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Systems Approach in Assessing Suitability of Groundwater for Irrigation in Western Region of Saudi Arabia

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ABSTRACT. One of the empirical parameters, most commonly used in assessing the quality of irrigation water is the sodium adsorption ratio (SAR). The other parameters are total dissolved solids (TDS), total ions (Ca^{++}, Mg^{++}, Na^{+}, K^{+}, HCO_3^{-}, CO_3^{--}, SO_4^{--}, CL^{-}, ...etc.) and trace metals. In order to minimize soil and crop problems, especially in arid areas due to high evaporation rates and subsequent salt build up, the SAR ratio must be close to the acceptable limits. In order to determine SAR values extensive water quality sampling analysis efforts, which are time and labor intensive, are needed. Groundwater quality data for 190 locations (wells) in the Western Region, Saudi Arabia, was collected. Out of this data, 138 points were used in developing regression models between TDS and: (1) SAR; (2) Total ions; (3) Major cations and Strontium (Sr) metal (most commonly found in the Western Region geological formations). The developed regression models have goodness of fit $(R^{-})^2$ ranging from 0.7 to 0.99 indicating a good relationship. The six data points were used to check the validity of regression models. The developed models offer convenient and easy approach in estimating SAR, Total ions and Sr, provided TDS value is known. Measurement of TDS is relatively easy. The calculated or estimated values of SAR help in the assessment of groundwater suitability for irrigation purpose.

KEY WORDS. Assessment, Groundwater Quality, Irrigation, Arid Areas, Sodium Adsorption Ratio.

Introduction

The major water user in the Kingdom is the agriculture or irrigation sector which makes up about 60 to 80% of the total water use (Fourth & Fifth Development Plan, 1980, 1985). The standards of water quality needed for agriculture or irrigation are less stringent than for the industrial, residential and others. One of the parameters, most commonly used in assessing the quality of irrigation water is the sodium adsorption ratio (SAR), (Schainberg and Oster 1978). Other parameters are major total ions (Ca^{++}, Mg^{++}, Na^{+}, K^{+}, SO_4^{--}, CL^{-}, NO_3^{-}, HCO_3^{-}, CO_3^{--}, ...etc.), total dissolved solids (TDS) and trace metals (National Academy of Sciences, 1973).

An excess of sodium adsorption in the soil will cause clay particle to disperse instead of aggregate and in some cases also to swell (Schainberg *et al.* 1980, Stewart and Meek 1977, U.S. Salinity Laboratory Staff 1954). This results in a soil with low porosity, poor permeability and poor operation, when wet. Therefore, irrigation waters with higher SAR values are not suitable for irrigation (Ayers and Tanji 1981). In order to minimize soil and crop problems, the SAR ratio must be close to the acceptable limits. In order to determine the SAR values of groundwater and its suitability for irrigation, extensive water sampling, analysis and other associated efforts are needed.

This paper aims to develop and present a simple approach for assessing the water quality for irrigation purposes by: (1) collecting the groundwater quality data (total ions, TDS, SAR and strontium metal) in the Western Region, (2) developing relationships of TDS with total major ions, cations, SAR and strontium, and (3) checking the validity of the developed regression models for determining the suitability of a groundwater for irrigation.

Data Collection, Compilation and Analysis

The Western Region of Saudi Arabia (Fig. 1) consists of several subregions (wadis) based upon the groundwater aquifers. The major wadis are Fatimah, Khulays, Naaman, Wijj and Bathan (Al-Aqiq) in which wells are located for supplying water to cities of Jeddah, Makkah, Taif and Madinah. Literature review (Al-Kabir 1985, Hussein 1985) revealed that some data regarding groundwater quality in the Western Region is available. Extensive groundwater quality monitoring program, over a period of one year, was carried out in various wadis of the region (Khan 1987). A total of about 190 wells are monitored. The collected groundwater samples were analyzed for major cations (Na^{+}, K^{+}, Ca^{++}, Mg^{++}), anions (Cl^{-}, SO_4^{--} and HCO_3^{-}), TDS and Sr. The concentrations of Ca^{++}, Mg^{++}, Cl^{-} and HCO_3^{-} were measured using standard methods (1989), while Na^{+}, K^{+} and trace metals were measured by special "plasma technique" available in the Faculty of Earth Sciences, King Abdulaziz University. Based upon the statistical analysis of data from different wells in the major wadis of the Western Region an average chemical analysis of groundwater is presented in Table 1. The concentration of various ions (Ca^{++}, Mg^{++}, Na^{+}, K^{+}, HCO_3^{-}, SO_4^{--}, Cl^{-}) were measured in mg/l, and later converted to meq/l. The concentration of Sr was measured in ppb.

