Hydrogeologic Controls on the Occurrence and Distribution of Radon-222 in Glacial Aquifers of Southern Rhode Island

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HYDROGEOLOGIC CONTROLS ON THE
OCURRENCE AND DISTRIBUTION OF
RADON-222 IN GLACIAL AQUIFERS
OF SOUTHERN RHODE ISLAND

BY

NICOLE C. RUDERMAN

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
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Abstract

A field study was conducted to evaluate the distribution of Radon ($^{222}$Rn) in the glacial aquifers of the Pawcatuck River Basin, Rhode Island. A total of 95 ground-water samples were collected from private wells in stratified-sediment and bedrock aquifers of the Upper Wood, Queen-Usquepaugh, and Chipuxet river basins. Gamma-ray (uranium, thorium, and potassium) emissions from the regolith material throughout the study area were measured. The ground-water samples were analyzed for basic chemical constituents as well as uranium and $^{222}$Rn to help evaluate the factors controlling $^{222}$Rn distribution. The granite of the Scituate Igneous Suite underlies the Upper Wood River and Queen-Usquepaugh aquifers. The granite gneiss of the Esmond Plutonic Suite underlies the Chipuxet and the Queen-Usquepaugh aquifers. The granite gneiss of the Sterling Plutonic Suite is found underlying the Upper Wood River aquifer. The uranium-bearing minerals (source of radon) found in the bedrock are zircon, allanite, sphene, and monazite. The average uranium content of the Esmond Gneiss is 1.9 ppm, Sterling Gneiss is 3.3 ppm, and Scituate Granite is 4.1 ppm (Nevins, 1991). All wells sampled in this study yielded radon levels above the proposed EPA limit of 300 pCi/L, with many being an order of magnitude or more greater. Wells in areas underlain by the Esmond Suite had the lowest radon content (range 500 to 30,400 pCi/L, median 1,400 pCi/L), areas underlain by the Sterling Suite were not significantly different but showed slightly higher concentrations (range 700 to 27,300 pCi/L, median 1,600 pCi/L), however, the areas underlain by the Scituate Suite had significantly higher levels (range 1,600 to 83,500 pCi/L, median 5,900 pCi/L).

Water chemistry factors play little if any role in influencing radon concentrations. High fluoride concentrations in ground water, however, indicate that the mineral fluorite is present in the underlying bedrock. Fluorite is commonly found with uranium-bearing minerals in A-type granites. The physical processes such as well yield and the siting of uranium are the controlling factors in the distribution of radon between surficial and bedrock wells. Bedrock aquifers exhibited higher radon concentrations than surficial-materials aquifers because surficial-materials aquifers have greater water-transmitting capacity, thus a greater volume of water to dilute the radon. Radon concentrations showed no correlation with the uranium content in the surficial material. However, higher radon levels in ground water correlate with
higher uranium contents in the underlying bedrock, therefore underlying bedrock uranium content is perhaps the most important factor in radon distribution. Although the EPA will most likely adopt a standard less rigorous than 300 pCi/L, this study reveals that much of the ground water in southern Rhode Island has elevated radon levels that may be cause for concern.
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Preface

This document is written in manuscript format, and consists of one manuscript. The manuscript follows the format used in the journal Ground Water. Supporting information is provided in the attached appendices.
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Introduction

Radon-222 (\(^{222}\text{Rn}\)) is a radioactive isotope with a half-life of 3.8 days. It is produced during the decay of uranium-238 to lead-206 (Figure 1). In an aquifer, radon-222 (hereafter radon) is ejected from the solid and into the adjacent pore space, mineral grain, or ground water (Wanty et al, 1993). Because of its short half-life and the relatively slow flow of ground water in most settings, radon is unlikely to be transported great distances in aquifers. Therefore, when high levels of radon are found in ground water, its source (uranium) is likely to be present in the surrounding rock or sediment. Previous studies, conducted in the United States, comparing radon in ground water to bedrock type and uranium content found higher ground-water radon concentrations in the bedrock containing the most uranium (Cothern and Smith, 1987; Hall et al, 1987; Nevins, 1991, Hollocher and Yuskaitis, 1993, and Folger et al, 1994). Because radon is undergoing nuclear disintegration when it decays, its concentration is reported as disintegrations per unit time. A becquerel (Bq) is one disintegration per second. Radioactivity in ground-water is usually reported as picocuries per liter (pCi/L); 1 pCi/L = 37 Bq/m\(^3\).

