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A Study of the Base of Fresh Water in the Southern San Joaquin Basin, California

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ABSTRACT

This paper presents a study done to determine the base of fresh water in the southern San Joaquin basin in California. Presented is a base of fresh water contour map for the study area as well as a R_{we} versus R_w correlation for determining R_w from the SP which was developed for fresh waters found in the study area.

INTRODUCTION

During the planning as well as the operational phase of oil and gas well drilling and production, fresh water aquifers must be protected from the effects of such operations. Knowledge of the base of these fresh water sands facilitates casing and cementing depth selection so that they are isolated from contamination by saline water, oil, and gas found in zones penetrated and produced by oil and gas wells. In addition, cement abandonment plug setting depths can also be properly selected so that these fresh water zones are protected once the well is no longer used.

Previous published work done on mapping the base of fresh water (BOFW) in the San Joaquin basin of Kern County, California was presented by Page in 1973 (Reference 1). This map is currently being used by the State of California's Division of Oil and Gas (DOG) for permitting and abandonment purposes (Reference 2). However, Page's map (Figure 1) stops at the Mount Diablo/San Bernardino Base and

Meridian junction. As a result, the map does not cover areas currently under oil and gas exploration and production in the southern part of the San Joaquin basin.

This paper summarizes the results of a study conducted to determine the BOFW in the southern San Joaquin basin not covered by Page's map. Included in this report is the criteria used for defining fresh water, log interpretation techniques used for BOFW determination, and a contour map defining the BOFW for the study area. The study area (Figure 2) covers T11N - T12N/R22W - R21W of the San Bernardino Base and Meridian as well as T32S - T30S/R25E - R27E of the Mount Diablo Base and Meridian so that a comparison to Page's map can be made.

FRESH WATER DEFINITION

Two criteria were used for defining fresh water: 1. electrical conductivity and 2. total dissolved solids (TDS). Page defines fresh water as that water having a maximum specific conductance of 3,000 micromohms/cm or a minimum resistivity of 3.33 ohm-m at 75 degrees F and a TDS of less than 2,000 mg/l.

Page justifies his fresh water definition on the grounds that mapping of the BOFW in the Sacramento Valley by Olmsted and Davis (Reference 3) was based on this definition and his work was a continuation of the Olmsted and Davis study. In addition, he stated that the Federal Water Pollution Control Administration considered 2,000 mg/l to be a limiting TDS content for the irrigation of most crops.

References and illustrations at end of paper.

Since the main purpose of the current study was to extend the Page BOFW map currently being used by the California DOG to cover areas in the southern San Joaquin basin under active oil and gas exploration and production, Page's definition of fresh water was used. However it should be pointed out that the definition of fresh water used in this study may not be the definition used by other regulatory agencies.

BASE OF FRESH WATER DETERMINATION

To determine the BOFW, electric well logs having a Spontaneous Potential (SP) curve were analyzed to determine formation water resistivities (see Appendix) at various depths. Once the water resistivities were calculated, the total dissolved solids were estimated. These calculations were done until a depth was reached below which only waters having a resistivity less than 3.33 ohm-m at 75 degrees F and a TDS greater than 2,000 mg/l exist. It is critical that this is done because in some areas, fresh water can be overlaid by saline waters as shown by Page.

CALCULATION OF R_w FROM THE SP

To determine water resistivities from the SP, a correlation of R_{we} versus R_w was developed for the fresh waters found in the study area (Table 1). This was done because most published correlations for conversion of R_{we} to R_w are based on pure sodium chloride solutions. Some correlations exist for fresh waters but do not extend to the resistivity of potable waters which are waters with a resistivity greater than 1 to 2 ohm-m (Reference 4).

To develop the R_{we} versus R_w correlation for the study area, three pieces of information were necessary: 1. laboratory measured formation fresh water resistivities, 2. an electric log with a SP through the zone from which the water sample was taken, and 3. a R_{mf} value for the drilling fluid in the well at the time the electric log was run. Once this data was obtained, the correlation was constructed by taking the following steps:

1. Correct R_{mf} to 75 degrees.
2. Determine the SP deflection in the zone from which a water sample was taken and the resistivity (R_w) measured. Correct for bed thickness.
3. Calculate R_{we} at 75 degrees F using Equation A4 assuming $R_{mf}=R_{mfe}$.
4. Plot the log of R_w versus the log of R_{we} .