The sodium adsorption ratio (SAR) values were computed using three major cations (Na^{+}, Ca^{++} and Mg^{++}) :

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{++} + Mg^{++}}{2}}} \qquad (1)$$

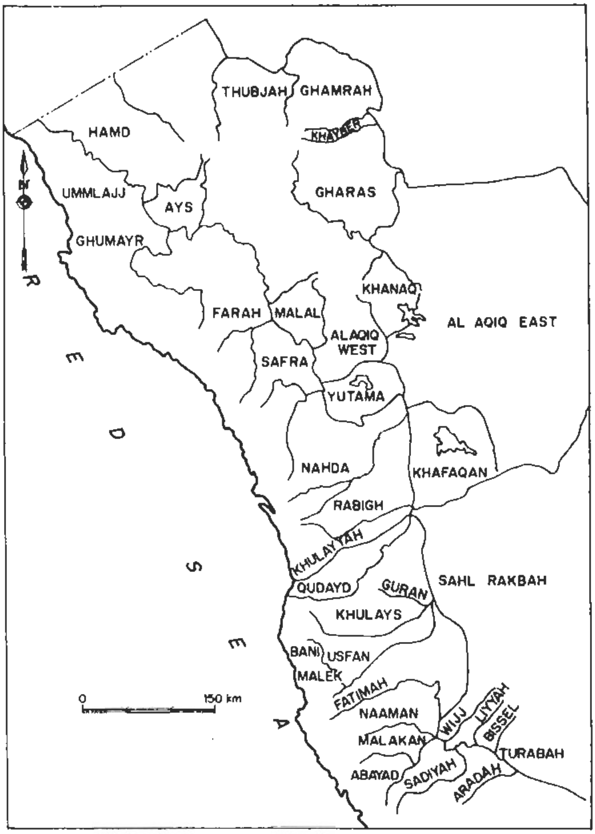

FIG. 1. Surface water catchments and major wadis in the Western Region.

TABLE 1. Average chemical analysis of representative groundwater samples of some wadis in the western region, Saudi Arabia. (Based upon the total 190 wells).

Sl. No.	Name of Subregion	Chemical Constituents (meq/l)							Strontium (p.p.b.)
		Ca^{++}	Mg^{++}	Na^{+}	K^{+}	HCO_3^-	SO_4^{--}	Cl^-	
1	Fatimah	3.50	2.60	*3.60	–	4.2	2.2	4.77	980
2	Naaman	8.0	6.2	*12.0	–	3.9	5.2	20.2	2300
3	Khulays	4.19	5.3	5.69	0.19	–	4.16	11.2	2100
4	Wijj	6.78	5.75	11.31	0.38	6.55	5.20	8.46	–
5	Guran	6.1	5.2	12.2	0.15	4.5	3.4	9.0	–
6	Bathan	1.99	4.11	13.05	0.25	6.5	3.12	9.87	206
7	Aradah**	2.49	1.64	2.61	0.07	5.24	1.35	2.82	–
8	Liyyah**	4.99	4.93	6.52	0.23	4.91	–	4.23	–
9	Turabah**	4.99	3.29	9.96	0.15	5.73	4.16	7.05	–

* Sodium + Potassium.

** Smaller number of wells sampled.

The SAR values were then adjusted to calculate SAR_{adj} by the following equation :

$$SAR_{adj} = SAR\,[9.4 - p(K_2 - K_c) - p(Ca + Mg) - p(Alk)] \qquad (2)$$

where pK_2 = negative logarithm of the second dissociation constant for carbonic acid, pK_c = solubility constant for calcite, and p = negative logarithm of ion concentrations (meq/l). Values of $p(k_2 - K_c)$, $p(Ca + Mg)$, and $p(Alk)$ in relation to Ca^{++} + Mg^{++} + Na^{+}, Ca^{++} + Mg^{++}, and CO_3^{--} + HCO_3^{-}, respectively, have been tabulated (Bouwer 1978).

The adjusted SAR values take into account the effects of precipitation and dissolution of calcium carbonate in the soil as related to the concentration of CO_3^{--} and HCO_3^{-} (Bouwer 1978).

The collected data (190 wells) was reviewed and after initial plotting, some data points (outliers and odd values) were screened out and the readjusted data (138 wells) for various parameters in each sub-region is presented in Table 2.

TABLE 2. Number of groundwater quality data points (in each parameters) collected and selected for utilization in the analysis and modelling.

Wadis	** No. of Data Points, Selected for Modeling in each wadi, after initial screening.				
	TDS	Total Ions	Major Anions and Cations	Sr	SAR_{adj}
Fatimah	43	21	21	27	43
Naaman	61	66	66	39	61
Khulays	6	6	6	*	6
Guran	14	13	13	*	14
Bathan	7	5	5	6	7
Wijj	7	7	7	10	7
Total Data Points in each Parameters	138	118	118	82	138

* Analysis not carried out.
** Based upon the literature available plus collected in the study.