The United States Environmental Protection Agency (USEPA) has determined that elevated levels of radon gas in indoor air is the second leading cause of lung cancer, cigarette smoking being the number one cause. Several studies on indoor-air radon in homes with high radon concentrations in their domestic water supplies have shown that higher indoor-air radon concentrations correlate with indoor well-water use (Figure 2) (Hess et al, 1985; Lawrence et al, 1992; Wanty et al, 1992, and Folger et al, 1994). Approximately 1 to 7 percent of radon-related deaths are the result of radon that is released from well water during normal household activities (Cothern et al, 1986).

The health risk of radon in well water is not from direct ingestion, rather the degassing of radon into the indoor air poses the threat (Aieta et al, 1987; Cothern, 1987; Crawford-Brown, 1990). When radon is inhaled, it and its α-emitting daughter products (see Figure 1) deposit on the lung tissue. Therefore, prolonged inhalation of \(^{222}\text{Rn}\)-rich air can cause carcinogenesis in the lung tissue (National Research Council, 1988).
Figure 1. The uranium-238 decay series. The mode of decay and half-life of each isotope in series is shown (from Nevins, 1991).
At the 1983 National Workshop on Radioactivity in Drinking Water, a population-weighted average radon concentration in public water supplies serving less than 1,000 people was estimated at 780 pCi/L (Cothern and Smith, 1987). Because of the potential health threat of radon, the USEPA originally proposed a maximum contaminant level (MCL) of 300 pCi/L for radon in drinking water. This MCL was not accepted by Congress and is currently under revision.

The small public-water suppliers and private wells throughout the United States are in greater danger of high radon levels because many of these small, private supplies are wells located in the less productive crystalline rock aquifers. Large public-water supplies consist of surface water bodies. Furthermore, the time between extraction from the aquifer and actual water use is less than one half life of $^{222}\text{Rn}$ in private wells. The USEPA predicted higher radon concentrations in much of New England as...
compared to the rest of the United States (Cothren et al, 1987). In 1986, the Rhode Island Department of Environmental Management (RIDEM) initiated a statewide, private well water quality survey and radon was detected in each of the 310 private wells tested (RIDEM, 1990). If the USEPA were to adopt an MCL of 300 pCi/L for radon, over 90% of these Rhode Island wells would exceed the standard. Studies were also conducted on indoor-air radon concentrations throughout Rhode Island. Using composition of underlying bedrock, glacial deposit distribution, and indoor radon data collected by Rhode Islanders Saving Energy (RISE) program, Nevins (1991) made a geologic radon potential map of Rhode Island. This radon potential map of the state showed that Rhode Island has moderate to high radon potential according to EPA's criteria.

In addition to the uranium content of the underlying bedrock, radon concentration in well water is also a function of the physical properties of the rock and sediment comprising the aquifer. Previous investigations of ground-water radon potential in other states have found that several factors including uranium mineralization, fracture aperture in the underlying bedrock, and degree of metamorphism also impact radon concentrations of ground water (LeGrand, 1987; Wathen, 1987, Krishnaswami and Seidemann, 1988; Hollocher and Yuskaitis, 1993; and Peter Folger, Colorado School of Mines, Dept. of Geology and Geologic Engineering, written communication, 1994).

Ground water is the potable water source for approximately 24% of Rhode Island as a whole, and for 100% of southern Rhode Island. Previous studies of crystalline rocks underlying the state have found significant amounts of uranium (Nevins, 1991). Furthermore, much of the surficial material originated from this uranium-bearing granitic bedrock. Therefore, the potential for high levels of radon exists in wells in surficial material as well as in the underlying bedrock.

The purpose of this study was to try to understand the influence of hydrogeologic factors on the occurrence of radon. The field assessment included the following objectives:

- measurement of $^{222}$Rn levels and chemical composition of ground-water in wells screened in glacial material as well as bedrock;
- determination of the variability of $^{222}$Rn within the three-dimensional framework of the aquifer;
• evaluation of the factors controlling $^{222}$Rn levels, for example: uranium content in the underlying bedrock, depth to bedrock, and chemical evolution of the groundwater; and

• development of a conceptual model for the distribution of $^{222}$Rn in the aquifers of the Pawcatuck River Basin, Rhode Island.