Figure 3 shows the resulting R_{we} versus R_w curve for the study area for values of R_{mf} between 0.79 and 9.58 ohm-m. Tables 2 and 3 summarize the locations of the wells and the data used to develop the correlation. For the Yowlumne area, a water resistivity versus depth plot was constructed using the data presented in Table 1 to allow oil well logs run through fresh water zones to be used even though actual fresh water samples were not taken from these wells. This was done due to the lack of data existing for the fresh water zones in the study area.

Table 4 shows a comparison of the calculated water resistivities using published curves for conversion of R_{we} to R_w for fresh waters (Reference 5) and Figure 3. Note that the use of Figure 3 reduces the average error in calculated water resistivity from +396.63% to -3.88%.

TDS DETERMINATION

To determine the TDS of the formation fresh water once the resistivity was calculated from the SP log, it was necessary to correlate water resistivity to TDS. To do this, several fresh water analyses (including water resistivity and TDS) in or near the study area were obtained from the Kern County Water Agency. This data is summarized in Table 5 and along with the data in Table 1 was curve fitted using regression analysis. Figure 4 shows the resulting plot of R_w versus TDS.

From Figure 4, note that the resistivity corresponding to a fresh water maximum TDS of 2,000 mg/l is 3.14 ohm-m. Since 3.14 ohm-m is less than the minimum resistance for fresh water of 3.33 ohm-m, TDS was the measure by which fresh water was distinguished from saline water for this study.

BASE OF FRESH WATER MAP

Figure 5 is a contour map of the BOFW for the study area as determined from oil and gas well logs using the calculation techniques previously outlined. Contour depths are reported as subsea depths in 500 foot increments. The dashed portions of the contours indicate that there is no data to support the interpretation of that piece of the contour line. Table 6 lists the wells used for developing the map as well as R_{mf} values at 75 degrees F, the elevation relative to the Kelly bushing, and the estimated subsea depth to the BOFW in that well. These points are also shown on Figure 5.

Note in Table 6 that the BOFW has been determined by visual inspection of the electric log for some of the wells used. This was done only for older wells which did not have reported R_{mf} values in areas where there was sufficient BOFW depth control as determined from newer wells having R_{mf} values.

From Figure 5 it can be seen that the BOFW tends to get shallower going east to west. This is the same trend mapped by Page. In addition, a comparison between Page's and the current study's map in the Mount Diablo Base and Meridian yields good agreement between the two maps in this area.

CONCLUSIONS

1. The resistivity corresponding to a fresh water maximum TDS of 2,000 mg/l is 3.14 ohm-m. Since 3.14 ohm-m is less than the minimum fresh water resistance of 3.33 ohm-m used in this study, TDS is the measure by which fresh water is distinguished from saline water.
2. The accuracy of conventional water resistivity determination from the SP for the southern San Joaquin basin has been improved through the development of a R_w versus R_{mf} correlation for fresh waters found in the study area. The correlation is valid for R_{mf} values between 0.79 and 9.58 ohm-m.
3. A correlation of TDS versus R_w has been presented for the southern San Joaquin basin.
4. A base of fresh water contour map has been constructed for the southern San Joaquin basin and there is good agreement with Page's map in the Mount Diablo Base and Meridian area where the two maps overlap one another.

NOMENCLATURE

- a_w = formation water chemical activity, dimensionless
 a_{mf} = drilling fluid filtrate chemical activity, dimensionless
 E_{sp} = SP deflection, mV
 R_{mf} = mud filtrate resistivity, ohm-m
 R_{mfe} = equivalent mud filtrate resistivity, ohm-m
 R_w = formation water resistivity, ohm-m
 R_{we} = equivalent formation water resistivity, ohm-m
 T_f = formation temperature, degrees F

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REFERENCES

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2. Jaszarowski, J. and Mitchell, D., State of California Division of Oil and Gas, Bakersfield, CA, Personal Communication.
3. Olmsted, F. H. and Davis, G. H., "Geologic Features and Ground Water Storage Capacity of the Sacramento Valley, CA," USGS Paper No. 1,497.
4. Evers, J. F. and Iyer, B. G., "A Statistical Study of the SP Log in Fresh Water Formations of Wyoming's Big Horn and Wind River Basins," paper presented at the 5th Formation Evaluation Symposium of the Canadian Well Logging Society, Calgary, May 5-7, 1975.
5. Schlumberger, "Log Interpretation Charts," USA, 1988, pp. 5, 9, 11.

