HYDROGEOCHEMICAL AND GEOMORPHOLOGICAL STUDIES OF SOME WADIS ON THE EASTERN SIDE OF THE GULF OF SUEZ, SINAI, EGYPT

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الخلاصـة :

تهدف هذه الدراسة إلى توضيح العلاقة بين الصفات الجيومورفولوجية والخصائص الهيدروكيميائية لأحواض بعبع، وفيران، وسدرا، والطيبة الواقعة على الجانب الشرقي لخليج السويس في سيناء (مصر).

وتَـمَّ في هذه الدراسة حساب وقياس رتبة المجرى، ونسبة التفرع، وتكرار المجرى، وكثافة وديان الصرف، وتحليل بيانات معدل سقوط المطر وأخيراً احتمالات المياه الجارية على سطح الأرض. وقد وجُد أن معدل سقوط المطر سنوياً يتراوح من ٢٠ مم / السنة في الجزء الشرقي من منطقة الدراسة إلى ٥٥ مم / السنة في اتجاه الغرب، قرب ساحل البحر الأحمر. ويختص حوض (فيران) بأعلى نسبة من مياه المطر السنوي وأيضاً المياه الجارية كما يتميز بأعلى نسبة ترشيح سنوياً.

وتحتوي الدراسة الهيدروكيميائية على تحليل الكاتيونات والأنيونات لمجموعة من عينات المياه الجوفية تمثل أنواعاً مختلفة من الخزانات الجوفية لكل حوض من الأحواض قيد الدراسة، وقد تم عمل نموذج رياضي لحساب معامل تشبع المياه الجوفية لمجموعة من المعادن وأيضاً نموذج رياضي لحساب معامل الارتباط لكل عينات المياه الجوفية، وقد تم توضيح وشرح علاقة كل هذه التحاليل والخصائص الهيدروكيميائية مع الخواص الجيومورفولوجية.

وأوضحت الدراسة أنه يوجُد ارتباط بين كل هذه العناصر سواء كان ارتباطاً موجباً أو ارتباطاً سالباً.

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ABSTRACT

The purpose of this study is to examine the relationship between the geomorphological characteristics and hydrochemical properties in the Baba, Feiran, Sudri, and El-Tayiba basins, located on the eastern side of Gulf of Suez, Sinai. In each catchment the stream order, bifurcation ratio, frequency, and drainage density for each basin, together with the rainfall analysis and possible runoff are measured or estimated. Rainfall varies from 20 mm/year in the eastern head water regions to 55 mm/year in the west, near the Red sea coast. The Feiran basin has the highest weighted average annual precipitation and hence, the value of runoff. Hydrogeochemical studies include analyses of major cations and anions in groundwater samples from different aquifers and from different hydrographic basins. Mineral saturation indices and correlation coefficients were computed for all the groundwater samples and interpreted in relation with the geomorphological parameters.

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INTRODUCTION

The study area is located on the west central part of the Sinai Peninsula, and occupies an area of about 4000 km^2 between latitude 28∗30′, 29∗15′ N, and longitude 33∗00, 34∗00 E (Figure 1). The study area is arid climate with low precipitation and hot summers. Rainfall records were abstracted from open files and published data of the Meteorological Organization of Egypt [1]. Precipitation shows a high variability in time and space, and occurs mainly in autumn, winter, and spring. Summers are dry. Rainfall commonly occurs as drizzle or very gentle of short duration, ranging between few minutes and few hours (Table 1).

TOPOGRAPHICAL AND GEOLOGICAL SETTING

The area is divided into a number of topographic and geologic units following Ball [2], El-Shazly, *et al.* [3], Saad, *et al.* [4], and Dames and Moore [5]. Each of these units affects the general hydrogeologic setting. The topographic units are as follows.

