Saltwater Inventories and Budgets

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Introduction:

Substantial effort has gone into developing an understanding of the amount of salt at each monitoring well site, the details of its distribution, the rates and patterns of change over time, and the hydrogeologic features that control these processes (OFR 94-28b-d). Although more data are needed, we have now reached a point where we can carry out some initial analysis of system-level characteristics and behavior. These results will have implications for the conceptual and numerical models under development, and will guide future measurements and calculations.

Budgetary analysis is a somewhat imprecise but very powerful tool for analysis of natural systems. Figure E1 illustrates its application in our particular case. We can identify a box representing some specific volume of the aquifer. It may be the volume around an individual well, or the total volume beneath a section, a township, or some larger region. That volume will contain a certain amount of water, and a certain amount of salt -- both of which might be relatively constant or might vary over time.

However, the total masses of both water and salt must be conserved; the change in volume (or inventory) within the box must be equal to the difference between the amount that comes in and the amount that goes out (this is exactly the same process used in the much more rigorous mathematical approach discussed in the report on modeling, OFR 94-28f). If the inventory is nearly constant, then inflow must equal outflow, and this equilibrium (or more accurately, quasi-equilibrium) condition is commonly referred to as "steady-state." If the relative proportions of the fresh water and the salt remain constant, then the same must be true, on average, for the ratios of freshwater inflow to salt inflow, and of freshwater outflow to salt outflow.

This simple set of conclusions provides a great deal of leverage for interpreting the situation. Salt may enter the box by upward flow from the bedrock or by lateral flow within the aquifer; it can leave by lateral groundwater flow or by discharge to outflowing surface water (in principle it can also leave by re-entry into the bedrock, but this pathway will be neglected initially). Freshwater can enter by all the same pathways, and also from recharge of both surface inflow and precipitation. It has the same outflow pathways as salt, with the addition of evapotranspiration.

Some of these budgetary terms are more easily measured or estimated than others. They have different characteristics of variability; for example, we may not know the groundwater inflow term with high accuracy, but because aquifer permeabilities do not change and head gradients vary only slightly, we know that the term is relatively constant. By comparison, we can measure streamflow or precipitation at a given point with high accuracy, but they are extremely variable in time and space. Because of this situation, the additional information that budget terms must add up to a certain value or remain in a fixed ratio to certain other terms is extremely important. The budgetary approach adds several equations to the assembly of unknown quantities that we are trying to decipher, and permits us to evaluate possible mechanisms. Budgetary failure -- that is,

