Evaluation of Aquifer Contamination from Salt Water Disposal Wells

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In the United States an estimated 140,000 Class II wells for salt water disposal and enhanced hydrocarbon recovery are presently injecting some 30 million barrels of brine per day into subsurface formations. While no systematic survey has documented the extent of shallow ground water contamination from these disposal practices, it is recognized as a major potential pollution source in leading hydrocarbon-producing states. The reliability of impact assessment calculations required under Underground Injection Control permit regulations for Class II wells can be improved by the correct application of existing techniques in predicting individual system operational performance. Modifications to some of these technical indicators include: (a) estimates of radius of endangering influence that require observed initial hydrostatic heads and aquifer hydraulic transmitting properties for the injection interval; and (b) the geochemical characterization of nearby suspected shallow ground water contamination using all major ion concentrations in a trilinear diagram, instead of using only chloride as a brine tracer. A field application demonstrates the relative importance of these and other techniques in characterizing shallow ground water contamination from a salt water disposal well in Oklahoma.

INTRODUCTION

Since the first U.S. hydrocarbon production wells were drilled in Pennsylvania in 1859, between 2.2 and 2.7 million additional wells have been completed. Approximately two million of these have been abandoned, and 140,000 converted to Class II (22) saltwater disposal (SWD) or enhanced recovery wells. Most of this activity is concentrated in the major hydrocarbon-producing states: Texas, Louisiana, Oklahoma, New Mexico, Kansas, Alaska, California, and Wyoming. It has been estimated that over 30 million barrels (one barrel equals 42 U.S. gallons) of brine per day are injected into the subsurface. While no systematic survey has been completed to determine the extent of shallow ground water pollution resulting from these disposal practices, this salt water is recognized as perhaps the largest single potential contaminant of potable subsurface waters.

Possible pathways for the underground migration of injection fluids have been discussed by Canter (3), the Environmental Protection Agency (21), and Fryberger and Tinlin (8). These include: (a) corroded or improperly plugged injection wells where the intended receiving interval or adjacent saline aquifers are not hydraulically isolated from freshwater geological horizons; (b) abandoned exploration wells located within the radius of endangering influence created from nearby active or recently active injection wells; (c) natural or artificially induced fracturing of geologic units resulting in the hydraulic interconnection of the injection horizon, adjacent saline aquifers, and/or freshwater aquifers; or (d) various combinations of the above. While the resulting contamination of freshwater aquifers is easily discernible long before toxic concentration levels are reached, the injection sources can render vast quantities of ground water resources useless for municipal, industrial, or irrigation purposes over prolonged periods. Once an aquifer is contaminated, these chloride-rich brines are not easily or inexpensively removed.

One might surmise that recent Federal and state regulations governing subsurface brine disposal would be sufficient to control these operations. While such efforts are commendable, some serious deficiencies still persist, as will be explained below.

ASSESSMENT TECHNIQUES

Management and regulatory review personnel have a number of proven technical indicators to predict performance of newly proposed injection well operations or to assess the contamination suspected of being associated with an existing well. These tools have evolved from the petroleum, subsurface hydrology, and geochemistry disciplines. The most useful of these include: (a) calculations of radius of endangering influence; (b) piezometric head contour maps; (c) formation hydraulic transmitting properties; and (d) water quality analyses using trilinear diagramming of major ion parameters. Each of these is briefly described below. A field application further illustrates their relative usefulness.

Techniques describing the computation of the radius of endangering influence have been summarized by Warner et al. (23). While several complex situations are considered in their analyses, insufficiency of subsurface data severely limit routine applications of all but one procedure. This case is equivalent to the Cooper-Jacob (4) method commonly employed in water well hydraulics, and is a special case of the Theis (19) nonequilibrium equation applicable at relatively late times or small distances from the injection well. The Cooper-Jacob equation is generally written as

$$s = Q/4\pi T \ln (2.25\ Tt/r^2S) \qquad (1)$$

where ln denotes the natural logarithm; *s* is the upconing piezometric head in the receiving interval at radius *r* in response to injection (measured as a vertical distance above the hydrostatic fluid level in the injection horizon); *Q* is a constant injection rate (volume per unit time); *T* and *S* are the injection interval hydraulic transmitting properties of transmissivity (length squared per unit time), and storage coefficient (dimensionless), respectively; *t* is time after injection begins; and *r* is the radial distance from the injection well. In Eq. 1 any consistent system of units may be used. A similar equation was developed by Mathews and Russell (14), and is listed by Warner et al. (23) as their Equation 4; however, these equations utilize a mixed system of oil-field units.