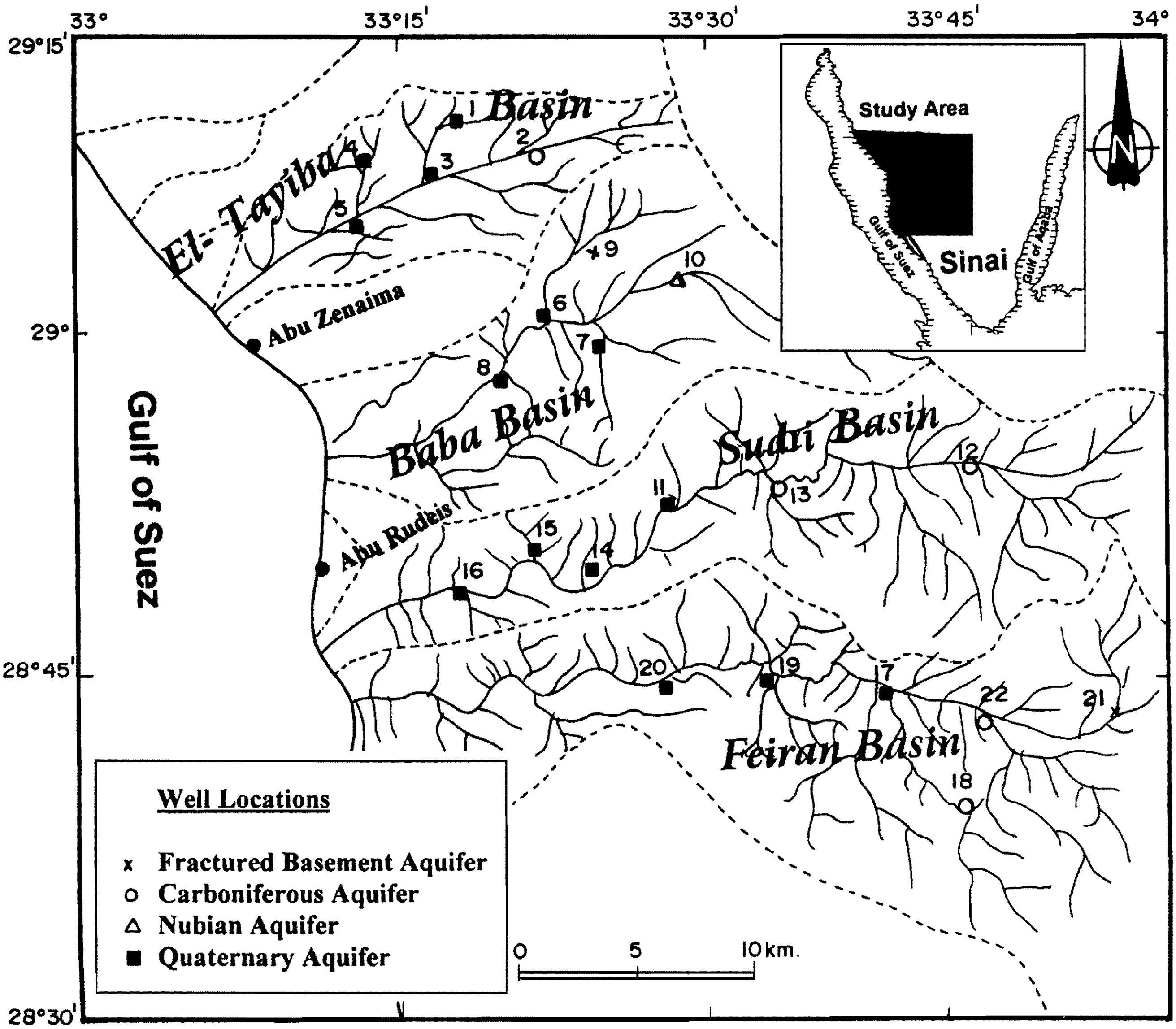

Figure 1. Drainage Map of the Study Area (Well Locations).

Escarpments

These are common in the study area and stand several hundreds of meters above the adjacent depression. The scarp forms a broad divide between the El-Arish hydrographic basin and those which drain southwest towards the Gulf of Suez.

Plains

These extensive sandy plains extend from the foot of the scarps, with an average width of about 5 km. The plain surface is covered by Quaternary sand sheets, on which local inhabitants have constructed several buried reservoirs collecting surface runoff during rainy seasons.

Mountainous Country

Much of the study area is mountainous. The relief of the mountainous country consists of rugged broken plateaux and high precipitous ridges with steep peaks separated by numerous deep gorges. Several wadis run along NNW–SSE and NW–SE fault zones. The mountainous country is dissected by the wadis El-Tayiba, Baba, Sudri, and Feiran. The channels and flood plains of these wadis and several of their tributaries are filled with calcareous alluvium, derived from the weathering limestones of the plateau. Their presence indicates that the evaporation exceeds the precipitation.

Coastal Plain

This is a depositional plain underlain by wash deposits representing the combined outwash fans of the wadis Baba and Sudri. The plain surface is filled by igneous and limestone Boulders and gravels of limestone and igneous rocks, together with other deposits transported by the two wadis, which form a thick wedge of alluvium up to xenolith beneath the plain.

SURFACE MORPHOLOGICAL SYSTEM

The geomorphological investigations of the basins are based on field observations, and analyses of topographic maps and aerial photographs. Studies of network geometry are concerned exclusively with the internal relationships of the networks, and take account of such features as order of streams, length of tributaries, stream density, and drainage density, which together indicate the efficiency of the drainage system.

The study area is traversed from north to south by four major basins, namely the El-Tayiba, Baba, Sudri, and Feiran basins (Figure 1), each of which runs essentially ENE–WSW or E–W towards the Gulf of Suez. Each hydrographic basin is characterized by particular drainage characteristics (Figure 1). The hydrographic characters of each basin are given in Table 2.

The El-Tayiba Basin is located on the northern part of the study area, and with an area of about 446 km^2 is the smallest of the catchments considered on the basis of the drainage area. It comprises 43 stream numbers with a stream length of 166 km. The tributaries are interconnected to supply water to the main stream which proceeds along a ENE–WSW course from source to sea. The Baba Basin occupies an area of 748 km^2, with 43 stream numbers, and a total stream length of 215 km. The Sudri Basin includes 99 stream numbers, with the total stream length of 391 km and extends over 1076 km^2. The Feiran basin, located at the southern part of the study area, runs E–W, is the largest of the basins considered with an area of 1758 km^2, 115 stream numbers, and a stream length of 539 km.

Table 1. Mean Monthly and Total Annual Precipitation (mm) In and Around the Study Area.

Station	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total (mm)
El-Arish	19.4	20.2	12.1	7	2	0	0	0	0	4	12.3	16	93
Nekhel	7.8	5.7	4.3	2	1.5	0	0	0	0	2.2	3.5	3.3	30.3
Thamad	3	8	6	2	1	0	0	0	0	4	16	4	44
Tor	2	2	2	0.3	0.1	0	0	0	0	0,8	2	2	11.2
Santa Katerina	1.5	1.4	10.2	7.9	6.4	0	0	0	0	4.6	22	7	61

The Network Geometry of the Study Area

The geomorphological parameters such as the stream order, stream number, bifurcation ratio, drainage area, stream frequency, drainage density as well as stream length are shown in Table 2. Some of these values are obtained from topographic maps and others have been calculated mathematically. The pattern or arrangement of the natural stream channels indicates the efficiency of the drainage system. These parameters are studied in relation to the hydrochemical characters of the groundwater in order to establish the relationship between surface and subsurface waters in the study area.

Stream Order and Stream Number

Order indicates the ranking position of a given stream in the network that contains it, and stream number is the number of streams per order. Number obviously increases as order decreases. The stream number is directly proportional to the size of catchment, to channel dimensions and stream discharge. A study of the drainage pattern of the four basins reveal that the lowest stream number of 43 is designated to El-Tayiba basin, and the highest stream number of the Feiran basin reached to 115. However, the Baba basin has the same stream number as El-Tayiba basin (43), though its catchment is larger.