In order to assess if any relationship exists between various parameters, especially that of TDS with the others, a correlation analysis (by finding correlation coefficients, R^-) was carried out for the major wadis, namely Fatimah, Khulays, Wijj and Naaman, between TDS and the other seven ions (Na^+, K^+, Ca^{++}, Mg^{++}, Cl^-, SO_4^{--}, HCO_3^-). The results of such correlation are presented in Table 3. The correlation coefficient (R^-) measures the response and strength of association of each ionic species with the total dissolved solids. The chlorides and sulfates have very high positive correlation with TDS in all wadis, while the bicarbonate has very low correlation. *Sodium has very high positive* correlation for Khulays, Fatimah and Wijj wadis, but relatively low for Naaman. Calcium has very high positive correlation for the wadis of Fatimah, Wijj and Naaman, but relatively low for Khulays. Calcium directly increases with total dissolved solids. Magnesium has high positive correlation with TDS for wadi Fatimah and relatively low correlation with TDS for Khulays.

TABLE 3. Correlation co-efficients (R^-) of seven major ions (meq/l) with respect to total dissolved solids (mg/l) in four major wadis of the western reigon.

Major Ions	Wadis			
	Fatimah	Khulays	Wijj	Naaman
Ca^{++}	0.95	0.81	0.97	0.94
Mg^{++}	0.96	0.40	0.87	0.72
Na^+	0.99	0.97	0.97	0.73
K^+	0.27	– 0.21	0.43	– 0.67
HCO_3^-	– 0.16	.026	– .10	0.34
SO_4^{--}	0.98	0.93	0.98	0.87
CL^-	0.99	0.98	0.99	0.92

The above correlation analysis (R^-) clearly indicates taht TDS has the maximum positive correlation with Na^+ and Cl^- ions, which means that with the higher TDS, the concentrations of Na^+ and Cl^- (individual ions) are expected to increase. The relationship of TDS with Cl^- is quite well known. The correlation of Na^+ with TDS indicates that higher TDS would indicate the probability of higher percentage of Na^+. Since Na^+ is the key element in the SAR, higher Na^+ (assuming Ca^{++} and Mg^{++} being constant in a certain water sample) would mean higher SAR values. Therefore, it seems, there must be a relationship (direct or indirect) between TDS and SAR values.

A statistical analysis and evaluation of the 138 data for whole (considering all major wadis) Western Region was carried out and the same is presented in Table 4.

TABLE 4. Statistical information about different major cations (meq/l), TDS (mg/l), SAR_{adj} and Sr (ppb) based upon the groundwater sampling in the western region.

Sl. No.	Description	Number of Data Points Utilized in Modelling (From Table 2)	Range of Actual Variable Values	*Statistical Mean Value	*Standard Deviation (σ)	***Confidence Level for Range of Variable Value Covered (90%)	**Confidence Level in Mean Value Range (95%)
1	Total Ions (meq/l)	118	10 to 150	38.6	25	7–70	34 to 43
2	Ca^{++} (meq/l)	118	2 to 20	6.4	4.3	1–12	5 to 7
3	Na^+ (meq/l)	118	2 to 35	9.5	6.6	1–18	8 to 11
4	Mg^{++} (meq/l)	118	2 to 15	4.7	3.4	0.4–10	4 to 6
5	SAR_{adj}	138	0.5 to 25	9.4	5.8	2–17	7 to 11
6	TDS (mg/l)	138	200 to 5000	1207	912	50–2400	1000 to 1400
7	Sr (ppb)	82	150 to 5000	1143	1000	100–2500	900 to 1400

*** 90% Confidence Level, that the Variable Range is Covered.

** 95% Confidence Level, that Mean Value will Fall Between these Ranges.

* Rounded to Nearest Decimal Numbers.

In addition to the mean value and standard deviations for the data, confidence levels of 95% and 90% for the "mean value" and the "range of parameter values" were used respectively in calculating such values. This analysis shows a fairly high level of confidence for various parameters measured in this sutdy. Six (6) values for various parameters (covering a wide range of values) were kept for the validation of any developed relationships and the remaining values were used in the development of such relationships.

Regression Models

The regression models are developed, based upon the assumption, that the groundwater quality parameters such as TDS, total ions, sodium, calcium and magnesium may have values close to zero, but never equal to zero. The regression plots may seem to initiate at zero values, but in the real sense, there is always a minimum value for each parameter (as indicated in equations 3 to 6 and figure 2 to 5). This assumption has been made because the data used in the regression models have some minimum values but not zero.

A linear regression analysis between TDS (mg/l) and total major ions (meq/l), using 118 values showed a very strong relationship (Fig. 2). The strength of relationship is evidenced by the coefficient of determination $(R^{-})^2$ and standard error of estimate (SEE).