APPENDIX

Use of the SP curve can yield good values of water resistivity when clean, thick sands are available. The SP deflection in these types of sands when drilled with water-base drilling fluids is related to the chemical activities of the formation water and drilling fluid filtrate by,

$$E_{sp} = -K \log (a_w/a_{mf}) \dots\dots\dots (A1)$$

where K is defined as,

$$K = 61 + 0.133 T_f \dots\dots\dots (A2)$$

For pure sodium chloride solutions, resistivities are inversely proportional to the chemical activity. Equation A1 is rewritten as,

$$E_{sp} = -K \log (R_{mf}/R_w) \dots\dots\dots (A3)$$

Equation A3 is not valid for high concentrations of sodium chloride or for all types of water. Therefore "equivalent resistivities" are used which, by definition, are inversely proportional to the activities. Equation A3 then becomes,

$$E_{sp} = -K \log (R_{mfe}/R_{we}) \dots\dots\dots (A4)$$

Determination of water resistivity using the SP curve is done as follows:

1. Determine the SP deflection in the zone of interest and correct for bed thickness using correlations such as those found in Reference 5.
2. Determine T_f and calculate K .
3. Correct R_{mf} to 75 degrees F and determine R_{mfe} using correlations such as those found in Reference 5.
4. Correct R_{mfe} to T_f .
5. Calculate R_{we} from Equation A4 and determine R_w using correlations such as those found in Reference 5.
6. Correct R_w to 75 degrees F.

Table 1 - Study Area Fresh Water Sample Analysis

Species	Yowlumne SW #1	Yowlumne SW #2	Yowlumne SW #4	Landslide SW #1	N. Coles Levee NW #5
Sodium	325	200	140	197	97
Potassium	8	7	10	8.7	NR
Calcium	290	190	130	120	43.2
Magnesium	91	74	46	26	1
Barium	0.1	0.1	0.1	NR	NR
Strontium	2.8	2	1.2	NR	NR
Total Iron	0.03	0.03	0.03	7.4	NR
Chloride	95	80	30	50	62
Carbonates	0	0	0	0	NR
Sulphates	1420	910	630	660	38
Bicarbonates	183	178	168	130	240
Hydroxyl	0	0	0	0	NR
pH Value	7.6	7.6	7.6	7.81	7.9
Resistivity @ 75 deg	2.97	5.25	7.59	7	9.05
TDS, mg/l	2415	1365	945	1025	481
SS Depth, ft	-1482	-1159	-199	-455	-120

Table 2 - Study Area R_w Versus R_{we} Correlation Data Well Location

Well Name	Location	R_{mf} @ 75 °F, ohm-m	Sample Depth, ft
Cohn #4G	S28/T29S/R29E	4.42	868
CL WW #5	S28/T30S/R25E	9.58	420
LS 63X-30	S30/T11N/R21W	3.89	1,500
LS WSW #1	S30/T11N/R21W	7.59	1,495
YOW 18-2	S02/T11N/R22W*	1.89	1,305
YOW 81X-9	S09/T11N/R22W	4.46	950
YOW 61X-14	S14/T11N/R22W*	0.79	1,380
YOW 65-4	S04/T11N/R22W*	1.32	1,000
YOW 65-4	S04/T11N/R22W*	1.32	1,370

* - no laboratory measured water samples.

Table 3 - Study Area R_w Versus R_{we} Correlation

Well Name	SP Deflection, mV	R_{we} @ 75 °F, ohm-m	R_w @ 75 °F, ohm-m
Cohn #4G	-2	4.14	16.95
CL WW #5	-30	3.62	9.05
LS 63X-30	-13	2.55	7.00
LS WSW #1	-37	2.29	7.00
YOW 18-2	-5	1.61	3.46
YOW 81X-9	-5	3.79	5.25
YOW 61X-14	-4	0.69	3.08
YOW 65-4	+3	1.45	5.62
YOW 65-4	-1	1.28	3.12