**Study Area/Geology**

Rhode Island is located within the Avalon lithotectonic zone, a zone containing approximately 10 structurally and stratigraphically distinct bedrock units (Plate 1- modified after Hermes et al, 1994). The study area is the Pawcatuck River Basin, located in southern Rhode Island (Figure 3). The Hope Valley Shear Zone runs through the western portion of the study area and divides the Avalon zone into two distinct subterranes, the Esmond-Dedham subterrane to the east and the Hope Valley subterrane to the west. The member of the Hope Valley terrane of interest is the alaskite gneiss of the Sterling Plutonic Group, dating to the late Proterozoic, approximately 600 million years before present (MYP) (Hermes and Zartman, 1985). This alaskite gneiss is a quartz-rich granitic gneiss containing sodic plagioclase and microcline, with accessory hornblende, magnetite, biotite, muscovite, sphene, and zircon. The augen granite gneiss of the Esmond Igneous Suite is a late Precambrian (approximately 620 MYP), calcalkaline rock containing quartz, plagioclase, biotite, potassium feldspar, and accessory epidote, chlorite, muscovite, sphene, monazite, apatite, and zircon (Hermes and Zartman, 1985). The final bedrock type in this study area, a member of the Esmond-Dedham terrane, is the granite of the Scituate Igneous Suite, located in the northern portion of the study area. This granite is Devonian in age (approximately 370 MYP) and is composed of quartz, plagioclase, potassium feldspar, and accessory biotite, allanite, sphene, fluorite, calcic hornblende, calcite, and zircon (Hermes and Zartman, 1985).

The alaskite gneiss of the Sterling Plutonic Group and the augen granite gneiss of the Esmond Igneous Suite are I-type granites formed from hydrous melts on continental plate edges in island arc environments (Hermes and Zartman, 1992). The granite of the Scituate Igneous Suite is and A-type granite, an anhydrous granite formed from high temperature melts, containing fluorine, and formed in stable fold belts and tensional regimes in continental crust (Hermes and Zartman, 1992). A-type granites
Figure 3. Location of Queen-Usquepaugh, Chipuxet, and Upper Wood River aquifers and the other major aquifers in the Pawcatuck River basin and generalized surficial geology (modified from Johnston and Dickerman, 1985).
differ from I-type granites in that they are enriched in large, high field-strength elements (like uranium), I-type granites have lower quantities of these elements (Collins et al, 1982).

Crystalline rocks differ from unconsolidated deposits in that they have little primary permeability, and therefore water flow through these crystalline rocks is along fractures. Wells completed in these crystalline bedrock aquifers have lower yields than stratified-sediment aquifers, ranging from 0.5 to 80 (median 10) gallons per minute (Johnston and Dickerman, 1985, and Dickerman and Bell, 1993).

The three aquifers included in this study are the Upper Wood River, Queen-Usquepaugh, and Chipuxet. The Upper Wood River is underlain by the granite gneiss of the Sterling Plutonic Suite and the granite of the Scituate Igneous Suite. The Queen-Usquepaugh aquifer is underlain by the granite gneiss of the Esmond Plutonic Suite and the granite of the Scituate Igneous Suite. The Chipuxet aquifer is underlain solely by the granite gneiss of the Esmond Plutonic Suite (Plate 1). Uranium is distributed both syngenetically and epigenetically in these crystalline rocks (LeGrand, 1987). Syngenetic uranium distribution is along granite or pegmatite veins in igneous rocks or in large intrusive granite bodies.