Bifurcation Ratio (R_b)

The dividing factor between one order and the next order is the bifurcation ratio. The bifurcation ratios for the study basins were calculated using the following formula [6]:

$$N_s = R_b^{K-s}$$

where (N_s) is the number of tributaries of order (S), and (K) is order of the trunk stream. Moreover, the bifurcation ratio is considered the slope of the straight line resulting from the plot of stream-order (S) *versus* the logarithm of the stream number (N_s) as portrayed in Figure 2. The ratio is an indication of the elongation or circularity of the basin and reflects the basin tendency towards flood . The mean bifurcation ratio for the network of the study area is slightly greater than 4.0. Many real networks have bifurcation ratios of 3.0–4.0 because low-order tributaries enter without promoting high-order trunk streams.

Table 2. Quantitative Analyses of the Hydrological Characteristics of the Basins of the Study Area.

Basin Name	Stream order	Stream number	Order K	ΣN_s	Log N_s	Bifurcation ratio (R_b)	Basin area km^2	Stream Frequency F_s km^{-2}	Drainage Density D_s km^{-1}	Stream Length (L_s) km
El-Tayiba	1st	32	4	43	1.51	3.182	446	0.0964	0.3727	166
	2nd	7			0.85					
	3rd	3			0.48					
	4th	1			0					
Baba	1st	30	4	43	1.48	3.058	748	0.0575	0.2878	215
	2nd	9			0.95					
	3rd	3			0.48					
	4th	1			0					
Sudri	1st	78	4	99	1.9	4.072	1076	0.092	0.3641	391
	2nd	18			1.26					
	3rd	2			0.3					
	4th	1			0					
Feiran	1st	92	4	115	1.96	4.179	1758	0.0654	0.307	539
	2nd	19			1.28					
	3rd	3			0.48					
	4th	1			0					

The El-Tayiba and Baba basins have a bifurcation ratio value of 3.182 and 3.058 respectively. This reflects that these basins are more or less circular, whereas the basins of Sudri and Feiran have bifurcation ratios of 4.072 and 4.179 indicating elongation of the basins. Hence, it is expected that the total runoff flow to the outlet takes longer from the Sudri and Feiran basins than from the El-Tayiba and Baba basins.

Stream Frequency (F_s)

According to Horton [6], stream frequency is defined as the ratio of the total number of stream order to the total basin area (A_k). It was found that the stream frequency of the study basins ranges from 0.0575 to 0.0964 km^{-2} for the Baba and El-Tayiba basins respective (Table 2). The values of the frequency reveal more possibilities of the basins towards flooding though the exact volume of runoff cannot be predicted.

Drainage Density (D_s)

Drainage density is expressed as the length of stream per unit area and varies inversely as the length of overland flow. It provides an indication of tendency of the basin towards flood. The drainage density was calculated by the application of the experimental relationship $D_s = \sqrt{F_S / 0.694}$ [7] which is applicable to all basins. Drainage density represents the closeness of the tributaries in the basin, therefore, it reflects the type of surface layer, roughness, and its permeability. Generally, the low values of the drainage density resulted from the small number and lengths of the tributaries and may indicate that the basins possess highly permeable subsoil or a flat area of dense plant cover. Moreover, basins of high values of drainage density are related to the large number and length of tributaries. Therefore, it is suggested that the basins are characterized by areas of low permeability and steep surface with less density of plant cover.

The Baba basin has the lowest values of the drainage density (0.2878 km^{-1}). This may indicate that the basin is characterized by highly permeable subsoil zone compared with the other basins. In addition this basin has also the lowest value of bifurcation ratio of 3.058 which showed that the contributaries of the surface water to groundwater is expected to be in reasonable quantities.

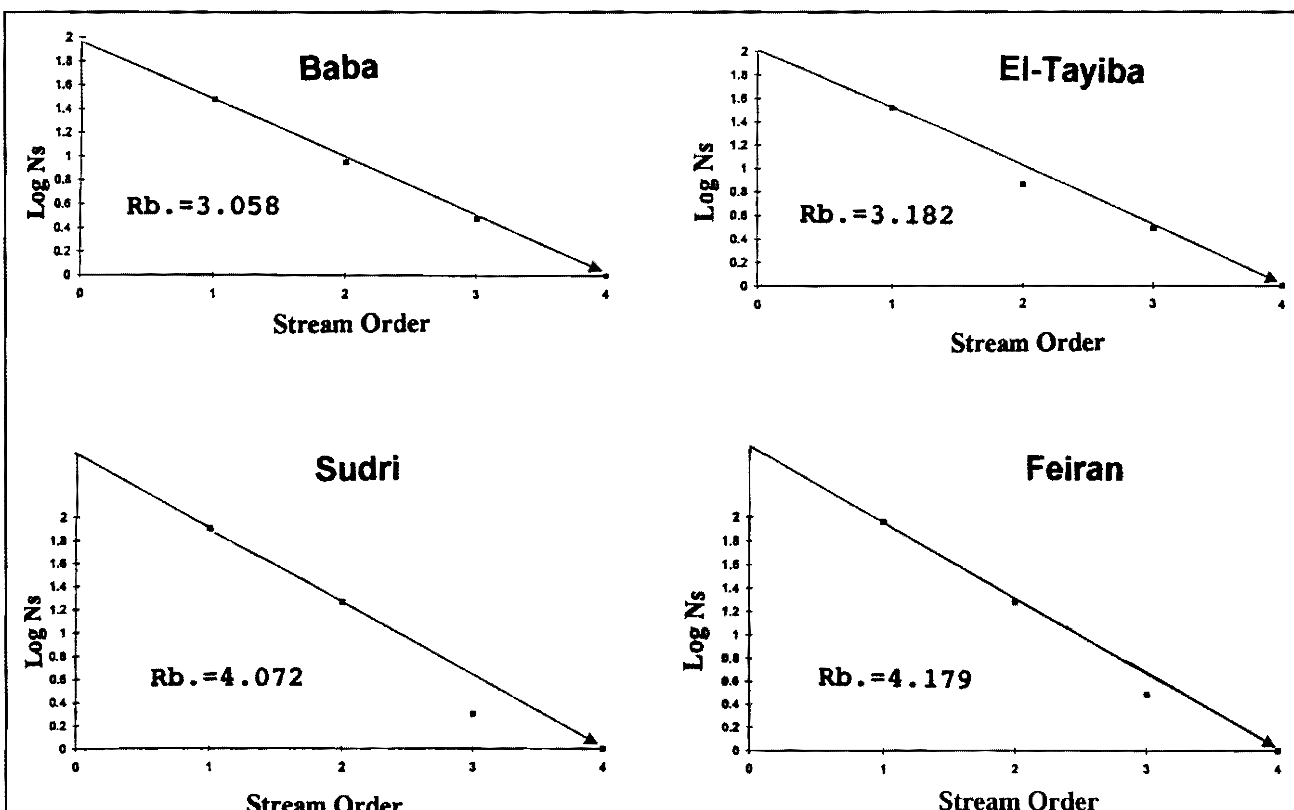

Figure 2. Determination of the Bifurcation Ratio from the Slope.