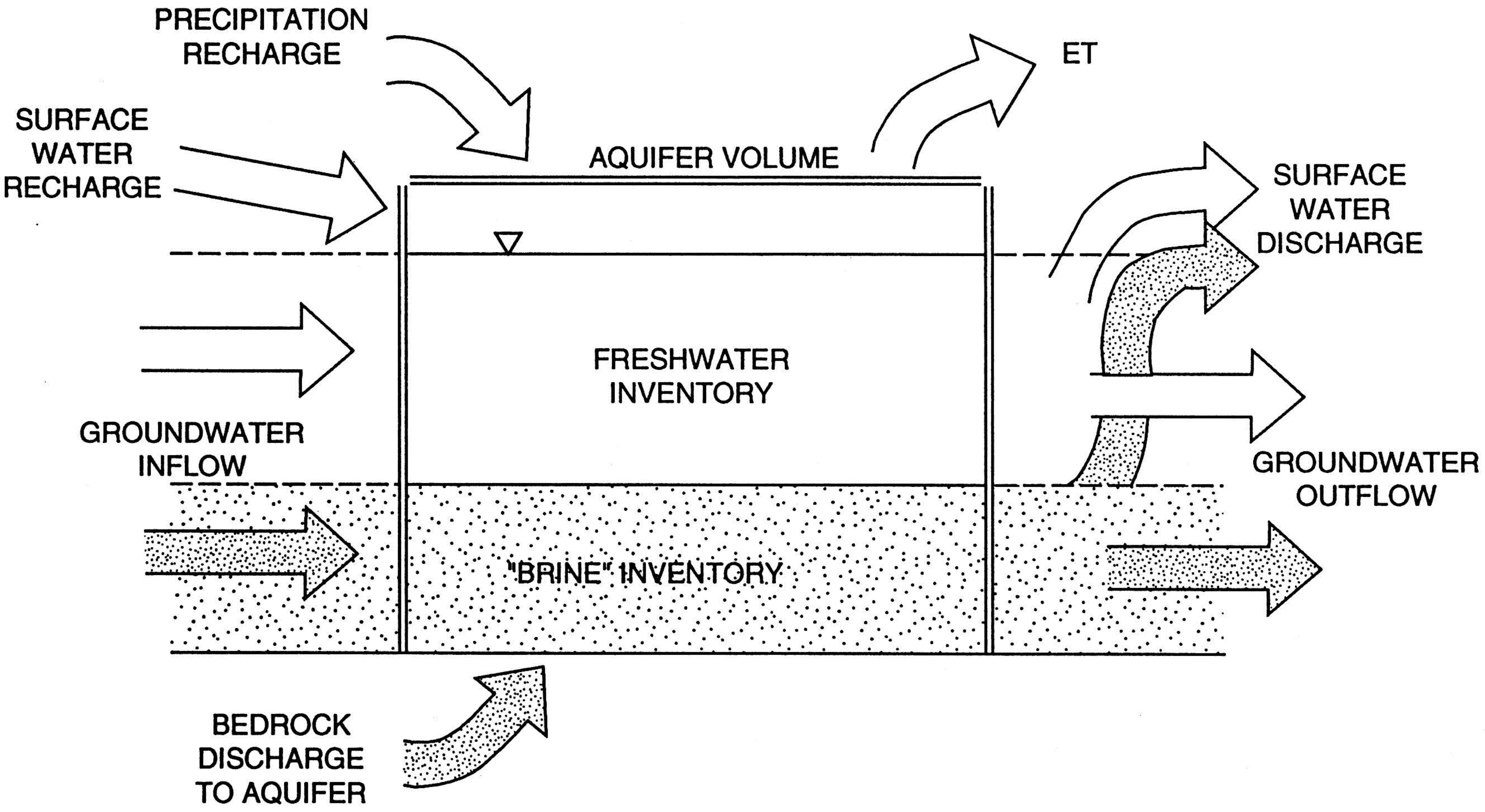

Figure E1. An illustration of the water and salt budget process. Conservation of mass requires that any difference between inflow and outflow must be reflected by a change in inventory. If the inventory is constant the fluxes are in balance and the system is said to be in "steady state".

when things "don't add up" -- are particularly helpful, since they let us know that we need to re-examine either our data or our hypotheses.

Salt Inventory:

Table E1 presents data for both 1993 and 1994 on the chloride mass (mg) per square foot of the aquifer surface for each of the sites where an inventory could be constructed by the methods described in OFR 94-28b. Sites 50-52 are included to show the calculated values from sites that do not have wells penetrating the Permian; all three overlie Cretaceous bedrock. Of the sites that overlie Cretaceous bedrock (4, 6, 7, 50, 51, and 52), only site 4 was found to have appreciable salinity at the base of the aquifer.

Table E1 shows that site 5 has by far (an order of magnitude) more salt within the aquifer compared to the other sites. Because site 5 required extrapolation of the deepest, saltiest portion of the chloride concentration profile to bedrock (~30 ft worth; methods explained in OFR 94-28b), the mass is influenced by the fitted-curve transition zone using a maximum of 42,000 mg/L. If the fitted curve is recalculated to a maximum of 32,000 mg/L (the approximate maximum concentration at the bottom of the actual logged profile), the mass is only reduced by about 10% -- still an order of magnitude greater than any other site. Site 5 is apparently atypical, compared to the other sites, in that it is located directly upon the Permian Cedar Hills Sandstone subcrop and is close to Rattlesnake Creek, a gaining stream. This location is probably responsible for the unusally thick and massive salt-water profile presented by site 5.