Regression fit of the data is $R_w = 2.56 e^{0.34R_{we}}$

Table 4 - Comparison of R_w Versus R_{we} Correlations

Well Name	R_w @ 75 °F, ohm-m		
	Measured	Reference 5 (Page 9)	Figure 3
Cohn #4G	16.95	155.05	8.48
CL WW #5	9.05	78.83	8.77
LS 63X-30	7.00	18.23	6.10
LS WSW #1	7.00	13.44	5.57
YOW 18-2	3.46	4.51	4.42
YOW 81X-9	5.15	97.30	9.29
YOW 61X-14	3.08	0.89	3.24
YOW 65-4	5.62	3.51	4.20
YOW 65-4	3.12	2.66	3.95

Reference 5 Average Error = +396.63%

Figure 3 Average Error = -3.88%

Table 5 - Water Resistivity as a Function of Total Dissolved Solids*

<u>TDS, mg/l</u>	<u>R_w @ 75 deg F, ohm-m</u>
2,415	2.9
1,365	5.1
945	7.4
1,025	6.8
138	36.4
148	34.9
106	58.5
197	31.8
92	61.3
91	59.5
691	10.9
356	18.8
330	19.4
512	11.7
267	20.4
257	14.2
2,340	2.6
1,480	3.9
4,060	1.5
209	29.4
103	56.5
111	52.6
131	40.0
158	23.4
112	44.8
115	45.0
140	34.6
190	31.7
171	35.9
182	33.0
347	18.4
137	46.5
112	58.8
166	37.9
112	61.3
113	59.5

* - linear regression fit of the data is $TDS = 6,518.2 R_w^{-1.033}$

Table 6 - Base of Fresh Water Map Data

<u>Well Name and Number</u>	<u>R_{mf} @ 75 deg F, ohm-m</u>	<u>Elevation RKB, ft</u>	<u>BOFW (SS), ft</u>
Aqueduct 55X - 6	1.08	555	-3,249
Aqueduct 78X - 6	0.84	555	-3,604
Landslide 48X - 19	1.63	970	-6,102
Landslide 63X - 30	1.79	1,025	-6,177
Landslide 65X - 30	1.67	1,063	-6,535
Landslide 85X - 30	2.92	986	-6,376
Paloma 14-4	1.62	301	-1,711
Paloma 55X - 31	2.92	317	-1,481
Paloma 45 - 32	---	302	-1,688*
Paloma 78 - 33	---	303	-1,812*
Paloma 47 - 34	---	307	-2,063*
Paloma 23 - 35	---	303	-2,917*
Paloma 18 - 36	---	303	-2,902*
North Paloma 1 - 25	1.60	332	-3,590
Rio Viejo 81X - 3	1.22	447	-4,769
Rio Viejo 77X - 28	0.89	406	-5,224
Rio Viejo 36X - 33	1.07	454	-4,316
Yowlumne 1 - 18	1.89	584	-2,937
Yowlumne 14 - 3	1.32	543	-3,053
Yowlumne 16 - 3	1.32	559	-2,900
Yowlumne 41X - 3	1.09	525	-3,346
Yowlumne 42X - 3	4.61	538	-3,499
Yowlumne 44X - 3	0.88	536	-3,139
Yowlumne 65X - 3	0.98	547	-3,114
Yowlumne 73X - 3	1.11	520	-3,091
Yowlumne 12X - 4	0.87	519	-2,540
Yowlumne 16X - 4	1.27	550	-2,609
Yowlumne 23 - 4	1.06	517	-2,748
Yowlumne 25X - 4	0.99	548	-2,466
Yowlumne 33X - 4	0.90	519	-2,717
Yowlumne 44X - 4	0.94	538	-2,764
Yowlumne 52X - 4	0.98	530	-2,647
Yowlumne 63X - 4	1.94	539	-2,905
Yowlumne 88 - 4	1.87	578	-3,007
Yowlumne 61 - 5	1.06	510	-2,478
Yowlumne 83 - 5	0.80	525	-2,504
KCL 27 - 10	1.40	625	-2,948
Yowlumne 31X - 10	1.27	585	-3,073
Yowlumne 43X - 10	1.21	612	-2,400
Yowlumne 63 - 10	1.40	607	-3,176
Yowlumne 22X - 14	1.99	719	-3,575
Yowlumne 48X - 32	1.19	501	-2,371
Yowlumne 54X - 33	1.09	476	-2,577
Yowlumne 58X - 33	1.04	521	-2,253
Yowlumne 85X - 33	0.86	486	-2,567
Yowlumne 38X - 34	1.29	518	-2,427
Yowlumne 44X - 34	1.20	483	-3,088

