DATING OF GROUND WATER WITH ISOTOPES-
A PRELIMINARY REPORT

BY

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DATING OF GROUND WATER WITH ISOTOPES - A PRELIMINARY REPORT

Introduction

The purpose of this project is twofold:

1. identify potential recharge areas;

2. gain information about the recharge mechanisms, i.e.

  a) how important are, for example, lineaments,

    intermittent streams and playa-like structures for

    contributing water to the Ogallala aquifer?,

  b) at what rate is the aquifer being recharged?

Studies using mathematical models to determine recharge rates and areas, flow, and general aquifer conditions of the Ogallala have been conducted (Reddell, 1970, Claborn, Austin, and Wells, 1970, Rayner, 1970), but no comparison was possible with actual field data. Recharge is a very sensitive parameter as far as models are concerned and a factor of "insecurity" as to how accurate and reliable those models are always remains.

It was decided to test the Ogallala aquifer for environmental (tritium, ^3H) and stable (oxygen-18, ^{18}O; deuterium, ^2H) isotopes, freon, atrazine and nitrates in order to be able to distinguish between older and modern waters and thus gain information about potential recharge areas and the rate of flow. In doing so a comparison of field data with existing models would be possible and the reliability of the models would be established or questioned.

Results of this project will help to improve water management in the investigated area, the management district, the water users, and those regulatory agencies concerned with sanitary- and hazardous-waste disposal will benefit.

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Northwest Kansas Groundwater Management District 4 was chosen as a study area (Fig.1).

The project was divided into two phases. Phase 1 was concerned with establishing the most suitable analytical methods to date the Ogallala ground water, and phase 2 will expand the sampling net in both the saturated and unsaturated parts of the Ogallala using the isotopes determined to be the most suitable.

For phase 1, nine wells were selected in early October 1987 in cooperation with the management district, using mainly proximity to lineaments as a selecting criterion (Fig.2). Seven of these wells were already existing wells, which we had information about and permission to use for sample collection. Because of lack of time and funds, only two monitoring wells were installed in late October 1987 by the Kansas Geological Survey. Table 1 gives the designated well names (also used for labelling water samples taken from the respective wells), legal locations, and counties for all nine wells. Table 2 gives total depth, screened depth, and use of the wells.

From November 10 through November 13, 1987, we collected water samples from the wells for the isotopes ^{18}O, ^{2}H and ^{3}H, and freon, atrazine, nitrate and general water chemistry. Where possible the samples were taken using a Bennett sample pump, provided by GWMD #4. In addition one precipitation sample was collected by the Kansas State University Experiment Station at Colby on November 8.

Analyses

Oxygen-18 and Deuterium

Both these isotopes are stable and occur naturally. 10^6 water molecules with the normal isotopic composition $H_2^{16}O$ contain about 2000 molecules $H_2^{18}O$ and about 320 molecules $HD^{16}O$
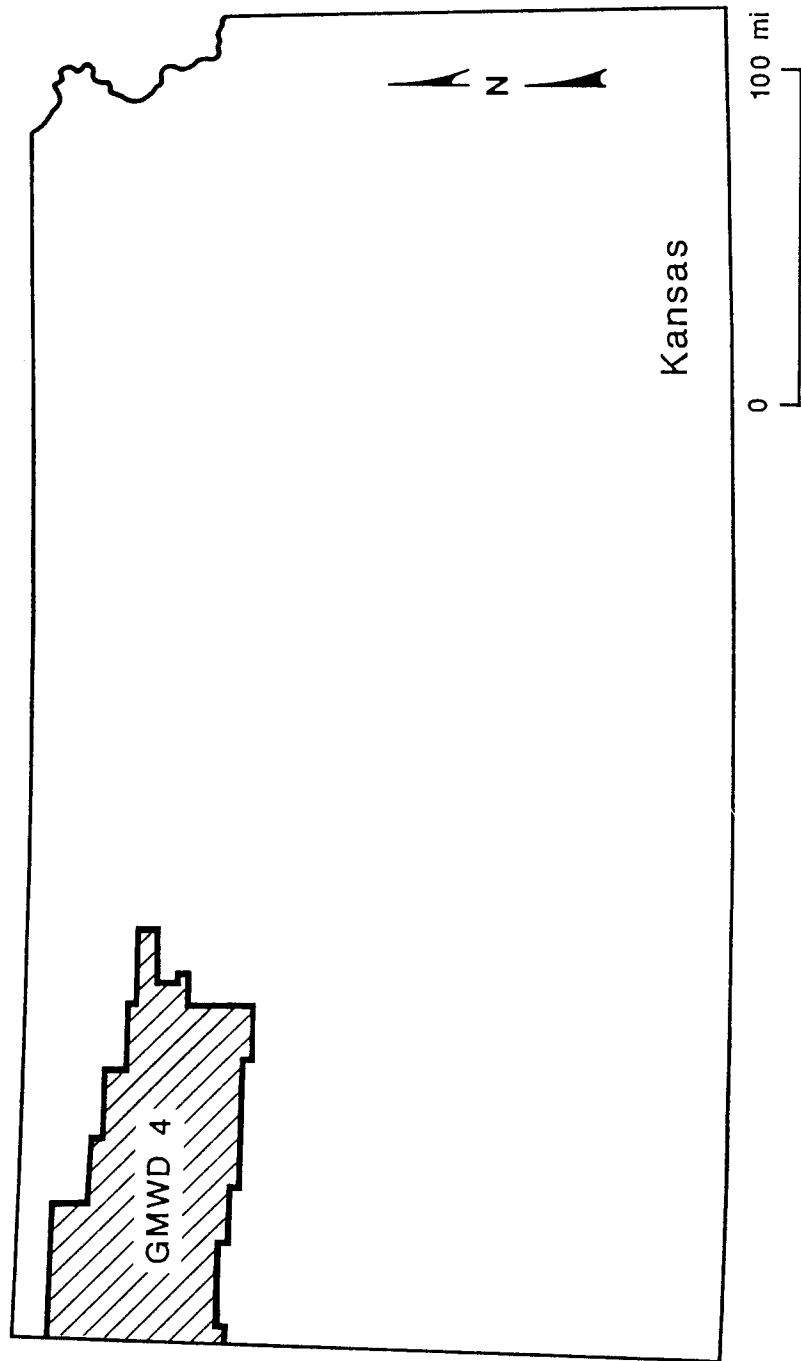
Figure 1. Study area.
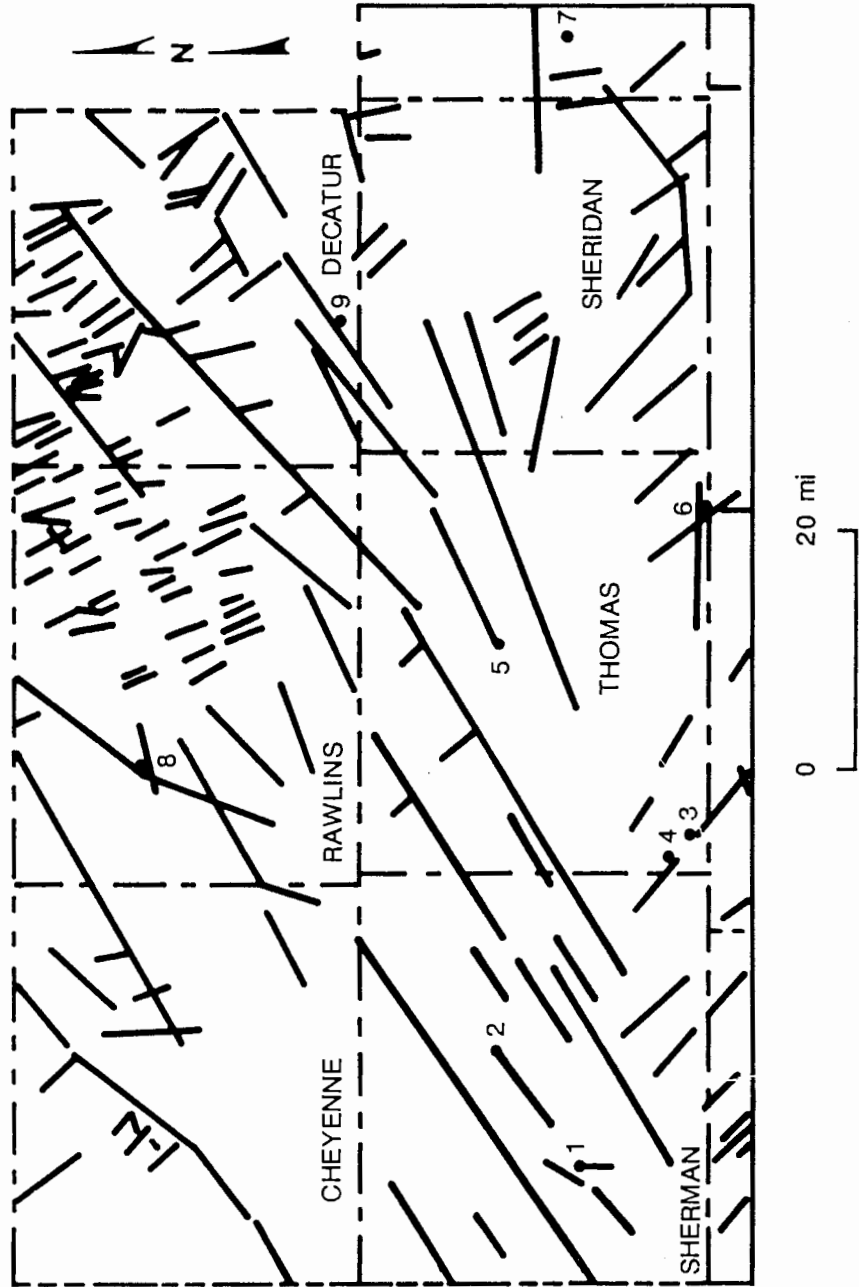
Figure 2. Lineaments and well locations (from McCauley, 1988).

