WRRI-UNC-87-230

Predicting the Occurrence of Radon-222 in North Carolina Groundwater

By

Dana P. Loomis
Research Assistant

James E. Watson, Jr.
Associate Professor

Douglas J. Crawford-Brown
Assistant Professor

Department of Environmental Sciences & Engineering
University of North Carolina
Chapel Hill, NC 27514

The research on which this report is based was financed in part by the Department of the Interior, U.S. Geological Survey, through the North Carolina Water Resources Research Institute.

Agreement No. 14-08-0001-G1243

WRRI Project No. 70068

USGS Project No. 03 (FY86)

May 1987

ACKNOWLEDGEMENTS

This work was performed within the Department of Environmental Sciences and Engineering of the School of Public Health at the University of North Carolina at Chapel Hill. Mr. Carl Bailey of the Groundwater Section of the North Carolina Division of Environmental Management provided helpful advice in planning the project and gave us access to the Division of Environmental Management's well permit files. Mr. Leon Pryor of the Water Supply Branch of the North Carolina Department of Human Resources helped us find additional data on water system location and ownership. We are indebted to the many water system owners and operators who cooperated in this project and allowed us to obtain water samples from their systems. Laboratory analyses for radon-222 in water samples were conducted by Mr. Kenneth Ladrach. Discussions with Dr. Richard Spruill, East Carolina University, regarding the significance of geologic regions of the State were most helpful. This manuscript was typed by Ms. Frances Dancy who also provided secretarial support throughout this project.

ABSTRACT

The intent of this study was to develop an understanding of some of the factors that effect the concentration of radon-222 (^{222}Rn) in drinking water supplies of North Carolina. Data for this investigation were collected on a sample of 96 North Carolina public water supply wells. Water samples were collected and analyzed for ^{222}Rn content. Data on well characteristics (discharge, specific capacity, depth, and casing length) were obtained from existing sources.

From an examination of the data collected in this study, it is concluded that there is a distinct and statistically significant difference in the mean ^{222}Rn concentrations of groundwater associated with different types of rocks. The data, however, also indicate that there is a great degree of variability in the ^{222}Rn concentrations of samples drawn from any given rock type. The situation is made slightly better by introducing a second variable given as the geologic region of a water supply. This study indicates that the highest ^{222}Rn concentrations are likely to be found in supplies located in granites and gneisses within the Blue Ridge, Inner Piedmont, and Raleigh Belt regions. Supplies located in the coastal plain have the least potential for high ^{222}Rn concentrations.

Regardless of the rock type/geologic region category, however, variability in subpopulations still is substantial. A fairly surprising finding of this study is the relative insignificance of discharge, specific capacity, depth, and casing length of wells as predictors of ^{222}Rn concentration. The

present study indicates that use of these variables as predictors does not significantly improve the likelihood of locating elevated water supplies in North Carolina.

DISCLAIMER STATEMENT

Table of Contents

List of Figures

List of Tables

SUMMARY AND CONCLUSIONS

The intent of this study was to develop an understanding of some of the factors that affect the concentration of ^{222}Rn in drinking water supplies of North Carolina. Data for this investigation were collected on a sample of 96 North Carolina public water supply wells. Water samples were collected and analyzed for ^{222}Rn content. Data on well characteristics (discharge, specific capacity, depth, and casing length) were obtained from existing sources.

It is anticipated that some water supplies will contain ^{222}Rn concentrations in excess of the planned EPA limit (which is expected to be somewhere in the neighborhood of 500 pCi/l according to Dr. C.R. Cothern, U.S. EPA Office of Drinking Water, personal communication). The conclusions of the present research will, therefore, focus on the degree to which information readily available to the state might be used in locating those water supplies in excess of any future EPA standard.

The first conclusion may be noted by examination of Table 3 (page 28), in which the mean ^{222}Rn concentration in water from each of 5 rock types is shown. These data indicate that there is a distinct, and statistically significant difference in the mean concentration between the types of rocks. As a result, attempts to locate water supplies containing high levels of ^{222}Rn should focus first on supplies located in granites then, in decreasing order, on supplies located in gneisses, mafics, metavolcanics, and the coastal plain.

The data, however, also indicate that there is a great degree of variability in the ^{222}Rn concentration of samples drawn from any given rock type. For example, the subpopulation of samples from granite contained both the maximum (30711 pCi/l) and minimum (24 pCi/l) concentrations found in this study. Clearly, then, focusing on a particular rock type in any future sampling program may aid in guiding resources towards an area most likely to contain elevated samples. This focus will not, however, ensure that resources are spent only on examining supplies representing a health risk, nor will it ensure that all significant sources of risk are located.

The situation is made slightly better by introducing a second variable given as the geologic region of a water supply. Subpopulations of samples characterized by both a rock type and geologic region display variability which is slightly below that of subpopulations characterized only by rock type. From Table 7 (page 41), it can be seen that the highest ^{222}Rn concentrations are likely to be found in supplies characterized by the following combinations: (1) Gneiss/Blue Ridge, (2) Gneiss/Inner Piedmont, (3) Gneiss/Raleigh Belt, (4) Granite/Blue Ridge, (5) Granite/Inner Piedmont, (6) Granite/Raleigh Belt, and (7) Mafic/Charlotte Belt. Samples from the Fall Line in general may also be high, but sampling was too infrequent in this category to yield good estimates of the mean. Regardless of the rock type/region category, however, variability in subpopulations still is substantial. The main conclusion to be drawn is that use of information on rock type and geologic region will aid in locating elevated water supplies in the most efficient manner possible, but that significantly contaminated supplies could be missed by choosing to focus only on a few categories as candidates for sampling.

A fairly surprising finding is the relative insignificance of discharge, specific capacity, depth, and casing length as predictors of ^{222}Rn concentration. The present study indicates that use of these variables as predictors does not significantly improve the likelihood of locating elevated water supplies in North Carolina. It must be noted, however, that this conclusion applies only to models which utilize these various parameters in the manner described in the text. It is possible that a more complicated combination of these factors might provide some predictive ability, but this combination is not clear at present. Until such a combination is determined (if one exists), it does not appear fruitful to employ variables other than rock type and geologic region in choosing the location of future samples.

In conclusion, use of the variabiles given as rock type and geologic region clearly aid in locating regions of North Carolina characterized by a high mean concentration of ^{222}Rn in water. Primary concern should be directed towards water supplies located in granites and in gneisses within the Blue Ridge or Inner Piedmont or Raleigh Belt. Essentially any other part of the state, however, could contain supplies in excess of future limits and must be considered as a candidate for remedial action. Until a more detailed understanding of the factors influencing ^{222}Rn concentration is obtained, the other variabiles explored in this study will not prove useful in locating elevated water supplies.

RECOMMENDATIONS

There are several features of the conclusions drawn here which suggest directions for future study. From Table 7 (page 41), it is clear that many categories of rock type/geologic region are only poorly characterized or uncharacterized. There is a need for a more comprehensive sampling program in all cells of this table to establish a detailed picture of the extent to which those variables act as good predictors of concentration. A first step would be to choose a rock type (probably granite or gneiss) and obtain representative samples from each geologic region. It is recommended that at least 20 samples from each region be obtained.

Several factors probably control the concentration of ^{222}Rn in a water supply. The flux of ^{222}Rn within the ground may be controlled by the radium-226 (^{226}Ra) concentration in the surrounding rocks, the emanation fraction for the ^{222}Rn from the rock matrix, and the permeability of the rock to ^{222}Rn movement. For a given flux, the concentration of ^{222}Rn in a water supply then would also be controlled by the ratio of aquifer surface area to volume. Any mechanistic model probably would focus on these four factors, in combination with the average length of time water remains in the aquifer. Unfortunately, data on these factors are not available for most wells. Future studies might, therefore, select several of the wells examined in the present study and perform a detailed analysis of the above factors. From this information, it should prove possible to develop a mechanistic model which would aid in predicting ^{222}Rn

concentrations in water, at least at locations where the model variables are measured or readily measureable. At the least, such a model could be used to explain the variability within the cells of Table 7.

Finally, the present study focused only on locating wells with a high concentration of ^{222}Rn. This information needs to be combined with demographic information to determine areas with the largest collective public risk.

INTRODUCTION

Radon-222 is a chemically-inert radioactive gas which is an intermediate product of the decay of uranium-238 (^{238}U). It is highly mobile and is nearly ubiquitous in environmental media including the Earth's crust, air, and water. Radon-222 is a frequently encountered radiological constituent in natural waters and typically exceeds the concentration of other radionuclides including uranium, thorium, and radium by orders of magnitude (Hess et al., 1985). The wide distribution and frequently high concentrations of ^{222}Rn in drinking water supplies are of concern because a significant public health risk from cancer is associated with exposure to ^{222}Rn. Estimates of this risk show that the average lifetime probability of cancer induction from exposure to ^{222}Rn in drinking water greatly exceeds that imposed by any other natural or anthropogenic environmental contaminant (Cross, Harley, and Hoffman, 1985).

The ^{222}Rn content of North Carolina groundwater samples has been determined by previous investigators (Aldrich, Sasser, and Conners, 1975; Mitsch, Watson, and Hayes, 1984; Strain, Watson, and Fong, 1979; US EPA, 1982). These studies have shown that the ^{222}Rn content of some North Carolina groundwaters is among the highest observed in the United States (Hess et al., 1985; Horton, 1983; 1985) and may represent a significant health risk to the state's population (Sasser and Watson, 1978). They have not, however, provided the knowledge necessary to characterize the geographic distribution of ^{222}Rn in groundwater, to explain its variability, or to predict ^{222}Rn concentrations in unsampled areas.

In this study we examine the utility of several hydrologic and geologic factors as predictors of regional differences in ^{222}Rn concentration in groundwater, with specific application to North Carolina. Radon-222 concentrations were measured in 96 public water supply wells and their association with 6 independent variables was tested using statistical techniques. The primary purpose of this work was to develop a predictive model for ^{222}Rn concentration which can be used by public health officials, water quality regulators, resource managers, and others who may need to identify probable areas of high or low ^{222}Rn concentration. Because our methods emphasize prediction, we cannot demonstrate a causal relationship between ^{222}Rn and any of the variables studied. Nevertheless, this examination of the associations among these variables suggests directions for future research on the mechanisms which regulate the concentration of ^{222}Rn in well water.

PREVIOUS RESEARCH

The distribution of ^{222}Rn in U.S. drinking water supplies has been reported by the U.S. Environmental Protection Agency (Horton, 1983; 1985) and by Hess et al. (1985). Radon-222 concentration in drinking water throughout the United States ranges from near zero to over 1×10^6 pCi/l. Surface waters typically contain very little ^{222}Rn, but high concentrations may occur in groundwaters (Hess et al., 1985). The largest areas of elevated ^{222}Rn concentrations in U.S. groundwater are in New England and the Appalachian and Piedmont provinces of the

Southeast. High concentrations have also been observed in groundwater in the Rocky Mountain states and California (Hess et al., 1985; Horton, 1985). Groundwaters in the Atlantic-Gulf coastal plain and the midwest region have substantially lower ^{222}Rn concentrations (Hess et al., 1985; Horton, 1985). In addition to variation associated with location and source, nationwide studies have shown that ^{222}Rn concentration varies among water systems of different sizes. The highest ^{222}Rn concentrations are found in private wells and small public water supplies, while large public water supplies typically have much lower ^{222}Rn content (Hess et al., 1985; Horton, 1983).

Although the ^{222}Rn content of drinking water varies geographically and with water system size, the largest variations in concentration are related to geologic factors. High ^{222}Rn concentrations in groundwater have been shown, in particular, to be strongly associated with some rock types. Groundwaters from aquifers in granites often contain high ^{222}Rn concentrations, sometimes over 100,000 pCi/l (Asikainen and Kahlos, 1979; Brutsaert, et al., 1981; Snihs, 1973). In contrast, groundwaters from sedimentary aquifers generally have ^{222}Rn concentrations of less than 500 pCi/l (Andrews and Wood, 1972; Gorgoni, Martinelli, and Sighinolfi, 1982; King, Michel, and Moore, 1982; Mitsch, Watson, and Hayes, 1984).