Also shown in Table E1 is the equivalent saturated thickness of typical Permian brine to which this amount of chloride would correspond. This latter value is based on estimates (D. O. Whittemore, pers. comm.) of typical concentration levels for the two end members of the groundwater mixing process. For the Stafford County area, native brine is taken as having a specific conductance of 100,000 uS/cm (or 10,000 mS/m), total dissolved solids (TDS) of 75,000 mg/L, and a chloride concentration of 42,000 mg/L. Uncontaminated fresh water in the upper part of the Great Bend Prairie aquifer is taken as having specific conductance equal to 400 uS/cm (or 40 mS/m), TDS = 250 mg/L, and chloride = 10 mg/L.

Using the equivalent volume of a concentrated source brine instead of the actual salt inventory (in mass of salt per unit area of aquifer surface) makes it much easier to visualize comparisons of salt and water, and it relates the salt back to some ultimate source. We have to be careful not to overuse this budgetary convenience, however, since we know that the actual concentrations of salt in the bedrock pore water are much less than the theoretical brine value in many areas.

The remainder of the discussion will focus primarily on the northern part of the study area; work on the less saline southern part is in progress and will be presented later. Figure E2 is a map of the northern region, showing relative inventories of brine and fresh water and the extent of the mixing between the two (indicated by the 500 mg/L chloride value). These values are scaled to the numerical values in Table E1. The addition of the

Table E1a.

Salt inventory at monitoring well sites in the Mineral Intrusion study area (1993).

SITE.well no.	DEPTH TO BEDROCK	DEPTH TO WATER TABLE	AREA UNDER CHLORIDE PROFILE	CHLORIDE MASS PER UNIT AREA	EQUIVALENT 42k CONCEN. SAT. THICK
1.1	146	5.3	6.43E+05	2.91E+06	15.308
SP	186	10.8	7.96E+05	3.60E+06	18.94
3.1	130	25.73	33561	1.52E+05	0.79907
4.1	129	8.7	1.91E+05	8.66E+05	4.5492
5.1	181	1.77	3.06E+06	1.39E+07	72.775
8.1	118.3(1)	8.8	68715	3.11E+05	1.6361
9.1	87	9	1.96E+05	8.89E+05	4.6693
10.1	156	18.3	84985	3.85E+05	2.0234
11.1	208	13.5	8.65E+05	3.92E+06	20.592
16.1	220	11.98	1.68E+06	7.60E+06	39.915
17.1	114	11.6	2.49E+05	1.13E+06	5.9393
18.1	214	19.25	8.52E+05	3.86E+06	20.295
21.1	137	21.6	2.67E+05	1.21E+06	6.3524
22.1	215	16.1	8.07E+05	3.66E+06	19.208
23.1	94	21.42	41453	1.88E+05	0.98698
24.1	123	21	3.65E+05	1.66E+06	8.6993
25.1	98	6.3	1.31E+06	5.95E+06	31.241
26.1	177	6.8	9.52E+05	4.31E+06	22.661
27.1	104	10.12	82905	3.76E+05	1.9739
30.1	138	14.54	56876	2.58E+05	1.3542
31.1	93	13.65	37273	1.69E+05	0.88746
32.1	172	2.6	2.48E+05	1.12E+06	5.9067
36.1	195	28	4.26E+05	1.93E+06	10.15
37.1	240	58.63	95705	4.34E+05	2.2787
42.1	160	13.03	1.53E+05	6.91E+05	3.6311
43.1	65	4.87	71699	3.25E+05	1.7071
50.1	223	26.15	13657	61885	0.32518
51.1	200	17.3	23314	1.06E+05	0.5551
52.1	221	30.79	15816	71667	0.37658

NOTES:

(1) Depth to bedrock changed from 117 ft based on inspection of conductivity log.

Depths and thicknesses in feet; Area - (mg-ft)/L; mass (mg/sq. ft).