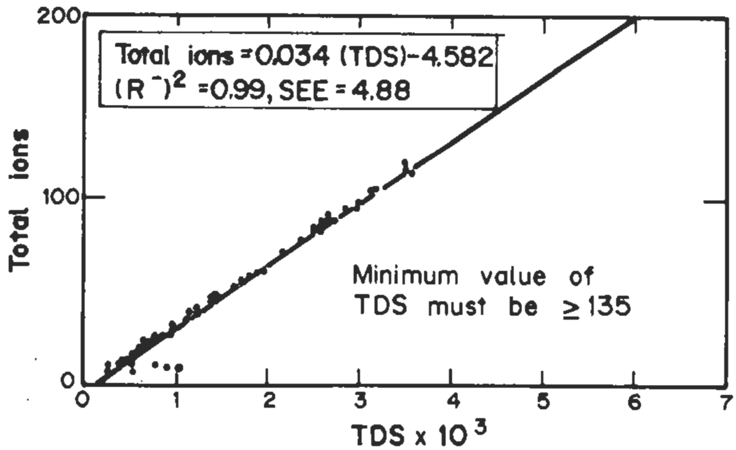

FIG. 2. Relationship of TDS (mg/l) with total ions (meq/l).

$$\text{Total ions} = .034\,(\text{TDS}) - 4.582$$
$$(R^{-})^2 = 0.99, \quad \text{SEE} = 4.88 \qquad (3)$$
$$\text{TDS must be} \geqslant 135 \text{ mg/l}$$

The following relationships were developed at 95% confidence level between total ions and three major cations, Na^{+}, Ca^{++}, and Mg^{++} (Fig. 3,4,5).

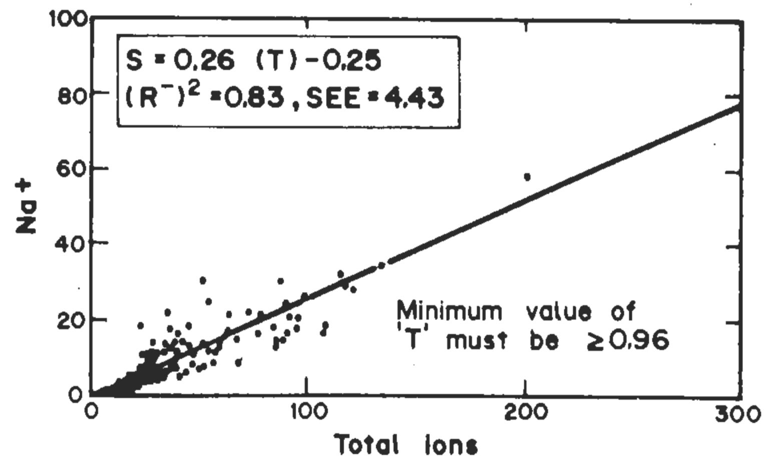

FIG. 3. Relationship of total ions (meq/l) with S (sodium ion) (meq/l).

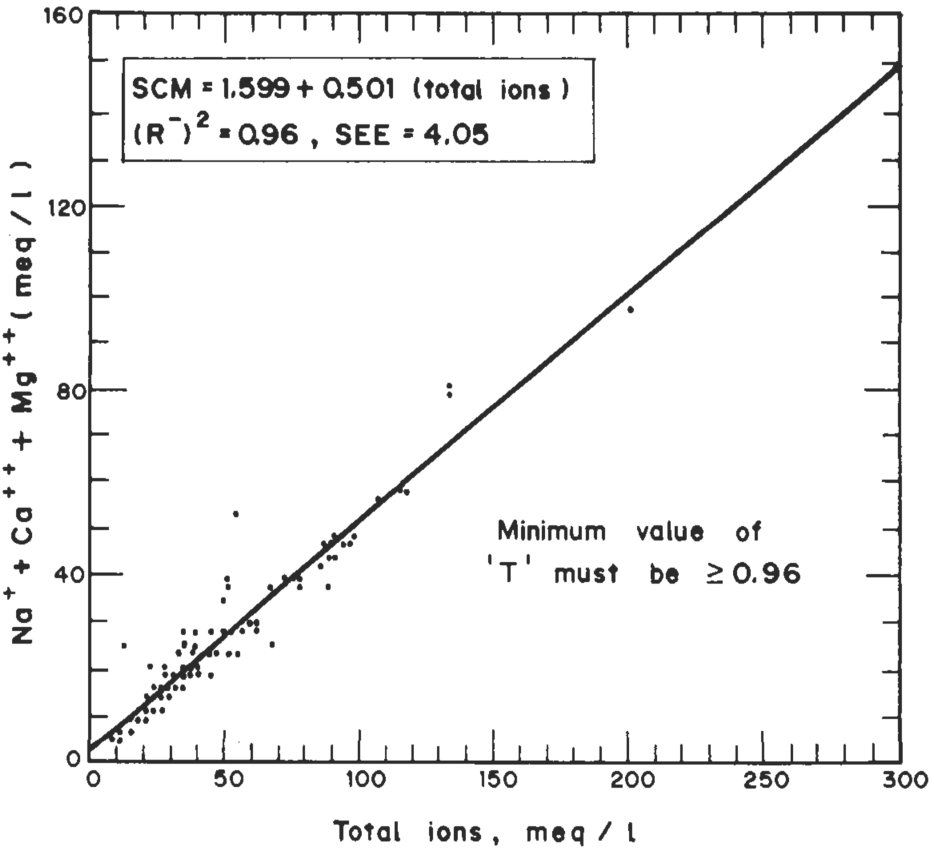

FIG. 4. Relationship of total ions (meq/l) with SCM (Na^+, Ca^{++} and Mg^{++}).