Previous studies of ^{222}Rn in North Carolina groundwater have been directed toward two areas of inquiry: 1) investigating ^{222}Rn occurrence in the eastern North Carolina phosphate district, and 2) establishing the statewide distribution of ^{222}Rn in groundwater and investigating its correlates. Strain, Watson, and Fong (1979) and Mitsch, Watson, and Hayes (1984) studied the local effects of ore mining and processing on the ^{222}Rn content of groundwaters in the phosphate district with emphasis on geologic and hydrologic factors. These researchers did not find generally elevated ^{222}Rn concentrations in wells near mined areas and found no evidence that mining operations have induced ^{222}Rn migration into the Castle Hayne aquifer which underlies the mineralized strata.

The occurrence of ^{222}Rn in North Carolina groundwaters has been surveyed in two statewide sampling studies conducted by the Radiation Protection Section of the North Carolina Department of Human Resources (Aldrich, Sasser, and Conners, 1975; Sasser and Watson, 1978) and the U.S. Environmental Protection Agency (Horton, 1983; 1985; U.S. EPA, 1982). These investigations show that ^{222}Rn concentrations range widely in the state, from analytical zero to over 46,000 pCi/l. This variability and its causes have been studied by other researchers.

Lee, Watson, and Fong (1979) investigated the relationship of ^{222}Rn and ^{226}Ra in selected North Carolina groundwaters and showed that high ^{222}Rn concentrations are generally unsupported by dissolved ^{226}Ra. Loomis (1987a, 1987b) reviewed previous statewide sampling data and investigated the relationship of groundwater ^{222}Rn concentration to bedrock geology and water system size. This work supported the earlier suggestion of Sasser and Watson (1978) that public exposure to ^{222}Rn in North Carolina may be significantly higher than for the nation as a whole. Whereas Hess et al. (1985) reported that only 15% of U.S. groundwater systems sampled contain more than 1000 pCi/l ^{222}Rn, in North Carolina 41% of 339 groundwater samples from previous statewide studies exceeded this concentration. Loomis (1987b) also showed that regional variations in average ^{222}Rn concentration are associated with different rock types in North Carolina. The relative concentrations of ^{222}Rn in groundwater from these aquifers are essentially consistent with relative average abundances of uranium in rocks. Although this apparent association with initial uranium concentration may explain much of the geographic variability of ^{222}Rn concentration, there remains a large degree of unexplained variation within rock type categories which may be attributable, in part, to other geologic and hydrologic variables not accounted for in the earlier analysis (Loomis, 1987b). The present research attempts to examine in detail more of the causes of radon concentration variability both within and between rock types through consideration of additional variables.

ORIGINS OF RADON IN GROUNDWATER

Concentration of parent radionuclides in adjacent rock material is a major controlling factor on the radon content of groundwater. Uranium is widely distributed in the Earth's crust, and average uranium concentrations in many minerals and rocks are well known. The following abundances are from Rogers and Adams (1969): uranium concentrations from 1 to 4 ppm are characteristic of silicic igneous rocks, (granites, rhyolites, quartz monzonites, etc.); somewhat lower concentrations are charactristic of intermediate rocks, and much lower concentrations, typically from .001 to 1 ppm, are found in mafic and ultramafic rocks. Variation between different rock bodies of the same type, or even within a single pluton, may be considerable, however. Sedimentary rocks have generally lower values, for example 0.45 ppm for quartz sandstones and 2.2 ppm for limestones, but marine phosphorites and some shales may contain concentrations in excess of those found in normal granites. The uranium content of metamorphic rocks is quite variable as might be expected from their diverse origins.

Although patterns of ^{222}Rn occurrence in groundwater in general reflect differences in average uranium concentration, other geologic and hydrologic variables which affect the distribution of parent nuclides, the escape of ^{222}Rn atoms from rock to water, and the migration of the gas from its source to the point where it is measured may have large effects on ^{222}Rn concentration in well water. These factors include:

1) Uranium-^{226}Ra geochemistry. Radon-222 in groundwater is formed directly by radioactive decay of ^{226}Ra atoms contained in rock, soil, and mineral grains. The local equilibrium of ^{226}Ra, the immediate parent of ^{222}Rn, with its progenitor ^{238}U in geologic materials is a function of geologic history and geochemical environment. Few data are available on ^{226}Ra concentrations in common rocks, but although ^{226}Ra and ^{238}U might be expected to be in global equilibrium in geologic media their solubility is quite different and the two elements may become locally separated.

2) Dissolved ^{226}Ra. Radon-222 in groundwater may be produced by decay of ^{226}Ra already in solution. In general, however,

dissolved ^{226}Ra concentrations are low and cannot theoretically support observed high ^{222}Rn concentrations (Rama and Moore, 1984). This has been confirmed in observational studies, where investigators have found no correlation between ^{226}Ra and ^{222}Rn concentrations in groundwater (Lee, Watson, and Fong, 1979; Snihs, 1972; Tanner, 1964a).

3) Meteorologic factors. Various investigators have reported conflicting findings on the temporal stability of ^{222}Rn concentrations in well waters. Seasonal variation by a factor of 2 to 3, positively correlated with precipitation, has been reported in the ^{222}Rn concentration of continuously monitored wells in England and Japan (Andrews and Wood, 1972; Fukui and Katsurayama, 1983), while no significant variations were reported in continuously observed wells in South Carolina and North Carolina (Michel and Moore, 1980; Mitsch, Watson, and Hayes, 1984). Radon-222 emanation from the ground also varies with barometric pressure (Steinhausler, 1975). This suggests another source of variability in groundwater if ground emanation competes with movement of ^{222}Rn into water.

4) Well and water system design and use. Since groundwater samples used in this and other studies of ^{222}Rn concentrations are obtained from wells, a number of variables related to well design and use may also affect the ^{222}Rn content measured in water samples. An inverse relationship has been reported between number of water system customers and ^{222}Rn concentration (Hess et al., 1985; Horton, 1983), but this effect may be due to differences in the aquifers used by large and small systems rather than to properties of the systems themselves (Loomis,

1987a). Brutsaert et al. (1981) reported a negative correlation between ^{222}Rn concentration and yield of 136 wells in Maine, and a positive correlation between ^{222}Rn concentration and well depth. Snihs (1973) found no evidence for the latter relationship in 37 wells in Sweden. Well pumping patterns may also affect the ^{222}Rn concentration of water samples; Fukui and Katsurayama (1983) reported small but consistent increases in ^{222}Rn activity after several hours pumping, presumably because induced flow brought new ^{222}Rn-laden water to the wellbore.

5) Geometry and mass of the ^{222}Rn source. Radon-222 concentrations in water may be affected not only by the concentration of parent nuclides in surrounding rocks, but by the absolute quantity of parent present and by its spatial distribution within the rock. Radon-222 accumulation in water would be particularly enhanced, for a qiven concentration of parent, in aquifers with a high ratio of surface area to volume and in which the source extended for large distances away from the well in which measurements are made.

6) Rock properties. Laboratory measurements have shown that rocks with high uranium concentrations do not necessarily release the greatest quantities of ^{222}Rn because there are large variations in the proportion of ^{222}Rn which is able to escape from rock solids, called the emanation fraction (Baretto, Clark, and Adams, 1972). Such discrepancies occur because rock characteristics have a very significant effect on the efficiency of ^{222}Rn escape from rock solids into pore spaces. These include grain size, weathering, rock microstructure, and spatial distribution of parent nuclides in and on mineral grains (Rama

and Moore, 1984; Tanner, 1964b). Radon-222 escape is inversely proportional to grain size (Andrews and Wood, 1972) and is greatly enhanced by pervasive microfracturing (Rama and Moore, 1984).

7) Radon transport. Radon-222 which has entered water-filled pore spaces is transported to wells by groundwater flow, which may be natural or induced by pumping. Transport is more rapid in open fracture networks than in intergranular porosity and becomes inefficient in rocks with low permeability (Tanner, 1964b). Since ^{222}Rn is removed in significant quantities from water only by radioactive decay (small amounts may be lost by diffusion to the atmosphere in phreatic aquifers), the amount of ^{222}Rn reaching a well at a distance from its source is determined by a balance between flow rate and radioactive decay in which rapid flow rates help to maintain high ^{222}Rn concentrations (Andrews and Wood, 1972). Because groundwater flow has vector properties, ^{222}Rn concentration at a given point is a function of direction to the ^{222}Rn source as well as distance.

The last three factors are the ones with which we are concerned in this investigation. Information is needed on the physical dimensions of the ^{222}Rn source, the movement of water within aquifers, and the geologic properties which control the production of ^{222}Rn and its escape from rocks to water. The variables on which this analysis are based were selected to measure these properties. Variable definition and measurement are discussed in detail in the following paragraphs.

METHODS

Because the goal of this research was to develop a practical predictive model for groundwater ^{222}Rn concentration which can be used by North Carolina state government agencies, we restricted data collection for variables other than ^{222}Rn concentration to sources which we judged accessible to the agencies without excessive expense or outside technical help. Principal data sources included well records on file at the Groundwater Section of the N.C. Division of Environmental Management (NCDEM), public water supply records maintained by the Water Supply Branch of the N.C. Deparatment of Human Resources (NCDHR), and geologic maps and publications produced by the N.C. Geological Survey.

Following these criteria for using available data we determined that from existing sources it would be practical to obtain data on several well and aquifer characteristics of theoretical interest, including rock type, geologic region, well depth, casing length, saprolite thickness, discharge, and specific capacity. Several of the rock characteristics discussed above, such as grain size, uranium concentration, and emanation fraction are generally measured by laboratory procedures and therefore could not be determined directly for the purposes of this study. These characteristics do, however, tend to vary with rock type and geologic history, so we grouped together similar rocks with similar geologic histories to reduce as much as possible the variability of these characteristics. The determination of rock type is straightforward, and the methods used are described below. To include information about geologic history we also determined the geologic region of each well sampled. The geology of North Carolina can be envisioned as a series of northeast-trending belts (Figure 1), each with a distinctive history and containing rocks of generally similar age (Fullagar, 1971). For example, granite plutons in the Charlotte belt tend to be more similar to each other than to granites in the Carolina slate belt (Butler and Ragland, 1969; Fullagar, 1971). By accounting for geologic region, the variation in factors such as uranium concentration should be reduced compared to accounting for rock type alone.

The physical dimensions of the ^{222}Rn source were measured by variables determined from well depth and casing length. Fractured crystalline rock aquifers in the Piedmont and Blue Ridge consist of two media, both of which may release ^{222}Rn: water is stored in the saprolite layer and transmitted to wells by fractures in the unweathered bedrock (Heath, 1980; LeGrande, 1967). These wells are generally constructed by setting casing on top of bedrock at the base of the saprolite layer. Saprolite thickness can be approximated by casing length, and the height of the bedrock aquifer by the length of uncased hole which penetrates bedrock. In screened coastal plain wells screen height is approximately equal to aquifer thickness.

A complex group of factors including groundwater flow rates, aquifer permeability, extent and interconnection of fracture systems, and distance over which ^{222}Rn may migrate to a well are measured by the variables discharge and specific capacity. Specific capacity can be used to approximate transmissivity (U.S. Bureau of Reclamation, 1977) and was chosen as a measure of well

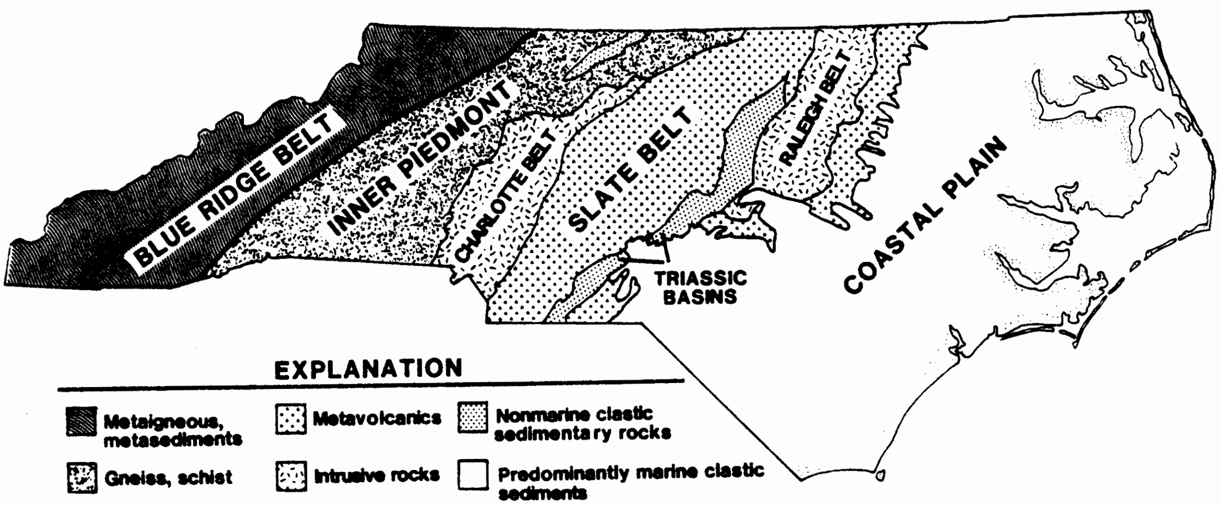

Figure 1. Geologic Map of North Carolina

performance that would allow comparison between Piedmont/Blue Ridge and coastal plain aquifers. Standard methods of estimating transmissivity may be inappropriate in North Carolina crystalline rock wells and the meaning of the parameter in this context is unclear (Welby and Wilson, 1982).