Table 6 (cont.) - Base of Fresh Water Map Data

<u>Well Name and Number</u>	<u>R_{mf} @ 75 deg F, ohm-m</u>	<u>Elevation RKB, ft</u>	<u>BOFW (SS), ft</u>
Yowlumne 56X - 34	2.85	506	-3,289
Yowlumne 67X - 34	1.36	510	-2,877
Boulder Creek 54X - 23	1.36	948	-4,462
Boulder Creek 55X - 24	2.29	969	-5,172
Los Padres 87X - 29	0.99	941	-6,365
West Pleito Fan 63X - 21	1.36	723	-4,979
South Rio Viejo 41X - 12	1.35	517	-4,830
East Pleito Fan 85X - 23	1.27	652	-4,849
Pleito Creek 86X - 18	1.20	500	-5,205
Landslide Creek 32X-20	2.45	799	-4,764
KCL #55 - 8	---	300	-4,040*
KCL Co. J - 1	7.13	301	-4,297
KCL 12 - 23	3.65	320	-2,983
KCL "N" 54 - 23	1.33	323	-3,013
KCL 14X - 7	1.71	375	-2,836
Panama Slough #78	4.14	340	-3,686
LAAC 28 - 6	---	302	-3,328*
SPLC #1	3.84	347	-3,929
B & N No. 1	1.63	310	-1,116
Hall #1	---	370	-3,845*
Tupman 23 - 9	---	457	-5,173*
Cerrina #1 - 32	3.42	406	-7,540
Ten Section 27X - 28	0.98	345	-2,215
Buena Vista Lake 22-11	0.77	294	-1,456
F & B #1	1.08	369	-2,945
Santiago "A" 72 - 30	0.99	1,063	-133
Santiago "B" 73 - 29	1.67	1,011	-137

* - determined by visual inspection of the E - log.

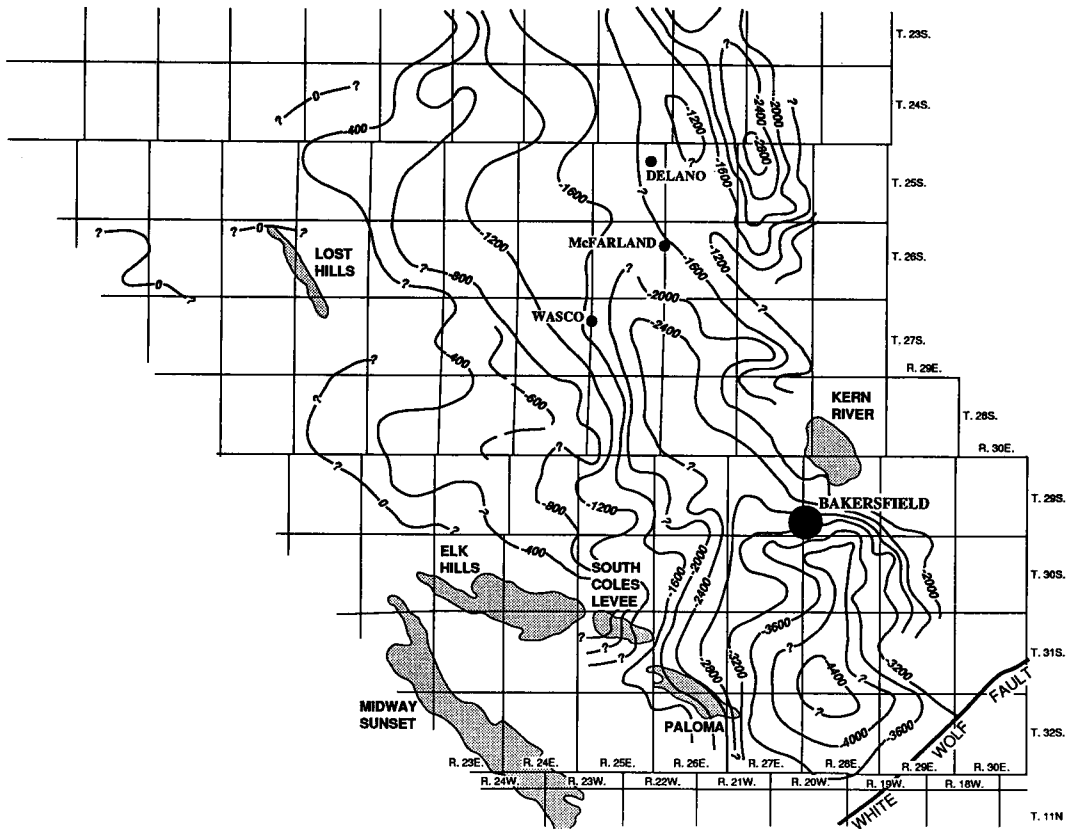


Fig. 1—Base of fresh water for the San Joaquin basin, CA (Ref. 1).