Epigenetic occurrences are the result of uranium redistribution in metamorphic rocks. Because uranium has a high valence and large ionic radii it is not one of the elements in common rock-forming minerals. Instead, $^{238}\text{U}^{4+}$ is included in accessory minerals such as sphene, allanite, or zircon. In sphene or allanite, uranium substitutes for Ca$^{2+}$, and in zircon, it substitutes for Zr$^{4+}$. The uranium-bearing minerals found in the bedrock include zircon, allanite, sphene (titanite), and monazite. Epithermal neutron activation analysis indicated the average uranium content of the gneiss of the Esmond Plutonic Suite is 1.9 ppm (range 1.5 to 2.3 ppm), gneiss of the Sterling Plutonic Suite is 3.3 ppm (range 1.7 to 5.8 ppm), and granite of the Scituate Igneous Suite is 4.1 ppm (range 2.2 to 13.2 ppm) (Nevins, 1991). Gamma-ray emission data from bedrock outcrops show average uranium concentrations of 5.5 ppm (range 2 to 14 ppm) for the Esmond Gneiss, 5.0 ppm (range 3 to 9 ppm) for the Sterling Gneiss, and 7.2 ppm (range 3 to 20 ppm) for the Scituate Granite (Veeger and Hermes, University of Rhode Island, Geology Department, 1994, unpublished data).
The three aquifers that comprise this study are unconsolidated aquifers of glacial origin deposited in southward-trending bedrock valleys during the retreat of the late Wisconsinan ice sheet (Hughes, 1985). The sides of these valleys are bedrock highs covered with a thin deposit of till. Large braided meltwater streams from the glaciers at the head of the valleys flowed south, depositing sediment along the valley floors in a deltaic sequence. This glacio-fluvial/glacio-lacustrine environment created a strongly heterogeneous materials distribution. The glacial deposits in the valleys consist of fine- to coarse-grained sand, with some gravel and silt, derived from granitic igneous and metamorphic rocks to the north. A generalized geologic cross-section of the Chipuxet aquifer is provided in Figure 4. Deposition in the Upper Wood and Queen-Usquepaugh produced a similar accumulation of sediment. The sand and gravel deposits are parts of the stream, delta slope, and delta-plain sequences, whereas the silt, and fine-grained sand deposits are part of a lacustrine environment. The gravel at the base of the stratified deposits in the Chipuxet is a buried esker, or ice tunnel deposit (Jeff Campbell, University of Rhode Island, Dept. of Geology, written communication). The aquifers vary in thickness, ranging from less than 50 feet of saturated thickness to greater than 150 feet of saturated thickness in the deepest portions of the bedrock valleys. Ground-water flow in these unconfined aquifers is in a southerly direction through the porous granular material. Well yields from the stratified sediment deposits generally range from 100 to 900 gallons per minute (Johnston and Dickerman, 1985). These aquifers are complex, and in some areas vertical mixing between the bedrock and surficial material aquifers may occur.

**Approach and Methodology**

Ground-water samples were collected from the stratified-sediment and bedrock aquifers within the three river basins. Wells completed in shallow surficial material and those close to the bedrock surface were sampled to obtain information concerning the distribution of radon within the surficial material. The samples from the stratified-sediment deposits close to bedrock will either represent the more chemically evolved stratified-sediment aquifer ground water, or a mixture between the underlying bedrock ground water and that of the surficial material just above it. Ground-water samples within the underlying bedrock were taken to evaluate the radon potential of these uranium-bearing bedrock units.
Figure 4. Geologic cross-section A-A' of the Chipuxet River valley, Rhode Island. (Jeff Campbell, University of Rhode Island, Dept. of Geology, written communication).
A gamma-ray spectrometer was used to measure the amount of radioactivity in the regolith material that can be attributed to uranium, thorium, and potassium, three naturally occurring radioactive elements that produce gamma rays. These gamma-ray emission data may provide insight into the radon potential of the surficial material throughout the study area.

Well-log data, where available, were obtained from the United States Geological Survey (USGS)-Water Resources Division, Providence, Rhode Island. Information of interest included stratified-sediment aquifer material (sand or gravel, for example), depth to bedrock, and well yield.

Surveys were sent to homeowners throughout the Upper Wood River, Queen-Usquepaugh, and Chipuxet basin aquifers asking for well and aquifer information (Appendix A). Wells were chosen on the basis of this survey and spatial distribution relative to the underlying bedrock. Each well was screened for possible contamination using electrical conductance. According to Johnston and Dickerman (1985), background electrical conductivity values in the study area should be less than 100 µS/cm. Wells with less than 200 µS/cm specific conductance were preferred because they had the least amount of input from anthropogenic sources. Using the homeowner's well pump, ground-water samples were collected after 3-well volumes had been evacuated from each well, and pH, temperature, and electrical conductivity had stabilized. The standard sampling procedures and a field sheet are included in Appendices B and C. Field analyses included temperature, pH, electrical conductance, and dissolved oxygen.