Additional data were available on water system characteristics, such as number of customers and type of treatment, but were not included in the study because of study design considerations. The approach of this investigation focuses on predicting the naturally occurring distribution of ^{222}Rn in groundwater before treatment. Radon-222 concentrations in water supplies may be changed in transit from well to consumer by mixing water from wells with different concentrations, by ^{222}Rn emanation to the atmosphere during aeration, and by radioactive decay in the distribution system. Although such changes may determine the actual exposure of water users they tend to obscure the natural distribution of ^{222}Rn in groundwater and the mechanisms that underlie it. To avoid this loss of information resulting from water treatment and distribution we obtained water samples for ^{222}Rn concentration measurement directly from the well head before treatment. Thus factors which affect ^{222}Rn concentration at later stages are not considered here.

Selection of Wells

Data for this investigation were obtained on a sample of 96 North Carolina public water supply wells using a strategy designed to facilitate comparison of ^{222}Rn concentrations and other characteristics among major rock types in the state. This protocol called for a target of 20 wells each in gneisses, granites, mafic rocks, metavolcanic rocks, triassic sediments and coastal plain sediments to be sampled. Wells which met the following criteria were eligible for study: 1) a construction permit was issued by NCDEM after 11/6/67 when comprehensive statewide permitting regulations were put into effect 2) well completion records, including a minimum 12-hour pump test, are on file at NCDEM, 3) the well supplys an active public water system registered with NCDHR, 4) the well is located in one of the six rock types specified. The initial strategy for selecting wells from among all those which met these requirements called for drawing a random sample within each category of rock type from NCDEM 1976-1982 permit lists, which specify those wells for which completion and pump test records are available. This procedure, however, did not produce a sufficient number of wells in any rock type except the coastal plain. To increase the number of eligible wells a second, more arbitrary strategy had to be used outside the coastal plain. NCDEM well records through 1978 are organized by county, so intensive searches were conducted of the 1967-1978 well records in selected counties containing the remaining five rock types. Counties were chosen on the basis of their geology and to provide an essentially contiguous sample across the major geologic regions of the state. All wells which met the inclusion criteria in each county were added to the list of eligible wells, and new counties were searched until at least 25 wells were found in each rock type. Some counties had no eligible wells, while the more populous counties, in particular, tended to have a large number. Even this process could not produce the required number of wells in Triassic sediments, so that category was eliminated from the study. The 23 intensively searched counties were Wake, Warren, Vance, Durham, Orange, Buncombe, Cabarrus, Caswell, Chatham, Alamance, Randolph, Guilford, Forsyth, Lee, Davie, Davidson, Rockingham, Stokes, Surry, Iredell, Cleveland, Mecklenburg and Anson. When the required number of eligible wells was achieved, a random sample of 20 study wells and a second random sample of five backup wells was drawn in each rock type category. This procedure produced a true random sample of public water supply wells in the coastal plain, but because of the method used to identify eligible wells in the Piedmont and Blue Ridge, the sample can be considered truly random only for those counties which were intensively searched. We believe, nevertheless, that within rock types, the counties not searched are sufficiently similar to the searched counties to warrant the assumption that the conclusions of this study can be safely extended to the entire state.

Other additions and deletions occurred during the data collection phase of the project. To obtain permission to collect water samples, we attempted to contact the owner of each well at the address and telephone number on file with the Water Supply Branch of NCDHR. Of the 100 wells in the original sample 6 owners could not be contacted, 5 refused to allow their wells to be sampled or otherwise would not cooperate, and 10 wells were no longer in service or were designed so that a sample of untreated water could not be collected. These wells were replaced by the geographically closest backup well in the same rock type to keep

20 wells in each category. Several other wells were found to be inoperable or otherwise impossible to sample but were replaced by nearby wells serving the same water system if well records could be obtained from NCDEM or directly from the owners. Sample size fell below 20 in the granite and mafic rock categories, however, because not enough eligible wells could be identified.

Data Collection

The paragraphs below give a brief description of the methods used to measure ^{222}Rn concentration and to determine each of the potential predictive factors examined in this study.

Radon Concentration

Water samples were collected from designated wells and transported to the Radiological Hygiene Laboratory of the University of North Carolina for analyses of ^{222}Rn concentrations. Laboratory analyses were performed using a standard emanation technique for transferring ^{222}Rn in a water sample to an alpha scintillation cell for counting.

A sample was collected from a tap as close to the well head as possible. Prior to sample collection, the tap was opened to purge the water line. This purging ensured that the water sample collected actually came from the ground. After purging, the flow rate from the tap was reduced and a rubber hose was attached to the tap. Next, approximately 15 ml of water was collected in an emanation bubbler (Figure 2) for ^{222}Rn analysis. Care was exercised to minimize any loss of ^{222}Rn due to aeration of the water during sample collection.

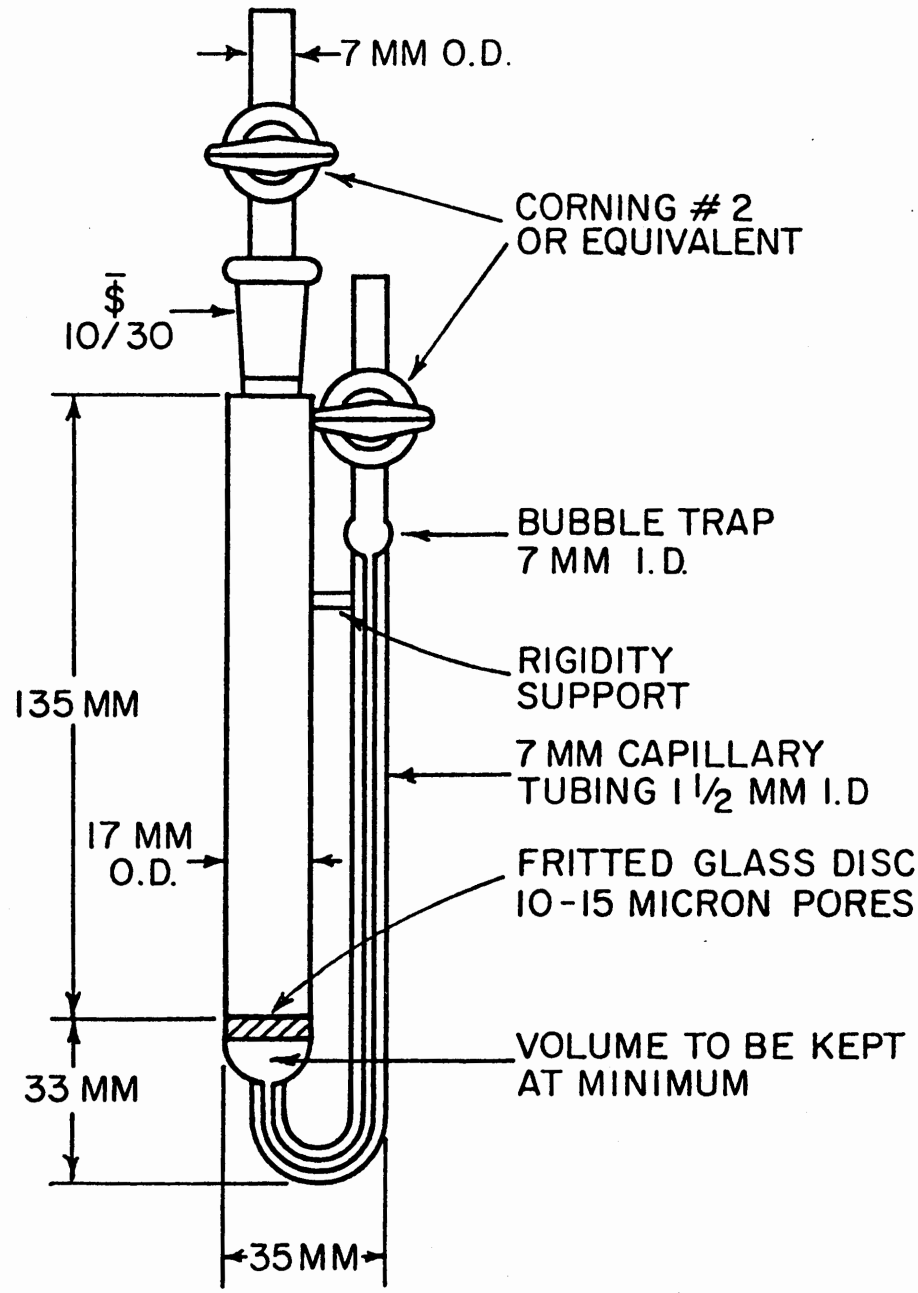

Figure 2. Radon Bubbler

To analyze a water sample, the ^{222}Rn in the emanation bubbler must be transferred to an alpha scintillation cell or Lucas cell (Figure 3). The cell was evacuated and helium was bubbled through the water sample in the bubbler to transfer ^{222}Rn from the bubbler to the alpha scintillation cell (Figure 4). The surface of the cell is coated with zinc sulfide, which is an efficient scintillator for the alpha particles emitted by ^{222}Rn and ^{222}Rn daughters. The scintillations (light) produced by the alpha particles were counted using a photomultiplier tube and associated electronic equipment. The electronic equipment consisted of a high voltage power supply, an amplifier, a counter-timer, and a pulse height analyzer. Calibration factors for the alpha scintillation cells were determined using water samples with known amounts of ^{222}Rn.

There are several sources of error inherent in the collection and measurement of ^{222}Rn in water samples. These are:

1) Uncertainty in the fraction of ^{222}Rn collected during sampling from a tap.
2) Loss of ^{222}Rn during transport to the lab.
3) Uncertainty in the fraction of ^{222}Rn transferred to the Lucas cell during emanation.
4) Fluctuations due to counting statistics and scalar errors.
5) Uncertainty in the volume of water sampled.
6) Uncertainty in the calibration factor.