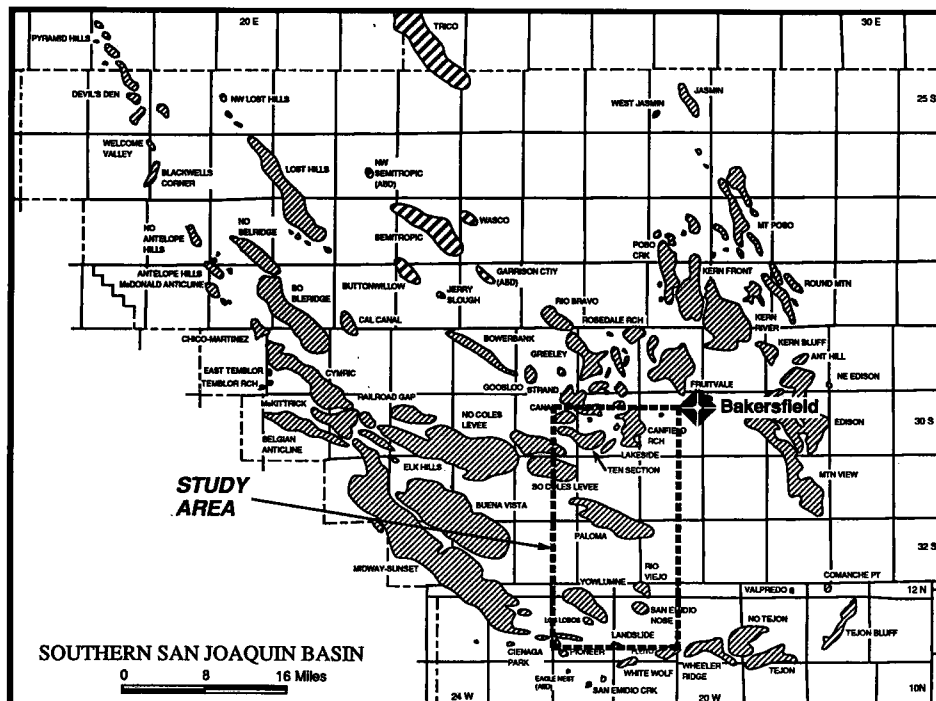


Fig. 2—Southern San Joaquin basin base of fresh water study area.