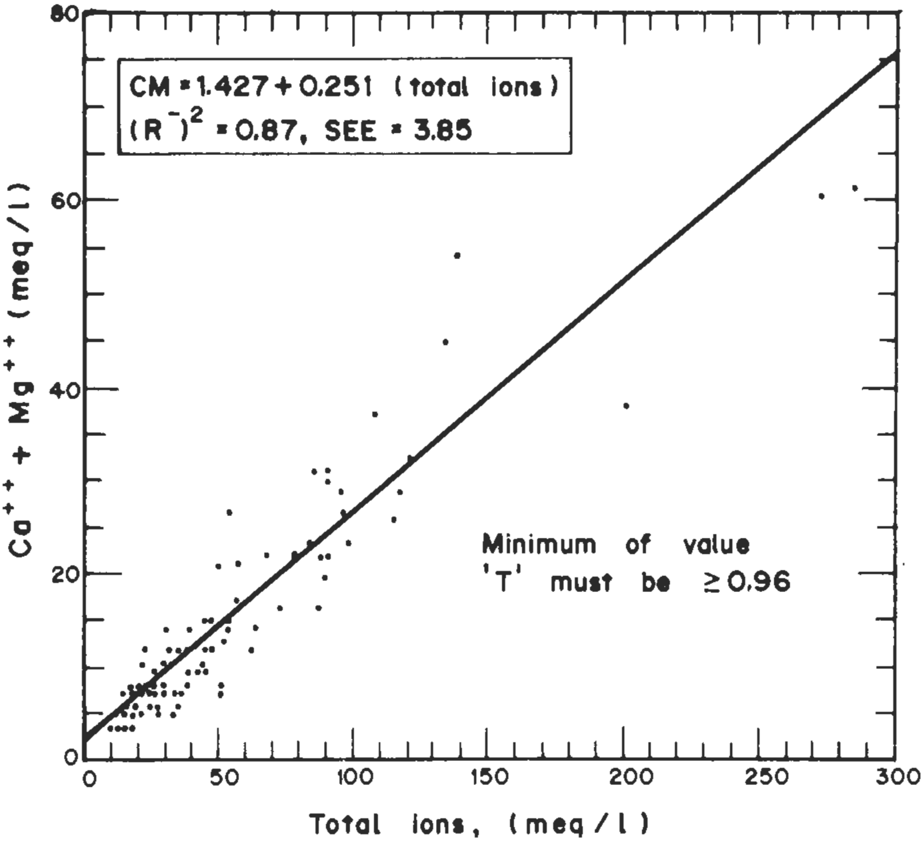

FIG. 5. Relationship of total ions (meq/l) with CM (Ca^{++} + Mg^{++}).

$$S = 0.26\,(T) - 0.25 \qquad (R^{-})^2 = 0.83, \quad SEE = 4.43 \tag{4}$$

The minimum value of "T" must be ≥ 0.96 in equations 4, 5 and 6.

$$CM = 1.427 + 0.251\,(T) \qquad (R^{-})^2 = 0.87, \quad SEE = 3.85 \tag{5}$$

$$SCM = 1.599 + 0.501\,(T) \qquad (R^{-})^2 = 0.96, \quad SEE = 4.05 \tag{6}$$

where T = total major ions, meq/l

S = Na^{+} ion, meq/l

CM = (Ca^{++} + Mg^{++}) ions, meq/l

SCM = (Na^{+} + Ca^{++} + Mg^{++}) ions, meq/l

$(R^{-})^2$ = Co-efficient of determination

SEE = Standard error of estimate

The review of $(R^{-})^2$ indicates that there is a very strong relationship between three major cations (Na^+, Ca^{++}, Mg^{++}) and the total ions.

A linear relationship between the actual SAR and SAR_{adj} values was also developed (Fig. 6), and is represented by equation 7. It was felt important to develop this relationship to calculate SAR_{adj} (from SAR), which is now more commonly used in assessing irrigation water suitability.