In the Upper Wood River aquifer, 29 out of 37 wells were sampled within or above the gneiss of the Sterling Suite, the remaining 8 wells were sampled within or above the granite of the Scituate Suite (Plate 1). Most of the wells (16 out of 21) in the Queen-Usquepaugh were sampled within and above granite of the Scituate Suite, 5 wells were sampled from within and above gneiss of the Esmond Suite. A total of 37 wells were sampled in the Chipuxet aquifer from within and above gneiss of the Esmond Suite. Ground-water samples were collected for the following laboratory analyses: radon, uranium, alkalinity, calcium, magnesium, sodium, potassium, iron, manganese, silica, fluoride, chloride, nitrate, phosphate, and sulfate. All samples (except for radon) were filtered through 0.45 µm filters and stored at 4 °C in high-density polypropylene bottles. Samples collected for cation analysis were acidified with concentrated
hydrochloric acid and those collected for uranium analysis were acidified with concentrated nitric acid, both to a pH of 2.

Because of the volatility of radon gas, a sampling procedure developed by the USGS was followed when collecting the $^{222}\text{Rn}$ samples (Rich Wasty, United States Geological Survey, Denver Federal Center, written communication, 1993). First, the flow rate was reduced so no agitation existed in the discharging well water. A 10 ml sample of ground water was collected from inside the hose with a pipette prior to the water coming into contact with the atmosphere. The sample was then dispensed into a vial containing 10 ml of mineral oil-based liquid scintillation cocktail. The sample was immediately capped and shaken so as to partition the $^{222}\text{Rn}$ into the scintillator phase.

The radon samples were analyzed within three days of collection at the USGS National Water Quality Laboratory in Denver, Colorado. The uranium analyses were completed at the USGS National Water Quality Laboratory in Lakewood, Colorado. The manganese analyses were performed in the University of Rhode Island, Department of Civil Engineering, Environmental Engineering Laboratory. All other analyses were performed in the University of Rhode Island, Department of Geology, Hydrogeology Laboratory. A summary of analytical techniques and ion chromatography accuracy are included in Appendices D and E.

A total of 47 gamma-ray emission readings were taken from stratified-sediment and till in the three river valleys. These data were used to calculate $\%\text{K}$ (potassium), $e\text{U}$ (uranium), and $e\text{Th}$ (thorium) content of the materials.

**Results**

**Water Chemistry**

Chemical composition of the ground-water samples are included in Tables 1, 2, and 3. In order to define the background chemistry of each of the aquifers, wells with conductivities above 200 $\mu$S/cm, chloride above 30 mg/L, or nitrate above 20 mg/L were not included in the water chemistry interpretation.
Table 1. Well data for Queen-Usquepaugh ground-water sampling sites (in mg/L, except as noted).