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Table 1. Well Designations and Locations of Ogallala Wells.

Site 1, Gannon   T9S, R41W, sec. 11, DDA   Sherman

Site 2, Goodland   T8S, R39W, sec. 8, BAB   Sherman

Site 3, Playa   T10S, R36W, sec. 21, BCC   Thomas

Site 4, Starns   T10S, R36W, sec. 18, BCC   Thomas

Site 5, Colby   T8S, R33W, sec. 4, ACA   Thomas

Site 6, Oakley   T11S, R31W, sec. 6, DCB   Gove

Site 7, Graham   T8S, R25W, sec. 36, CAA   Graham

Site 8, Rawlins   T2S, R35W, sec. 34, AAA   Rawlins

Site 9, Dairy   T5S, R29W, sec. 25, CBA   Decatur

Graham County
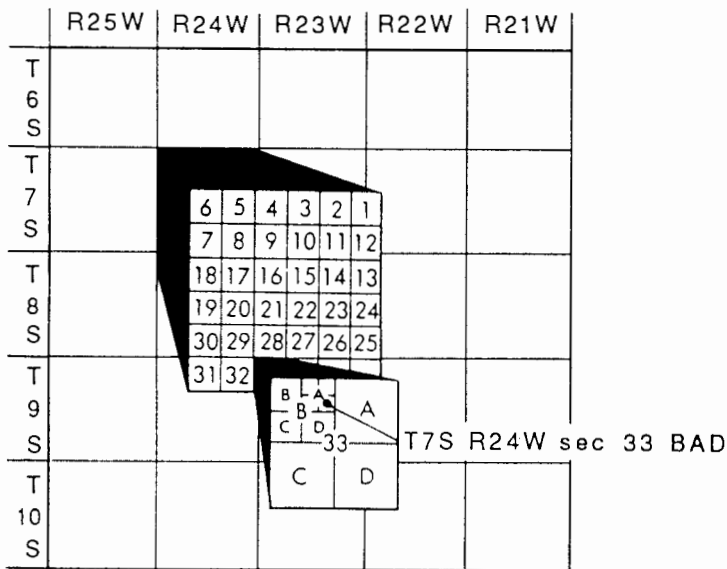
In the well location number, letters indicate the subdivision of the section in which the well is located. The first letter denotes the quarter section or 160-acre tract, second letter the 40-acre tract, and third letter the 10 acre tract. The 160-acre, 40-acre, and 10-acre tracts are designated a, b, c, and d in a counter-clockwise direction, beginning in the northeast quarter.

Table 2.   Total Depth, Screened Depth, and Use of Wells.

Well	Total Depth	Screened Depth	Use
Site 1, Gannon	298 ft	168-298 ft	monitor
Site 2, Goodland	197 ft	147-197 ft	monitor
Site 3, Playa	152 ft	122-152 ft	monitor
Site 4, Starns	137 ft.*		irrigation
Site 5, Colby	200 ft	155-195 ft	monitor
Site 6, Oakley	190 ft	170-190 ft	none
Site 7, Graham	32 ft	21-31 ft	monitor
Site 8, Rawlins	90 ft	80-90 ft	domestic
Site 9, Dairy	180 ft	126-176 ft	Dairy

*Estimated depth from surface elevation and bedrock-contour maps.

as far as natural waters are concerned (Moser and Stichler, 1971). Since the concentration of ^{18}O and ^{2}H in water is, among other factors, temperature dependent (Dansgaard, 1964), these isotopes provide a good tool to distinguish between Pleistocene and modern waters.