The last four sources of error (3 to 6) generally are insignificant and, in the present studies, contributed only a 5% variability in repeated measurements on a solitary sample (i.e. the precision is $\pm$ 5%). A larger source of uncertainty arises

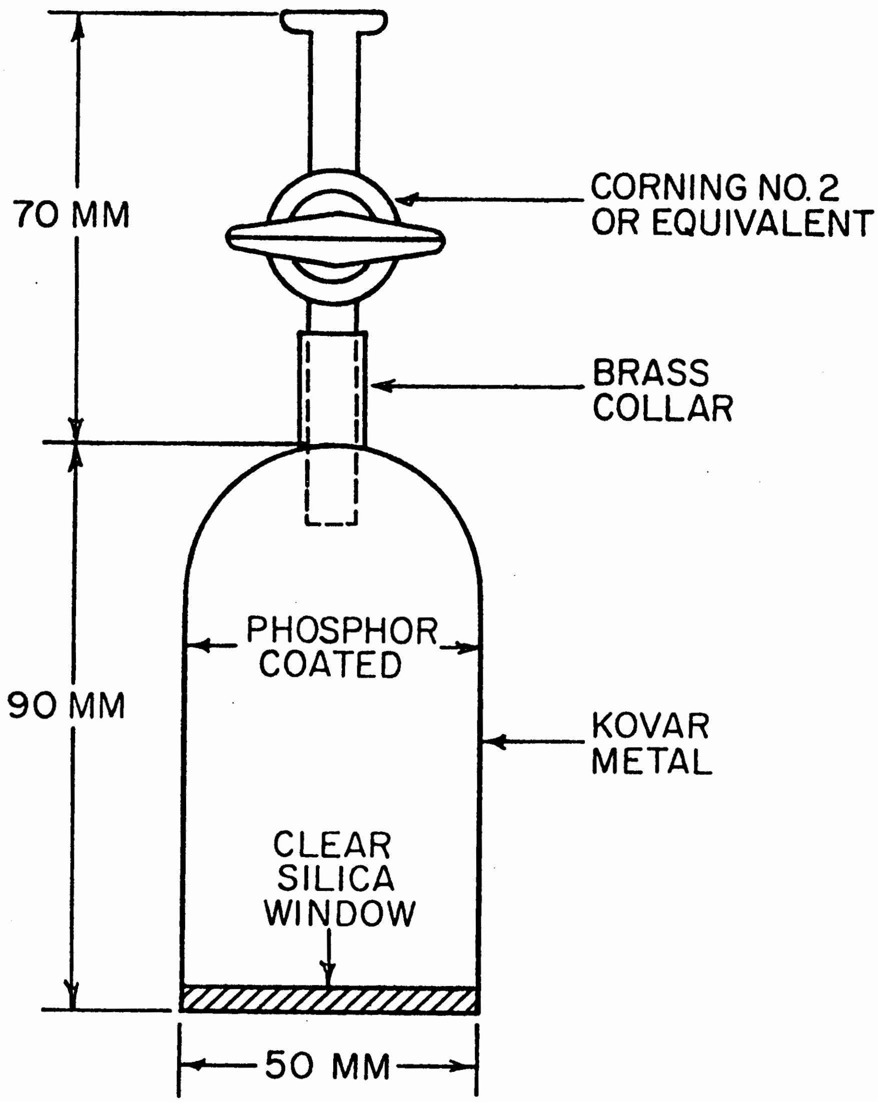

Figure 3. Alpha Scintillation Cell

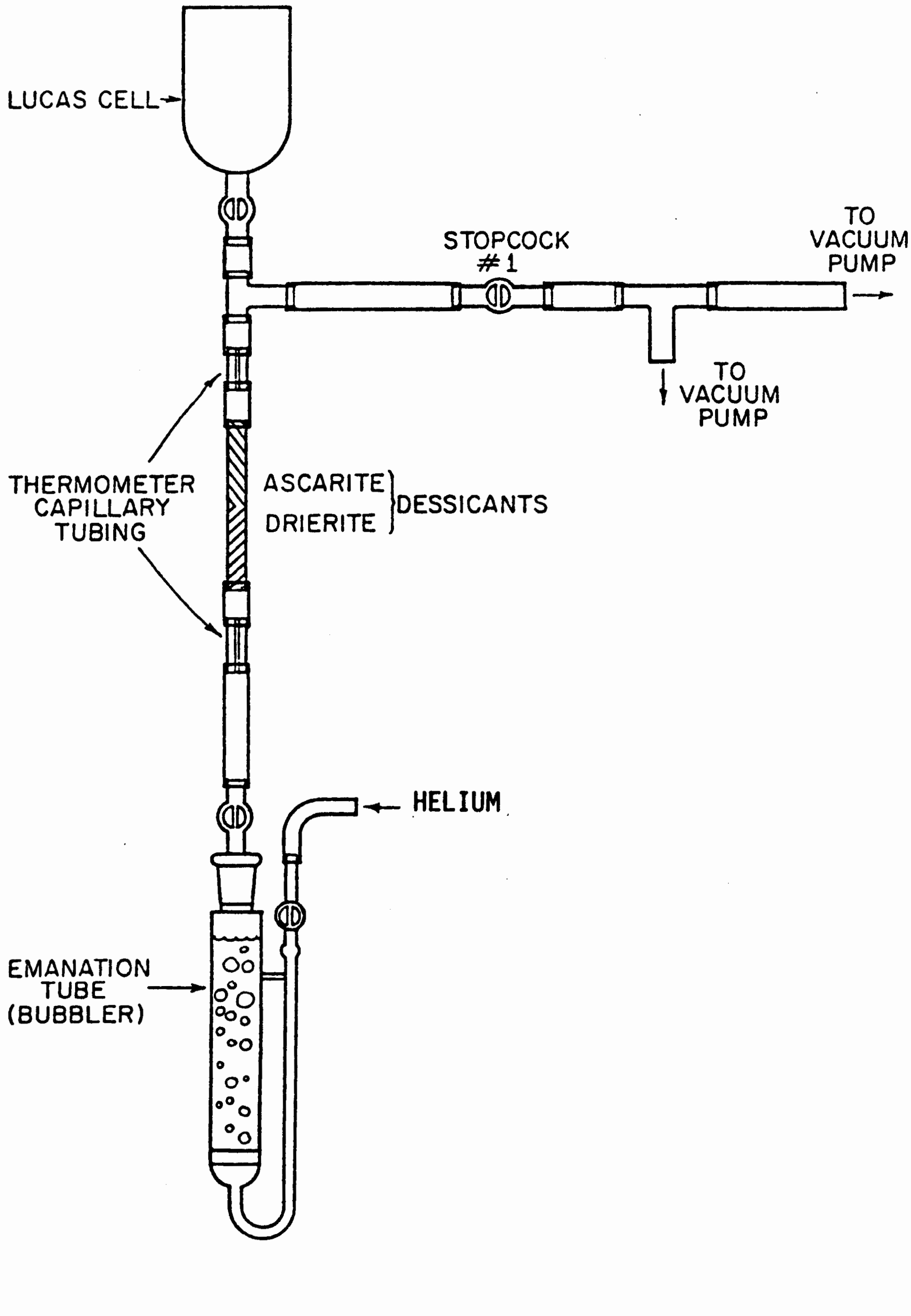

Figure 4. Emanation System

from loss of accuracy by the first two factors. The method used to collect samples in this study was identical to the method used in a recent EPA study of the accuracy of ^{222}Rn measurement methods (Research Planning Institute, Inc., 1986). That study indicated an accuracy of about ±10% from the first two sources of error above. As a result, it is reasonable to assume that all measurement results in the present study were accurate to within ± 15%, which is much smaller than the standard deviation of the sample populations.

Rock Type

The wells included in this study belong to the general lithologic types of gneisses, granites, mafic rocks (gabbros and diorites), metavolcanic rocks (all types), and coastal plain sediments. Each well which met the other initial sampling criteria was assigned a rock type based on the surface bedrock geology where the well was drilled. To determine rock type the well's location was plotted on a geologic map, using the most detailed map available for the area, and the well was included in the study if the geologic unit mapped at the well location could be assigned to one of these lithologic categories. In addition, 15 of the wells were inspected in the field by an experienced geologist and in all cases the geology at the well site was consistent with the rock type determined from geologic maps.

Geologic Region

The geologic region (Figure 1) of each well was also determined from its geographic location and rock type. Wells in the study were assigned to the inner or outer coastal plain, Fall

Line, Raleigh belt, Carolina slate belt, Durham-Sanford basin, Charlotte belt, inner Piedmont, or Blue Ridge regions.

Specific Capacity and Discharge

Specific capacity and discharge were determined from pump test records for each well. Because pump rates varied during testing for most of the study wells, discharge (gpm) was calculated as time-weighted average flow during testing. Similarly, specific capacity (gpm/ft) was calculated as time-weighted average discharge per foot of drawdown. Discharge and specific capacity were calculated at three times, after 12 and 24 hours of pumping and when drawdown stabilized, but were all essentially identical. Twelve and 24-hour figures for discharge and specific capacity are highly correlated ($r = 0.999$, $p < 0.0001$), so 12-hour measurements were used in the analysis because they could be calculated for all wells in the sample, whereas some wells were tested for less than 24 hours and some did not stabilize.

Other Well Characteristics

Well depth and casing length were taken directly from well completion records. Uncased length was determined by subtracting casing length from total depth. All of the crystalline rock wells and some wells in the coastal plain are of open-hole construction, and in these wells uncased length is equal to the thickness of rock exposed in the well bore. In screened wells uncased length is equal to total screen height. In crystalline rock wells saprolite thickness is also approximately equal to casing length.

Data Analysis

The well data collected in this investigation were first examined using plots and descriptive statistics to identify patterns and relationships between variables. The predictive utility of the geologic and hydrologic variables was tested quantitatively by multiple linear regression, using overall and multiple-partial F-tests to evaluate statistical significance of models and groups of variables. All analyses were conducted using the SAS system.

RESULTS

Radon-222 concentrations were measured in 96 public water supply wells which were eligible to be included in this study according to the study criteria discussed above. Approximately equal numbers of wells were sampled in coastal plain sediments, gneisses, granites, mafic rocks, and metavolcanic rocks divided among nine geologic regions of the state, as shown in Table 1. All of the sampled wells are drilled wells, and all of the wells in the Piedmont and Blue Ridge regions are drilled through the saprolite layer into bedrock. Table 2 shows the types of water systems served by the sampled wells: most of the wells are used for municipal and subdivision water supplies, and the remainder serve trailer parks, schools, and other generally small water systems. Only one well was sampled in each separate water system.

Table 1. Number of Wells Sampled by Rock Type and Geologic Region

Geologic Region	Rock Type				
	Coastal Plain	Gneiss	Granite	Mafic	Metavolcanic
Blue Ridge	0	12	1	0	0
Charlotte Belt	0	0	2	14	0
Carolina Slate Belt	0	0	4	0	21
Durham Basin	0	0	0	2	0
Fall Line	1	0	1	0	0
Inner Piedmont	0	5	3	0	0
Inner Coastal Plain	12	0	0	0	0
Outer Coastal Plain	7	0	0	0	0
Raleigh Belt	0	3	7	1	0

Table 2. Type and Number of Water Supplies Sampled.

Type	Number	Percent
Municipal	28	29
School	13	14
Subdivision	32	33
Trailer Park	4	4
Other	19	20

Radon Concentrations

Radon-222 concentrations measured in the 96 wells range from 24 to 30711 pCi/l, with a median of 1005 pCi/l. The concentrations are approximately lognormally distributed with a sample geometric mean and geometric standard deviation of 843 pCi/l and 4 respectively. It should be emphasized, however, that this figure is derived from a sample with equal numbers of wells in each rock type and therefore is not a good estimate of the overall mean concentration of ^{222}Rn in North Carolina well water. Such an estimate would have to be based upon the actual proportion of all wells in each rock type.

The distribution of ^{222}Rn concentration in the wells is shown in Figure 5. It is conspicuously bimodal, with one cluster of measurements in the range of 100-500 pCi/l and another in the 1000-5000 pCi/l range. The highest concentrations (over 5000 pCi/l) are primarily in water from wells in granite and the lowest ones are from wells in the coastal plain (Figure 5). Differences in the average ^{222}Rn concentrations of water from the five rock types can be seen in Table 3.