The Feiran basin showed a slightly higher values of drainage density than the Baba basin which reached (0.307 km^{-1}). This means that the basin has a highly permeable subsoil. This basin also displays the highest values of the bifurcation ratios (4.179). Accordingly, the surface runoff takes a longer time to reach the outlet, permitting infiltration of the surface water into the subsurface.

The Sudri basin showed a slightly higher values of drainage density (0.3741 km^{-1}) reflecting the semi-permeable nature of the soil, but in the zoned lower stream numbers, and the main channel of the Wadi, the drainage area exhibited a permeable subsoil zone. Also, this basin has a slightly higher value of bifurcation ratio (4.072) which indicates the elongate shape of the basin. The runoff takes longer to reach the basin outlet, enabling infiltration to take place into the groundwater. However, the El-Tayiba basin has the highest values of the drainage density (0.3727 km^{-1}), so the basin is characterized by low-permeability subsoil zones and its bifurcation ratio (3.182) suggests a circular shape basin, in which the recharge from rainfall may be neglected or insignificant.

Main Stream Length (L_s)

This can be calculated from the drainage density D_s (km^{-1}) and the basin area A_k (km^2) according to the relation $L_s = D_s A_k$.

The stream length is the average length of stream per order. Mean length increases as order increases. Steep well-drained areas usually have numerous small tributaries, whereas in plains regions where the soils are deep and permeable only relatively long tributaries are maintained as perennial streams. As shown in Table 2, the El-Tayiba basin has the shortest stream length of 166 km and the Feiran basin has the highest stream length of 539 km.

HYDROLOGICAL CHARACTERISTICS OF THE BASIN

Hydrography describes the chronology of the changing rate of flow from a catchment due to a rainfall event.

The non-homogeneous meteorological records from El-Tor and Abu Rudies stations have been collected, and the isohyetal contours and the maximum rainfall per day maps prepared for the study area. Generally, the annual rainfall ranges from 20 mm/year in the eastern inlet part to 55 mm/year in the western direction towards outlet near the Abu Rudies. The hydrographic basin analyses of the four basins are shown in Table 3. Figure 3 shows the areal distribution of the isoheytal contour map of the study area. In the Wadi El-Tayiba rainfall ranged from 25–30 mm, with an average annual of 27.28 mm. These values are small when compared to the other basins. In the Baba basin annual rainfall ranged between 25–40 mm with a weighted average annual rainfall of 30.42 mm. The Sudri basin received an annual rainfall of 20–50 mm decreasing westward; the weighted average annual rainfall was calculated to be 37 mm. It is obvious that the Wadi Feiran received the highest annual rainfall of 20–55 mm, and the weighted annual average rainfall of 42.87 mm.

Rainfall Maxima

The high rainfalls of shorter durations cause floods. Most rainfall data are in the form of daily totals, and maximum daily falls have been noted. The computed maximum daily rainfall (Figure 4) has been utilized to show the importance of floods. Maximum rainfall ranges from 32 mm/day in the northern part of the Wadi El-Tayiba to 70 mm/day in the southwest corner of Wadi Feiran (Figure 4). The maximum runoff expected for each basin has been calculated (Table 3).

The preliminary computation of the probable maximum runoff can be achieved by using the weighted average of the maximum daily rainfall for each basin and by the application of Ball's equation [8] $V = 750A(R-8)$ where V is the expected

Table 3. Hydrological Basin Analyses in the Study Area.

Basin Name	Basin area Km^2	Weighted average over a year of the daily rainfall (mm)	Weighted average quantities of rainfall (million m^3)	Weighted average of maximum rainfall in one day (mm)	Maximum quantity of rainfall million m^3/day	Maximum quantity of runoff possible in one day (million m^3)
EL-Tayiba	446	27.5	12.27	36.33	16.2	9.48
Baba	748	32.5	24.31	42.2	31.57	19.19
Sudri	1076	35	37.66	48.31	51.98	32.53
Feiran	1758	37.5	65.93	56.35	99.06	63.75

maximum value of the runoff in (m^3), R is the average weighted maximum rainfall depth per day (mm), and A is the basin area (km^2).

The large catchment of the Wadi Feiran received the highest volume of runoff of 63.75 million m^3/day in addition to its large drainage area. The Wadi El-Tayiba received about 9.48 million m^3/day on its catchment of 446 km^2. The probable maximal runoffs do not occur regularly but represent the maximum values of runoff that flood each basin.

Water-Bearing Formations

There are four major aquifers in the study area. They are listed below, from oldest to youngest.

Precambrian Fractured Basement Rock Aquifers

Two sites have been encountered in these aquifers (Figure 1). In well No.9 (Baba basin) the water seepages from fractured granites as springs along dikes. Well No. 21 (Feiran basin) is located in a shear zone in acidic metamorphic rocks. Storage from these rocks seeps into the alluvial sediments of the Wadi. These rocks lose their hydrogeologic importance due to the high rate of evaporation and less precipitation.