Table E1b.					
Salt inventory at monitoring well sites in the Mineral Intrusion study area (1994).					
			AREA UNDER	CHLORIDE	EQUIVALENT
	DEPTH TO	DEPTH TO	CHLORIDE	MASS PER	42k CONCEN.
SITE.well no.	BEDROCK	WATER TABLE	PROFILE	UNIT AREA	SAT. THICK
1.1	146	6.35	6.10E+05	2.76E+06	14.517
SP	186	11.3	8.05E+05	3.65E+06	19.172
3.1	130	20.54	32818	1.49E+05	0.78138
4.1	129	7.87	2.17E+05	9.82E+05	5.1603
5.1	181	2.08	3.05E+06	1.38E+07	72.522
8.1	118.3(1)	11.1	75413	3.42E+05	1.7955
9.1	87	9.36	2.07E+05	9.39E+05	4.9332
10.1	156	13.75	79998	3.62E+05	1.9047
11.1	208	11.39	8.04E+05	3.64E+06	19.135
16.1	220	7.64	1.66E+06	7.50E+06	39.412
17.1	114	10.54	2.57E+05	1.16E+06	6.1104
18.1	214	11.02	8.59E+05	3.89E+06	20.454
21.1	137	23.07	2.16E+05	9.80E+05	5.1505
22.1	215	12.71	8.09E+05	3.67E+06	19.267
23.1	94	22.4	40763	1.85E+05	0.97055
24.1	123	23.9	2.57E+05	1.16E+06	6.1079
25.1	98	6.02	1.32E+06	6.00E+06	31.535
26.1	177	8.76	1.03E+06	4.66E+06	24.47
27.1	104	11.22	1.09E+05	4.92E+05	2.5833
30.1	138	17.19	47496	2.15E+05	1.1308
31.1	93	15.06	35320	1.60E+05	0.84096
32.1	172	9.1	2.60E+05	1.18E+06	6.1963
36.1	195	27.84	4.30E+05	1.95E+06	10.249
37.1	240	57.1	92821	4.21E+05	2.21
42.1	160	13.01	1.50E+05	6.79E+05	3.5671
43.1	65	5.14	81034	3.67E+05	1.9294
49.1	106	1	196670	8.91E+05	4.6826
50.1	223	22.34	14846	67271	0.35348
51.1	200	13.68	24149	1.09E+05	0.57498
52.1	221	23.67	16859	76390	0.40139
NOTES:					
(1) Depth to bedrock changed from 117 ft based on inspection of conductivity log.					
Depths and thicknesses in feet; Area - (mg-ft)/L; mass (mg/sq. ft).					

