

RADIUM-226 AND RADON-222 IN DOMESTIC WATER
OF HOUSTON-HARRIS COUNTY, TEXAS

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INTRODUCTION

Ingestion or inhalation of radium (Ra) and products of its decay are considered a health risk. In the human body bones, myeloid stem cells, and lungs are particularly sensitive to radiation exposure. Epidemiologic studies have established a strong association between certain occupational and therapeutic exposures to isotopes of Ra and bone cancer [1-5]. Radon (Rn)-222, an airborne progeny of decay of Ra-226, has been associated with lung cancer in miners [6,7], and recently has received national attention because of high concentrations observed in houses in some parts of the United States [8,9]. Studies have also raised the issue of cancer risk associated with Ra and Rn in domestic water [8-12].

Regulatory standards for radioactivity in water have been established for Ra but not Rn. The combined activity of the two isotopes of Ra (226 and 228) should not exceed a maximum contaminant level (MCL) of 5 pCi/l [13,14]. Rn in water is not yet regulated by Federal and State standards, although this is expected to change in the near future.

Ra regulation under the Safe Drinking Water Act of 1974 and related amendments went into effect in 1977, but because of the sheer number of public water systems in a State as large as Texas, the assessment of Ra concentrations and compliance with EPA and State regulations is a formidable task, not yet completed. In addition, approximately 4 million people in Texas use private water supplies which are not covered by current regulations and for which data on Ra are not available. No regulatory agency now routinely monitors Rn, in either public or individually-owned supplies.

Deposits of uranium, the progenitor of Ra-226 and Rn-222, occur in Texas [15]. The major deposits occur in Eocene and younger formations and it is believed to be predominantly associated with volcanic ash in the Catahoula formation of the Miocene Age [16,17]. In 1984, taking advantage of the cost-effective testing procedure available at the University of Texas at Houston, School of Public Health laboratory, a study was initiated by Cech and co-investigators [18], in cooperation with several ground water districts and river authorities in Texas, to assess the geographic distribution of Ra-226 and Rn-222 in domestic water in selected regions of this State. Anomalously high Ra and Rn concentrations were found in the Gulf Coast area including Harris County (Figure 1); Ra in excess of 20 pCi/l and 3000 pCi/l for Rn were observed in some public water supplies in this county.

Harris County, with a 1980 population of 2,684,000, has the largest number of people among Texas counties and contains 18 percent of the State population. The water supply and distribution system in Harris County is complex. The City of Houston alone operates over 200 wells. A water well field may contain from 1 to 11 wells, and pump water from various depths into several collecting plants. The eastern half of the City of Houston, roughly 50 percent of the population of over one million, is supplied primarily by surface water from Lake Houston (Figure 2); the western half is supplied by ground water. The boundaries of areas served by each well, well field, or by surface water cannot be defined accurately because systems are interconnected; these boundaries vary with variations in demand, pressure in water lines, season, and even time of day.

Population growth and the rapid development of new suburban subdivisions on the fringes of the City of Houston resulted in numerous smaller water utilities. Approximately 300 such municipal utility districts (MUDs) and 1700 community water systems supply ground water in Harris County besides the City of Houston. Most of the wells with Ra concentrations that exceed MCL were from these smaller utilities.

Approximately 150,000 people in the rural parts of Harris County, and an estimated 10 percent of urban residents, are supplied by water from individually-owned wells. Northwest, northeast, and southwest Harris County contain undeveloped areas. All projections of urban growth indicate that these areas will be developed in the near future. Pockets of Ra-rich water found in MUD's in these parts of Harris County suggest that future subdivisions might encounter problems. However, no reliable guidance for well location is presently available to well developers in the County.

A more detailed sampling of ground and surface water was necessary in this area to assess patterns of distribution of Ra and Rn, so that some predictive tool could be developed to guide present and future water works. Thus, during 1985 and 1986, an intensive sampling for Ra-226 and Rn-222 was conducted in Houston-Harris County.

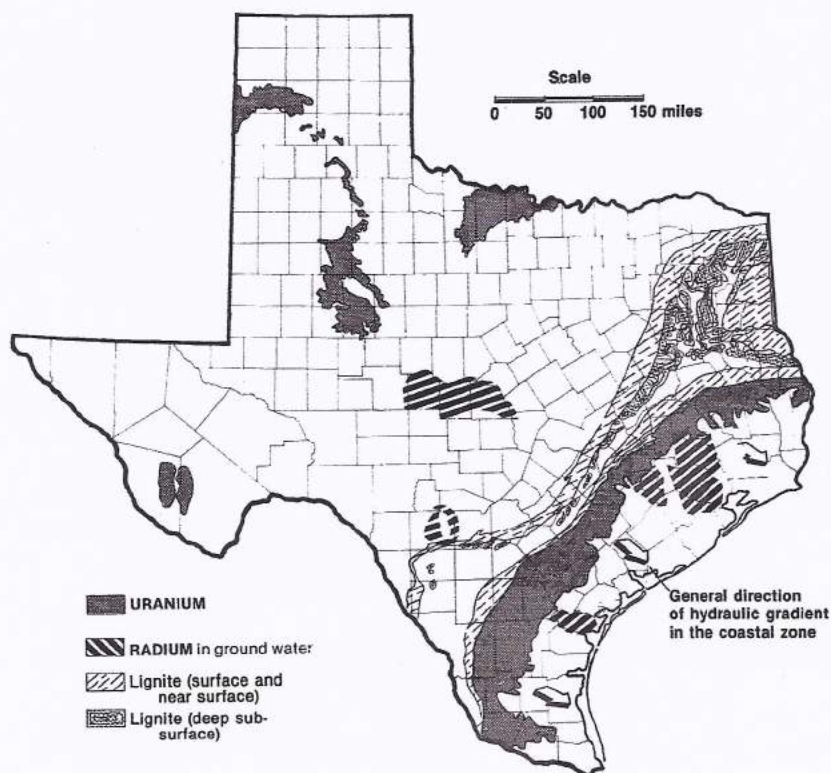


Figure 1. Radioactive deposits in Texas. Compiled by superimposing Ra-226 field data gathered by Cech et al. [18] on a map of uranium deposits adapted from Kier et al. [15]. Additional sources were Texas Water Development Board [19] and Brock [20].

METHOD

One hundred sixteen samples were collected, 77 of them from distribution systems and 39 directly from wells. Of the samples collected from distribution systems, 27 were taken from various small municipal utilities districts in northwest Harris County. Of the 39 samples taken directly from wells, 26 were from southwest Houston. The rest of the samples were collected from public and individually owned wells throughout the County. Several samples were collected in neighboring Fort Bend and Montgomery Counties to estimate regional concentrations.