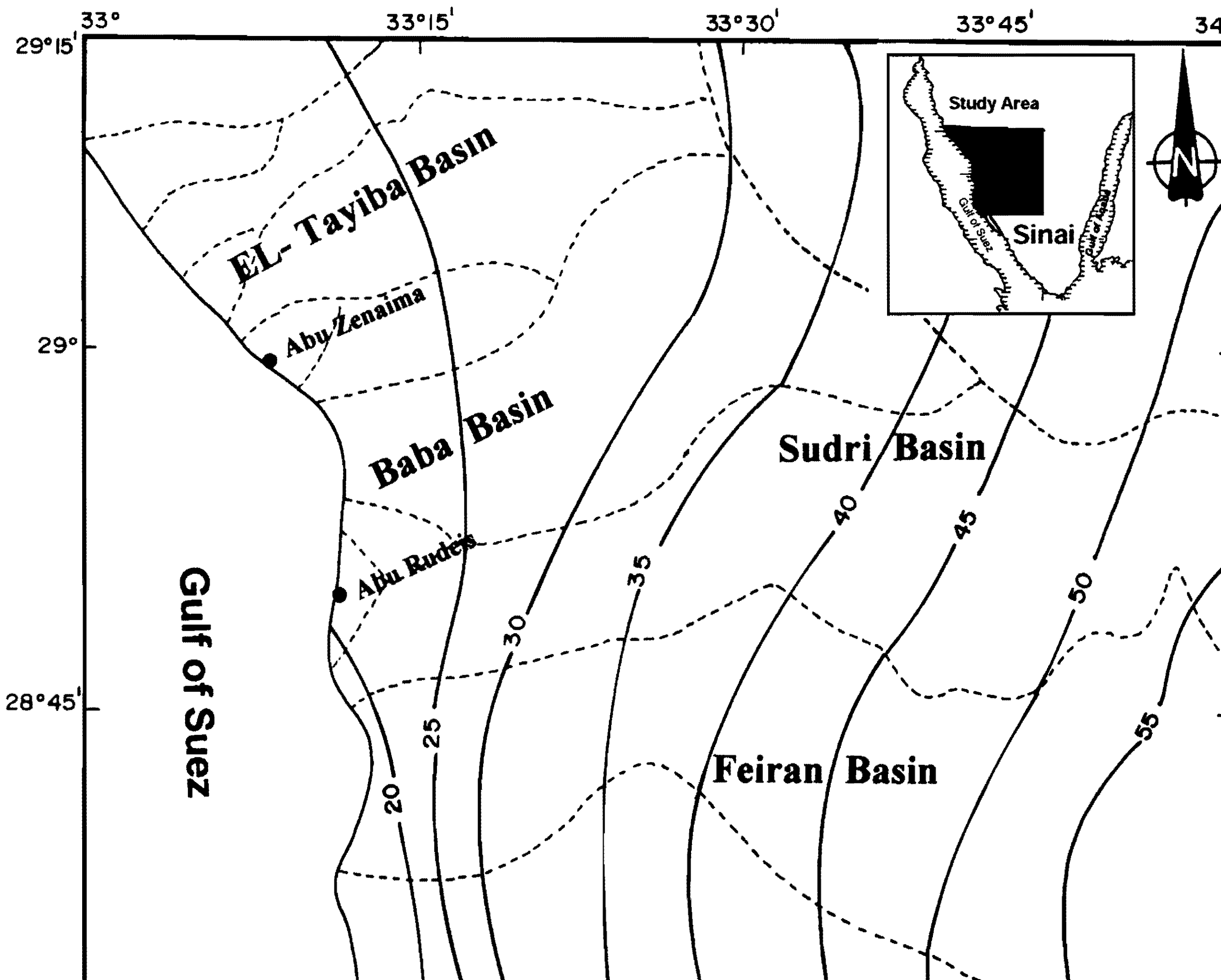

Figure 3. Isohyetal Contour Map of the Study Area.

Carbonaceous Sandstone Aquifers

These sandstones form good aquifers in which five water wells have been established. The hydraulic characters of these rocks are enhanced by their highly fractured nature. At many localities, small springs issue from these fractures, as in well No. 2 (El-Tayiba basin). The Carboniferous aquifers meet the basement aquifer in faulted boundaries. The recorded shallow depth to water at the proven water sites, well Nos. 12 and 13 (Sudri basin) and well Nos. 18 and 22 (Feiran basin) showed that the evaporation process takes place by means of capillary forces.

Nubian Sandstone Aquifers

These aquifers form the most important hydrogeologic unit all over the central and northern parts of Sinai, where groundwater exists under artesian conditions at great depths. These sandstone aquifers are of upper Jurassic to lower Cretaceous age [9]. The sandstone layer overlies sticky dark clays which act as an impermeable base.

Shallow phreatic water occurs in the local exposures of the Nubian Sandstones exposed in the downstream sectors of Wadis Baba and Sudri, shallow excavations with an average depth to water of about 3.5 m from the ground surface are represented by well No. 10 in Wadi Baba.

