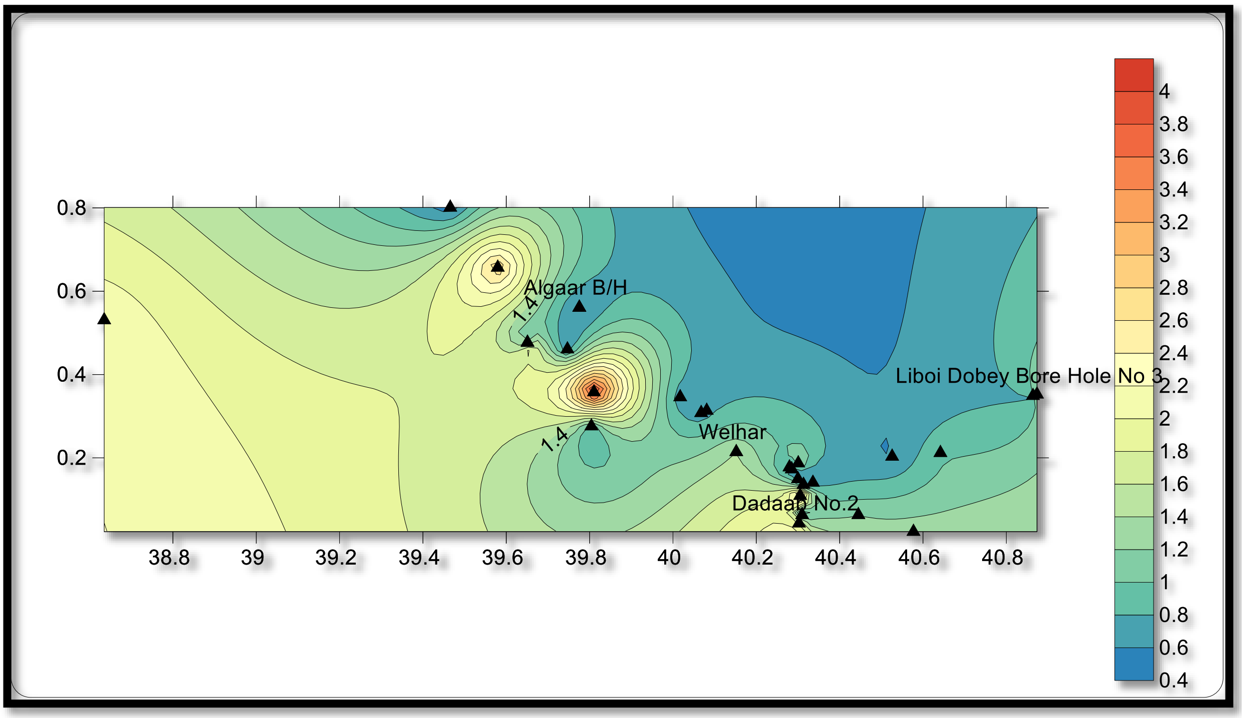


Figure 8: Fluoride distribution (mg/l) in the study area in selected towns within Garissa County.