As a first step in this investigation, samples were gathered from residential and commercial dwellings. Testing of water at the household tap involved visiting residences where permission was

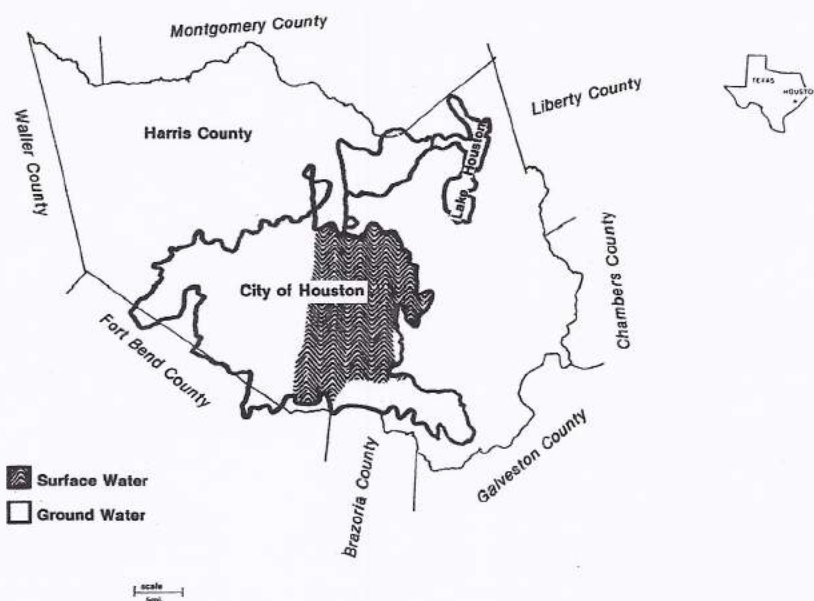


Figure 2. Greater Houston-Harris County, Texas: Approximate boundaries for surface water-ground water service areas, 1980.

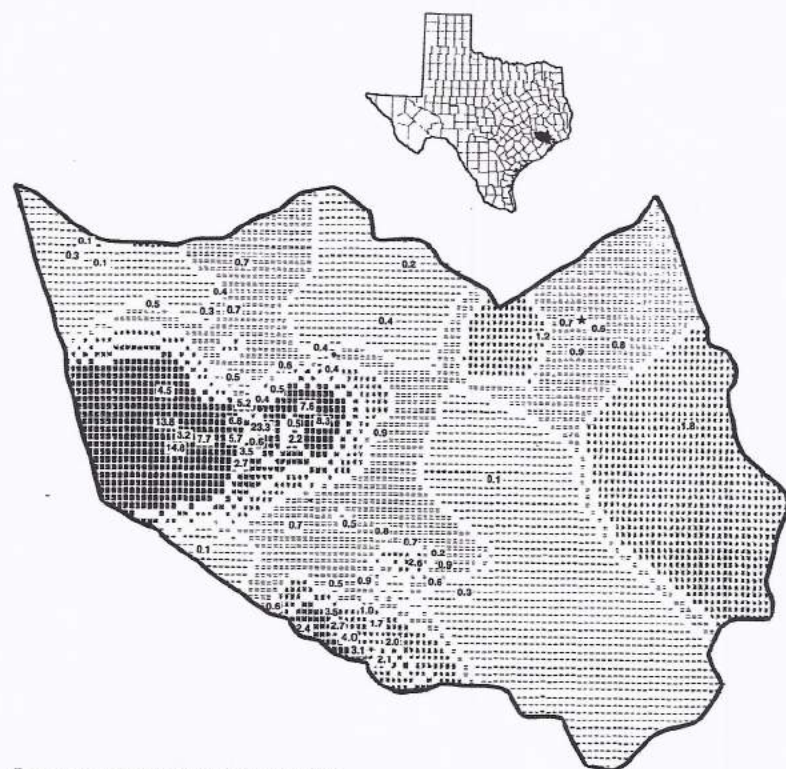
secured from heads of households to collect one-liter water samples. Duplicate samples were taken to assure the reproducibility of the laboratory results.

Analyses for Ra-226 and Rn-222 were conducted with modifications of liquid scintillation techniques described in [21]. Ra-226 was extracted from the 0.5 to 1 liter water samples by passage through a 10 ml bed of cation resin (Dowex 50W-X8, 20-50 mesh). The resin beds were rinsed with distilled water, transferred to a 20 ml liquid scintillation vials and covered with distilled water. A 10 ml layer of toluene containing 5 g/l of 2,5-diphenyloxazole was added, and the vials were sealed and stored for at least a week prior to analysis. Three to twelve hours before the analysis, the vials were vigorously shaken to ensure adequate contact between the aqueous and the organic phases. The Rn content of the organic phase was then assayed using a liquid scintillation counter, with windows optimized for Rn in toluene. Because Rn originally present in the water sample is not retained in the rinsed resin, any Rn detected in the assay was due to ingrowth from Ra entrained in the resin.

Radon-222 concentrations were determined by drawing 15 ml samples directly from a source into a clean syringe. Care was taken to prevent aeration of the samples in the process. The samples were then injected beneath 5 ml layers of a mineral oil-based scintillation solution in 20 ml vials. The vials were

vigorously shaken to promote phase contact, held for at least three hours to permit Rn daughter ingrowth, and assayed with a liquid scintillation counter. The results were corrected for the amount of Rn decay between sampling and assay.

The information obtained on this phase of the investigation was mapped using the computer technique SYMAP [22], as shown on Figures 3 and 4, and this helped to identify areas where further sampling, directly from wells, could provide additional, clarifying information. The subsequent step was to identify wells in the distribution network which caused Ra and Rn to appear in the residential water. This was a straightforward task when small single-source utilities were concerned. More difficult was to pinpoint Ra and Rn sources within interconnected multiple-well municipal systems.



* Concentration of Radium 226 up to 22.6 pCi/l has been reported previously in this location.

Figure 3. Concentrations of Ra-226 observed in tap water in Harris County, Texas, 1985-1986.