The abundance of ^{18}O is reported as $\delta\,^{18}O$, the relative ratio to the more abundant isotope ^{16}O, compared to a standard. Here the reference standard is SMOW (Standard Mean Ocean Water), as established by Craig, 1961.

Thus:

$$\delta\,^{18}O = \left[\frac{(^{18}O/^{16}O)sample}{(^{18}O/^{16}O)standard} - 1 \right] \times 1000$$

or, in a general form:

$$\delta^{18}O = \left[\frac{R\ sample}{R\ standard} - 1 \right] \times 1000$$

The unit is parts per thousand or permil (0/00).

A negative δ value indicates a sample depleted in the heavy isotope with respect to the standard, a positive δ value characterizes a sample enriched in the heavy component. Deuterium is reported as $\delta\,^{2}H$ or δD, and the same general equation as above applies. The standard again is SMOW.

The abundance of ^{18}O and ^{2}H in precipitation is dependent on several factors. Dansgaard (1964) established the "temperature effect" and the "amount effect" for these stable isotopes. Generally speaking, the higher the temperature the more enriched is the precipitation in ^{18}O and ^{2}H. The "amount effect" shows a correlation between the amount of rainfall and the abundance of ^{18}O and ^{2}H - the more rainfall the less abundant are these stable isotopes. The temperature dependency of ^{18}O and ^{2}H leads to various other effects:

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-altitude effect: the higher the altitude, the more depleted are ^{18}O and ^2H

-latitude effect: with increasing latitude ^{18}O and ^2H decrease

-continental effect: ^{18}O and ^2H decrease with increasing distance from the coast

-seasonal variations: winter precipitation is depleted in ^{18}O and ^2H compared to

summer precipitation.

The correlation between ^{18}O and ^2H in meteoric water was established by Dansgaard, 1964, and Craig, 1961. The equation

$$\delta D = 8 \, \delta \, ^{18}O + d$$

shows the linear relationship for these stable isotopes and describes the meteoric water line. d is the "deuterium excess parameter" (Dansgaard, 1964) and may vary from location to location. Craig (1961) found that d=10 0/00 as far as a global mean for fresh meteoric water is concerned.

Tritium

Tritium or ^3H is a radioactive hydrogen isotope. It has a half-life between 12.26 years (Dincer and Davis,1968) and 12.43 years (Ferronsky and Polyakov,1982). Naturally derived tritium is produced mainly in the upper atmosphere by the interaction of cosmic rays with nitrogen and oxygen atoms. "The rate of natural production is estimated at about 0.25 atoms/cm^2/sec" (Dincer and Davis,1968). The tritium thus produced enters the hydrologic cycle via precipitation, which can show tritium background levels, depending on location, between 5 and 20 TU (Larson, Delcore and Offer,1987). Tritium is reported in tritium units (TU), where 1 TU equals 1 tritium atom per 10^{18} hydrogen atoms.

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Because of atmospheric thermonuclear weapons tests beginning about 1953/1954 and lasting to the mid 1960's, a significant amount of ^3H has been added to the precipitation. Thus bomb tritium is a good tool for identifying recharge which took place after the early 1950's. Fig. 3 shows tritium data for the United States in 1964 as compiled by the IAEA (International Atomic Energy Agency), which monitors several stations throughout the world on a monthly basis for ^3H, ^2H, and ^{18}O.

The amount of ^3H in recharge waters is governed by several factors:

-seasonal variations: a pronounced ^3H increase occurs in late spring/early summer due to a larger exchange of air masses between the troposphere and the stratosphere. Evapotranspiration during the growing season can diminish this effect.

-latitude effect: the exchange of ^3H between stratosphere and troposphere occurs mainly at higher latitudes.   Thus there is a gradient of ^3H concentration from the polar regions to the equator.

-continental effect: air masses over continents are much more enriched in tritium than air masses above oceans. Also, there is a general increase of ^3H with increasing distance from the coast (Fig.4). This effect is mainly due to the fact that "the continental atmospheric moisture is constantly enriched with tritium by its removal from the stratosphere through the troposphere with the absence of molecular exchange which does take place with oceanic water" (Ferronsky and Polyakov,1982). In addition, the moisture that is re-evaporated from the continents has more or less the same ^3H content as the atmospheric fall-out. Thus there is a constant supply of ^3H to the air.
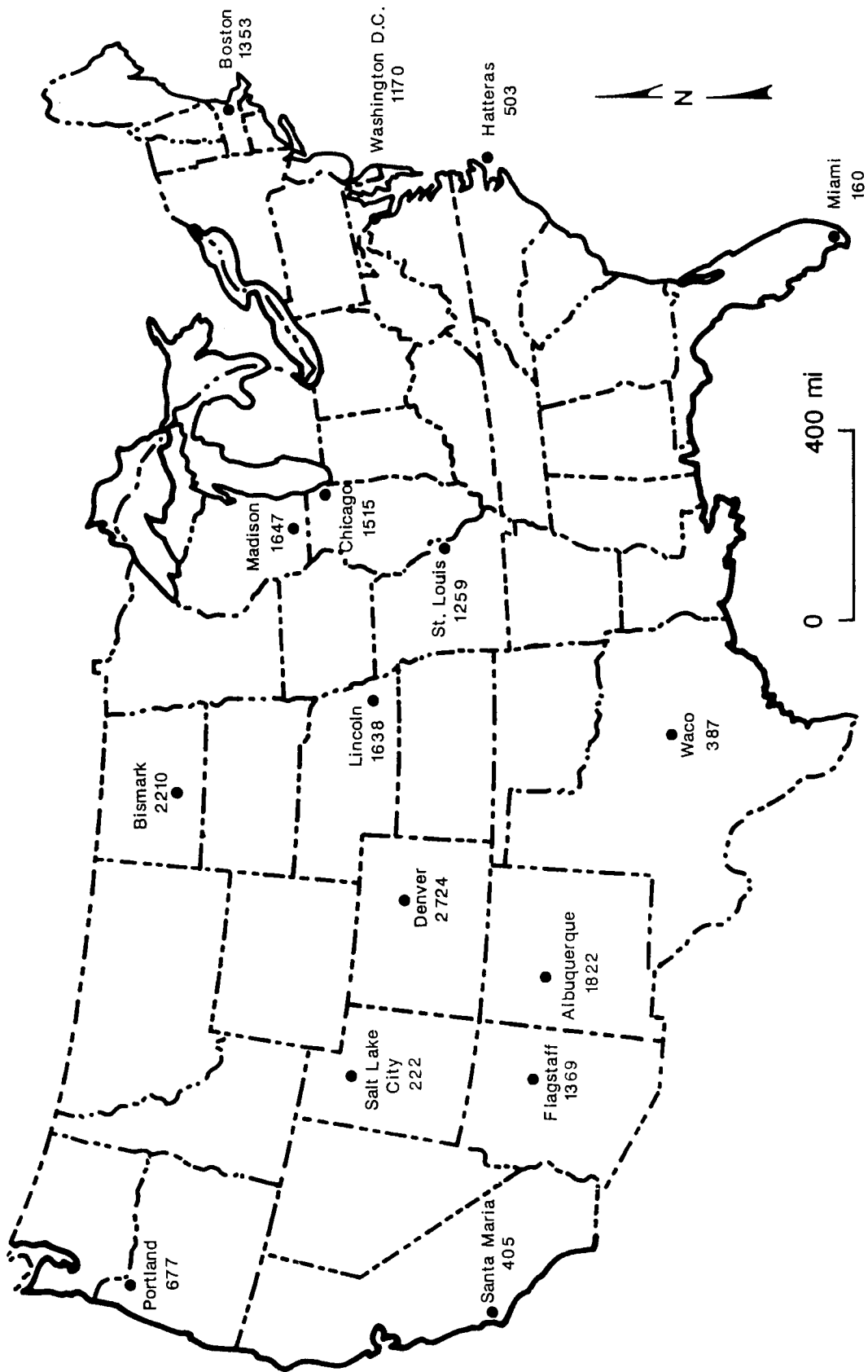
Figure 3. Mean annual tritium fall—out in precipitation; average for 1969.