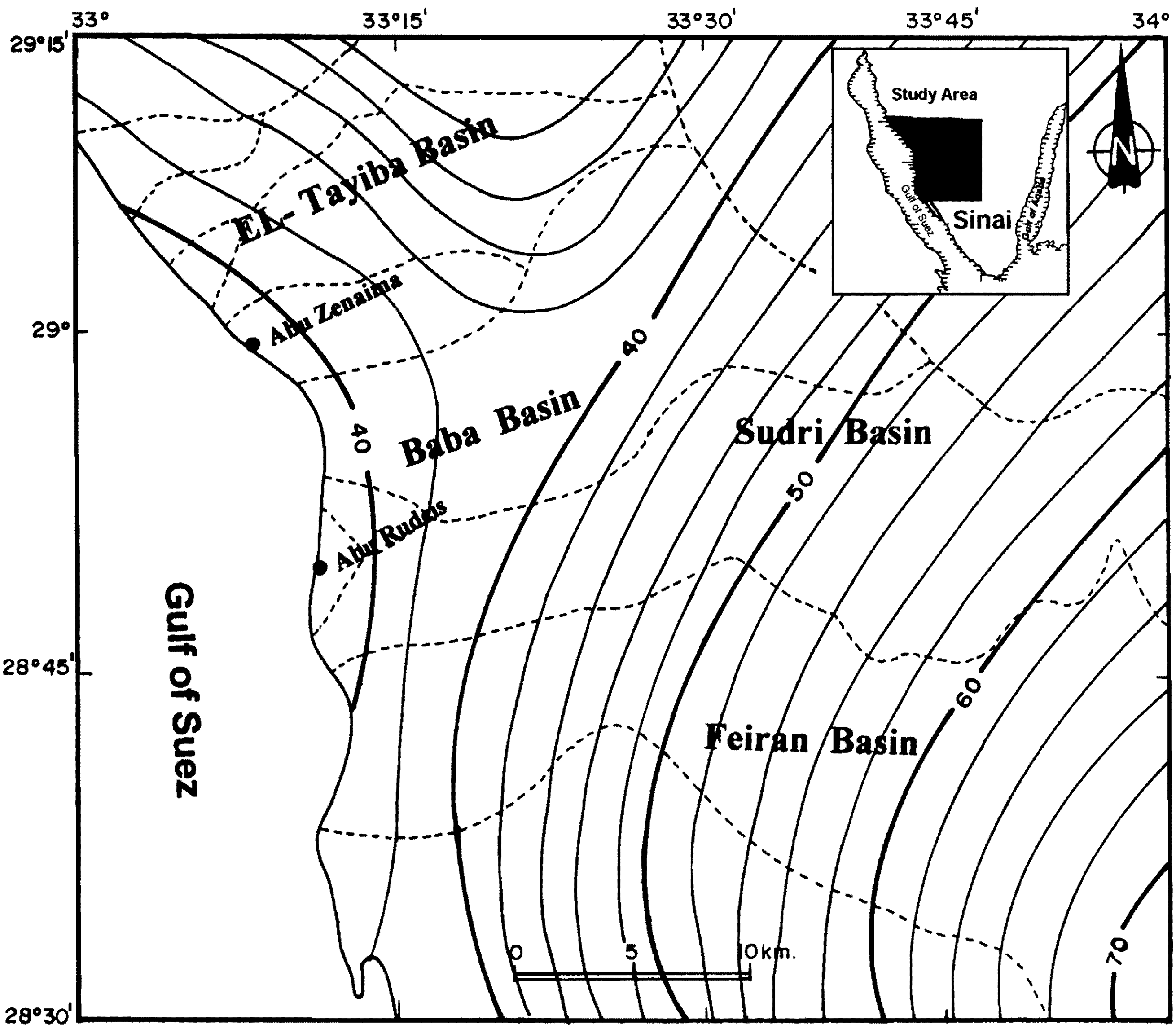

Figure 4. Maximum Daily Rainfall in the Study Area.

Quaternary Deposits Aquifers

These deposits form unconfined aquifers in which water moves under the influence of the natural hydraulic gradient towards the Gulf of Suez. The Quaternary deposits are of eolian and fluvial origin and take the form of a sand sheet extending along the main Wadi, all along the coastal plain. The wadi filling deposits form good aquifers where numerous wells occur, about 14 wells occurring in the study area (Figure 1).

Hydrogeochemical Aspects

Hydrogeochemical aspects of the investigated area are based on a series of chemical analyses for the main anions and cations composition. The samples were collected from four basin areas representing different aquifers to study the effect of the infiltrated surface water on groundwater chemistry. Generally, the Baba basin shows the lowest salinity value ranging from 590 to 940 mg/l with an average of 790 mg/l. Samples from Wadi El-Tayiba exhibit the highest value of the salinity ranges from 1860 to 2210 mg/l with an average of 1995 mg/l. This discrepancy in aquifer salinity may be related to the presence of the permeable sub-soil zone in the Baba basin which allows the infiltration of fresh surface water contrasted with low permeability in the El-Tayiba basin. This salinity shows a close agreement with the drainage density, rainfall, and runoff (Tables 2 and 3). The range in aquifer salinities in the wadis may reflect the influence of the seasonal meteoric water recharges. The concentration of Cl^- ions is dominant among the anionic compositions, followed by SO_4^{2-} and HCO_3^- respectively. The concentration of Na^+ ion is the highest among the cations and is consistently followed by Ca^{2+} and Mg^{2+} respectively.

The increase of Na^+ and HCO_3^-, and the decrease of SO_4^{2-} in some water sites was explained by ion-exchange of Na^+ on the solids for Ca^{2+} and Mg^{2+} in solution. The increase of dissolved HCO_3^- was interpreted as the dissolution of carbonate minerals in response to cations exchange and attributed to the decrease in dissolved SO_4^{2-} (Table 4).

Mineral Saturation Indices

Theoretical saturation states of anhydrite, aragonite, calcite, dolomite, gypsum, huntite, magnesite, and PCO_2 were calculated for water samples with the field measurement of pH and temperature using the computer program [10]. The mean saturation indices (SI) of the groundwater with respect to the specified minerals are summarized in Table 5. The groundwater shows a supersaturation with respect to aragonite, calcite, dolomite, and magnesite, and also exhibits undersaturation with respect to anhydrite, gypsum, and huntite. These results indicate that the groundwater is at or near equilibrium with respect to dolomite and calcite. These minerals are considered the dominant carbonate minerals in the major aquifers. Based on the observed SO_4^{2-} distributions and the calculated saturation index, the behavior of SO_4^{2-} is not constrained by gypsum solubility.

The calculated log PCO_2 values of groundwater samples show a range from –1.585 to –2.464. The log PCO_2 values of Wadi Baba are most likely to be near the log partial pressure of CO_2 ($10^{-3.5}$), indicating that the water is in contact with the atmosphere due to the high rainfall and the high permeable sub-soil zone. The log PCO_2 is calculated from the pH and carbonate concentrations and it is found that the trend in PCO_2 is similar to that of HCO_3^- and CO_3^{2-}.

Multivariate Statistical Analysis

Correlation analyses of 22 cases were carried out for the study area using the hydrochemical compositions of major elements in groundwater. The variables are namely: TDS, pH, K^+, Na^+, Mg^{2+}, Ca^{2+}, Cl^-, SO_4^{2-} and HCO_3^- as shown in Table 6.