The criterion for using Eq. 1 instead of the Theis equation is that *u* be less than 0.01, where $u = r^2S/4Tt$. The percent relative error (*RE*) introduced into Eq. 1 can be computed from

$$RE = [w - W(u)] * 100/ W(u) \qquad (2)$$

where *w* equals the natural logarithmic term in Eq. 1, and *W*(*u*) is the Theis well function corresponding to the value of *u*. Tables for *W*(*u*) have been computed (6), and are commonly summarized in most ground water textbooks.

In actual application Eq. 1 should be modified to incorporate

$$h = H + s \qquad (3)$$

where *H* is the initial undisturbed piezometric head in the receiving horizon prior to any injection and is measured as the vertical elevation to any convenient horizontal reference datum; *s* is given by Eq. 1; and *h* is the total predicted piezometric head at radius *r*. The radius of endangering influence (*R*) is defined as the radius *r* = *R* where *h* is equal to the datum-referenced piezometric head in the lowest freshwater aquifer overlying the injection interval. Normally this piezometric surface is unknown, so *R* is more commonly defined as the radius where *h* is equal to the datum elevation of the base of the lowest freshwater aquifer. Anywhere inside this radius, the injection zone has a sufficiently large piezometric head that fluids can physically migrate vertically upward into the lowest freshwater aquifer if a permeable conduit exists. If *H* is unknown then these calculations are subject to large errors. Warner et al. (23, p. 8) imply that in these situations *H* should be set equal to the injection interval hydrostatic head resulting from the entire saturated thickness of the overlying rock. If one assumes that this saturated thickness is located somewhere between the top and bottom of the lowest freshwater aquifer, then Eq. 3 can often yield an *R* greater than 10,000 feet. When *H* is below the base of the lowest freshwater aquifer, then smaller *R* values are expected. Finally, if *H* is near the top of the deep injection zone, then this zone is said to be accepting fluids under a vacuum and *R* will approach zero for shallow freshwater aquifer situations.

Under the current Underground Injection Control (UIC) program guidelines established by the Safe Drinking Water Act of 1974, these calculations may be used to establish the zone of influence, or *R* may be set at some minimum fixed distance. In Oklahoma the Oil and Gas Conservation

Division of the Corporation Commission maintains jurisdiction of the UIC program for Class II wells, requiring new injection well permit applicants to perform only the first part of the above calculations. They do not require that any hydrostatic fluid levels in receiving intervals be established before injection begins, nor do they require any periodic measurements of h to be reported during system operation. Furthermore, no physical measurements for T and S, or their petroleum equivalent parameters, are required in support of radius of endangering influence calculations. Hence, large errors in R can be routinely anticipated. To complicate matters even further, abandoned exploration or production wells are often located within 660 feet of injection wells. These abandoned wells were usually plugged in compliance with the existing regulations of the day, but such plugging is commonly inadequate by current standards. Other states have varying requirements within the framework of Federal regulations. For example, Texas currently sets the radius of influence at a minimum of 1320 feet.