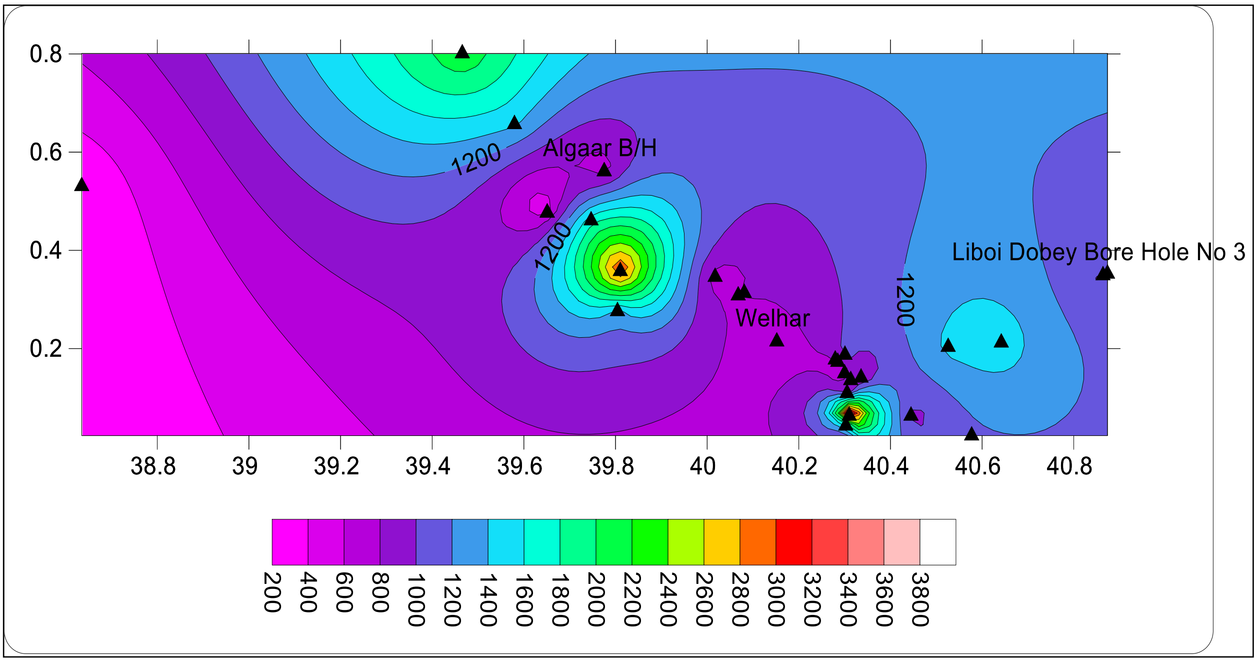


Figure 9: Shaded EC contours in the study area.

The highest Total Dissolved Solids (TDS) levels appear to be the zones far away from Dadaab. The merti flow is the signgle most important factor nin determinng water quality in then area. The Tana River recharges wells located nearest to it via lamina flow, hence the low values of TDS.

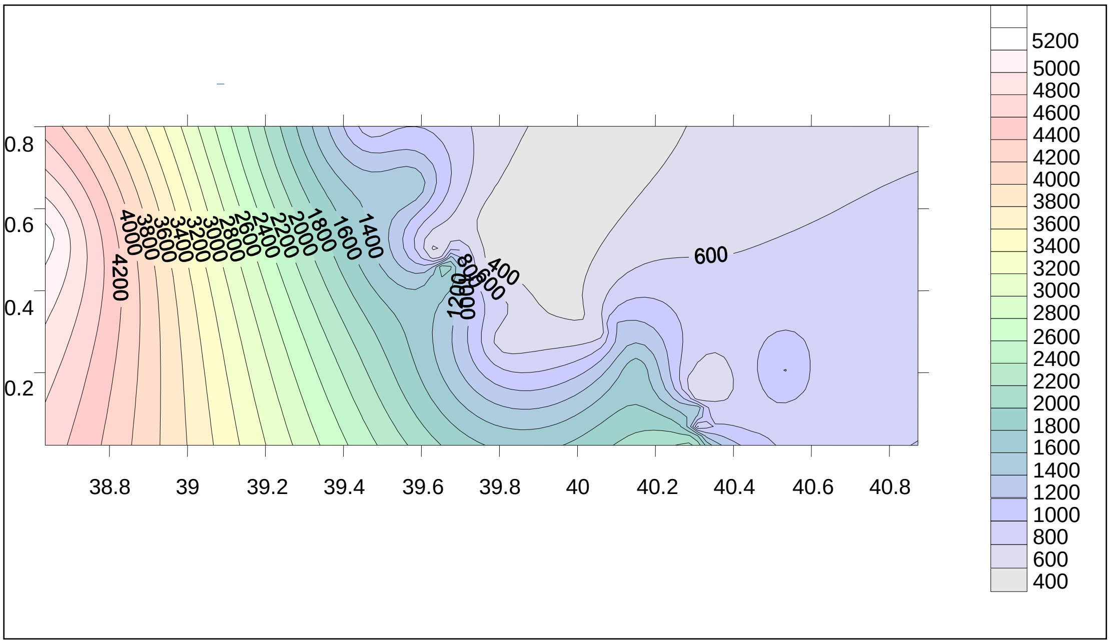


Figure 10: Electrical conductivity (mg/l) contours in the study area.