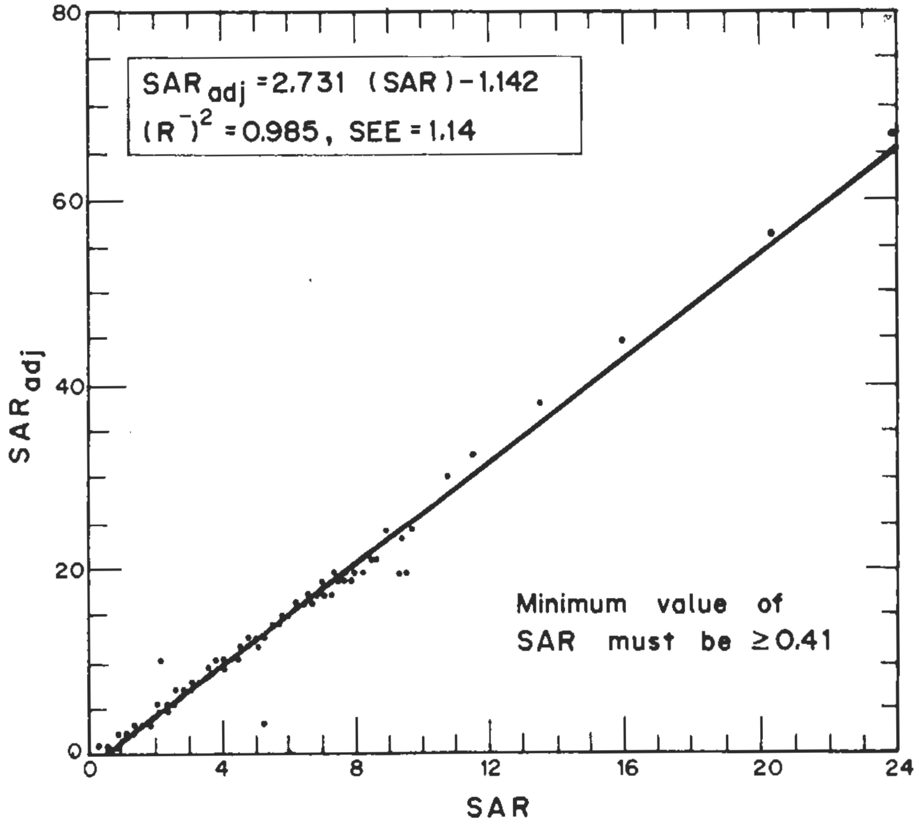

FIG. 6. Relationship of SAR with SAR_{adj}

$$SAR_{adj} = 2.731\ (SAR) - 1.142$$
$$(R^{-})^2 = 0.985, \quad SEE = 1.14 \qquad (7)$$

The minimum value of SAR must be ≥ 0.41

The Western Region groundwaters have very high concentration of strontium (ppb) (Khan and Adham 1987) as compared to the other trace metals such as lead, zinc, copper etc. Review of data indicated that as the concentration of Sr increased in the groundwaters, the concentration of TDS also increased. A regression analysis between Sr and TDS, showed a good relationship as evidenced by the $(R^{-})^2$ of 0.62 and SEE 342 (Fig. 7).

$$TDS = 503.93 + .388\,(Sr) \qquad (8)$$

where TDS = Total dissolved solids, mg/l
Sr = Strontium concentration, ppb

The review of the above analysis indicates that if the TDS value is known directly or indirectly (from electrical conductivity or strontium) for a groundwater, then SAR and SAR_{adj} values can be computed using equations 3 to 6, equation 1 and equation 2 or 7 respectively.

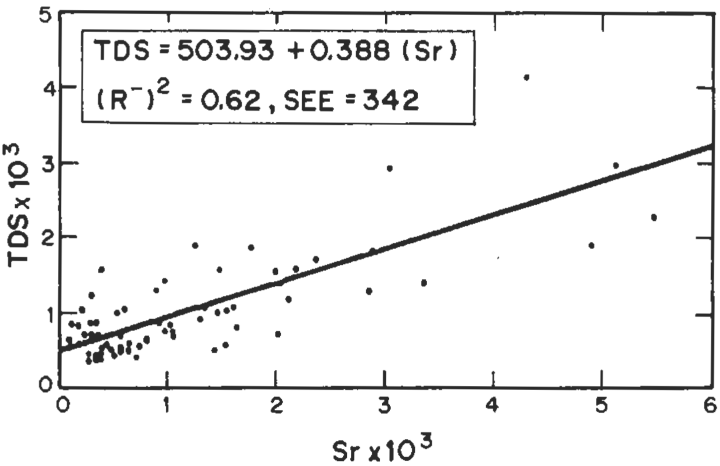

FIG. 7. Relationship of TDS (mg/l) with Strontium (Sr)