Water level measurements from spatially distributed wells that are completed into the same hydrogeological horizon can be used to construct piezometric contour maps. This routine technique of ground water flow analysis is one of the fundamental models that hydrologists use to characterize subsurface fluid environments. A minimum of three wells is required to establish a preliminary two-dimensional (2-D) estimate of subsurface flow direction for a given hydrogeologic unit. Additional well data will allow the construction of a 2-D piezometric contour map. Techniques for construction can be found in any introductory text. The contour map should be based on data collected at approximately the same time. Surface elevations can be estimated from topographic maps, but a physical survey from a known benchmark is the preferred technique if only small differences in water levels are encountered. If measurements or estimates of hydraulic conductivity and effective porosity are available, then the 2-D ground water flow velocity can be inferred from the piezometric map by using Darcy's law. These velocity estimates can yield travel times between the contaminant source and suspected point of contamination. Extension of this technique to 3-D flow fields is straightforward, but requires substantially more physical observation.

Verification of integrity of the injection well isolation between the brine and freshwater aquifers can be accomplished via water quality analyses. If concentration levels of major ions (i.e., sodium, potassium, calcium, magnesium, chloride, sulfate, bicarbonate, and carbonate) are available from the same wells used to construct the piezometric map, then a geochemical characterization of ground waters can be made. These concentrations are routinely reported in milligrams per liter (mg/L). Conversion to milliequivalents per liter allows one to compute a simple cation-anion balance, and to graphically represent water quality analyses on a trilinear diagram. Details can be found in Todd (20) or Freeze and Cherry (7). The trilinear diagram was originally developed by Piper (16); a microcomputer program written in HP-BASIC for automated plotting was presented by Morris et al. (15). In Oklahoma this technique is not commonly used in practice since unreported bicarbonate analyses are not directly associated with brine contamination. Routine analyses are vital, however, since bicarbonate concentrations reflect the degree of atmospheric and vadose zone fluid interconnection to ground water supplies. Brines are typically low in bicarbonate and high in chloride; uncontaminated shallow ground waters will usually show the reverse. Through trilinear diagram plotting, these and other differences in major ion compositions will become readily apparent. Furthermore, the concepts of a model with two- or three-end-member mixing can often help to explain contamination of shallow ground waters by oil field brines, especially when used in conjunction with the previous techniques presented above. The example given below illustrates this point.

CASE HISTORY: DEVORE SWD WELL

In 1948 the DeVore No. 1 hydrocarbon exploration well was completed in the NE, SE, NW of Section 2, T21N, R2W, Noble County, Northcentral Oklahoma. Shortly thereafter it was abandoned as a dry hole, and was subsequently converted to a salt water disposal well. It has operated almost continuously since then under several different owners; corroded injection tubing and packers were repaired in late 1984. This well is currently permitted to inject up to 400 barrels of salt water per day, at an injection pressure not to exceed 300 pounds per square inch gage (psig). Similar operational conditions have apparently existed since the early 1950s.

Within and surrounding the well site, only a thin veneer of soils have developed. Surface sedimentary rock exposures have been identified as four unnamed units within the Wellington Formation of the Permian System (1,11, 17). The DeVore SWD well is located within the uppermost of these four units. The most striking features of these Wellington sequences of sandstones and mudstones are the dominant red color, and frequent facies changes where lenticular sandstones laterally grade into red mudrock and thin dolomites. Salt-bearing sequences of Permian age are noticeably absent from surface and near-surface horizons in this area of Oklahoma (12). Sandstones within this upper unit of the Wellington Formation reflect an average paleocurrent direction of North 5 degrees East (N5E), with secondary directions as both west and east. Shelton et al. (17) also report orthogonal joint-strike frequency directions of N45W and N50E, which are associated with faulted anticlinal structures in the western third of Noble County, including the DeVore well site.

During October, 1984, the Oil and Gas Division of the Oklahoma Corporation Commission directed the current owner to install four shallow monitoring wells around the SWD well because of suspected ground water contamination. These were completed in November, and sampled several times during 1985. Figure 1 shows these well locations with respect to the SWD well. Each of these PVC-cased wells penetrates 25 to 62 feet of red mudstone within the Wellington Formation before encountering a four- to eight-foot sandstone layer of continuous areal extent. Hydraulic conductivities for each monitor well were obtained using the in-situ technique of Bouwer and Rice (2). These values range from 5 to 25 feet per day, and represent essentially horizontal permeability.