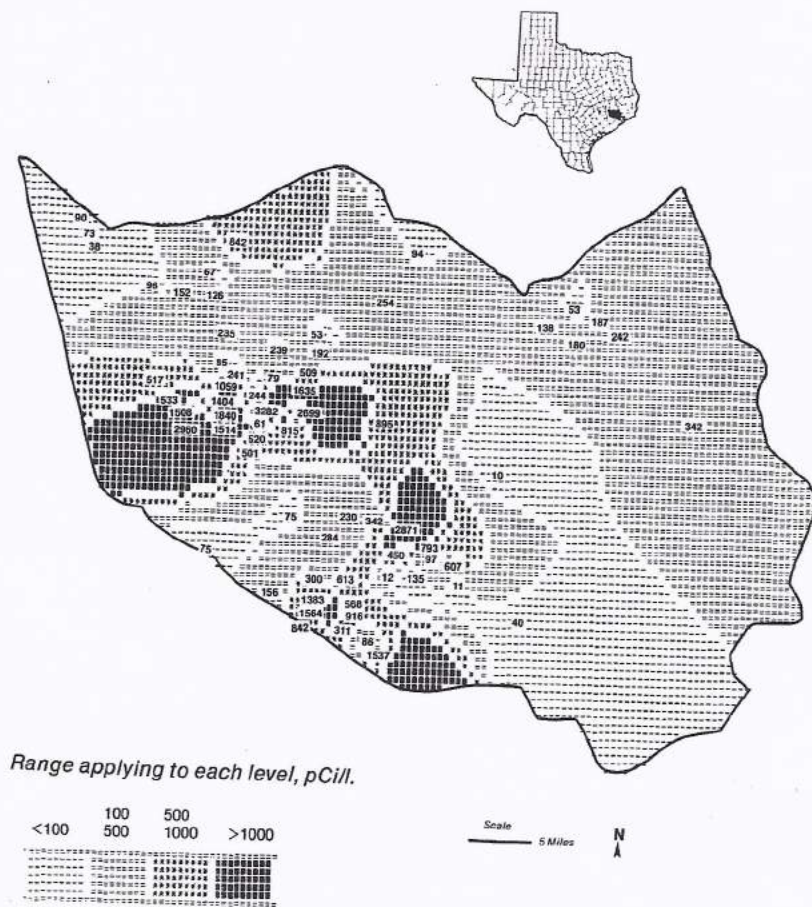


Figure 4. Concentrations of Rn-222 observed in tap water in Harris County, Texas, 1985-1986.

In order to assess variations in Ra and Rn as related to location and depth of wells, a subset of 64 points representing a diverse geographic distribution of water sources was formed and subjected to statistical analysis. This subset included 39 samples taken directly from wells and 25 other points taken from service areas of small utilities where the source-well definitely was known. The point-source locations are shown in Figures 5 and 6 (except for additional points to the north, in adjacent Montgomery County).

The general hypothesis investigated in this study was that Ra and Rn concentrations are a function of a) pumping depth, b) distance from uranium deposits in sandstone aquifers, and c) some modifying local structural features, in particular, the proximity

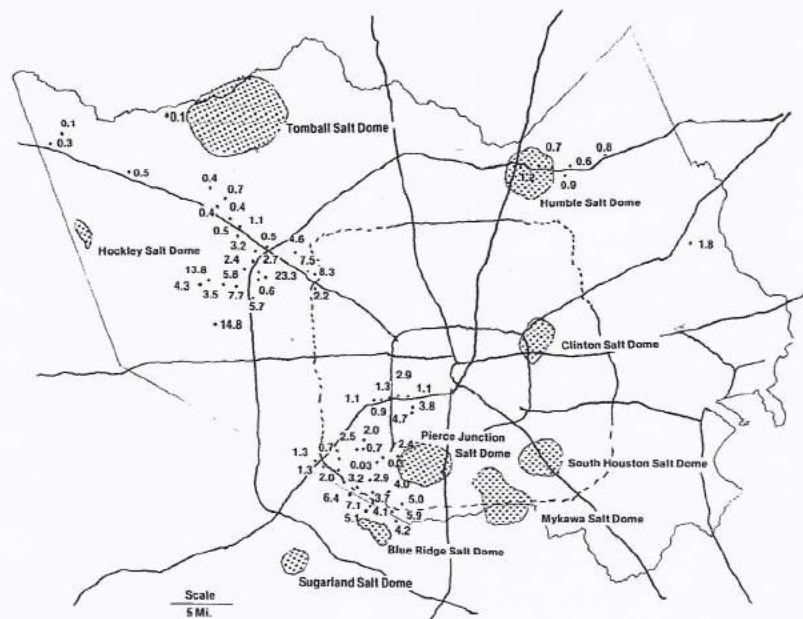


Figure 5. Point-source measurements of Ra-226, Harris County, Texas, 1985-1986. Samples were obtained either directly at well heads or from single-source municipal utility districts. Shown also are locations of salt domes.

of salt domes. The variables that might have influenced the distribution of radiochemicals were defined as follows:

Water-Bearing Formation and Pumping Depth

Depth to water sources varied from zero for surface water to about 610 meters (m) for wells. The data on depths of wells and water-producing formations were derived from the materials of the United States Geological Survey, [23]. Because many wells in the Gulf Coast region have multiple screens, the well depth in the statistical analyses was represented by upper and lower limits of pumping ranges.

Location

Well location was represented by the distance (downdip) from a reference line chosen approximately where known uranium deposits occur [15]. On the Gulf Coast, the uranium-bearing formations crop out parallel to the coast northwest of the study area and roughly

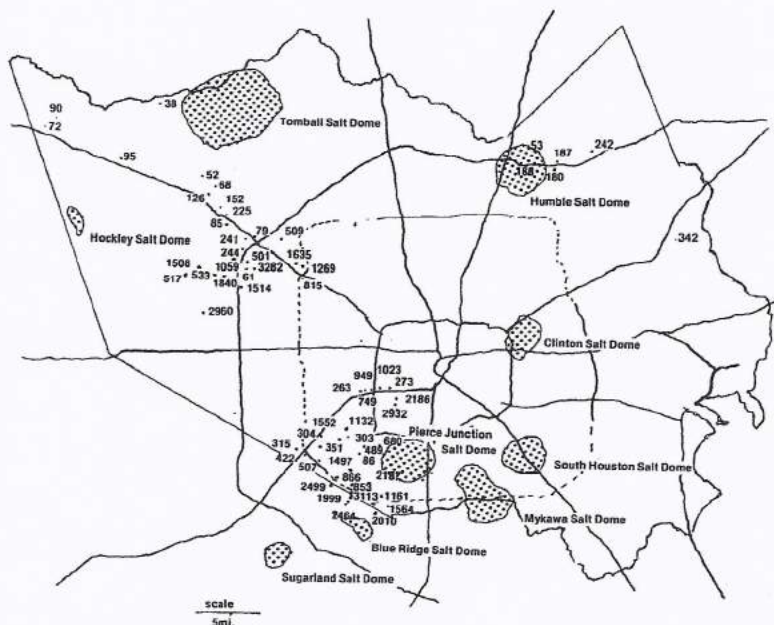


Figure 6. Point-source measurements of Rn-222, Harris County, Texas, 1985-1986.

coincide with the recharge zone of the Gulf Coast aquifers. The distance from the outcrop to the well was measured in the southeast direction to correspond with the general direction of hydraulic gradient [24-28].