Boston 1353
Washington D.C. 1170
Hatteras 503
Miami 160
Madison 1647
Chicago 1515
St. Louis 1259
Lincoln 1638
Bismark 2210
Waco 387
Denver 2724
Albuquerque 1822
Salt Lake City 222
Flagstaff 1369
Portland 677
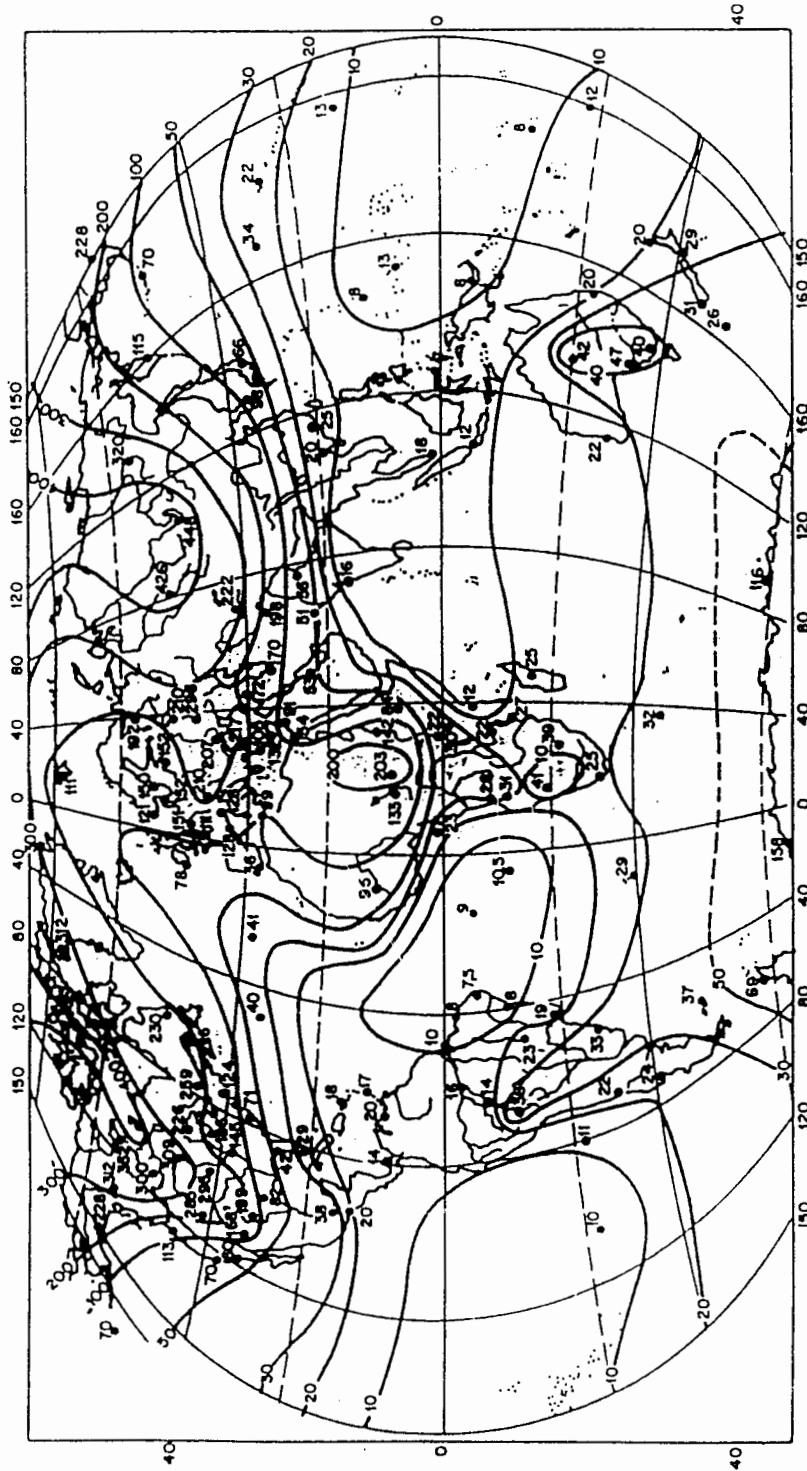Santa Maria 405

400 mi
0

Figure 4. Global distribution of tritium in precipitation; average for 1969 (after Romanov, 1978; reproduced by permission of the author);

from: Ferronsky, V.I. and Polyakov, V.A., Environmental isotopes in the hydrosphere, 1982.

In interpreting tritium results the following fact needs to be considered as well:

Laboratory results show that when tritium is interacting with clay minerals (Stewart,1965), it exchanges with tightly bound hydrogen or possibly with structural hydroxyles. As a possible reason for this phenomenon, enhanced reaction kinetics is mentioned, "resulting from the ionizing effects of the tritium-decay" (Stewart,1965). It can not be inferred from the sparse data available at what rate this exchange occurs.