Only four water level measurements from the shallow sandstone were available to construct the piezometric contour map depicted in Figure 1. These measurements were supplemented by three surface stream elevations taken from locations where this same sandstone horizon outcrops in the unnamed tributary stream channel located west of the SWD well, and five additional surface stream elevations. As such, these twelve data points form the basis of the piezometric contour map, and represent the best available picture of shallow subsurface hydraulic conditions within the sandstone zone. With this piezometric map and the measured hydraulic conductivity values, the ground water near the SWD well is computed to have a flow velocity of about 180 feet per year, oriented at approximately N60W. This calculation is based upon Darcy's law with a geometric mean hydraulic conductivity of 6.4 feet per day, an assumed sandstone thickness of 10 feet, an effective porosity of 0.25, and an anisotropy ratio of two in aquifer transmissivity, with the major axis oriented east-west. The ten-foot thickness value represents a conservative approximation to the reported four- to

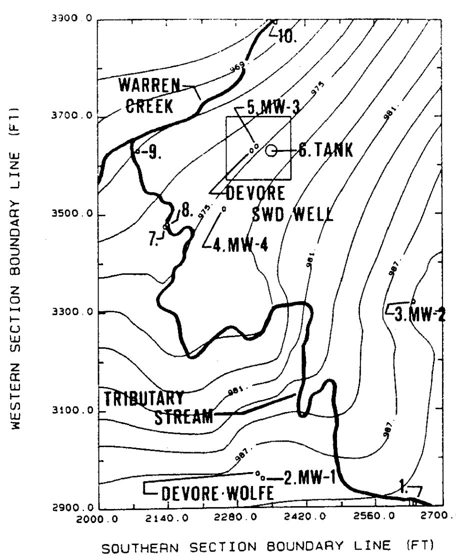

FIGURE 1. Piezometric map for the sandstone unit, showing sequentially numbered surface and ground water sampling points. Monitor wells are designated as MW-1 to MW-4. Contour from 967 to 989 ft at 2 ft intervals.

eight-foot values from the monitor well drilling logs, whereas the 0.25 porosity value is typical of sandstone. The assumed anisotropy ratio is subjectively based upon paleocurrent orientation values reported in Shelton et al. (17), and the observed surface drainage pattern near the SWD well. The magnitude of the computed ground water flow velocity is not overly sensitive to an order of magnitude change in the anisotropy ratio. For example, if the value of the minor axis transmissivity is reduced by a factor of ten, the resultant velocity decreases to 160 feet per year; however, the predicted average flow direction would be almost due west. If the original major transmissivity axis were shifted to a north-south orientation, then the predicted flow direction would be about N25W, at about 190 feet per year

According to Bingham (in 17) the shallow ground water within Noble County is of only fair quality. Only limited historical water quality analyses are available from wells in Noble County. The total dissolved solids (TDS) concentration of samples reported by Shelton et al. (17) ranges from 522 to 1160 mg/L. Bingham and Bergman (1), however, report that TDS ranges from 60 to 4610 mg/L with concentration of 500 to 2000 mg/L more typical. Ground waters containing 2000 to 4600 mg/L TDS are generally limited to small local areas, and probably could be traced to local oil and gas drilling or production activities. Numerous shallow wells in the Wellington Formation yield water with TDS concentrations between 60 and 500 mg/L. Examination of the Oklahoma Water Resources Board water quality data base (J. Black, pers. comm., May, 1985) confirms these general observations. On June 14, 1985, the TDS levels of shallow ground water at the DeVore site ranged from a low of 848 mg/L in PVC well MW-2, to a high of 196,000 mg/L in PVC well MW-3. The DeVore injection well showed a TDS level of 257,000 mg/L. Similar levels have existed since early February, 1985, when these same wells were first sampled.

The historical water quality analyses reported by Shelton et al. (17) are depicted on the trilinear diagram of Figure 2. In this diagram major water quality parameters are plotted as percentages of total milliequivalents per liter so that chemical similarities or differences are more readily discernible. More detailed explanations and alternate graphical representations are available (9,13,16,18). The historical data presented in Figure 2 may be viewed as an approximate background snapshot of average quality shallow ground water within Noble County, and can be used as a basis for comparison of water samples collected from other locations.