A systematic approach for calculating SAR_{adj} and the suitability of groundwater is presented in Fig. 8. A simple illustration will explain the use of various equations. Assume that the total dissolved solids value of a groundwater sample is 1000 mg/l. Then the calculations of SAR and SAR_{adj} are as follows :

$$\begin{aligned}\text{Total ions} &= .034\,(1000) - 4.582 \\ &= 29.41\end{aligned} \qquad (3)$$

$$\begin{aligned}CM &= 1.427 + 0.251\,(29.41) \\ &= 8.90\end{aligned} \qquad (5)$$

$$\begin{aligned}SCM &= 1.599 + 0.501\,(29.41) \\ &= 16.33\end{aligned} \qquad (6)$$

$$S = 0.26\,(29.41) - 0.25 = 7.39 \qquad (4)$$

$$SAR = \frac{S}{\sqrt{\frac{CM}{2}}} = \frac{7.39}{2.09} = 3.53$$

$$\begin{aligned}SAR_{adj} &= 2.731\,(3.53) - 1.142 \\ &= 8.49\end{aligned} \qquad (7)$$

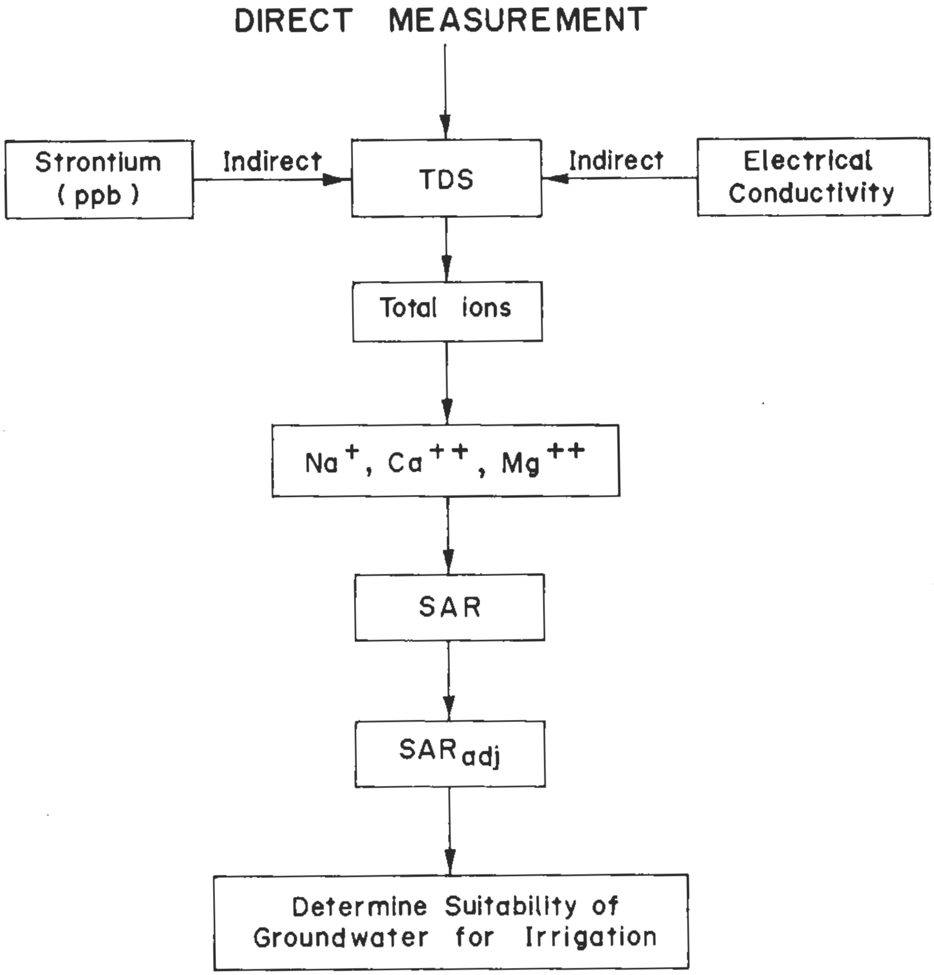

FIG. 8. A systematic approach for calculating SAR_{adj} and determining the suitability of groundwater for irrigation.

The value of S, SC and SCM can be used to calculate the individual cations Na^{+}, Ca^{++} and Mg^{++} in meq/l. The SAR_{adj} values, as listed in Table 5 can be used to determine the suitability of a certain groundwater for the purpose of irrigation.

Validation of Developed Regression Models

Six (6) actual data points, covering a wide range of values, as presented in Table 6, were used in checking the accuracy and validity of the developed models. The SAR_{adj} values computed by the model were compared with the actual values. The variation in the computed and actual values for the total major ions is 1 to 5%, for the Na^{+} ions is 4 to 10%, for (Ca^{++}, Mg^{++}) ions is 5 to 10% and for SAR_{adj} values is 5 to 12%. The variation in the actual and computed values is not significant, thus validating the developed regression model(s) for estimating the SAR_{adj} values, to be used in determining the suitability of groundwater for irrigation purposes.

TABLE 5. Determining suitability of water for irrigation purposes based upon the SAR_{adj} values. (Bouwer and Idlovitch, 1987).