Freon

Freon (Trichlorofluoromethane, CCl_3F), trade name Freon-11, is an entirely human-made component and was first commercially produced in 1931. Mainly it was used then by the refrigeration and air-conditioning industry. By 1943 the aerosol industry began to use it as a propellant for spray cans. In addition freon is now used widely as a foaming agent and a solvent. Consequently, it is present in significant amounts in the atmosphere and will be picked up by precipitation in a proportional amount. Thus freon should represent a good dating tool. Freon is highly stable in water and is most soluble in waters at low temperatures (Hayes and Thompson, 1977).

A study in the unsaturated zone of the southern High Plains of Texas (Weeks, Earp and Thompson,1982) showed detectable amounts of freon at depths as great as 43.9 m (about 132 ft).

Freon does not tend to be sorbed strongly on silicates and inorganic materials in general, but "although some sorption is usually apparent on natural silicates, it appears to be reversible" (Thompson and Hayes,1979). Organic materials seem to absorb freon to a greater extent and permanently.

Generally, the occurrence of freon is said to be parallel to that of tritium.

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Atrazine

Atrazine is one of the most widely used herbicides in the midcontinent (including Kansas) and belongs to the big group of the triazines. It was first introduced in the early 1960's and thus may represent a good tracer.

Its persistence in soils is more than 60 weeks (Maier-Bode and Haertel,1981) and the adsorption onto clays is considerably less than for other herbicides. Atrazine was found in ground water in Iowa, Nebraska, and Wisconsin in concentrations of 0.3 to 3.0 ppb (Jury, Winer, Spencer and Focht,1987).

The persistence of atrazine and its degradation in ground water is more or less unknown. It is inferred that it may persist for a long period of time.

Nitrate

Nitrates may be introduced into the unsaturated zone and ground water with the use of nitrogen fertilizers. Since extensive use of fertilizers began in the 1960's - parallel to that of pesticides - the presence of significant amounts of nitrate in ground water may support evidence of recharge indicated by tritium, deuterium, and oxygen-18. However, much caution is needed in interpretation of nitrate data because loss of nitrate due to denitrification or the fixation of nitrate may take place. In addition evidence that mineral nitrogen may be present in significant quantities in the thick loess deposits that underlie the upland surfaces (Boyce et al., 1976) of southwest Nebraska may also be present in northwest Kansas, but no studies have been done in Kansas to measure nitrate values below the root zone in the unsaturated loess deposits.

Discussion

Since we sampled only nine wells from different parts of the aquifer over a widespread area, there can not be a conclusive interpretation of the data. It can be shown that some of the applied methods of analysis worked, whereas others did not. It is possible to see certain trends displayed by the data but in order to establish these, much more data have to be gathered.

Stable Isotopes

Fig. 5 depicts a plot of ^{18}O versus ^{2}H. The meteoric water lines were calculated using the equations $\delta D = 8 \, \delta^{18}O + 10$ (Craig, 1961) and $\delta D = 8 \, \delta^{18}O + 5$ (Epstein, et al., 1965, 1970) respectively. The area bounded by these two lines is called the meteoric field.

Note that nearly all points are located within the field. Only one well (no. 3) plots outside but is still very close to it. This shows that all ground water samples are of meteoric origin.

Since the occurrence of ^{18}O and ^{2}H is temperature dependent, climatic changes are reflected in the isotopic composition of water. Large differences are associated with the glacial stages of the Pleistocene. Ice and meltwaters from this period are heavily depleted in both ^{18}O and ^{2}H as compared to modern precipitation (Gat, 1971). Dansgaard (1964) gives an equation for calculating mean annual surface temperatures in ^{o}C at the time of recharge:

$$T(^{\circ}C) = \frac{\delta^{18}O + 13.6}{0.69}$$

Table 3 shows the values calculated according to that equation for all nine wells sampled plus the calculated temperature for the precipitation sample. These data coincide very well with the plot in Fig. 5. The more depleted waters plot to the left of the table and all of them show low mean annual surface temperatures at the time of recharge. Water from wells 6 and 3 has

1 4
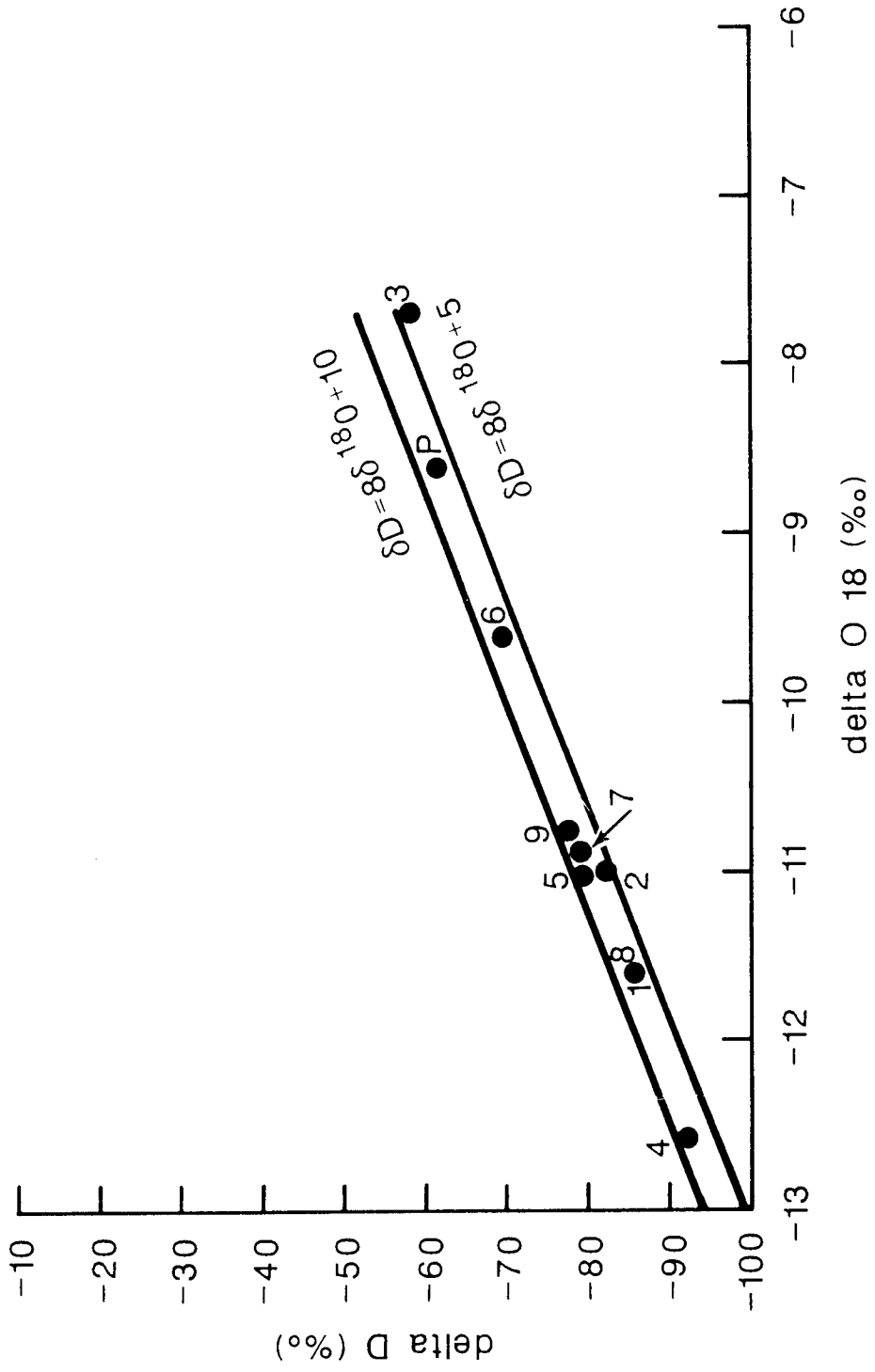
Figure 5. Stable Isotopes.