Both arithmetic and geometric mean concentrations are given in Table 3. Radon-222 concentration is lognormally distributed within all rock types except gneisses and coastal plain sediments: concentrations in the gneiss group are approximately normally distributed, and observations from the coastal plain failed statistical tests for both normality and lognormality. Comparison of mean concentrations by rock type shows that coastal plain sediments have the lowest concentrations (geometric mean 204 pCi/l) and mafic and metavolcanic rocks are higher by a

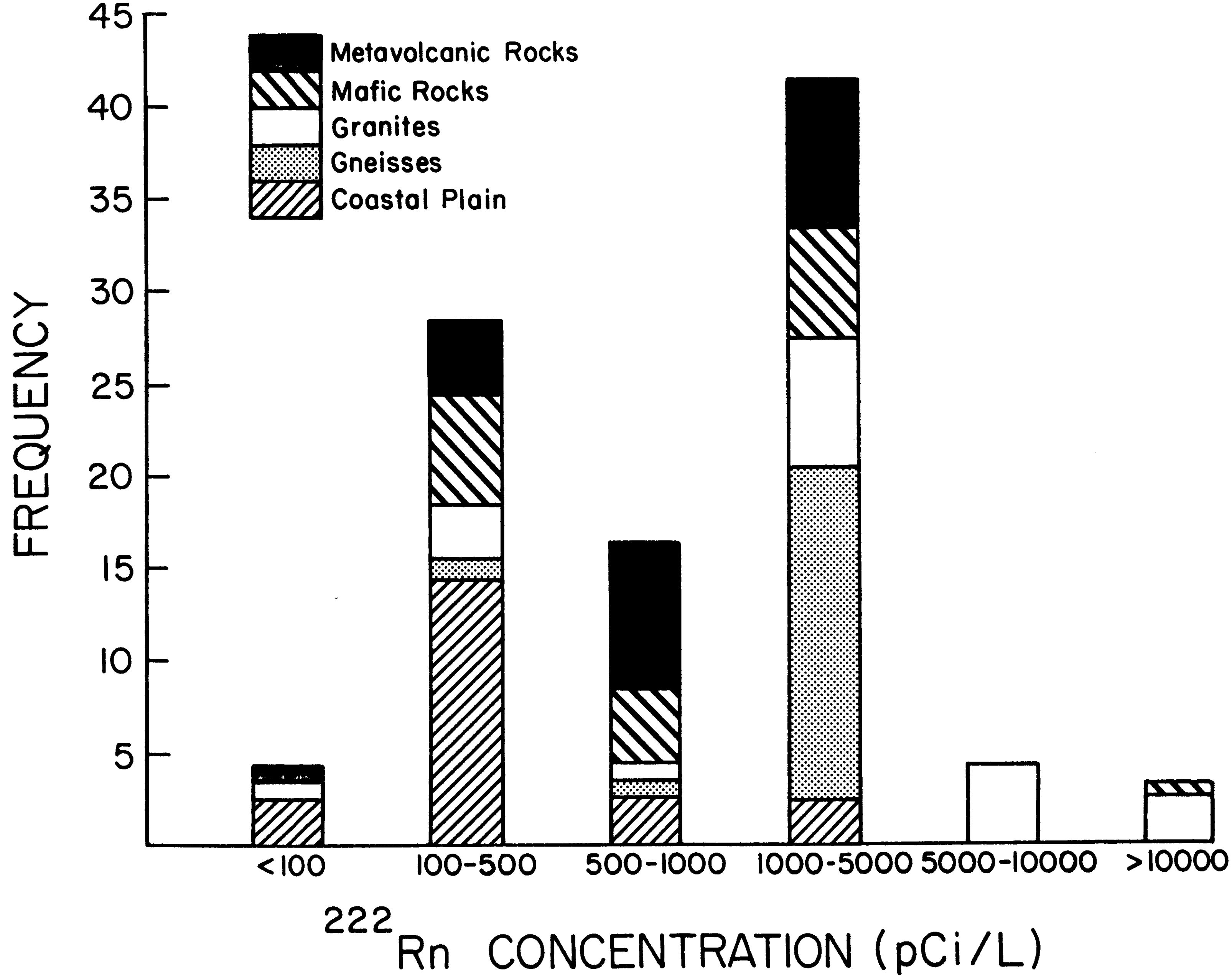

Figure 5. Radon-222 Concentration by Rock Type.

Table 3. Average ^{222}Rn Concentration (pCi/l) by Rock Type: $\bar{x}$ = Arithmetic mean, $\bar{x}g$ = Geometric Mean.

Rock Type	N	$\bar{x}$	$\bar{x}g$	Max	Min
Coastal Plain	20	354	204	2031	64
Gneiss	20	2416	2109	4107	274
Granite	18	5382	1614	30711	24
Mafic	17	1825	828	13269	104
Metavolcanic	21	1129	728	4679	88

factor of 3 to 5 (geometric means 828 and 728 pCi/l, respectively). The highest average ^{222}Rn concentrations are either in wells in granite or gneiss, depending upon whether the arithmetic or geometric mean is used for comparison. However, the mean for granites is reduced by a single low observation of 24 pCi/l (Table 3) and would probably be higher than the mean for genisses if that outlier was removed. The ranges of ^{222}Rn concentrations shown in Table 3 demonstrate that a high degree of concentration variability remains, even within rock types, and particularly for granites. This variability is shown clearly in Figures 6-10, which show the distribution of ^{222}Rn concentrations within rock types.

Measured ^{222}Rn concentrations for all the sampled wells, along with well location and well data, are given in the appendix.

Correlations

The overall correlation of ^{222}Rn concentration to the variables well discharge, specific capacity, depth, casing length, and uncased length is shown by the correlation coefficients and associated significance tests given in Table 4. The natural log of ^{222}Rn concentration is used here and in all further analyses to transform the distribution of the concentrations to one that is approximately normal. Both standard (Pearson) and non-parametric (Spearman) correlation coefficients, which are distribution-free, are given in Table 4 for comparison. The non-parametric approach is preferable here because several of the variables are not normally distributed.

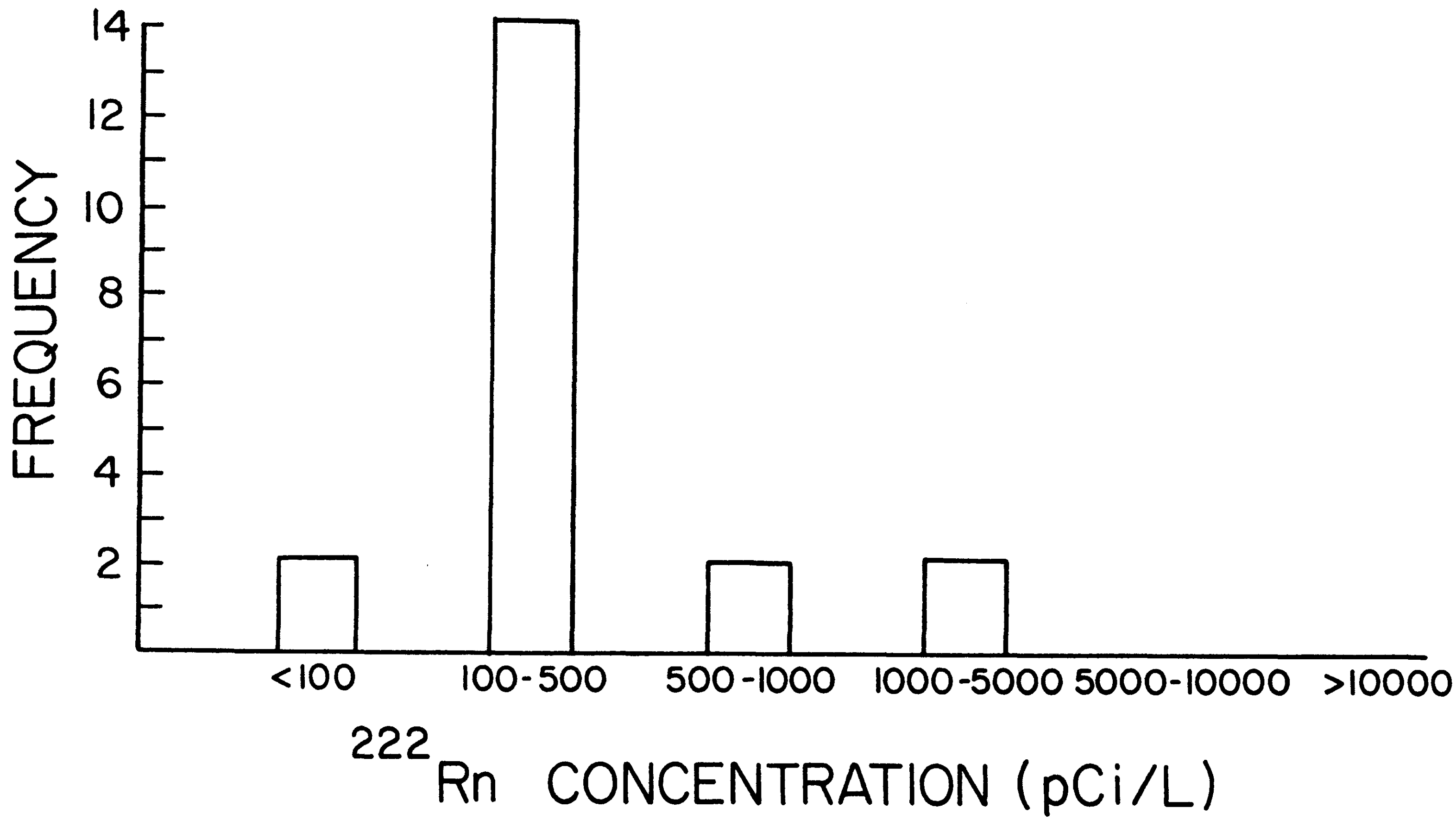

Figure 6. Radon-222 Concentration: Coastal Plain.