The TDS shows a good correlation with all variables except the ionic concentration of HCO_3^- in Wadis Baba and Sudri. The correlation is positive in Wadi Baba, but the correlation coefficient lies below the threshold value (*r* 0.6). In the Wadi Sudri, on the other hand, the correlation is negative. This indicates that the recharge process is not local and the bicarbonates were precipitated as carbonates along the recharge route. But the recharge in Wadi Sudri may be attributed to the local recharge process due to the negative correlation of TDS with HCO_3^-. And the carbonates were precipitated as the carbonates from shallow meteoric percolation or directly from the atmosphere.

The good positive correlation between the ionic concentrations of Cl^- and SO_4^{2-} may be related to the mixing processes between different water geneses. The ionic concentration of HCO_3^- is correlated fairly well with K^+, which refers to the release of K^+ ions from rock material influenced by the percolation of meteoric water.

Table 4. Chemical Composition of the Representative Groundwater Samples from the Study Area.

Basin	Sample	Water	Temp.	TDS	pH	Exp. of	Cations				Anions		
Name	No.	depth (m).	0C	mg/l		analysis	K	Na	Mg	Ca	Cl	SO_4	HCO_3
	1	4.9	34	1860	7.4	ppm	35	320	47	202	550	216	482
						epm	0.9	13.91	3.9	10	15.52	4.5	7.9
	2		39	1900	7.9	ppm	39	322	49	204	558	215	501
						epm	1	14	4.1	10	15.72	4.5	8.21
El-Tayiba	3	10.2	36	1970	7.6	ppm	47	329	52	210	572	230	519
						epm	1.2	14.3	4.3	11	16.11	4.8	8.51
	4	4.3	34	2030	7.4	ppm	55	336	54	216	586	239	543
						epm	1.4	14.61	4.5	11	16.51	5	8.9
	5	9	35	2210	7.5	ppm	63	359	58	236	622	263	604
						epm	1.6	15.61	4.8	12	17.52	5.5	9.9
	6	24	38	590	7.9	ppm	27	59	16	60	49	2	376
						epm	0.7	2.57	1.3	3	1.38	0	6.16
	7	20.5	37	590	7.8	ppm	31	64	22	59	145	4	258
						epm	0.8	2.77	1.9	3	4.07	0.1	4.22
Baba	8	18.9	37	940	7.8	ppm	35	118	24	110	236	55	355
						epm	0.9	5.14	2	5.5	6.65	1.2	5.81
	9	—	39	900	7.9	ppm	10	143	13	123	255	103	250
						epm	0.3	6.22	1.1	6.2	7.18	2.2	4.1
	10	3.5	34	940	7.4	ppm	16	127	30	97	185	5	476
						epm	0.4	5.52	2.5	4.9	5.21	0.1	7.8
	11	2	33	1550	7.3	ppm	62	275	42	132	497	125	400
						epm	1.6	11.97	3.5	6.6	14	2.6	6.55
	12	3.2	34	1150	7.4	ppm	23	188	27	92	185	35	599
						epm	0.6	8.17	2.3	4.6	5.2	0.7	9.81
	13	4.3	34	1520	7.4	ppm	47	278	33	110	392	25	622
Sudri						epm	1.2	12.08	2.8	5.5	11.04	0.5	10.2
	14	26.5	38	1600	7.8	ppm	20	208	57	174	306	166	665
						epm	0.5	9.04	4.8	8.7	8.62	3.5	10.9
	15	13	36	1620	7.6	ppm	52	265	52	144	447	240	412
						epm	1.3	11.52	4.3	7.2	12.59	5	6.75
	16	8.15	35	1510	7.5	ppm	55	214	54	134	348	160	534
						epm	1.4	9.3	4.5	6.7	9.8	3.3	8.75
	17	14.1	36	675	7.6	ppm	5	98	21	71	159	8	308
						epm	0.1	4.26	1.8	3.6	4.48	0.2	5.05
	18	3.6	34	780	7.4	ppm	12	109	25	81	184	13	351
						epm	0.3	4.74	2.1	4.1	5.18	0.3	5.75
	19	20.25	37	1000	7.8	ppm	20	148	26	117	272	60	351
Feiran						epm	0.5	6.44	2.2	5.9	7.66	1.3	5.75
	20	2.5	33	1190	7.3	ppm	47	164	26	127	269	45	509
						epm	1.2	7.13	2.2	6.4	7.58	0.9	8.34
	21	8	35	1265	7.5	ppm	12	196	23	164	337	86	445
						epm	0.3	8.52	1.9	8.2	9.49	1.8	7.3
	22	4	34	1180	7.4	ppm	47	193	38	85	295	69	451
						epm	1.2	8.39	3.2	4.3	8.31	1.4	7.39

Table 5. Summary of the Saturation Indices.

Phase Name	Anhydrite	Aragonite	Calcite	Dolomite	Gypsum	Huntite	Magnesite	PCO_2
El–Tayiba Basin								
Min.	–1.329	0.691	0.829	1.461	–1.166	–1.56	0.037	–2.193
Max.	–1.225	1.248	1.382	2.619	–1.054	0.85	0.64	–1.674
Mean	–1.289	0.915	1.052	1.94	–1.122	–0.557	0.292	–1.84
Standard Deviation	0.035	0.194	0.193	0.4	0.039	0.83	0.207	0.19
Baba Basin								
Min.	–3.546	0.495	0.632	1.202	–3.393	–1.944	–0.117	–2.464
Max.	–1.643	0.85	0.984	1.754	–1.495	–0.864	0.227	–1.702
Mean	–2.703	0.694	0.829	1.496	–2.544	–1.431	0.07	–2.2
Standard Deviation	0.751	0.161	0.16	0.221	0.748	0.445	0.128	0.262
Sudri Basin								
Min.	–2.413	0.36	0.498	0.93	–2.236	–2.498	–0.162	–1.974
Max.	–1.382	1.22	1.355	2.696	–1.217	–0.753	0.745	–1.596
Mean	–1.8	0.692	0.829	1.626	–1.63	–1.43	0.203	–1.77
Standard Deviation	0.401	0.264	0.263	0.55	0.395	0.604	0.288	0.154
Feiran Basin								
Min.	–2.922	0.308	0.446	0.825	–2.756	–2.7	–0.216	–2.228
Max.	–1.699	0.851	0.986	1.784	–1.528	–0.879	0.202	–1.585
Mean	–2.227	0.536	0.673	1.197	–2.054	–2.032	–0.071	–1.881
Standard Deviation	0.434	0.197	0.196	0.307	0.434	0.586	0.145	0.213