Salt Domes

There are numerous salt domes in the study area (Figure 5). The proximity of salt deposits is a pertinent regional feature. Because the general trend in ground water movement may have been interrupted locally by pumping, the distance to salt domes was measured as the distance to the nearest dome, regardless of direction.

RESULTS

Figures 3-6 present Ra and Rn concentrations observed in the distribution systems and at the well heads in Greater Houston-Harris County in 1985-86. Concentrations of Ra and Rn were below limits of detection in the southeast part of the study area which is supplied by surface water, whereas detectable concentrations of these radioisotopes were present in virtually every sample

of well water. In northwest and southwest Harris County ground waters exhibited concentrations greater than trace levels of Ra and Rn; several wells in these areas had concentrations in excess of the maximum allowable for Ra.

The major "hot" spot was located in northwest Harris County. Up to 23 pCi/l of Ra-226 (more than four-fold in excess of the maximum allowable) and up to 3300 pCi/l of Rn-222 were observed in an area geographically adjacent to Logenbaugh and White Oak Creeks, about 13 to 16 kilometers (km) south-southeast of the salt domes near Hockley and Tomball.

The second anomaly, with concentrations up to 7 pCi/l of Ra-226 at the well heads and up to 4 pCi/l in the distribution system, was found on the border between Harris and Fort Bend Counties (far southwest Houston). Of the 11 wells in this section, five had concentrations of Ra-226 greater than 5 pCi/l (the maximum allowed for total Ra), and the lowest concentration (one well) was about 3 pCi/l. Rn concentrations in this area were up to 3100 pCi/l. These wells were developed near the piercement-type salt dome, Blue Ridge. Some of the wells were located in the adjacent Fort Bend County but belonged to the City of Houston (Figures 5 and 6).

In the southwest-central part of Harris County, Rn concentrations up to 2900 pCi/l were observed near the salt dome at Pierce Junction. Ra-226 concentrations up to 4.7 pCi/l were present at the well heads and about 3 pCi/l was observed in the distribution system. In northeast part of Harris County, a concentration of 22 pCi/l of Ra-226 was encountered earlier by others in a well developed near a piercement-type salt dome at Humble [29].

Figure 7 shows variations in the concentration of Rn-222 in well water as related to the concentration of its progenitor, Ra-226. The coefficient of correlation (R) between these two variables was 0.77 and the slope of linear regression was positive and significant (probability *p* of this correlation to be found by chance was less than 0.01). The empirical equation relating waterborne concentration of Rn to Ra was

$$\hat{Rn} = 307 + 187 Ra, \quad /1/$$

where $\hat{Rn}$ is an estimate of Rn, in pCi/l.

The proportion of variation in Rn concentrations which could be accounted for by Ra was 59 percent. This shows that Ra and Rn measured under field conditions correlated reasonably well, although not perfectly. The remaining scatter probably was due to differences in the underground retention opportunities for gas Rn and dissolved Ra. This, in turn, implies that our understanding of the distribution of Ra and Rn in water supplies may further profit from exploring the roles that pumping depth and well location play in this distribution.

The relationship of Ra and Rn concentrations to pumping depth was investigated first by fitting linear regression models to respective data sets. For Ra-226, the slope of regression was not significant, which indicated that the linear model was inappropriate, and this becomes immediately apparent when one inspects the scatter-plots on Figures 8a and 9a. On each of these figures, a

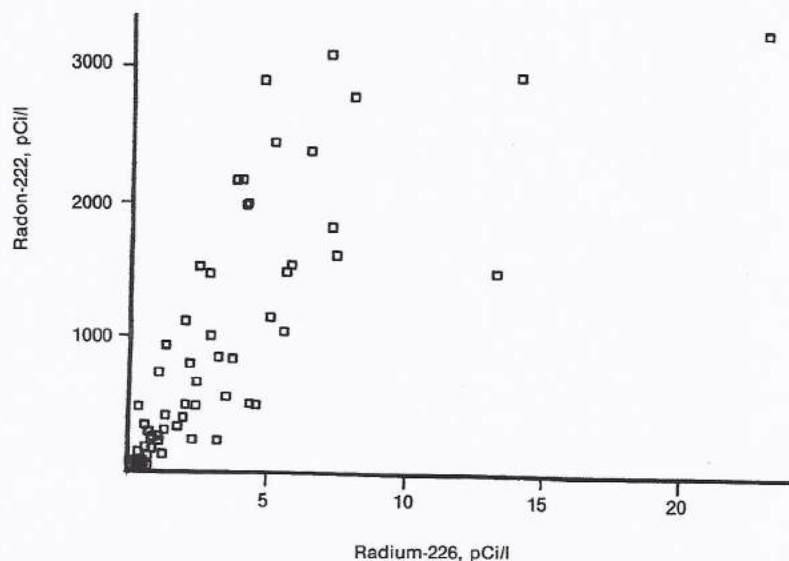


Figure 7. Relationship between concentrations of Ra-226 and Rn-222 in well water, Harris County, Texas, 1985-1986.

non-linear distribution of Ra with depth was evident. The concentrations were observed to peak in a zone between 180 m (Figure 8a) and 320 m (Figure 9a), which corresponded to a fringe zone between Chicot and Evangeline aquifers (Figure 10a). Further increase in depth caused concentrations of Ra to decrease, although not to zero. This distribution suggests introducing a quadratic term into a previous model. If this is done, the resulting fit becomes statistically significant ($p < 0.05$).

The greatest concentrations of Rn also were observed between 180 and 320 m below the surface (Figures 8b-10b) but, differently from Ra, there was an overall underlying tendency for Rn concentrations to increase with depth. The linear model was appropriate to describe the vertical concentration profile for Rn ($p < 0.01$) and the addition of a quadratic term to the linear model was not an improvement.

The distance from the outcrop of known uranium deposits was not a statistically significant predictor for Ra, nor did the addition of a quadratic term to a linear model improve the fit. Examination of the scatter-plot on Figure 11a indicates that Ra distribution along the northwest to southeast axis down-dip from uranium deposits was bi-modal, with the first increase in concentrations observed at about 90 km southeast from a reference line and the second, after 115 km. The location of the first anomaly coincided with the area of geological faulting stretching between the Hockley and Tomball salt domes, about 13 to 16 km southeast of the domes [30]. The location of a second, comparatively less severe Ra anomaly coincided with the area of the fault system associated with the Blue Ridge salt dome.