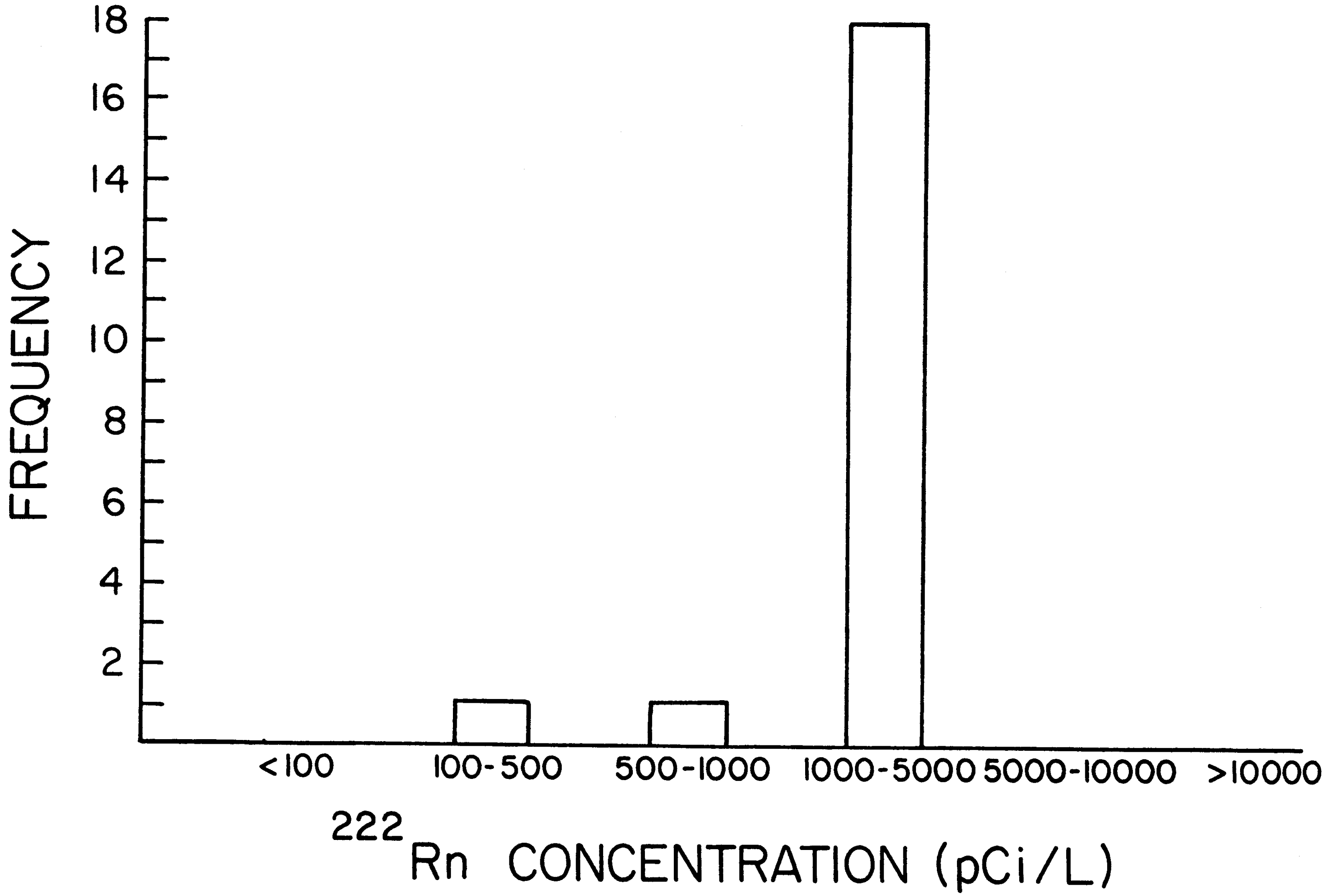

Figure 7. Radon-222 Concentration: Gneisses

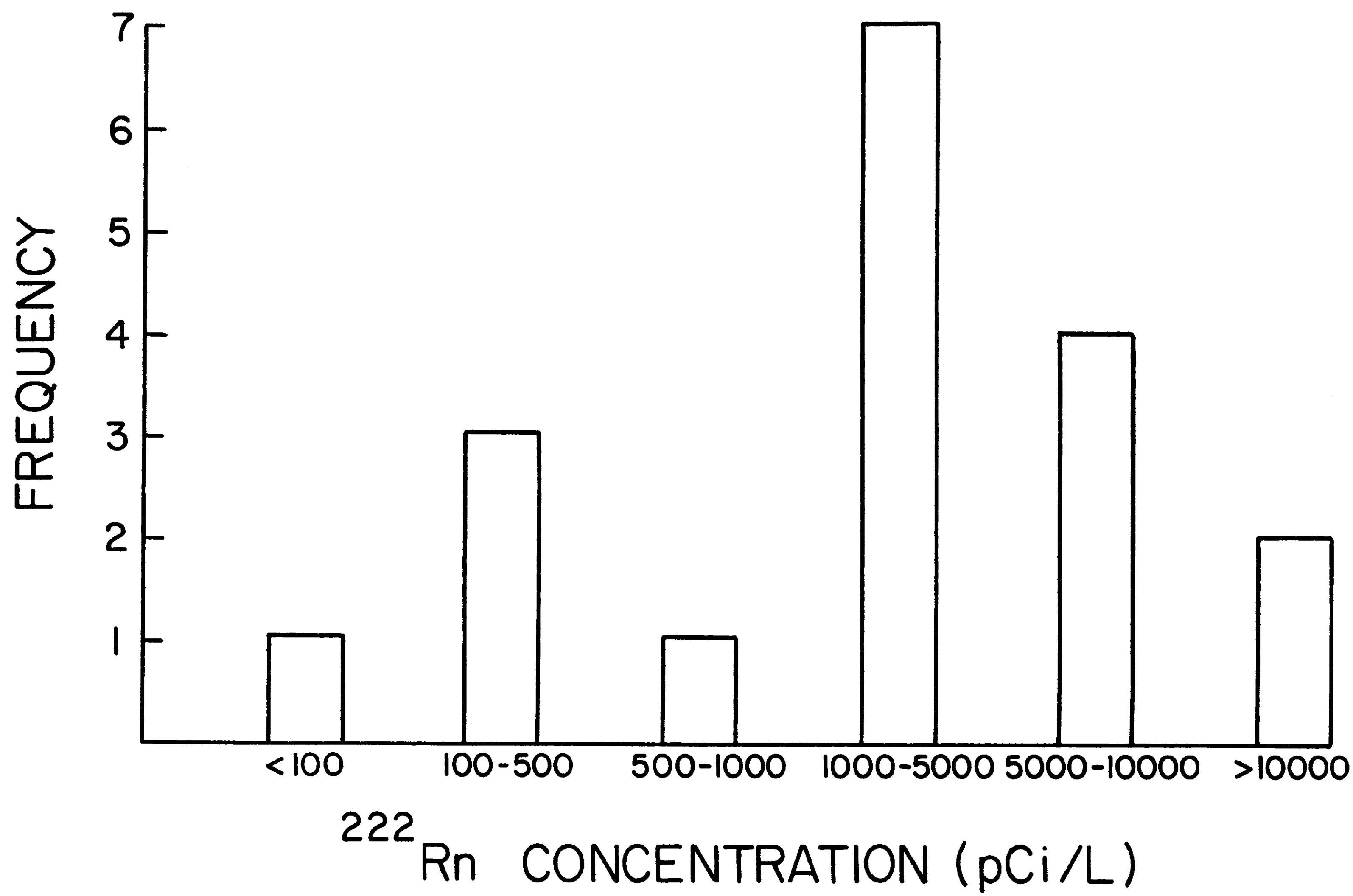

Figure 8. Radon-222 Concentration: Granites.

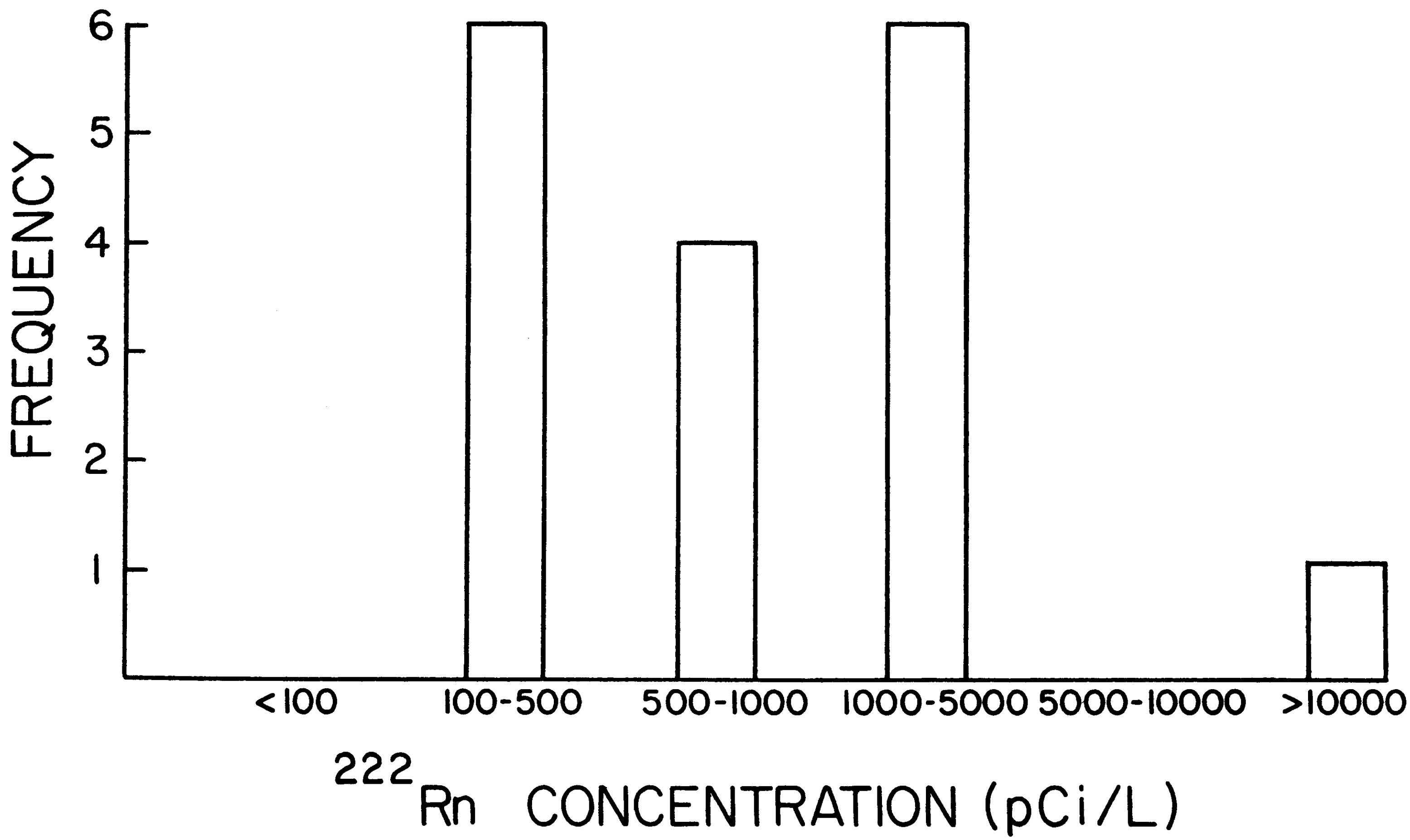

Figure 9. Radon-222 Concentration: Mafic Rocks.

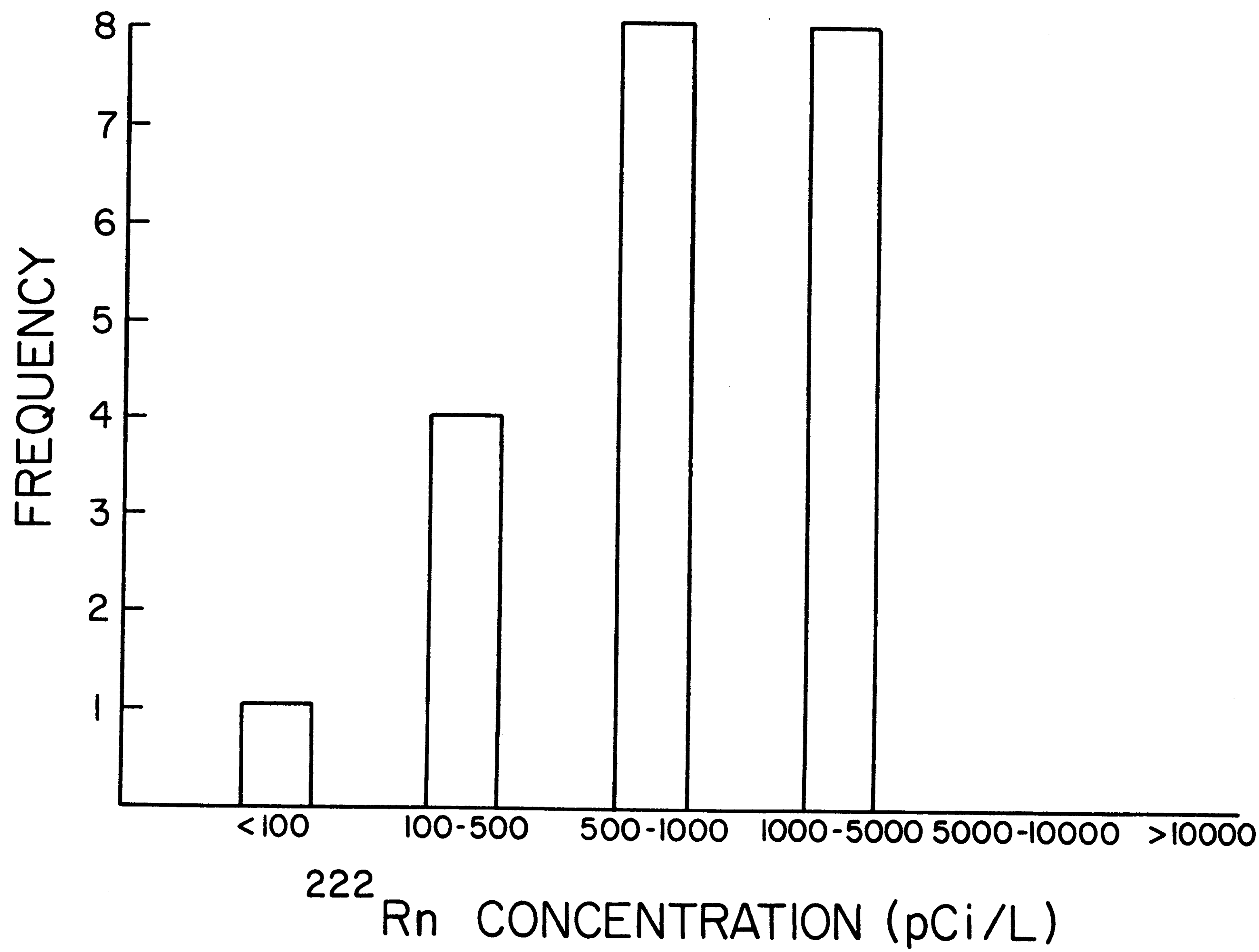

Figure 10. Radon-222 Concentration: Metavolcanic Rocks.

Table 4. Correlation of Variables.