SAR_{adj} Value	Suitability for Irrigation
0 – 3	Sodium problems, suitable for most crops on most soils.
3 – 6	Moderate sodium problems, suitable in most instances with moderate drainage soils.
6 – 9	Increasing sodium problems, suitable for salt tolerance plants on adequately drained soils.
9 – 12	Severe sodium problems, suitable for special circumstances with very salt tolerant plants and excess leaching.
> 12	Very severe sodium problems, not suitable for irrigation.

TABLE 6. Comparison of actual and computed SAR_{adj} values.

Sl. No.	TDS (mg/l)	Total Ions (meq/l)		Major Cations (meq/l)				SAR_{adj}	
				Na^+		$(Ca^{++}) + (Mg^{++})$			
		Actual	* Computed	Actual	** Computed	Actual	*** Computed	Actual	**** Computed
1	752	21.14	20.99	4.1	5.20	6.3	6.69	5.79	6.56
2	1615	52.90	50.32	11.9	12.80	14.71	14.1	11.41	12.02
3	2856	94.54	92.52	22.80	23.80	26.80	29.1	14.71	15.90
4	3495	120.1	114.24	27.8	29.70	32.0	30.10	17.37	18.76
5	6078	199.7	202.07	58.7	52.30	48.24	50.71	28.15	27.12
6	8903	299.4	298.12	86.6	77.30	69.5	76.25	35.86	33.07

* Using equation 3. ** Using equation 4. *** Using equation 5, 6. **** Using equation 7.

Conclusion

The study results indicate a very high correlation of TDS with individual ions as well as with the sum of the major ions. The co-efficient of determination $(R^-)^2$ varies from 0.8 to 0.99. The developed regression models for individual cations and SAR_{adj} are based upon the accurate data with a very high level of confidence (90 to 95%).

A strong correlation between TDS and Sr also exists for the Western Region groundwater.

The actual and the computed values for various cations such as Na^+, Ca^{++}, Mg^{++} and SAR_{adj} varied in a very narrow range of 1 to 10%. The developed models require a simple "input" of total dissolved solids (mg/l) in a groundwater sample. Even though the models are based upon using the groundwater quality data for the Western Region, Saudi Arabia, yet because of the diversity of the water quality parameters and a very large size of sample i.e. 120 to 140, the application is not limited to the Western Region. These models should be applicable to other wadis and groundwater aquifers with similar characteristics and climatic conditions (arid, semi-arid).

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مـــدخل النظم لتقـــدير صلاحيـــة المياه الجوفيـــة لأغراض الري في المنطقـــة الغربيـــة بالمملكـــة العربيـــة السعوديـــة

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جامعة الملك عبد العزيز ، جـــدة ، المملكة العربية السعودية

المستخلص . تعتبر نسبة امتزاز الصوديوم (SAR) من أكثر المعاملات استخداما لتقدير نوعية مياه الـري وجـودتها . وتتضمن المعاملات الأخرى المستخدمة كمية المواد الصلبة الكلية الـذائبـة (TDS) ، وجميع الأيونـات (كا$^{++}$ ، مغ$^{++}$ ، ص$^{+}$ ، بو$^{+}$ ، يدك أ$_{3}^{-}$ ، ك أ$_{3}^{--}$ ، كب أ$_{4}^{--}$ ، كل$^{-}$ . . . ، إلخ) والمعادن النادرة . وحتى نقلل من مشاكل التربة والمحصول ، وبوجه خاص في المناطق القاحلة نتيجة لمعدلات البخر المرتفعة وما يتبعها من تراكم الأملاح ، فإن نسبة SAR يجب أن تكون قريبة من الحدود المقبولة . ويتطلب تعيين قيم SAR جهدًا كبيرًا لتحليل جودة العديد من عينات المياه .

وقـد تم تجميع بيانات جودة المياه الجوفية لـ ١٩٠ موقعًا (بئرًا) في المنطقة الغربية من المملكة العربية السعودية . واستخدم من هذه البيانات عدد ١٣٨ نقطة في إنشاء نماذج ارتـــداد بين TDS و : (١) SAR ، (٢) الأيونـات الكلية ، (٣) أغلب الكـاتيونـات والإسـترونشيم (سر) (وهو موجود بشكل عام في أغلب التكوينات الجيولوجية في المنطقة الغربية) . ولهذه النماذج معامل تطابق $(R^{-})^{2}$ يتراوح بين ٠,٧ و ٠,٩٩ ، الأمر الذي يدل على علاقة جيدة . وقد استخدمت بيانات النقاط الست لاختبار صحة نماذج الارتداد . وتُقدم النماذج مدخلا ميسرا وسهلا لتقدير SAR الأيونات الكلية والإسترونشيم ، أخذا في الاعتبار أن قيمة TDS معروفة ، وأن قياس TDS عملية سهلة نسبيا . وتساعد قيم SAR المحسوبة أو المقدرة في تقييم صلاحية المياه الجوفية لأغراض الري .

الكلمات المفتاحية : تقدير نوعية المياه الجوفية ، ري ، مناطق قاحلة ، نسبة امتزاز الصوديوم .