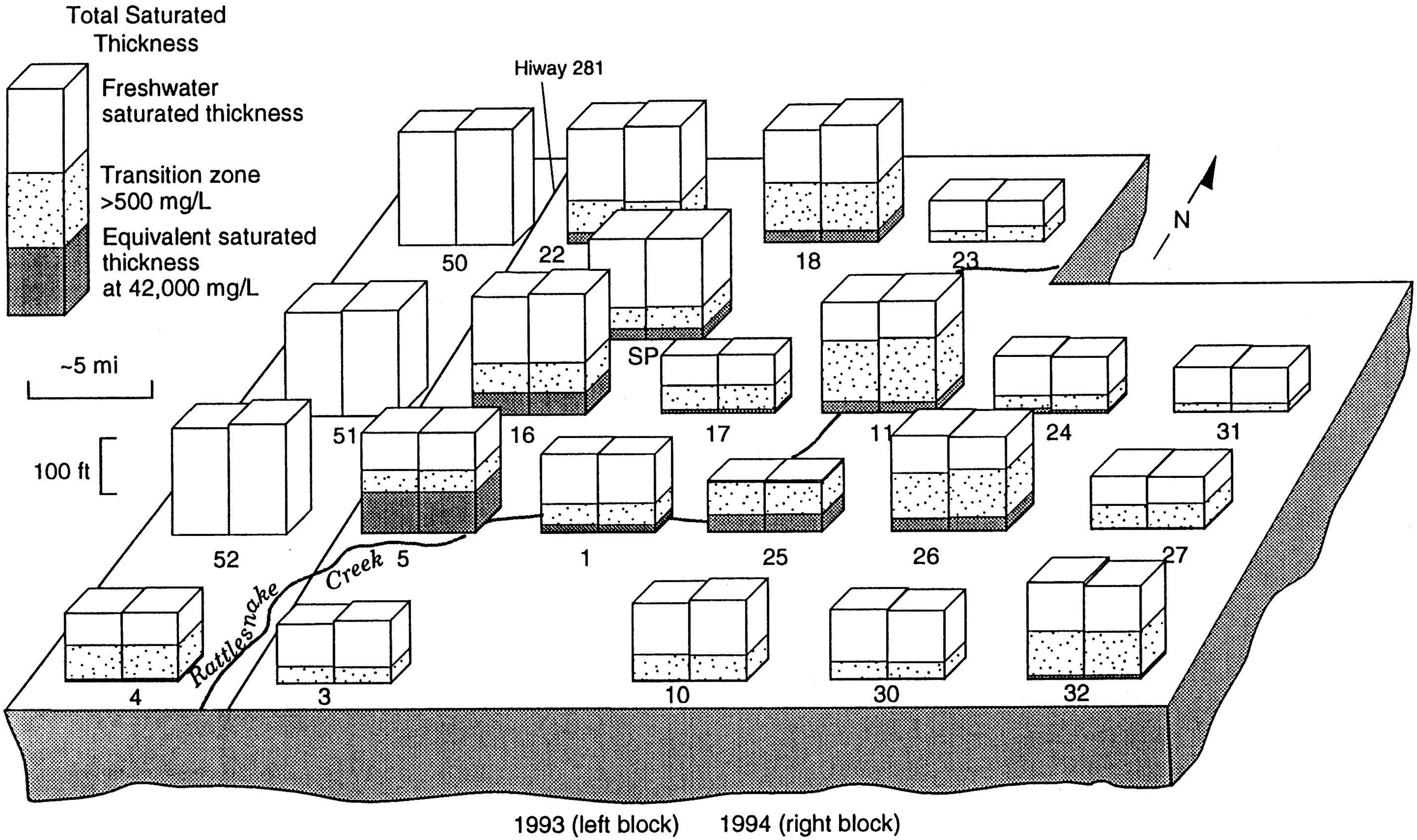

Figure E2. A representation of the total saturated thickness (height of column) and the saturated thickness that would be occupied by the volume of Permian brine equivalent to the salt content of the total water column (height of dark column). At each site, 1993 values are on the left, 1994 on the right. The height of 500 mg/L limit of the mixed zone is shown by light stippling; this has no budgetary significance, but shows the extent of vertical mixing and the amount of usable fresh water at each site.

zone of mixed salt- and freshwater is of little use from a budgetary standpoint because of concentration variations within the mixed zone, but it is of great practical importance. Waters with 3,000 mg/L chloride and with 10,000 mg/L are very different from a salt budget viewpoint, but are essentially the same from a water quality standpoint -- unusable for most purposes. Further, the extent of mixing gives us valuable process information about the extent of vertical water movement within the aquifer and about the horizontal coupling between "boxes."

The data in Table E1 and Figure E2 demonstrate some things that are well known; for example, the very thick transition zone and the near absence of usable fresh water in the vicinity of the Quivira marshes (see also Figures C9 and C10, OFR 94-28c). However, it also shows that the actual equivalent brine inventories are higher in the western part of the study area than in the east. This same observation holds in the less saline southern part of the study area, where the highest equivalent brine concentrations are at sites 36, 37, 42 and 43 (see site maps, OFR 94-28 a and c). This geographic association does not prove, but tends to support, the idea that the subcrop of the Cedar Hills Sandstone (see Fig. A2, OFR 94-28a) may be a larger source of brine discharge than the other Permian formations farther to the east. Further implications of the inventory variations will be discussed below.

Budget and Flux Considerations:

The first point to consider is whether we can legitimately apply steady-state assumptions to the system. The data in OFR 94-28b indicate clearly that there has been less than a one percent variation in salt inventories between 1993 and 1994, and the concentration elevations discussed in OFR 94-28c confirm the stability of the system on this time scale. Head and salt concentration (Whittemore, 1993) measurements over the approximately 15-year period since the monitoring well network was installed suggest that there have not been major changes in the system on this time scale. Overall, we can reasonably treat the salt content as being in steady-state as a first approximation.