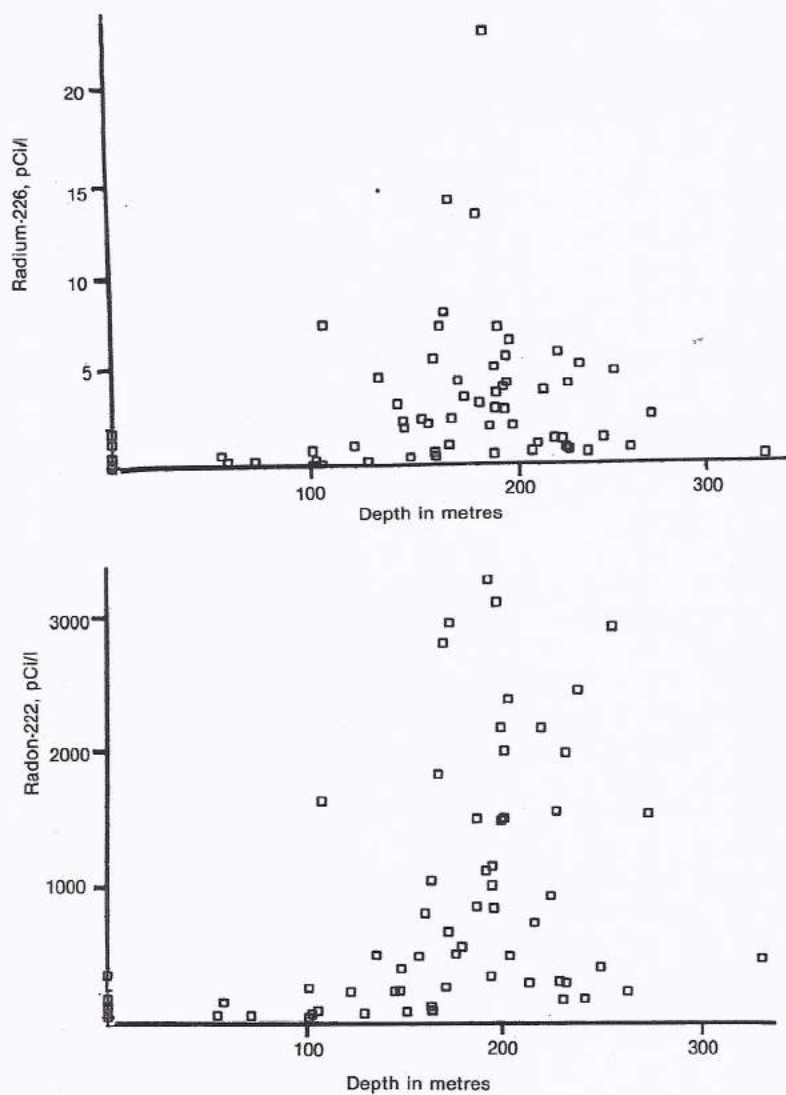


Figure 8. Distribution of (a) Ra-226 and (b) Rn-222 with depth; upper limit of pumping range.

These data indicate that Ra travels in a more complex path than could be expressed by a linear distance from known deposits of uranium and their Ra in Houston-Harris County water wells probably relates to local sources, instead of distant deposits in the outcrop.

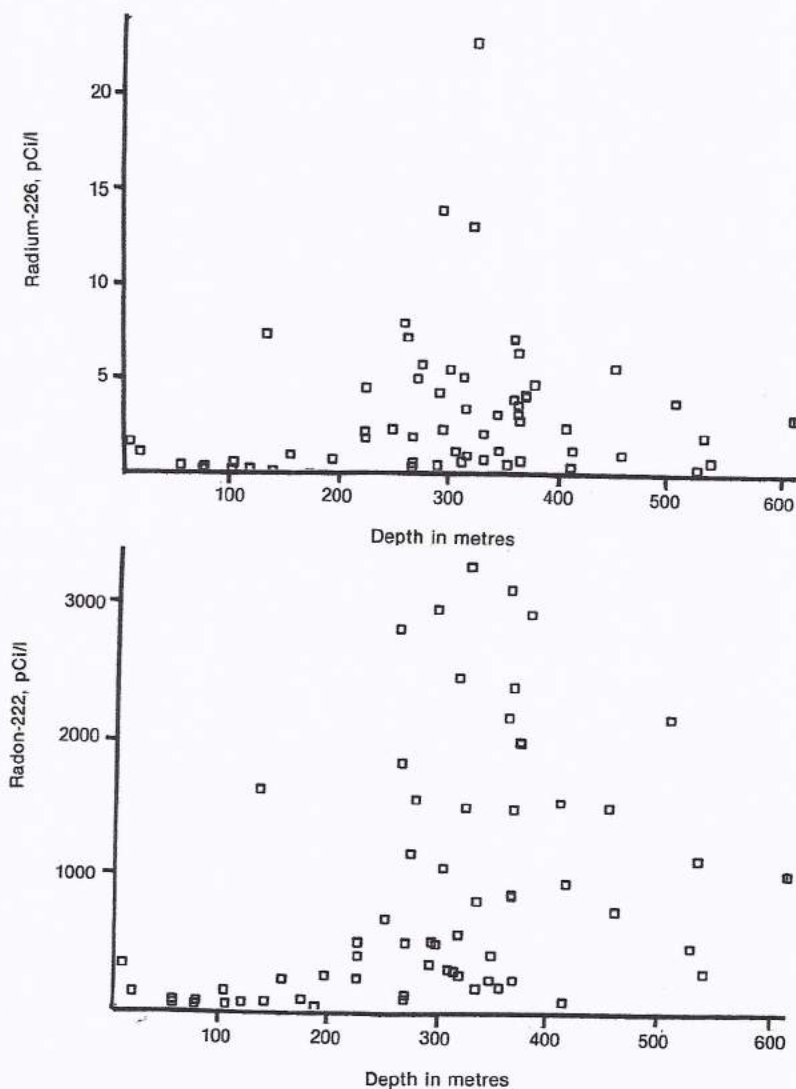


Figure 9. Distribution of (a) Ra-226 and (b) Rn-222 with depth; lower limit of pumping range.

The bi-modal distribution with distance was also noted for Rn (Figure 11b) but, again, differently from Ra, there was an underlying tendency for Rn concentrations to increase toward the coast. The linear model fitted to this distribution had a positive slope and was statistically significant ($p < 0.01$).