Pearson Correlation Coefficients: r, p, n

	Discharge	Specific Capacity	Depth	Casing Length	Uncased Length
Log_e ^{222}Rn	-0.3835 0.0001 96	-0.1773 0.0890 93	0.1743 0.0894 96	-0.3386 0.0011 90	0.3490 0.0007 90
Discharge		0.5894 0.0001 93	0.1166 0.2578 96	0.7795 0.0001 90	-0.4032 0.0001 90
Specific Capacity			0.1470 0.1597 93	0.6416 0.0001 87	-0.3605 0.0006 87
Depth				0.2301 0.0291 90	0.7679 0.0001 90
Casing Length					-0.4466 0.0001 90

Spearman Correlation Coefficients: r, p, n

	Discharge	Specific Capacity	Depth	Casing Length	Uncased Length
Log_e ^{222}Rn	-0.2082 0.0418 96	-0.3121 0.0023 93	0.1739 0.0901 96	-0.0678 0.5255 90	0.3391 0.0011 90
Discharge		0.8116 0.0001 93	0.0571 0.5805 96	0.3094 0.0030 90	-0.2087 0.0484 90
Specific Capacity			-0.2034 0.0506 93	0.3209 0.0024 87	-0.5081 0.0001 87
Depth				0.2459 0.0195 90	0.7516 0.0001 90
Casing Length					-0.2937 0.0050 90

Log ^{222}Rn concentration is correlated with uncased length and negatively correlated with discharge using either parametric or non-parametric methods. Specific capacity is also negatively correlated with log ^{222}Rn concentration when using the preferred non-parametric method, but not using parametric methods. The reverse is true for casing length. These results suggest that discharge, uncased length, specific capacity, and perhaps casing length may be useful as predictors of ^{222}Rn concentration. Depth, in contrast, is not significantly correlated with log ^{222}Rn concentration using either method and appears to have little utility as a predictor of ^{222}Rn concentration. Similar correlation analyses were conducted within each rock type, but the coefficients were generally non-significant because of the small number in each group. This dilemma is circumvented in the next phase of analysis by examining the simultaneous association of ^{222}Rn with rock type and other variables.

Prediction of Radon Concentrations

To quantitatively test the utility of the study variables as predictors of ^{222}Rn concentration, we used multiple linear regression models, with log ^{222}Rn concentration as the dependent variable. Independent variables were the study variables rock type, discharge, specific capacity, casing length, and uncased length. We also included geologic region as an additional independent variable because of the importance, discussed above, of controlling for regional differences in rocks of the same type. Depth was omitted because it was not correlated with ^{222}Rn concentration in the preceding analysis.

Four separate regression models were fit to the data and tested statistically to determine which group of variables provides the best prediction of ^{222}Rn concentrations. The initial model tested the simultaneous influence of rock type, geologic region, and the four variables related to well characteristics. Regression coefficients and significance tests for the model are given in Table 5. The model is statistically significant overall, but the coefficients for discharge, specific capacity, casing length and uncased length are quite small and their effect on ^{222}Rn concentration is therefore correspondingly weak. None is statistically significant when considered individually. A simultaneous test of these four variables together was non-significant ($p > 0.25$), indicating that the variables discharge, specific capacity, casing length, and uncased length add no statistically detectable improvement to the ability to predict ^{222}Rn concentrations above that provided by rock type and geologic region together. This test is summarized in Table 6.

In subsequent tests both rock type and geologic region, taken separately, were found to be statistically significant predictors of ^{222}Rn concentration (Table 6). Adding geologic region significantly improved the model containing rock type only. However, adding rock type to a model already containing geologic region did nothing to statistically improve prediction even though the overall significance of the model was somewhat higher (Table 6). These last tests indicate that among the variables examined in this study ^{222}Rn concentrations are predicted best by either a combination of rock type and geologic region, or by

Table 5. Summary of Initial Regression Model Containing Rock Type, Geologic Region, and Hydrologic/Geologic Variables.

F for Overall Regression = 3.47, $p = 0.0002$

Model $R^2 = 0.44$

Variable	Coefficient	P-Value
Discharge	-0.002	0.31
Specific Capacity	0.009	0.76
Casing Length	0.0007	0.78
Uncased Length	0.0007	0.57

Table 6. Summary of Hypothesis Tests.

A. Joint significance test for discharge, specific capacity, casing length, uncased length, controlling for rock type and geologic region.

Multiple-Partial $F = 0.42$, $p > 0.25$

R^2 for model with rock type and geologic region only = 0.43

B. Significance test for rock type, controlling for geologic region.

Multiple-Partial $F = 1.54$, $p < 0.25$

R^2 for model with geologic region only = 0.42

C. Significance test for geologic region, controlling for rock type.

Multiple-Partial $F = 2.96$, $p < 0.05$

R^2 for model with rock type only = 0.34

D. Overall significance test for geologic region and rock type combined.

Overall $F = 5.97$, $p = 0.0001$

Model $R^2 = 0.46$

geologic region alone. Since none of the other variables was significant, expected ^{222}Rn concentrations for any well in this data set can be best represented by the mean ^{222}Rn concentration in each cell of a table which is cross-classified by rock type and geologic region (Table 7).

DISCUSSION

The range and the bimodal distribution of ^{222}Rn concentrations in the groundwater samples collected in this study are similar to those reported in North Carolina by previous investigators (Loomis, 1987b; Sasser and Watson, 1978; US EPA, 1982). The large variability in ^{222}Rn concentrations observed by these earlier investigators was also manifested in our data. We believe that the range of ^{222}Rn concentrations in North Carolina groundwater is now well established and that there are unlikely to be any undiscovered large areas where ^{222}Rn exposures are extremely high (in excess of 10,000 pCi/l).

Our quantitative analysis does not, however, "explain" in a mechanistic sense the reasons for large variations in the ^{222}Rn concentration of well water. Although we selected the variables discharge, specific capacity, depth, casing length, and uncased length for analysis because they measure properties that in theory or in other observational studies have been shown to influence ^{222}Rn concentration, we failed to find a strong effect by any of these variables on ^{222}Rn. In addition, none of the variables was statistically significant as a predictor of ^{222}Rn concentration when rock type and geologic region were also

Table 7. Average ^{222}Rn Concentration (pCi/l) by Rock Type and Geologic Region.

Region		Coastal Plain	Gneiss	Granite	Mafic	Metavolcanic	Total
				Rock Type			
Blue Ridge	Sample Size:		12	1	0	0	13
	Arithmetic Mean:		2074	3954			2219
	Geometric Mean:		1816	3954			1928
	Range:		274-3637	-			274-3954
Charlotte Belt		N/A	0	2	14	0	16
				1535	1978		1922
				1534	989		1044
				1502-1567	217-13269		217-13269
Carolina Slate Belt		N/A	0	4	0	21	25
				528		1129	1033
				283		728	626
				24-1084		88-4680	24-4680
Durham Basin		N/A	N/A	N/A	2	0	2
					1592		1592
					565		565
					104-3079		104-3079
Fall Line		1	0	1	0	0	2
		2031		1931			1981
		2031		1931			1980
		-		-			1931-2031
Inner Piedmont		N/A	5	3	0	0	8
			3190	3227			3204
			3105	565			1639
			2353-4107	119-9400			119-9400
Inner Coastal Plain		12	N/A	N/A	N/A	N/A	12
		248					248
		169					169
		64-787					64-787
Outer Coastal Plain		7	N/A	N/A	N/A	N/A	7
		297					297
		203					203
		105-1093					105-1093
Raleigh Belt		N/A	3	7	1	0	11
			2491	10876	149		7614
			2011	5951	149		3167
			712-3486	1183-30711	-		149-30711

considered. Our failure to find a relationship between ^{222}Rn concentration and the study variables does not mean that none exists. The results of statistical tests are a function of sample size and variance, and of the analytical methods used. Because the variance of the ^{222}Rn concentrations in this study (as in others in North Carolina) is quite high and the sample size only moderate, some relationships may have been missed that could, perhaps, have been detected in a larger or differently designed study. It should be noted, in addition, that ^{222}Rn measurements for this study were made during severe drought conditions in the summer of 1986, while the pump tests from which well parameters were calculated had been conducted previously. Other investigators, cited above, have reported changes in ^{222}Rn concentration with precipitation. Thus, the relationship of ^{222}Rn concentration to these previously measured factors may have been biased in a way that made it difficult to detect. Nevertheless, the small regression coefficients of these variables (Table 5) show that their effect on ^{222}Rn concentration is not strong, and we feel that they would provide relatively little information about ^{222}Rn concentration variations even if they were statistically significant.

The lack of a strong effect by other variables simplifies the task of prediction because it demonstrates that ^{222}Rn concentrations can be best characterized by geologic information that is readily available in the field and from geologic maps. Radon-222 concentration was predicted equally well by using geologic region alone, or a combination of geologic region and rock type. Geologic region has not been identified as a predictor of ^{222}Rn concentration in other studies, but it is clear that inter-region differences in geologic history may cause variations in rock properties that may be as great or greater than average differences among rock types. Like rock type, geologic region does not cause ^{222}Rn concentrations to change, but it can serve as a predictive variable because it measures many other factors, such as uranium concentration and geologic age, which may have an actual effect on ^{222}Rn concentration. We suggest that although geologic region alone is a statistically significant predictor of ^{222}Rn concentration, the most conceptually appropriate predictor is the combination of rock type and geologic region shown in Table 7. Information on rock type is easy to acquire, and rock type has been previously shown to be associated with large variations in ^{222}Rn concentration (Brutsaert et al., 1981; Loomis, 1987b). In spite of the statistical significance of rock type and geologic region as predictors in this analysis, the variability of ^{222}Rn concentrations within each category is still high (Table 7). Additional work could still be done to explain more of this variation. In addition, our information on the way in which ^{222}Rn concentrations within rock types differ by geologic region is incomplete. It can be seen in Tables 1 and 7 that several of the means in the rock type-geologic region cross-classification are based on small numbers. Additional work is needed to characterize ^{222}Rn concentrations in well water from these areas.

REFERENCES

Aldrich, LK, Sasser, MK and Conners, DA. "Evaluation of radon concentrations in North Carolina ground water supplies." North Carolina Department of Human Resources, Raleigh, NC. 1975.

Andrews, JN and Wood, DF. "Mechanism of radon release in rock matrices and entry into groundwaters." Institute of Mining and Metallurgy Transactions Sect. B. Vol. 81, No. 792, p. B198-209. 1972.

Asikainen, M and Kahlos, H. "Anomalously high concentration of uranium, radium, and radon in water from drilled wells in the Helsinki region." Geochimica et Cosmochimica Acta, Vol. 43, p. 1681-1686. 1979.

Baretto, PMC, Clark, RB and Adams, JAS,. "Physical characteristics of Rn-222 emanation from rocks, soil, and minerals: Its relation to temperature and alpha dose." in Adams, JAS, Lowder, WM and Gesell, TF, eds., Natural Radiation Environment II, p. 731-738, 1972.

Brutsaert, WF, Norton, SA, Hess, CT and Williams, JS. "Geologic and hydrologic factors controlling radon-222 in groundwater in Maine." Ground Water, Vol. 19, p. 407-417. 1981.

Butler, JR and Ragland, PC. "A petrochemical survey of plutonic intrusions in the Piedmont, Southeastern Appalachians, USA." Contributions in Mineralogy and Petrology, Vol. 24, p. 164-190. 1969.

Cothern, CR. US Environmental Protection Agency, Personal Communication to D.J. Crawford-Brown, Sept. 1985.

Cross, FT, Harley, NH and Hoffman, W. "Health effects and risks from ^{222}Rn in drinking water." Health Physics, Vol. 48, p. 649-670, 1985.

Fukui, M., Katsurayama, K. "Rn-222 content of groundwater in strata of the Plio-Pleisocene Osaka group in the Sennan Area, Japan." Journal of Hydrology, Vol. 60, p. 197-207, 1983.

Fullagar, PD. "Age and origin of plutonic intrusions in the Piedmont of the Southeastern Appalachians," Geological Society of America Bulletin Vol. 82, p. 2845-2862, 1971.

Gorgoni, C., Martinelli, G., Sighinolfi, GP. "Radon distribution in groundwater of the Po sedimentary basin (Italy)." Chemical Geology, Vol. 35, p. 297-309, 1982.

Heath, RC. "Basic elements of groundwater hydrology with reference to conditions in North Carolina." US Geological Survey Water Resources Open File Report of 80-44, 1980.

Hess, CT, Michel, J, Horton, TR, Prichard, HM and Coniglio, WA. "The occurrence of radioactivity in public water supplies in the United States." Health Physics, Vol. 48, p. 553-586, 1985.

Horton, TR. "Methods and results of EPA's study of radon in drinking water." U.S. Environmental Protection Agency, EPA 520/5-83-027, 1983.

Horton, TR. "Nationwide occurrence of radon and other natural radioactivity in public water supplies." US Environmental Protection Agency, EPA-520/5-85-008, 1985.