Freshwater inventories are somewhat more variable on a short time scale. However, 1993 was a year of unusually high (perhaps record) recharge, so we can compare this change with the inventory. Figure C2 in OFR 94-28c shows that the northern monitoring well sites experienced water table recharge ranging from one to eleven feet in 1993. Even after allowance for saltwater in the saturated thickness, most of these sites have a freshwater inventory (total saturated thickness minus equivalent brine thickness) equivalent to a saturated thickness of 100 ft or more, so changes of several feet are only a few percent of the freshwater inventory -- and that in an extreme year. On the longer term, we know that present water levels in the area are within 10 ft or so of estimated predevelopment levels (Mitchell et al 1994). To a good first approximation we may therefore also treat the freshwater inventory as being in steady state.

Young (1992, figures 9 and 10) presented maps of the potentiometric surfaces of both the Great Bend Prairie aquifer and the Cedar Hills Sandstone formation. These indicate that groundwater flow in both the Quaternary and Permian aquifers is to the east or east-northeast in the area of interest. This means that the west-to-east decrease in salt inventory requires explanation. Although averaging a spatially variable quantity such as salt inventory is not a precise approach, we can make some sub-regional estimates by considering the five "saltwater" townships for which we have at inventory data at least on the township corners. These are T21S, R11-12W and T22S, R10-12W. Table E2 presents average inventory data in terms of saturated thickness of equivalent brine, based on the data in Table E1 for 1994. Because we are comparing units of the same surface area, the height of the brine-saturated thickness is directly proportional to the volume of brine and the mass of salt.

Table E2: Estimated 1994 Salt Inventory (Average Equivalent Brine Saturation).

TOWNSHIP	SAT (ft)	BRINE (ft)	% BRINE	SITES
21S12W	179	20.9	12	22, 16, 17, 18, SP
21S11W	144	11.7	8	18, 17, 23, 11
22S12W	159	33.1	21	16, 5, 17, 1
22S11W	133	17.8	13	17, 1, 11, 25
22S10W	139	20.3	15	11, 24, 25, 26

If the groundwater flow direction is basically from west to east, and groundwater flow is the primary mechanism for salt transport, we would expect the salt inventories to remain constant from west to east if the Cedar Hills is the sole source of salt discharge, and to increase from west to east if there is general salt discharge from the Permian all along the flow path. Instead, the data suggest that there may be a decrease in inventory from west to east. Some of the possible explanations for that, and their implications for future research, are:

1. The observed variation is the result of random noise due to the fact that inventory estimates are crude and based on a small number of data points. Estimates can be substantially improved by the application of geostatistical techniques such as those described in OFR 94-28f.

2. There is a substantial loss of salt inventory due to discharge to the surface and outflow in streams. This can be tested by constructing salt budgets for the streamflow based on existing data and by expanding stream chemistry measurements.

3. Groundwater flow is non-uniform, and saltwater is preferentially exiting through bedrock channels that are not intercepted by the monitoring wells and/or may be sustaining higher discharge rates than the general aquifer flow rates. This is a special case of #1, and can be addressed by a combination of geostatistical techniques and computer simulation.

4. The system is not in steady-state on the time scale of groundwater flow. The evidence for equilibrium is on the time scale of years to a few decades, whereas flow rates in the

Great Bend Prairie aquifer are such that it will take centuries for water to move across a township. If there has been a shift in discharge patterns due to climate change or human intervention we could be seeing the "old" pattern in the east and a "new" pattern developing in the west. This possibility has to be considered because the Cedar Hills has been used for oil brine disposal to the west of the study area, and heads or flow rates may have been altered during the last several decades. It is hoped that this possibility can be examined by combining regional modeling with fluid level and disposal data obtained for the Cedar Hills by the Kansas Corporation Commission.

All of the above approaches will be addressed in an effort to refine our understanding of the salt inventory and the processes that control it.

Another aspect of the budgetary approach is the estimation and comparison of discharge, recharge and groundwater flux terms in the water budget equation. A few preliminary estimates of the Permian discharge were presented in OFR 94-28d. It is worthwhile to expand on the comments there to illustrate how this approach can be applied.