| well n | screened material | yield (gallon/min.) | well type | well depth (ft) | depth to bedrock (ft) | bedrock type | temperature (°C) | conductivity (µS/cm) | pH | dissolved oxygen (pCi/L) | radon (pCi/L) | alkalinity (as CaCO₃) |
|--------|-------------------|---------------------|-----------|-----------------|----------------------|--------------|------------------|---------------------|-----|--------------------------|---------------|-----------------------|
| 1      | sand and gravel   | 0.7                 | surf-shal | 20              | 30                   | Eag          | 9.0              | 96                  | 4.4 | 6.0                      | 2600          | 0.4                   |
| 2      | fine-grained sand | 12                  | surf-shal | 12              | 19                   | Sg           | 7.8              | 226                 | 4.4 | 8.8                      | 3000          | 2.9                   |
| 3      |                    | 12                  | surf-shal | 10              | 15                   | Sg           | 4.9              | 40                  | 5.3 | 8.8                      | 3400          | 2.9                   |
| 4      | sand and gravel   | 0.25                | surf-shal | 10              | 10                   | Sg           | 6.8              | 43                  | 4.2 | 9.3                      | 15400         | 1.1                   |
| 5      | sand and gravel   | 12                  | surf-shal | 15              | 15                   | Sg           | 5.0              | 53                  | 5.0 | 5.7                      | 1600          | 1.3                   |
| 6      | fine-grained sand | 25                  | surf-deep | 77              | 100                  | Eag          | 9.5              | 42                  | 5.1 | 6.9                      | 700           | 6.8                   |
| 7      | sand               |                     | surf-deep | 58              | 60                   | Sg           | 7.0              | 79                  | 5.5 | 9.8                      | 10700         | 1.5                   |
| 8      | sand and gravel   | 35                  | surf-deep | 25              | 25                   | Sg           | 6.6              | 110                 | 5.6 | 9.0                      | 2400          | 4.2                   |
| 9      | fine-grained sand | 1.5                 | surf-deep | 25              | 25                   | Sg           | 4.0              | 104                 | 4.4 | 9.9                      | 3600          | 7.9                   |
| 10     | sand and gravel   | 20                  | surf-deep | 60              | 65                   | Sg           | 5.0              | 71                  | 5.2 | 4.3                      | 5900          | 11                    |
| 11     | sand and gravel   |                     | surf-deep | 20              | 25                   | Eag          | 8.0              | 72                  | 5.3 | 6.5                      | 6800          | 20                    |
| 12     | sand and gravel   | 2                   | bedrock   | 185             | 15                   | Eag          | 9.0              | 114                 | 5.4 | 7.4                      | 13900         | 22                    |
| 13     | bedrock           | 162                 | bedrock   | 162             | 25                   | Sg           | 8.5              | 81                  | 7.1 | 9.8                      | 8000          | 7.9                   |
| 14     | bedrock           | 400                 | bedrock   | 400             | 61                   | Sg           | 7.7              | 137                 | 6.3 | 4.9                      | 20000         | 39                    |
| 15     | bedrock           | 280                 | bedrock   | 280             | 60                   | Eag          | 8.2              | 104                 | 6.9 | 0.8                      | 16500         | 40                    |
| 16     | bedrock           | 360                 | bedrock   | 360             | 25                   | Sg           | 8.2              | 149                 | 5.4 | 0.7                      | 11300         | 48                    |
| 17     | bedrock           | 350                 | bedrock   | 350             | 28                   | Sg           | 6.7              | 163                 | 6.5 | 8.3                      | 18000         | 60                    |
| 18     | bedrock           | 177                 | bedrock   | 177             | 25                   | Sg           | 7.8              | 237                 | 6.3 | 7.6                      | 33500         | 42                    |
| 19     | bedrock           | 85                  | bedrock   | 85              | 25                   | Sg           | 6.0              | 128                 | 5.8 | 3.5                      | 82900         | 40                    |
| 20     | bedrock           | 200                 | bedrock   | 200             | 20                   | Sg           | 7.8              | 453                 | 5.3 | 8.5                      | 8500          | 2.2                   |

1 Eag: auger granite gneiss of the Esmond igneous suite; Sg: granite of the Scituate Igneous Suite.
Table 1 continued. Well data for the Queen-Usquepaugh ground-water sampling sites (in mg/L, except as noted).