In June of 1985 ten water samples were collected for detailed laboratory analyses from ground and surface sampling points surrounding the DeVore well site. Four of these samples were from the PVC monitor wells, one was from the DeVore injection well fiberglass storage tank, and five were from nearby streams. All of these sample points are shown in Figure 1; Figure 2 shows results of the respective analyses on the trilinear diagram. This graph shows that major ion levels for samples recovered from PVC monitor wells MW-3 and MW-4 (samples 4 and 5) are geochemically identical to the DeVore injection well waters (sample 6). In addition, stream samples 8 and 9 are geochemically similar to injection waters, showing some minor dilution from uncontaminated surface waters. This graphical representation indicates that the DeVore SWD well has contaminated the surrounding shallow ground water and the unnamed tributary stream lying to the immediate west of the SWD well. This conclusion is further supported by the piezometric contour map in Figure 1, and by the fact that no other source area is located sufficiently near the site which could account for the abnormally high contaminant levels observed at MW-3 and MW-4. Figure 3 shows other oil and gas exploration wells drilled within Section 2, T21N, R2W, and clearly illustrates this point.

The sample from well MW-2 (sample 3) appears to be chemically similar to historical ground water samples obtained from unrelated sites in Noble County (see the lettered points in Figure 2), and to surface sample 1. These samples reflect uncontaminated waters and can be used for background comparison purposes. Surface samples 7 and 10 appear to be somewhat

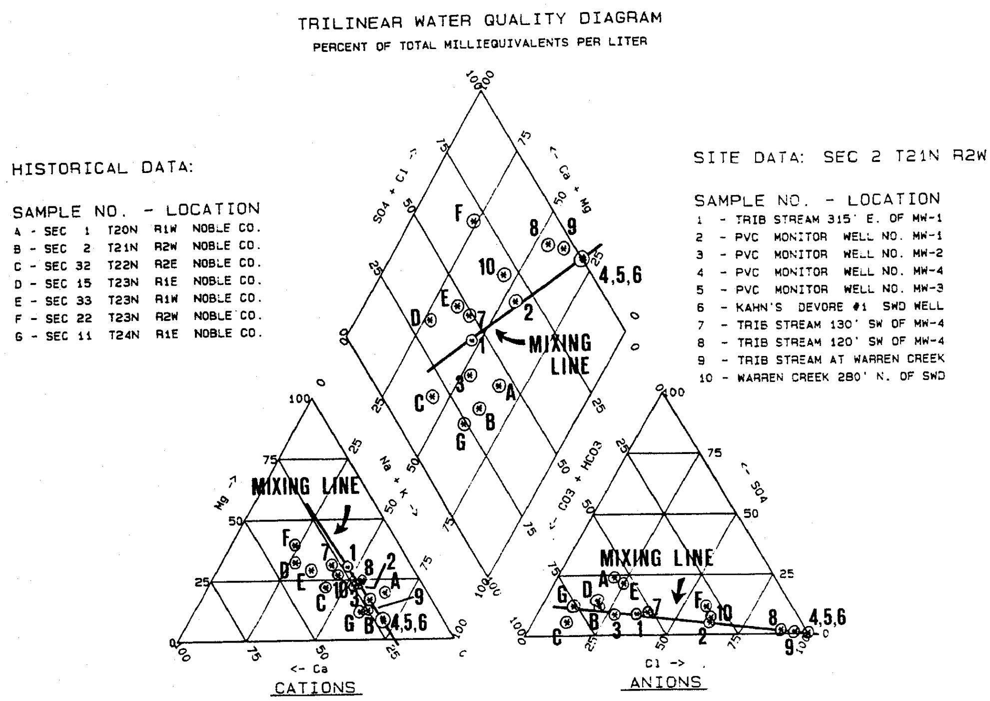

FIGURE 2. Piper plot of historical background (letters) and site (numbers) water quality analyses.