The proximity of a salt dome was an important predictor for the presence of both Ra and Rn in well water. The inverse rela-

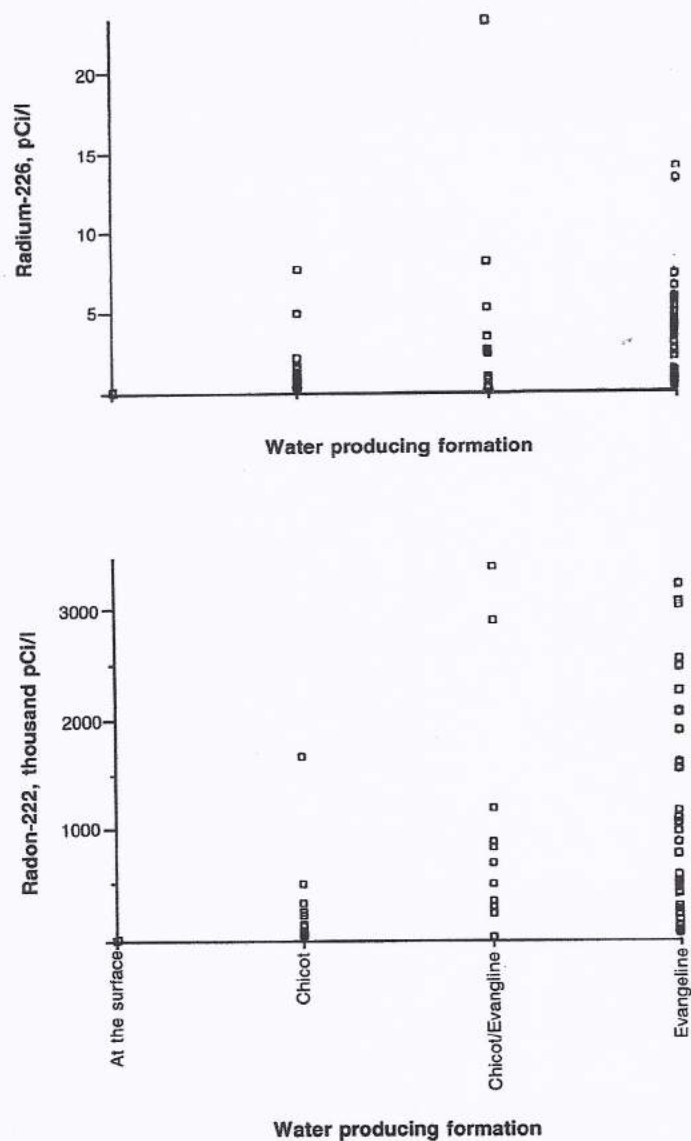


Figure 10. Distribution of (a) Ra-226 and (b) Rn-222 depending on water-producing formation.

tionship, the increase in concentrations as distances to the domes decreased, was particularly evident for wells developed near Blue Ridge and Pierce Junction salt domes (Figures 12a and b). Because of the rural location, no deep municipal wells were present in the vicinity of the Hockley and Tomball salt domes and this fact might

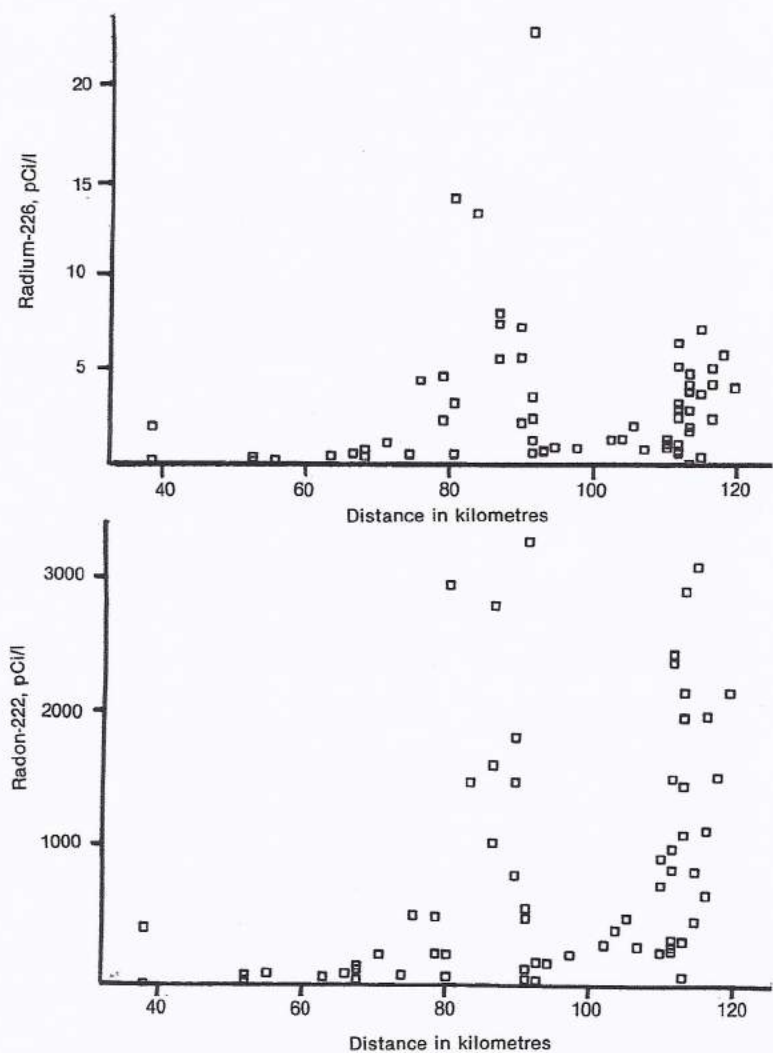


Figure 11. Distribution of (a) Ra-226 and (b) Rn-222 with the distance from the outcrop of known uranium deposits.

have obscured the statistical association. The correlation of Ra with other salt domes in Harris County could not be made because they were situated in a part of Harris County which was supplied by surface water.

Multivariate analyses showed that a combination of factors provided still a better fit. Where Ra is concerned, both pumping depth and the distance from the nearest salt dome were significant