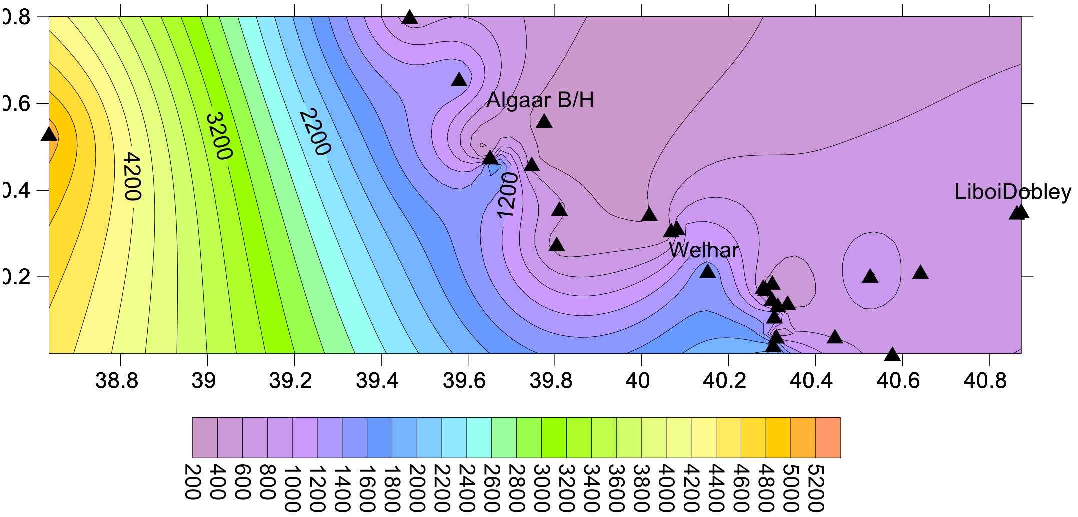


Figure 11: TDS in mg/l in the study area.

In Figure 11, 21 boreholes were sampled and it may be noted that the favorable wells lie within the central Merti aquifer. There are over 80 operational boreholes within the Merti Aquifer with an annual abstraction of 2.5x10^6 cubic meters (m^3) of water per year which represents 44.6% of the annual recharge [22].

Table 2*:* Salinity status classifications, by total salt concentration. Source - [23].

Salinity status	Salinity (mg/l)	Description and use
Fresh	< 500	Drinking and all irrigation
Marginal	500 –1 000	Most irrigation, adverse effects on ecosystems become apparent
Brackish	1 000 – 2 000	Irrigation certain crops only; useful for most stock
Saline	2 000 – 10 000	Useful for most livestock
Highly saline	10 000–35 000	Very saline groundwater, limited use for certain livestock
Brine	>35 000	Seawater; some mining and industrial uses exist

The maps demonstrate that the boreholes with fresh water may be limited by poor recharge or the presence of adjacent saline groundwater. The freshwater aquifer zone at Habaswein has a width of approximately 15-30 km but broadens to 70 km near Dadaab and the geological structure may be limiting regional groundwater flow [24]. Similarly faults and fracture zones may also form preferential horizontal flow paths, such as through the secondary porosity of broken rocks or form preferential flow paths for vertical flow, even in areas where lateral hydraulic head gradients suggest that they impede flow [25]. Rotated layered sediments can also impede flow or influence flow directions as well [26].

As observed during the fieldwork, the site is underlain by a thick layer of sandy soils. These are directly underlain by a thin layer of sandy clays, limestone and assorted sands and sandstones. The thickness of each of these layers varies significantly from site to site. Further, each of these sediments are intercalate with each other up to depths in excess of 3000 m. bgl. Geologically, these Laghas tend to follow lines of fractures and lineaments. The sandy deposits that define the terrain in the study area may be as deep as 1.0 m. depth and are able to replenish shallow aquifers.

Table 3: Prediction results of the algorithm used in this study.

Runs	Longitude	Latitude	Altitude (m)	Depth (m)	Mean ρ	Prediction value	Salinity status	True value in data frame
1	39.6366	0.4695	53.4	30	55	1.00	fresh	fresh
2	40.08092	0.3134	126.1	220	13.18	0.00	saline	saline
3	40.375	0.005348	89	190	21.91	1.00	fresh	fresh

4. Conclusions

The water quality may be predicted using the existing hydrochemical and hydraulic data, using the logistic regression equations to evaluate the geospatial and hydraulic parameters. The result showed strong correlation between the independent variables, namely, depth, mean resistivity, longitudes and latitudes on one hand, and dependent variable freshness/salinity status of aquifers. It is therefore possible to know the water quality of a location in the study area before an actual drilling is executed. These findings prove the usefulness of the proposed methods in predicting and identifying sites of high groundwater accumulation and groundwater salinity in an arid region.

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