affected by the DeVore SWD well, but high surface runoff may be masking its true influence because of dilution. It should be noted that all samples were obtained within one week after an intense 24-hr, four-inch rainfall event when streams were running nearly full with uncontaminated surface runoff. Hence, a surface dilution effect had undoubtedly masked the full extent of contaminated surface waters. A simple two-end-member mixing line can be drawn in all three plotting positions of the trilinear diagram, as seen in Figure 2. It is interesting to note that in the diamond area, surface project samples appear above this mixing line, while ground water samples appear on or below it. This observation suggests that one or two separate three-end-member mixing models might actually be affecting the diagram. Additional water quality information would be required to substantiate this interpretation.

The sample recovered from well MW-1 (sample 2) shows chemical characteristics midway between uncontaminated surface (sample 1) and contaminated subsurface (samples 4, 5, and 6) waters. It has apparently been influenced by an unknown chloride source. Inspection of the piezometric contour map would suggest that this contamination has a source separate from the DeVore SWD well. However, a radius of endangering influence calculation suggests otherwise. Well MW-1 is completed within 10 feet of the abandoned Devore-Wolfe exploration well (see Figure 1), and is about 670 feet south of the DeVore SWD well. Plugging records indicate that the DeVore-Wolfe well was drilled deeper than the SWD well's injection interval at 3200 feet below ground surface. Surface casing in the DeVore-Wolfe well was set at 120 feet and cemented; most of the remaining steel casing was removed in 1950, and the open borehole was filled with bentonite mud. If a standard (10 pounds per gallon) mud weight were used and it had a 15 percent weight reduction due to settlement or degradation after 35 years, then the DeVore-Wolfe wellbore would have a pressure of about 1413 psig at 3200 feet.

Figure 4 summarizes one possible radius

of influence calculation for the DeVore SWD well; several individual parameters are estimated in the calculation since observations are unavailable. These critical injection zone parameters include: (a) an assumed permeability of 40 millidarcys (equivalent to a transmissivity of about 5.9 feet squared per day); (b) an assumed initial undisturbed piezometric head located 300 feet below ground surface; and (c) an assumed freshwater aquifer base located 200 feet below ground surface. None of this information is required by the Oklahoma Corporation Commission in support of UIC permit applications. The injection rate, time, interval thickness, and injection zone depth were all obtained from required information in the original permit application; injection fluid properties are typical of Oklahoma deep basin brines. The aquifer storage coefficient (S) was estimated from the relationship $S = \gamma b(\alpha + n\beta)$, where γ is the injection fluid specific weight of 64.3 pounds per cubic foot, b is the injection zone thickness of 75 feet, α is the injection zone rock compressibility, n is the porosity, and β is the compressibility of water. Domenico (5, p. 216-235) lists typical values for α according to rock type. For this calculation α was assumed to be 1.6E-8 feet squared per pound, a typical value for mildly fissured to solid rock. The computed value of S = 1.022E-4 is characteristic of a confined aquifer.