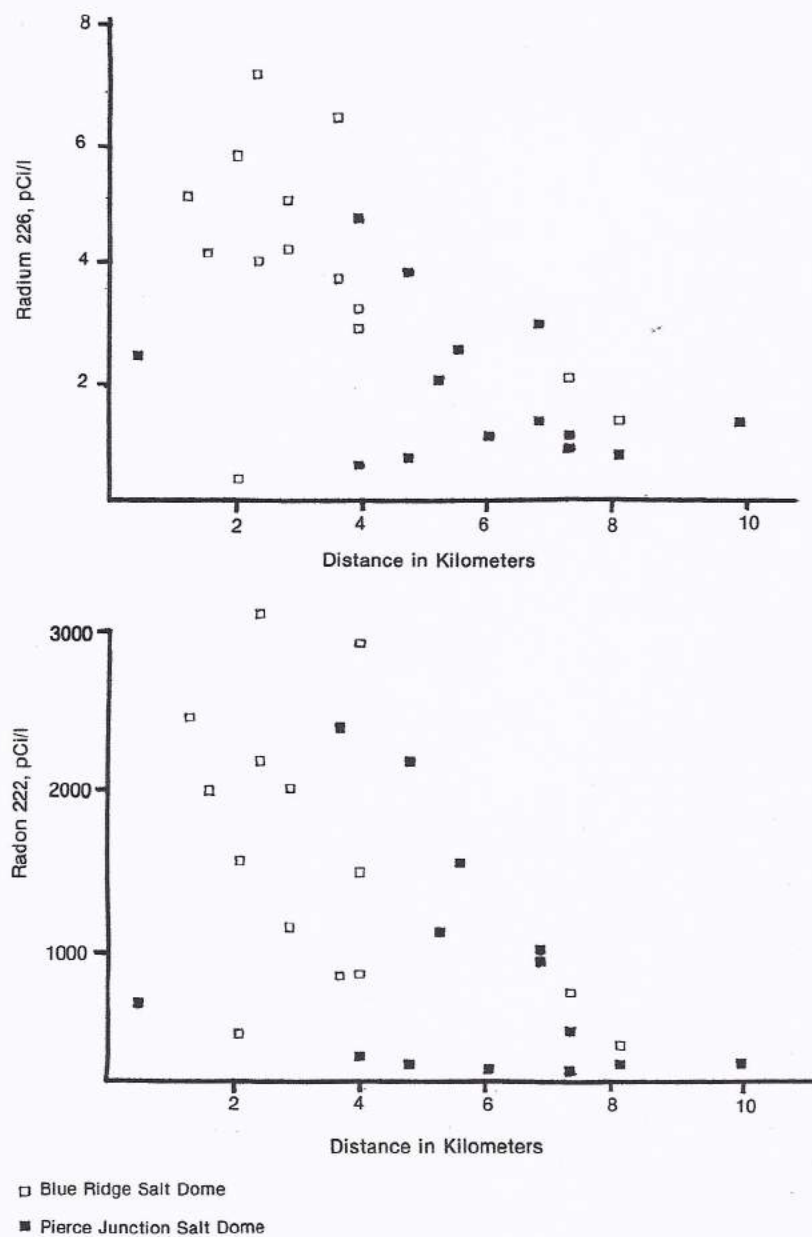


Figure 12. Distribution of (a) Ra-226 and (b) Rn-222 with the distance to Blue Ridge and Pierce Junction salt domes.

factors ($p < 0.01$) and the equation relating waterborne concentrations of Ra to these factors was

$$\hat{Ra} = 0.06 + 0.04(\text{DEPTH}) - 0.09 \times 10^{-3}(\text{DEPTH})^2 - 0.60(\text{DNS}) + 0.04(\text{DNS})^2, \quad /2/$$

where (DEPTH) stands for pumping depth (m) measured to the top screen of pumping range and (DNS) was the distance from the nearest salt dome (km). Because the proximity of salt domes was measured as the distance (km) from the dome nearest to each well and regardless of direction, the model in equation 2 includes quadratic terms for this variable as well as for the variable of depth. The statistical analysis supporting equation 2 is illustrated in Table 1.

Table 1. Multiple Regression Analysis Report for Ra-226 vs. Pumping Depth and Location.

Source	df	Sequential				Last	
		Sum-Sqr	R ²	F-Ratio	Tail Prob	Sum-Sqr	F-Ratio
Constant	1	632.33					
DEPTH	1	42.37	4.67	4.66	0.037	55.43	5.83
(DEPTH) ²	1	50.73	10.25	5.33	0.023	21.15	2.22
DNS	1	141.47	25.83	14.88	0.001	50.96	5.36
(DNS) ²	1	112.44	38.21	11.82	0.000	112.44	11.82
Model	4	347.0188	38.21	9.12			
Error	59	561.0715					
Total	63	908.0902					
Mean Square Regression		86.7569					
Mean Square Error		9.509686					

Parameter Estimation			
Variable	Regression Coefficient	Standard Coefficient	Standard Error
Constant	5.98E-02	0	0
DEPTH	3.91E-02	.7475541	1.62E-02
(DEPTH) ²	8.66E-05	-.4710227	5.81E-05
DNS	-.62	-.9650517	.27
(DNS) ²	4.49E-02	1.42079	1.30E-02

DEPTH - Depth of pumping, top screen, m;

DNS - Distance from salt domes, km

The R^2 equal to 38 indicated that two basic factors, pumping depth and distance from salt domes, accounted for 38 percent of the variations in Ra.

An alternative expression, for depth measured to the bottom of the pumping range, was

$$\begin{aligned}\hat{Ra} = & -0.13 + 0.02(\text{DEPTH}) - 0.03 \times 10^{-3}(\text{DEPTH})^2 \\ & - 0.61(\text{DNS})^2 + 0.04(\text{DNS})^2.\end{aligned}\quad /3/$$

For Rn, the best combination of variables was

$$\begin{aligned}\hat{Rn} = & -413 + 4(\text{DEPTH}) + 11(\text{DDR}) - 197(\text{DNS}) \\ & + 12(\text{DNS})^2\end{aligned}\quad /4/$$

for the top of the pumping range and

$$\begin{aligned}\hat{Rn} = & -190 + 2(\text{DEPTH}) + 10(\text{DDR}) - 216(\text{DNS}) \\ & + 12(\text{DNS})^2\end{aligned}\quad /5/$$

for the bottom of the pumping range.

The variable (DDR) in equations 4 and 5 represents distance (km) down dip from the recharge zone, as explained in the "Method" section. The statistical analysis that led to derivation of these equations is illustrated in Table 2. The combination of three basic variables describing pumping depth and location of water source accounted for 42 percent of the variations in Rn.

If data on Ra concentrations are available, the Rn concentrations can be estimated as

$$\begin{aligned}\hat{Rn} = & -367 + 171(\text{Ra}) + 2(\text{DEPTH}) + 9(\text{DDR}) \\ & - 104(\text{DNS}) + 4(\text{DNS})^2\end{aligned}\quad /6/$$

for the top of the pumping range, and

$$\begin{aligned}\hat{Rn} = & -266 + 173(\text{Ra}) + (\text{DEPTH}) + 8(\text{DDR}) \\ & - 112(\text{DNS}) + 5(\text{DNS})^2\end{aligned}\quad /7/$$

for the bottom of the pumping range. This combination of factors described 74 percent of variations in Ra (Table 3).