| well # | uranium (ppb) | F  | Cl   | Br  | NO₃ | PO₄ | SO₄ | Na  | K  | Mg | Ca | Fe¹ | Mn  | SiO₂ | chrg. bal. error (%) | samples not incl. |
|--------|--------------|----|------|-----|-----|-----|-----|-----|----|----|----|-----|-----|------|----------------------|-------------------|
| 1      | 0.4          | 0.1| 11   | <1  | 20  | nd  | 5   | 8   | 1.2| 1.0| 3  | 0.1 | nd  | 13  | -5.9                | *                 |
| 2      | 1.0          | 0.3| 23   | <1  | 49  | nd  | 18  | 16  | 7  | 1.9| 12 | nd  | 0.3 | 16  | -4.7                | *                 |
| 3      | 0.3          | 0.1| 4    | nd  | <1  | 18  | 3   | 0.5| 0.4| 2  | 2  | nd  | 10  | -9.7               | *                 |
| 4      | 0.3          | 0.1| 8    | <1  | <1  | nd  | 6   | 4   | 0.3| 0.6| 2  | 0.1 | nd  | 8   | -5.3                | *                 |
| 5      | 1.0          | 0.8| 5    | <1  | <1  | nd  | 7   | 4   | 0.3| 0.5| 1  | nd  | nd  | 10  | -5.3                | *                 |
| 6      | 0.3          | 0.4| 6    | <1  | <1  | nd  | 7   | 4   | 0.3| 0.5| 2  | 2   | nd  | 10  | -7.5                | *                 |
| 7      | 0.2          | 0.1| 6    | <1  | 1   | nd  | 3   | 5   | 0.5| 0.3| 1  | nd  | nd  | 25  | -9.6                | *                 |
| 8      | 0.7          | 0.1| 12   | <1  | 2   | <1  | 9   | 8   | 0.7| 0.9| 3  | <1  | nd  | 12  | 1.3                 | *                 |
| 9      | 0.9          | 0.1| 17   | <1  | 2   | nd  | 16  | 11  | 0.8| 1.3| 5  | <1  | nd  | 11  | -5.3                | *                 |
| 10     | 0.3          | 0.1| 12   | <1  | 12  | nd  | 7   | 7   | 1.5| 1.2| 7  | nd  | nd  | 9   | -2.4                | *                 |
| 11     | 0.2          | 0.1| 6    | <1  | 2   | nd  | 9   | 6   | 0.5| 1.0| 3  | 1.1 | 0.1 | 12  | -4.9                | *                 |
| 12     | 14.3         | 0.8| 5    | <1  | <1  | nd  | 7   | 5   | 0.7| 0.5| 8  | <1  | nd  | 11  | -3.8                | *                 |
| 13     | 5.2          | 0.5| 10   | <1  | 4   | nd  | 9   | 8   | 0.7| 1.2| 9  | <1  | nd  | 16  | -3.3                | *                 |
| 14     | 0.2          | 0.1| 12   | <1  | <1  | <1  | 8   | 8   | 0.8| 1.0| 3  | <1  | nd  | 17  | -6.4                | *                 |
| 15     | 5.3          | 1.3| 10   | <1  | 1   | nd  | 10  | 8   | 1.0| 1.7| 16 | nd  | nd  | 17  | -1.3                | *                 |
| 16     | 9.7          | 1.3| 3    | <1  | <1  | <1  | 1   | 8   | 0.7| 1.4| 9  | nd  | nd  | 17  | -2.2                | *                 |
| 17     | 1.7          | 3.5| 4    | <1  | <1  | <1  | 9   | 15  | 1.2| 1.0| 15 | nd  | 0.8 | 30  | 2.2                 | *                 |
| 18     | 0.6          | 3.0| 4    | <1  | <1  | <1  | 6   | 15  | 0.5| 1.5| 20 | <1  | 0.3 | 26  | 2.6                 | *                 |
| 19     | 296          | 0.4| 15   | <1  | 40  | <1  | 6   | 11  | 1.2| 3.2| 20 | nd  | nd  | 23  | -3.2                | *                 |
| 20     | 0.7          | 3.4| 13   | <1  | <1  | nd  | 6   | 10  | 1.3| 0.9| 11 | 6   | 0.3 | 33  | -2.4                | *                 |
| 21     | 1.1          | 0.6| 120  | <1  | 7   | nd  | 9   | 70  | 1.6| 1.4| 6  | 0.6 | 0.3 | 10  | -4.4                | *                 |

¹ measured in the form of the uranyl ion.
² total dissolved.
³ charge balance error (in %).
⁴ samples not included in chemical analysis (*).
⁵ non detect.
Table 2. Well data for the Upper Wood ground-water sampling sites (in mg/L, except as noted).