King, PT, Michel, J and Moore, WS. "Groundwater geochemistry of ^{228}Ra, ^{226}Ra, and ^{222}Rn." Geochimica et Cosmochimica Acta, Vol. 46, p. 1173-1182, 1982.

Lee, RD, Watson, JE and Fong, SW. "An assessment of radium in selected North Carolina drinking water supplies." Health Physics, Vol. 37, p. 777-779, 1979.

LeGrande, HE. "Groundwater resources of the Piedmont and Blue Ridge Provinces in the southeastern United States." US Geological Survey Information Circular 538, 1967.

Loomis, DP. "The relationship between water system size and ^{222}Rn concentration in North Carolina public water supplies." Health Physics, Vol. 52, p. 69-71, 1987a.

Loomis, DP. "Radon-222 concentration and aquifer lithology in North Carolina." Ground Water Monitoring Review, Vol. 7, 1987b (In Press).

Michel, J and Moore, WS. "Sources and behavior of natural radioactivity in fall line aquifers near Leesville, SC." Water Resources Research Institute Report, No. 83, Clemson University, Clemson, SC, 1980.

Mitsch, BF, Watson, JE and Hayes, JA. "A study of radium-226 and radon-222 concentrations in ground water near a phosphate mining and manufacturing facility with emphasis on the hydrogeologic characteristics of the area." Water Resources Research Institute Report No. 216, 1984.

Rama and Moore, WS. "Mechanism of transport of U-Th series radiosotopes from solids into groundwater." Geochimica et Cosmochimica Acta., Vol. 48, p. 395-399, 1984.

Rogers, JJW and Adams, JAS. "Uranium," in Wedepohl, KH, ed., Handbook of Geochemistry, Springer, Berlin, Chapter 92, 1969.

Research Planning Institute, Inc., "Statistical analysis of analytical methods for radionuclides in drinking water." Report to US Environmental Protection Agency, Office of Drinking Water, Washington, DC. 1986.

Sasser, MK and Watson, JE. "An evaluation of the radon concentration in North Carolina ground water supplies." Health Physics, Vol. 36, p. 667-671, 1978.

Snihs, JO. "The content of some natural radioactive elements, especially Rn-222, in some potable waters in Sweden." Nordic Hydrology, Vol. 4, p. 256-274, 1973.

Steinhauser, F. " Long-term measurements of ^{222}Rn, ^{220}Rn, ^{214}Pb and ^{212}Pb concentrations in the air of private and public buildings and their dependence on meteorological parameters." Health Physics, Vol. 29, p. 705-713, 1975.

Strain, CD, Watson, JE and Fong, SW. "An evaluation of radium-226 and radon-222 concentrations in ground and surface water near a phosphate mining and manufacturing facility." Health Physics, Vol. 37, p. 779-783, 1979.

Tanner, AB. "Physical and chemical controls on distribution of radium-226 and radon-222 in ground-water near Great Salt Lake, Utah," in Adams, JAS and Lowder, WM, eds. The Natural Radiation Environment. University of Chicago Press, Chicago, 1964a.

Tanner, AB. "Radon migration in the ground: a review." in Adams, JAS and Lowder, WM, eds., The Natural Radiation Environment, University of Chicago Press, Chicago, p. 161-190, 1964b.

U.S. Bureau of Reclamation. Ground Water Manual. Washington, D.C. 1977.

U.S. Environmental Protection Agency. Environmental Radiation Data Report 28, EPA 520/1-83-002, 1982.

Welby, CW and Wilson, TM. "Use of geologic and water yield data from ground water based community water systems as a guide for ground water planning and management." University of North Carolina Water Resources Research Institute Report 184, 1982.

APPENDIX: WELL DATA

Permit Number	County	Rn pCi/l	Rn σ pCi/l	Rock Type	Geologic Region	Discharge 12-HR gpm	Specific Capacity 12-HR gpm/ft	Depth ft	Casing Length ft
2303	Alamance	1084	47	GR	CSB	63.45	.5930	200	46
1299	Alamance	603	35	GR	CSB	19.02	.1045	240	27
593	Alamance	601	36	MV	CSB	9.91	.1077	140	20
1667	Alamance	128	16	MV	CSB	47.41	.9876	120	103
1980	Alamance	402	28	GR	CSB	60.08	.9849	300	55
2487	Bladen	127	17	CP	OCP	71.67	1.4052	143	133
2454	Bladen	259	24	CP	OCP	200.0	7.1429	450	405
2369	Bladen	125	17	CP	OCP	572.0	12.435	476	409
09-123-96	Brunswick	1093	45	CP	OCP	20.0	1.5385	55	24
2739	Buncombe	3637	95	GN	BR	44.67	.1175	505	97
1536	Buncombe	2507	74	GN	BR	4.72	.0241	360	57
1162	Cabarrus	993	44	MA	CB	100.00	1.4286	323	64
2426	Carteret	242	25	CP	OCP	773.83	51.589	375	325
	Chatham	3079	73	MA	DSB	7.04	.0301	300	38
383	Chatham	579	31	MV	CSB	18.9	.2032	300	28
1819	Cleveland	2559	77	GN	IP	100.07	1.3343	300	42
23-19-24	Columbus	127	15	CP	OCP	500.0	9.0909	310	287
2376	Columbus	105	14	CP	OCP	620.47	13.488	325	245
2462	Cumberland	787	40	CP	ICP	68.67	1.9074	78	38
2398	Cumberland	717	40	CP	ICP	60.0	2.8571	80	59
2437	Cumberland	447	31	CP	ICP	65.68	1.2631	89	73
1567	Cumberland	2031	61	CP	FL	42.24	.1427	400	129
918	Davie	485	32	MA	CB	27.63	.2093	305	40
919	Davie	217	24	MA	CB	42.55	.2626	285	21
2025	Davie	1502	54	GR	CB	29.29	.999	250	102
30-32-38	Duplin	102	16	CP	ICP	400.0	9.5238	275	240

Permit Number	County	Rn pCi/l	Rn σ pCi/l	Rock Type	Geologic Region	Discharge 12-HR gpm	Specific Capacity 12-HR gpm/ft	Depth ft	Casing Length ft
30-73-43	Duplin	107	16	CP	ICP	427.80	6.200	350	
	Durham	104	18	MA	DSB	68.99	1.1694	250	20
2591	Durham	812	43	MV	CSB	99.75	.4006	400	21
2422	Durham	785	43	MV	CSB	14.76	.0572	500	21
2326	Durham	1229	50	MV	CSB	12.26	.1552	200	21
2579	Durham	653	35	MV	CSB	13.09	.2379	260	21
61	Forsyth	4050	90	GN	IP	33.17	1.0699	500	31
83	Forsyth	9400	145	GR	IP	62.83	.4797	250	40
2459	Forsyth	2882	87	GN	IP	83.75	1.9034	205	
1102	Forsyth	1567	56	GR	CB	23.26	.1698	500	95
650	Forsyth	4188	90	MA	CB	200.33	1.3356	500	62
242	Franklin	30711	254	GR	RB	27.70	.1514	325	83
1552	Guilford	160	21	GR	IP	74.40	.5470	380	43
1324	Guilford	1271	53	MV	IP	145.95	2.2805	230	
1350	Guilford	119	17	GR	IP	9.16	.3159	175	29
1192	Halifax	1240	48	GR	RB	106.48	.9507	545	38
1364	Iredell	4107	94	GN	IP	124.17	1.7488	300	44
1985	Iredell	2353	69	GN	IP	63.02	63.02	505	
49-113-30	Jackson	1963	62	GN	BR	130.00	1.9697	470	43
50-184-0045	Johnston	1931	60	GR	FL	305.57	4.6601	260	51
2503	Lenoir	151	18	CP	ICP	510.51	10.01	384	324
56-155-38	Macon	274	26	GN	BR	31.18	.2759	350	49
2464	Mecklenburg	4679	101	MV	CSB	43.67	.1804	420	120
2438	Mecklenburg	715	38	MV	CSB	15.17	.1785	500	84
2110	Mecklenburg	665	37	MV	CSB	51.65	.3538	460	60
2014	Mecklenburg	1285	53	MA	CB	15.01	.0548	500	97
1610	Mecklenburg	4086	91	MV	CSB	56.08	.3642	460	100
1575	Mecklenburg	1550	59	MA	CB	75.01	4.1671	300	70

Permit Number	County	Rn pCi/l	Rn σ pCi/l	Rock Type	Geologic Region	Discharge 12-HR gpm	Specific Capacity 12-HR gpm/ft	Depth ft	Casing Length ft
1474	Mecklenburg	689	38	MA	CB	31.47	.1492	300	21
1396	Mecklenburg	321	27	MA	CB	70.00	2.4138	345	48
998	Mecklenburg	1316	59	MA	CB	30.00	.4000	270	126
997	Mecklenburg	719	39	MA	CB	62.30	.3520	320	23
2044	Mecklenburg	632	35	MA	CB	25.00	.1984	330	130
1040	Mecklenburg	328	26	MA	CB	24.08	2.1888	300	95
2078	Mecklenburg	1699	56	MA	CB	19.65	.0744	385	132
2144	Mecklenburg	13269	173	MA	CB	6.03	.0267	450	61
1669	Orange	1307	47	MV	CSB	50.00	.5210	300	28
498	Orange	427	28	MV	CSB	.50	0.3788	175	32
2681	Orange	139	17	MV	CSB	55.27	1.2015	180	42
1184	Orange	1842	64	MV	CSB	100.0	2.1739	400	55
2740	Orange	664	35	MV	CSB	104.76	1.0073	300	21
2615	Pitt	182	20	CP	ICP	387.82	4.5095	444	394
1564	Randolph	24	8	GR	CSB	102.03	.5967	330	29
297	Randolph	347	25	MV	CSB	120.34	.7917	350	51
494	Randolph	88	16	MV	CSB	35.88	.1250	440	26
2333	Robeson	107	16	CP	ICP	614.76	43.911	408	354
2738	Rowan	1675	60	MV	CSB	145.83	.7292	533	75
79-184-29	Rowan	1016	48	MV	CSB	72.35	.2804	600	100
2367	Sampson	111	17	CP	ICP	151.0	2.0133	206	
2403	Sampson	75	13	CP	ICP	58.99	3.9324	37	
1676	Surry	2531	78	GN	BR	81.98	.6405	315	73
1547	Surry	1527	55	GN	BR	47.61	.6706	245	101
1251	Surry	1818	69	GN	BR	35.98	.2351	300	73
686	Surry	1329	57	GN	BR	91.25		285	71
684	Surry	2151	73	GN	BR	48.38	.2103	305	85
2028	Surry	2664	74	GN	BR	26.00		300	90

Permit Number	County	Rn pCi/l	Rn σ pCi/l	Rock Type	Geologic Region	Discharge 12-HR gpm	Specific Capacity 12-HR gpm/ft	Depth ft	Casing Length ft
2029	Surry	1884	67	GN	BR	79.93	.3843	260	73
2031	Surry	3954	112	GR	BR	197.64	2.7450	215	31
2125	Surry	2605	75	GN	BR	27.51	.0611	555	24
548	Vance	6585	119	GR	RB	146.38	1.1901	260	33
1570	Wake	6403	118	GR	RB	22.23	.5053	59	40
	Wake	3274	76	GN	RB	25.66	.1929	300	45
91-716-152	Wake	149	20	MA	RB	29.65	.1306	300	42
407	Wake	24276	216	GR	RB	75.00	.7288	160	25
2247	Wake	1183	50	GR	RB	78.67	1.5733	195	48
2722	Wake	712	37	GN	RB	38.06	.1662	530	25
1985	Wake	3486	81	GN	RB	127.81	.9757	360	42
1666	Warren	5731	106	GR	RB	48.85	.3112	400	113
2571	Wayne	64	14	CP	ICP	76.23	1.5246	75	60
95-222-81	Wayne	129	16	CP	ICP	337.31	8.0311	155	112

Explanation of symbols

Rock Type

CP = Coastal Plain
GN = Gneiss
GR = Granite
MA = Mafic
MV = Metavolcanic

Geologic Region

BR = Blue Ridge
CB = Charlotte Belt
CSB = Carolina Slate Belt
DSB = Durham-Sanford Basin
FL = Fall Line
IP = Inner Piedmont
ICP = Inner Coastal Plain
OCP = Outer Coastal Plain
RB = Raleigh Belt