Table 3.　Mean annual air temperature (°C) at Time of Recharge.

Well	Temperature
Site 1, Gannon	2.9
Site 2, Goodland	3.8
Site 3, Playa	8.5
Site 4, Starns	1.5
Site 5, Colby	3.8
Site 6, Oakley	5.8
Site 7, Graham	3.9
Site 8, Rawlins	2.9
Site 9, Dairy	4.0
Precipitation	7.24

temperatures of 5.8 ᵒC and 8.5 ᵒC respectively, which matches more with present-day temperatures.

According to the data, well 4 shows the probable oldest water of all wells sampled, wells 8, 1, 2, 7, 5, and 9 represent a mixture of older and modern waters, and wells 6 and 3 display a much stronger influence of modern waters on the isotopic composition than all the others. Thus it appears that the Ogallala aquifer in the vicinity of wells 6 and 3 is being recharged.

Well 6 is a former oil-field water-supply well which is capped and not currently used. Its location is in an upland area. No obvious features that would enhance recharge could be identified in the field. The well is sitting directly on a lineament, and it seems possible that this is the reason for the apparent recharge.

Well 3 was drilled by the Kansas Geological Survey in a playa-like structure. The landowner reported several occasions where there were about 3 feet of standing water in parts of the playa. Studies in Texas have shown that there is a considerable amount of recharge associated with playas (Reeves,1987; Stone,1987).

The fact that well 3 plots slightly outside the meteoric field can be explained by evaporation. This process influences the isotopic composition of water; the residual water becomes enriched in isotopes and thus plots further away from the meteoric line.

Tritium

Tritium was detected in only four of the nine well samples (Table 4): wells 1, 2, 3 and 7. There is essentially no tritium in all the other samples, i.e. the tritium concentration is below the detection limit (0.8 TU).

Well 1 was put in by the Kansas Geological Survey in an upland area with known nitrate problems. The well is 298 ft. deep and is drilled to bedrock. The general chemistry analysis (Table 5) shows excess nitrates (as NO_3) of 60 ppm. The primary drinking-water standard for

Table 4. Tritium Data.

Well	Tritium (TU)	
Site 1, Gannon	2.8	±0.5
Site 2, Goodland	23.	±1.7
Site 3, Playa	1.6	±0.6
Site 4, Starns	<0.8	±0.5
Site 5, Colby	<0.8	±0.5
Site 6, Oakley	<0.8	±0.5
Site 7, Graham	5.6	±0.7
Site 8, Rawlins	<0.8	±0.5
Site 9, Dairy	<0.8	±0.7
Precipitation	14.9	±1.2

Table 5. Inorganic Chemistry Data.

Site #	Field Sp. Cond.	Lab Sp. Cond.	Lab pH	SiO2 ppm	Ca ppm	Mg ppm	Na ppm	K ppm	Sr ppm	HCO3 ppm	SO4 ppm	Cl ppm	F ppm	NO3 ppm	NO2 ppm	Fe ppb	Mn ppb	B ppb	Ba ppb
1/ Gannon	745	705	7.8	47	81	27	30	6.1	1.2	226	99	14	0.8	60	1.9	51	42	163	96
2/ Goodland	1160	1150	7.6	70	134	47	63	12	2.1	608	69	30	0.4	37		<22	<4	277	191
3/ Playa	615	570	7.9	32	70	18	26	12	0.8	276	28	15	0.8	28		<22	<4	96	168
4/ Starns	410	410	8.0	33	41	19	20	6.6	0.8	232	15	4.6	0.8	8.9		251	8	70	119
5/ Colby	465	435	8.0	55	47	17	19	7.1	0.7	214	21	8.8	1.6	16		<22	<4	79	99
6/ Oakley	510	480	8.1	36	42	19	33	7.5	1.0	226	28	16	0.9	13		<22	<4	126	76
7/ Graham	1900	1850	8.2	55	166	31	166	11	1.2	260	77	359	0.5	74		2170	938	86	361
8/ Rawlins	555	485	8.1	73	36	20	37	12	0.8	225	37	7.4	1.8	18		<22	<4	127	53
9/ Dairy	445	420	8.2	60	47	18	14	8.9	0.7	237	15	5.1	0.8	7.5		43	<4	63	125

Nitrate, reported as nitrate, is 45 ppm. The occurrence of tritium combined with nitrate indicates a certain amount of modern water in the ground water at this site. Modern water in this case would mean water less than 20 years old, if one assumes the maximum background level in precipitation to be 20 TU.

One possible explanation for the enhanced recharge and thus the nitrate problem is the existence of unplugged or poorly plugged seismic shotholes that were put in November 1981 and other kinds of boreholes. These would provide conduits for water movement down to the aquifer. Another possibility is the application of excess irrigation waters which results in an increase of return flow. It could also be that a close-by lineament influences the recharge in this area.

The precipitation sample taken by the Kansas State University Experiment Station shows 14.9 TU. But this value and those for ^{18}O, ^2H, and freon are probably not very reliable. The sample was taken November 8 and was stored at the Experiment Station without refrigeration in a jug with about 2 - 3 inches of head space. Due to exchanges between air and water, it is possible that the isotopes got depleted, because the preferable direction of transfer is from the water to the air and not vice versa. This exchange effect is especially true for freon, because it is a volatile component.