Sophocleous (1992a), using optimized computer (MODFLOW) simulations, has suggested that in the lower Rattlesnake basin recharge represents about 80% of the input of fresh water on a predevelopment basis, and a similar percentage at present if changes in storage due to pumping are neglected. Most of the rest is groundwater inflow, with a minor amount due to stream-derived recharge. A summary of recharge estimates for the area shows (Sophocleous 1992b) that the long-term average recharge is probably about 2"/yr, and certainly in the range of 1-6".

If we assume steady state and consider the brine/freshwater ratios implied by Table E2, then the average brine-equivalent Permian discharge should be on the order of 10-20% of the freshwater recharge; that is, on the order of magnitude of about 0.0001 ft^3/ft^2/day of end-member brine. There are either head gradient, or flux data, or both available for seven sites in the northern saline region (OFR 94-28d): sites 1, 5, 16, 17, 18, 25, 27, and SP. Density corrected head data suggest that the vertical head gradient favors upward flow (discharge from the Permian) at all but site 17. Because of known problems with the wells or the permeability determinations, we do not trust the very high values of Permian discharge that could be derived from sites 1 and possibly 5; however, both have substantial salt inventories, so positive discharge values are consistent with the observations. Of the remaining five wells, the estimated fluid fluxes range from 0.001 to 0.03 ft^3/ft^2/day; 4 are positive (discharge) and site 17 is negative. These values are 1 to 2 orders of magnitude higher than the steady-state brine-equivalent discharge estimated from recharge rates. As above, we can consider the possible explanations:

1. First, it was noted in OFR 94-28d that the flux estimates were probably upper limits for two reasons:

a. The density-corrected Permian heads could be overestimates if the wells had not been fully developed. This will be addressed experimentally by running fluid conductivity logs in the wells, which should permit calculation of acceptably accurate gradients.

b. The slug test permeability estimates may be overestimates of vertical permeability relevant to discharge into the GBPA, both because of anisotropy within the Permian and because of the possible presence of clay layers on top of the bedrock. These problems are difficult to address in a quantitative experimental fashion, but can be studied by use of calculations or simulations based on a reasonable range of estimates consistent with available data and qualitative observations. The range of uncertainty here is large enough to account for order-of-magnitude differences.

2. The fluxes estimated by Darcy's Law calculations are fluid fluxes at the ambient concentration, not the brine-equivalent fluxes. To compare the fluxes with the salt budget we need to adjust for the actual bedrock chloride concentration values, which Whittemore (1993) indicates range from nearly 100% to less than 10% of the brine-equivalent values. When this correction is evaluated it will reduce the major discrepancies by a factor of two to three.

3. The statistical sampling concern is even greater for flux estimates than for the inventories, for which we have a larger number of samples. It is quite possible that our observations are skewed by chance inclusion of atypical sites or undetected errors in measurement or assumed conditions. Additional permeability determinations, combined with more rigorous site assessment and application of geostatistical techniques, may help with this problem.

4. As with item 4 in the preceding list, we must consider the possibility that the system actually is out of equilibrium, in spite of the appearance of short-term steady state. Annual recharge is less than one percent of the total inventory, so if the Permian discharge rate (necessarily a fraction of the total recharge rate) has changed recently, it will take careful monitoring over a number of years to detect systematic changes in the large existing inventory of salt -- an example of the classic problem of reliably detecting small differences in large numbers. The flux estimates available could be argued to be consistent with an increase in the Cedar Hills discharge, but uncertainties are so great that the values cannot be treated as serious evidence at this point. This reinforces, however, the importance of obtaining the Cedar Hills data referred to in item #4 above.

Discussion:

The foregoing material both illustrates the importance of the budgetary approach, and provides a first listing of important questions and needed work. It seems likely that brine discharge occurs predominantly in the western part of the study area, with mixing occurring near discharge sites and during the course of eastward flow. Short-term data suggest an approximately steady-state inventory of salt, but both the spatial distribution and flux rate estimates hint at the possibility of disequilibrium. It will be very important to obtain a better evaluation of the budget terms, both by site-specific measurements and by refined calculations and modeling, in order to evaluate whether the present inventory really is in approximate equilibrium with the present discharge rates. Many of these efforts will be the focus of work in the coming year.

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