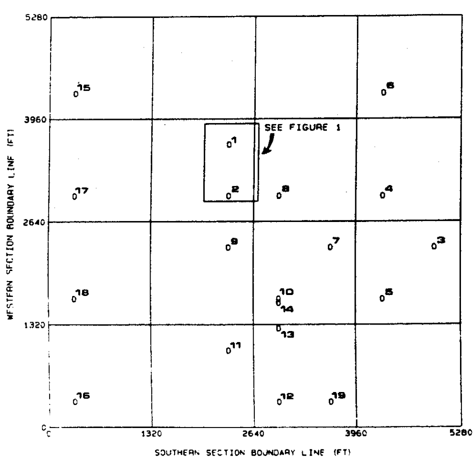

FIGURE 3. Locations of oil and gas exploration wells adjacent to the disposal site. Identification of wells with (year-of-completion; total depth in ft) follows:
1 = Devore SWD (1948; 5141);
2 = Plugged Devore-Wolfe (1949; 5118);
3 = Wiegel #1 (1947; 5139);
4 = Albright #1 (1947; 5137);
5 = Plugged Wiegel #2 (1947; 5138);
6 = Albright #2 (1948; 5157);
7 = Wiegel #3 (1948; 5113);
8 = Albright #3 (1948; 5100);
9 = Wiegel #4 (1948; 5117);
10 = Plugged Dayton #1 (1948; 5106);
11 = Plugged Dayton #2 (1948; 5136);
12 = Wiegel #5 (1949; 5020);
13 = Wiegel #6 (1949; 4994);
14 = Wiegel Twin #6 (1949; 4994);
15 = Plugged Wiegel #7 (1954; 2325);
16 = Christian #1 (1981; 5270);
17 = Floris Dayton #1 (1981; 5233);
18 = Verl Hentges #1 (1981; 5180);
19 = Cinnamon #3 (1981; 5195).

Calculations using Eqs. 1 and 3 yield an R of about 7200 feet, as seen in Figure 4. They also indicate that a resultant downhole pressure in excess of 1400 psig will be produced at the DeVore-Wolfe well after 30 years due to salt water injection at the disposal well. This pressure would be sufficient to allow DeVore SWD brines to migrate up the DeVore-Wolfe wellbore and enter the freshwater aquifer near MW-1. Furthermore, by using the developments of Hoopes and Harleman (10), it can be shown that sufficient time has elapsed to allow undiluted SWD brines to travel in the injection interval to the DeVore-Wolfe wellbore. This interpretation is further supported by the trilinear diagram characterization of shallow ground waters, and would not have been possible if only chloride concentrations had been available.

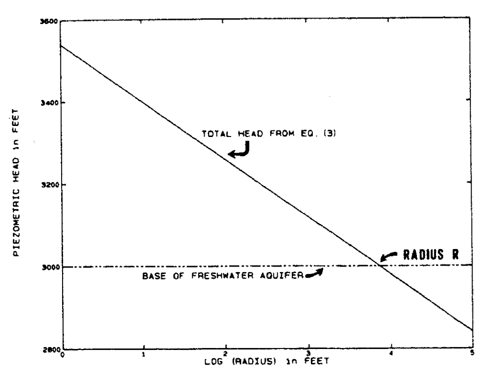

FIGURE 4. Graphical representation of the radius of endangering influence calculation for the DeVore SWD well.

CONCLUSIONS

This paper has presented several management tools that can be used to assess potential environmental impacts resulting from salt-water injection wells. A simple case history has demonstrated their relative importance in practical problems. While this technology has existed for many years, certain fundamental implications have apparently gone unnoticed in the implementation of the UIC program as it applies to Class II injection wells. Hence, the objective of presenting this case history is to refocus attention on the supporting information required in individual state UIC permit applications. Most hydrologists will immediately recognize the importance of requiring SWD well operators to physically measure hydrostatic pressure levels in potential injection intervals. This information should be required on all permit applications where the radius of endangering influence calculation is made. Furthermore, a sensitivity analysis of transmissivity (T) in the Cooper-Jacob equation will quickly demonstrate its importance in computing an upconing value for s. In those situations where the injection zone's initial hydrostatic pressure is near the base of the lowest freshwater aquifer, then physical measurements for T (or its petroleum effective equivalent of permeability) should also be required if the injection well is adjacent to other abandoned or production wells, or is located in geologic settings where extensive vertical fracture permeability is expected. If these parameters are fixed via physical observations, then variations in the expected range of the aquifer storage coefficient (S) will be of secondary importance. For existing injection wells where this information has not been documented, then a shallow ground water monitoring network could be installed. While a more detailed assessment would still be advocated by many, it is imperative to initiate these fundamental requirements if a meaningful UIC program for Class II wells is to be maintained.

Finally, the trilinear diagram technique of water quality analysis can be extremely useful in differentiating uncontaminated and brine-contaminated shallow ground and surface waters. These analyses require that all major ion parameters be measured, instead of simply using chloride as a brine tracer.

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