DISCUSSION

The Gulf Coast is underlain by productive ground water aquifers, an important factor which has facilitated the urban and industrial development of the Greater Houston-Harris County area. For years all of the water needs in the City of Houston and Harris County have been satisfied entirely by ground water. However, years of pumping large volumes of water have caused a decline in

Table 2. Multiple Regression Analysis Report for Rn-222 vs. Pumping Depth and Location

Source	df	Sequential				Last	
		Sum-Sqr	R ²	F-Ratio	Tail Prob	Sum-Sqr	F-Ratio
Constant	1	5.41E+07					
DEPTH	1	9408528	17.62	18.08	0.000	4851181	9.32
DDR	1	2793209	22.85	5.37	0.023	2443481	4.69
DNS	1	2863555	28.22	5.50	0.012	5003873	9.61
(DNS) ²	1	7618718	42.49	14.64	0.001	7618717	14.64
Model	4	2.27E+07	42.49	10.90	0.000		
Error	59	3.07E+07					
Total	63	5.34E+07					
Mean Square Regression		5671002					
Mean Square Error		520469					

Parameter Estimation			
Variable	Regression Coefficient	Standard Coefficient	Standard Error
Constant	-413.01	0	0
DEPTH	4.37	.345	1.43
DDR	10.72	.25	4.95
DNS	-197.16	-1.27	63.58
(DNS) ²	11.79	1.54	3.08

DEPTH - Depth of pumping, top screen, m;

DDR - Distance downdip from recharge km;

DNS - Distance from salt domes, km

the potentiometric pressure and subsidence of the land, especially in southeast Houston [31]. Since the 1950's the prevailing philosophy behind water development in Houston has been that a) reorientation of the water supply system is necessary from total dependence on ground water to a combination of surface and ground water sources; and that b) wells need to be redistributed to reduce the rate of subsidence, phasing out most of the wells in the southeast and developing new wells in northwest Harris County, closer to the recharge zone.

In 1954 the first surface water from the San Jacinto River via Lake Houston was provided to the east side of Houston. On the other hand, the development of ground water has been actively pursued in northwest, northeast, and southwest Harris County to accommodate urban expansion in these directions.

Coast aquifer complex. It crops out inland from the study area and dips toward the Gulf at a rate of about 17 m per km; near the coastline it is approximately 1.6 km below the land surface [28].

The formations which constitute the Gulf Coast aquifer range in age from the Oligocene and Miocene eras for the Catahoula sandstone to the Quarternary period for shallow alluvium. The actual production of well water involves strata of the Pliocene-Pleistocene age (Evangeline and Chicot aquifers) rather than the Miocene age. The presence of Ra and Rn in well water derived from the Evangeline and Chicot aquifers may be evidence of a cross-formational flow where deeper water with greater potentiometric head from Miocene strata leaks upward through confining strata [24;27;37;38]. Such seepage would be most prominent up the flanks of piercement-type salt domes or associated faults.

The vertical concentration profile exhibited by Rn supports the hypothesis of an upward flow from greater depths. However, the non-linear distribution with depth observed for Ra and a rather narrow range of pumping depths in which Ra concentrations occur suggest a source in the upper Evangeline aquifers. In addition, any Ra from a Catahoula source should have decayed to below detection levels considering the long flow paths down dip from a uranium deposit in the Catahoula to a dome, up the dome flanks, and then into the Evangeline and Chicot aquifers. Because the half-life of Ra-226 is 1600 years, Ra will decay to concentrations below detection limits in a ground water flow system if travel times for the Ra are more than a few thousand years. The areas of high Ra and Rn concentrations in the Evangeline aquifer are 80 to 120 km down dip from its outcrop. At a flow rate of 1 m per year, these waters are older than measurable by Ra concentrations. If a flow path through the Catahoula is envisioned, travel time will be even greater.

Ra as a ground water tracer may give conservative ground water flow velocities because of its chemically reactive nature. Dissolved Ra should function chemically similarly to dissolved calcium. Tanner [39] proposed that in saline waters the abundant cations compete with Ra for exchange sites and thus a greater portion of Ra ions remains in solution. Conversely, waters with low ionic strengths are favorable for Ra adsorption onto the aquifer matrix. Kraemer and Reid [40] studied Ra in deep saline formation waters and observed this direct correlation between salinity and Ra activity. In the Evangeline aquifer the migration of Ra may be retarded by ion exchange or conversely enhanced if dome dissolution increases the salinity around a dome.

In our study, the proximity of salt domes was found to be a strong predictor of Ra and Rn presence in well water, particularly in combination with a certain range of pumping depths. Whether Ra is related to uranium associated with salt domes or to brine leakage up the flanks of salt domes cannot be answered at this time. We advise, however, against developing domestic wells near salt domes, especially medium-to-deep wells (180 m and deeper).

The health significance of Ra and Rn-rich water in Harris County is not known. All the water wells in question were located in subdivisions that have existed for only about 10 to 15 years. In northwest Harris County the customers were notified by the respective MUD's that Ra levels in their water were in excess of MCL. In southwest Houston, where a blend of water from several

wells is distributed, the city, technically, is not under obligation to notify customers regarding Ra concentrations present in specific component-wells, as long as the levels in the distribution system are not in excess of the maximum allowable.

Blending water may not be the most reliable option, however, for dealing with Ra and Rn, since resultant concentrations vary depending on several, not entirely predictable factors, i.e., how many wells are in operation at any given time, the pumping rate of each contributing well, pressure in water lines, and demand. The boundaries of service areas for each particular component in the distribution system are not known. It would be advisable, instead, for the City of Houston to take steps toward replacing, re-working, or treating problem wells.

The EPA has published two booklets advising homeowners on methods to reduce indoor concentrations of Rn [8,9]. In these documents, users of private wells were informed that domestic water might contribute Rn to the indoor air. However, the EPA said this usually is not a problem when large community water supplies are concerned, since water supposedly releases most of its Rn before reaching individual houses. In our study in Houston-Harris County, parallel measurements of Rn made at municipal well heads and at consumers' taps indicated that the en route self-aeration of well water does not occur. There was no evidence of appreciable drop in Rn concentrations in municipal well water upon its arrival at household taps.

Water treatment for Ra and Rn is available. The technology of Rn and Ra removal does not differ much from other gases or alkaline earth elements, i.e., well-known and common technology for removal of calcium or magnesium hardness. The economics of rehabilitation by lime or lime-soda softening, weak acid ion exchange, or reverse osmosis have been reviewed recently by Snoeyink et al. [41] and Brock [20]). To date, some MUD's in Harris County have been successful in reducing levels of Ra and Rn by altering screening depths in their wells.

SUMMARY

This study showed that anomalous concentrations of Ra-226 and Rn-222 exist in parts of the upper Texas Gulf Coast. While all factors influencing the distribution and fate of pollutants in underground porous media might not be easy to measure or even identify, often the very expectation of this great complexity prevents one from observing patterns that otherwise might be quite helpful. The findings summarized in this communication present an encouraging picture for predicting depths and locations in the Gulf Coast where elevated Ra and Rn concentrations may be encountered. Two to four key variables accounted for the statistically significant variation (from 38 to 74 percent) in concentrations observed under field conditions.

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