Well 2, a monitoring well owned by Sherman County, displays the highest tritium level of all well samples. Also it is the only well where a certain amount of freon (10.5 ppb) was detected. One explanation is the unique location of the well: it is situated on the edge of an old landfill between a sewage lagoon and an irrigation well. The drawdown cone of the irrigation well extends south to include the monitoring well itself as well as the sewage lagoon. All data strongly indicate water movement from the lagoon to the well. The high bicarbonate, calcium, magnesium, and boron values (Table 5) of the water sample support this theory since they can be interpreted as evidence for recycled waters. It is also possible that a close-by lineament could influence the recharge process.

Well 3 is located in the playa where recharge should be expected. The relatively low tritium content can be explained by looking at the screened depth of the well (Fig.6). The well is screened only at the bottom 30 ft. Since tritium tends to concentrate in the top zone of an aquifer, especially if the aquifer saturated thickness is large and the ground water is not well mixed, it is not surprising to see low concentrations here. In addition we were not able to develop that well properly. It remains questionable if all the water used for drilling and flushing the well was removed, and we sampled 100 % formation water. The well was drilled and flushed with Colby municipal water which comes from wells that are 281 ft and 261 ft deep respectively. Both city wells are located close to the same lineament that well 5 is very close to. Well 5 is 200 ft deep and did not show any tritium at all. If this similarly is true for the Colby city wells, then the tritium in the playa well originated from formation waters.

Well 7 is located on the discharge boundary of the Ogallala and is the shallowest of all wells sampled. When drilled in July 1987 by the Kansas Department of Health and Environment, the well was 52 ft deep. When we sampled in November 1987, it was filled with fine sediment to a depth of 35.3 ft. The water level in November 1987 was 23.4 ft. It is assumed that the shallow water level and the depth of the well account for the tritium in the well sample.

According to the plot of $\delta^{18}O$ versus δ^2H in Fig. 5, one would expect to see some tritium in well 6. Fig.6 shows the screened depth of well 6, only the bottom 20 ft are screened, the water level is about 61 ft above the screen. Thus it is very likely that the tritium did not reach down to the screened area.

It is very important to know from what part of the aquifer samples are taken. Some constituents do not reach the lower part of the aquifer, and it could be very misleading to compare samples from different depths without considering the depth factor.

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Figure 6. Screened well depth and water levels.

Screened depth (ft)

Well numbers

TD = total depth

TD, 11-12-87

TD, 7-7-87

▼ = water level
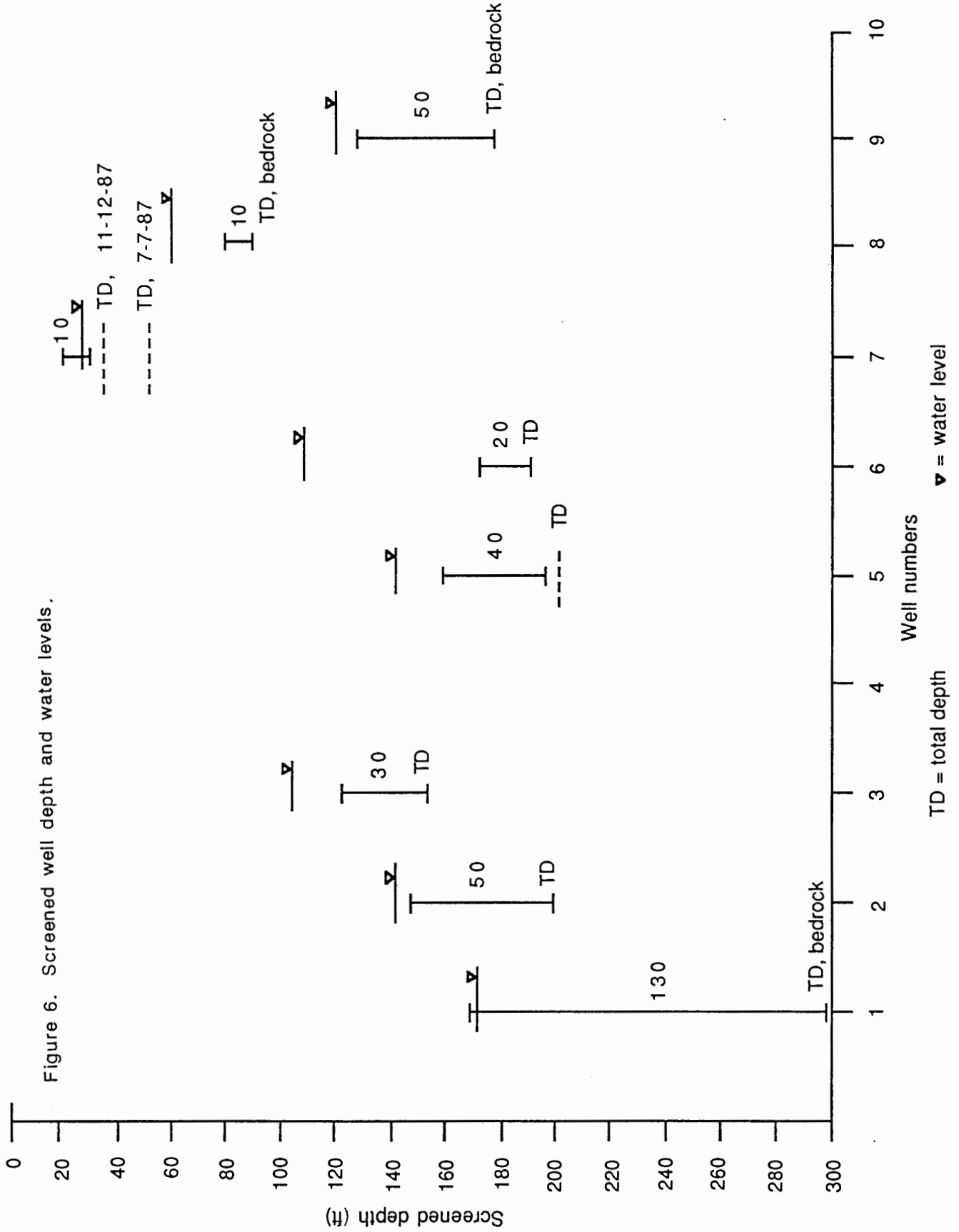
Freon

As mentioned above only well sample 2 contained some freon. The reason can be seen in flow from the sewage lagoon to the well and possibly in the existence of a lineament close by. Also the old landfill could contain some material that emits freon (solvents, air-conditioning units, styrofoam containers, etc).

The precipitation sample did not show any freon, which might be due to the above-mentioned exchange effects with the head-space air in the sample container.