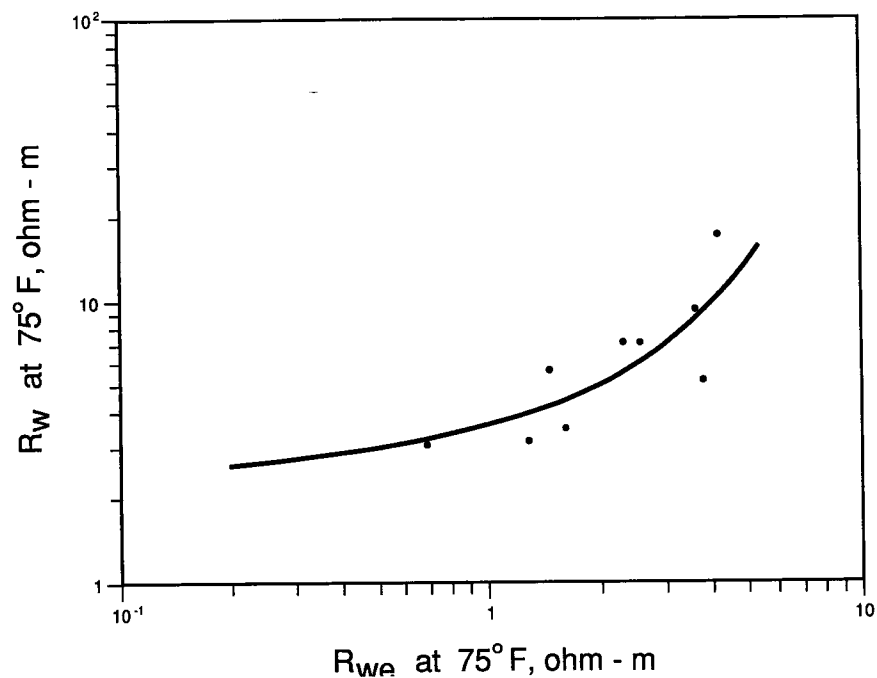
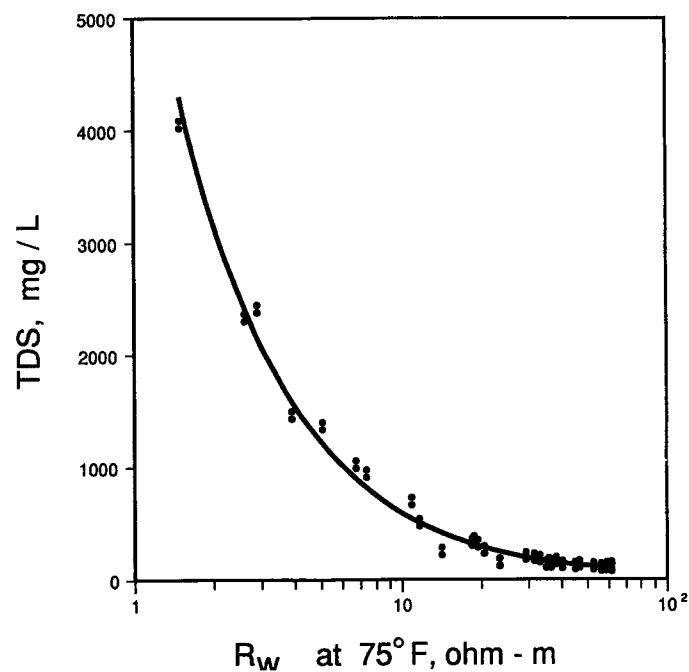
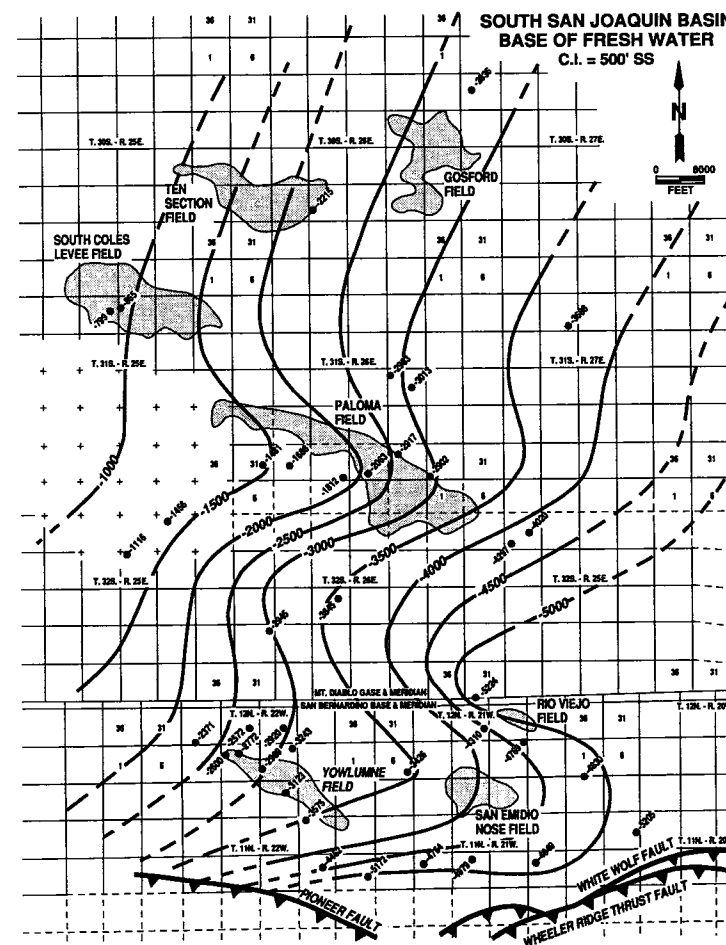
Fig. 3—Southern San Joaquin basin R_{wa} vs. R_w correlation.Fig. 4—Southern San Joaquin basin R_w vs. TDS correlation.

Fig. 5—Southern San Joaquin basin base of fresh water contour map.