CONCLUSIONS

Quantitative geomorphological and hydrogeochemical investigations were carried out on a study area located on central western part of the Sinai Peninsula. The study of the drainage pattern of the four basins reveals that the lowest stream number is assigned to El-Tayiba basin and the highest to the Feiran basin. The mean bifurcation ratio of the network of the study area is slightly greater than 4.0. El-Tayiba and Baba basins possess a circular shape, while the Sudri and Feiran basins exhibit an elongation according to their bifurcation ratio. Therefore, it is expected that the total runoff to the outlet in the former basins will take a considerable longer time than in the latter basins. The Baba basin has the lowest value of the drainage density, while Feiran basin has the highest value indicating a considerable infiltration of surface water to the groundwater. El-Tayiba has the shortest stream length while the Feiran basin has the longest stream length reaching 539 km.

The Feiran basin has a weighted average annual precipitation of 42.87 mm. Therefore, it received the highest volume of runoff of 63.75 million m^3/day and El-Tayiba received the least volume of runoff.

The Baba basin exhibited the lowest salinity among the basins with an average of 790 mg/l while Wadi El-Tayiba basin showed the highest salinity of 1995 mg/l. The increases of Na^+ and HCO_3^- and decreases in SO_4^{2-} ions may be due to the ion exchange process. The groundwater shows a supersaturation with respect to aragonite, calcite, dolomite, and magnesite and undersaturation with respect to anhydrite, gypsum, and huntite.

The multivariate statistical analyses indicated that the TDS is in a good correlation with all variables except the ionic concentration of HCO_3^- in Wadi Sudri. The negative relation of TDS with HCO_3^- in Sudri basin suggested that the recharge process is not local and the bicarbonates were precipitated as carbonates along the recharge route. The good positive correlation between the ionic concentration of Cl^- and SO_4^{2-} may be related to the mixing processes between the water types.

Table 6. Correlation Matrix of Nontransformed Data Input of the Hydrochemical Variables of the Study Basins ($r \geq 0.6$).

Baba Basin

	TDS	pH	K	Na	Mg	Ca	Cl	SO_4	HCO_3
TDS	+1.00								
pH	−0.44	+1.00							
K	−0.47	+0.15	+1.00						
Na	**+0.97**	−0.36	−0.64	+1.00					
Mg	+0.25	−0.82	+0.40	+0.09	+1.00				
Ca	**+0.95**	−0.18	−0.57	**+0.97**	−0.04	+1.00			
Cl	**+0.**	−0.26	−0.37	**+0.83**	+0.20	**+0.80**	+1.00		
SO_4	**+0.71**	+0.26	−0.40	**+0.78**	−0.31	**+0.87**	**+0.79**	+1.00	
HCO_3	+0.27	−0.72	+0.13	+0.09	**+0.63**	+0.02	−0.25	−0.41	+1.00

Feiran Basin

	TDS	pH	K	Na	Mg	Ca	Cl	SO_4	HCO_3
TDS	+1.00								
pH	−0.30	+1.00							
K	**+0.74**	−0.45	+1.00						
Na	**+0.97**	−0.23	**+0.70**	+1.00					
Mg	+0.49	−0.31	**+0.79**	+0.56	+1.00				
Ca	**+0.78**	+0.00	+0.29	**+0.70**	−0.13	+1.00			
Cl	**+0.97**	−0.09	**+0.64**	**+0.97**	+0.45	**+0.80**	+1.00		
SO_4	**+0.95**	−0.01	**+0.67**	**+0.96**	+0.50	**+0.76**	**+0.99**	+1.00	
HCO_3	**+0.89**	−0.66	**+0.80**	**+0.83**	+0.47	**+0.61**	**+0.76**	**+0.72**	+1.00

Sudri Basin

	TDS	pH	K	Na	Mg	Ca	Cl	SO_4	HCO_3
TDS	+1.00								
pH	+0.40	+1.00							
K	+0.45	−0.53	+1.00						
Na	**+0.63**	−0.34	**+0.75**	+1.00					
Mg	**+0.79**	**+0.67**	+0.17	+0.09	+1.00				
Ca	**+0.82**	**+0.73**	+0.00	+0.13	**+0.94**	+1.00			
Cl	**+0.85**	−0.11	**+0.79**	**+0.88**	+0.49	+0.49	+1.00		
SO_4	**+0.62**	+0.52	+0.21	+0.04	**+0.90**	**+0.82**	+0.44	+1.00	
HCO_3	−0.33	+0.36	−0.74	−0.57	−0.23	−0.14	−0.66	−0.52	+1.00

El-Tayiba Basin

	TDS	pH	K	Na	Ca	Mg	Cl	SO_4	HCO_3
TDS	+1.00								
pH	−0.26	+1.00							
K	**+0.96**	−0.30	+1.00						
Na	**+0.99**	−0.30	**+0.92**	+1.00					
Mg	**+0.98**	−0.24	**+0.99**	**+0.95**	+1.00				
Ca	**+0.99**	−0.29	**+0.93**	**+1.00**	**+0.95**	+1.00			
Cl	**+1.00**	−0.28	**+0.96**	**+0.99**	**+0.98**	**+0.99**	+1.00		
SO_4	**+0.98**	−0.39	**+0.95**	**+0.98**	**+0.97**	**+0.98**	**+0.99**	+1.00	
HCO_3	**+0.99**	−0.23	**+0.96**	**+0.98**	**+0.98**	**+0.99**	**+0.99**	**+0.98**	+1.00

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