Atrazine

None of the nine wells sampled contained atrazine, although it is reportedly the most commonly used herbicide in that area. Most of the soils in western Kansas are neutral to alkaline, and atrazine does not show a high tendency to get adsorbed onto clays in this kind of an environment, but it will get adsorbed to a certain degree (Weber, 1970). If 1 lb/A of atrazine is applied to the soil, its persistence is greater than 60 weeks, but these data were derived from greenhouse experiments and can not be transferred as such to field conditions. The half-life for atrazine in soils is 18 days, thus it can very well be that it is degraded before it reaches the ground-water level.

Nitrate

In general, analyses for nitrate can serve to support or supplement age determinations by other means (tritium, deuterium, oxygen-18) but cannot provide reliable data on age determinations alone. Nitrification and denitrification may be present in the thick loess deposits, and the amount of organic material and clay in the unsaturated zone as well as the pH of the sediments are factors that may affect the movement of nitrate into ground water. Therefore,

nitrate values in the ground-water samples cannot be used as an age indicator or a measure of ground-water recharge rates.

Summary

Of all the methods tested, the stable isotope (oxygen-18 and deuterium) and tritium method worked best for distinguishing between waters of different ages. Freon and atrazine are not suitable for the study area because both these constituents were not found in the wells sampled (except freon in well 2).

In order to sample for tritium and to be able to compare and correlate results, it is very important to know with certainty from what part of the aquifer the samples are taken. It seems that the bulk of the tritium has not reached the water table yet. If the annual average tritium fallout in precipitation for 1964 for Denver and Lincoln are considered (2724 TU and 1638 TU, respectively) and interpolated, an approximate fallout value for western Kansas results: 2181 TU. Calculating with a half-life of 12.4 years, the concentration of tritium left in 1988 is on the order of 545 TU. This figure does not account for evapotranspiration or other effects but is probably very well within the range. Thus it is very likely that most of the tritium emitted during the thermonuclear bomb tests is still in transit in the unsaturated zone.

A further study should include installment of lysimeters and well nests in different areas to gain information about ^3H in transit, aquifer stratification as far as isotopes are concerned, and the importance of lineaments, intermittent streams, and playas for recharge.

With the sparse data from this phase 1 study, it is not possible to make any conclusive statements about the above-mentioned factors.

REFERENCES

Claborn, B.J., Austin, T.A., and Wells, D.M.,1970: Numerical model of the Ogallala as a management tool, Ogallala Aquifer Symposium, Lubbock, Texas, pp. 89-110.

Craig, H.,1961: Isotopic variations in meteoric waters, Science, vol. 133, pp. 1702-1703.

Boyce, J.S., Muir, A.P., Edwards, A.P., Seim, E.C., and Olson, R.A.,1976: Geologic nitrogen in Pleistocene loess of Nebraska, Journal of Environ. Quality, vol. 5, no. 1, pp. 93-96.

Dansgaard,W.,1964: Stable isotopes in precipitation,Tellus, vol. 16, no .4, pp. 436-468.

Dincer, T., and Davis, G.H.,1968: Some considerations on tritium dating and the estimates of tritium input function, IAEA, Memoires, vol. 8, pp. 276-286.

Epstein, S., Sharp, R.P., and Gow, A.J.,1965: Six-year record of oxygen and hydrogen isotope variations in south pole firn, Jour. Geophys. Res., vol. 70, pp. 1809-1814.

Epstein, S., Sharp, R.P., and Gow, A.J.,1970: Antarctic icesheet: Stable isotope analysis of Byrd station cores and interhemispheric climatic implications, Science, vol. 168, pp. 1570-1572.

Ferronsky, V.I., and Polyakov, V.A.,1982: Environmental isotopes in the hydrosphere, John Wiley & Sons, 466 p.

Gat, J.R., 1971: Comments on the stable isotope method in regional groundwater investigations, Water Resources Research, vol. 7, no. 4, pp. 980-992.

Hayes, J.M., and Thompson, G.M.,1977: Trichlorofluoromethane in groundwater - a possible indicator of groundwater-age, Purdue Univ., Lafayette, Ind., Water Resources Research Center, 25 p.

International Atomic Energy Agency, 1970: Environmental isotope data no. 2: World survey of isotope concentration in precipitation (1964-1965), Technical Reports Series no. 117, p. 404.

Jury, W.A., Winer, A.M., Spencer, W.F., and Focht, D.D.,1987: Transport and transformations of organic chemicals in the soil-air water ecosystem, in: Reviews of environmental contamination and Toxicology, vol. 99, pp. 119-164.

Larson, G.J., Delcore, M.R., and Offer, S.,1987: Application of the tritium interface method for determining recharge rates to unconfined drift aquifers, I. homogenous case, J. Hydrol., 91, pp. 59-71.

McCauley, J.R.,1988: Landsat lineament map of western Kansas, Kansas Geological Survey, Open File Report 88-20.

Maier-Bode, H., and Haertel, K.,1981: Linuron and monolinuron, in Residue Reviews, vol. 77, 364 p.

Moser, H., and Stichler, W.,1971: Die Anwendung des Deuterium - und Sauerstoff-18-Gehalts bei hydrogeologischen Untersuchungen, Geologica Bavarica, 64, pp. 7-35.

Rayner, F.A.,1970: Dynamic model of the Ogallala Aquifer,Ogallala Aquifer Symposium, Lubbock, Texas, pp. 111-117.

Reddell, D.L.,1970: Mathematical model for determining areal distribution of natural recharge in northern High Plains of Colorado, Ogallala Aquifer Symposium, Lubbock, Texas, pp. 165-181.

Reeves, C.C.,Jr., 1987: Evidence for sequential development of playa lake basins, southern High Plains, Texas and New Mexico, Symposium on the Quaternary Blackwater Draw and Tertiary Ogallala Formation, Lubbock, Texas, abstracts, p. 18.

Stewart, G.L.,1965: Experiences using tritium in scientific hydrology, 6th international conference, radiocarbon and tritium dating, Pullman, Washington, pp. 762.

Stone, W.J.,1987: Natural recharge of the Ogallala aquifer through playas and other non-stream-channel settings, east central New Mexico, Symposium on the Quaternary Blackwater Draw and Tertiary Ogallala Formation, Lubbock, Texas, abstracts, p. 23.

Thompson, G.M., and Hayes, J.M.,1979: Trichlorofluoromethane - a possible tracer and indicator of groundwater age, Water Resources Research, vol. 15, no. 3, pp. 546-554.

Weber, J.B.,1970: Mechanisms of adsorption of triazines by clay colloids and factors affecting plant availability, in: Residue Reviews, vol. 32, pp. 93-130.

Weeks, E.P., Earp, D.E., and Thompson, G.M.,1982: Use of atmospheric fluorcarbons F-11 and F-12 to determine the diffusion parameters of the unsaturated zone in the southern High Plains of Texas, Water Resources Research, vol. 18, no. 5, pp. 1365-1378.