| well # | screened yield (gallon/min.) | well type | well depth (ft) | depth to bedrock (ft) | bedrock type<sup>*</sup> | temperature (°C) | conductivity (µS/cm) | pH | dissolved oxygen (pCi/L) | alkalinity (CaCO₃) (mg/L) |
|--------|----------------------------|-----------|----------------|----------------------|--------------------------|------------------|---------------------|----|-------------------------|--------------------------|
| 22     | sand and gravel surf-shal  | 207       | 80             | HVa                  | 7.8                      | 104              | 4.2                 | 5.0 | 2400                    | 6.2                      |
| 23     | sand and gravel surf-shal  | 15         | 80             | HVa                  | 14.9                     | 172              | 4.9                 | 6.5 | 100                     | 4.4                      |
| 24     | sand and gravel surf-shal  | 23         | 80             | HVa                  | 10.0                     | 95               | 4.9                 | 3.6 | 1800                    | 8.1                      |
| 25     | sand and gravel surf-shal  | 10         | 50             | HVa                  | 12.5                     | 347              | 5.0                 | 3.5 | 1900                    | 34                       |
| 26     | sand surf-shal             | 20         | 50             | HVa                  | 10.0                     | 93               | 4.7                 | 1.5 | 1100                    | 2.4                      |
| 27     | gravel surf-shal           | 35         | 70             | HVa                  | 10.9                     | 71               | 5.0                 | 3.1 | 700                     | 2.6                      |
| 28     | sand and gravel surf-shal  | 25         | 45             | Sg                   | 9.8                      | 69               | 5.5                 | 9.4 | 2500                    | 9.7                      |
| 29     | sand and gravel surf-shal  | 20         | 60             | HVa                  | 10.9                     | 341              | 6.6                 | 10  | 2000                    | 7.9                      |
| 30     | sand and gravel surf-shal  | 18         | 45             | Sg                   | 11.9                     | 62               | 5.2                 | 1.3 | 1600                    | 9.2                      |
| 31     | sand surf-shal             | 15         | 25             | Sg                   | 13.9                     | 201              | 6.0                 | 0.3 | 3000                    | 14                       |
| 32     | sand surf-shal             | 16         | 20             | Sg                   | 11.9                     | 53               | 5.0                 | 2.8 | 2000                    | 6.2                      |
| 33     | sand surf-deep             | 30         | 40             | Sg                   | 10.0                     | 301              | 5.2                 | 9.3 | 3200                    | 5.9                      |
| 34     | sand surf-deep             | 39         | 60             | HVa                  | 9.1                      | 143              | 3.6                 | 8.7 | 700                     | 3.1                      |
| 35     | sand surf-deep             | 35         | 45             | HVa                  | 10.0                     | 650              | 5.9                 | 11  | 1600                    | 11                       |
| 36     | sand surf-deep             | 32         | 70             | HVa                  | 10.5                     | 83               | 5.1                 | 9.6 | 800                     | 7.7                      |
| 37     | sand and gravel surf-deep  | 96         | 100            | HVa                  | 12.0                     | 102              | 4.9                 | 0.6 | 1200                    | 8.4                      |
| 38     | sand and gravel surf-deep  | 65         | 65             | HVa                  | 11.0                     | 201              | 6.0                 | 11  | 1100                    | 37                       |
| 39     | sand and gravel surf-deep  | 30         | 70             | HVa                  | 10.5                     | 184              | 4.2                 | 8.2 | 800                     | 4.4                      |
| 40     | sand surf-deep             | 109        | 110            | HVa                  | 9.5                      | 133              | 5.0                 | 15  | 2500                    | 8.1                      |
| 41     | sand and gravel surf-deep  | 35         | 50             | HVa                  | 10.4                     | 280              | 5.3                 | 2.4 | 800                     | 0.4                      |
| 42     | sand and gravel surf-deep  | 50         | 60             | HVa                  | 8.5                      | 152              | 4.9                 | 11  | 1100                    | 6.4                      |
| 43     | sand and gravel surf-deep  | 60         | 60             | HVa                  | 9.0                      | 133              | 4.9                 | 12  | 1100                    | 5.3                      |
| 44     | sand and gravel surf-deep  | 39         | 60             | HVa                  | 12.2                     | 83               | 4.4                 | 10  | 800                     | 4.6                      |
| 45     | sand surf-deep             | 36         | 70             | HVa                  | 9.0                      | 287              | 5.2                 | 7.0 | 10000                   | 16                      |
| 46     | sand surf-deep             | 130        | 130            | HVa                  | 9.4                      | 55               | 7.4                 | 10  | 2500                    | 15                      |
| 47     | bedrock                    | 140        | 35             | HVa                  | 13.0                     | 165              | 6.8                 | 2.7 | 3000                    | 24                      |
| 48     | bedrock                    | 200        | 40             | Sg                   | 8.9                      | 140              | 6.8                 | 7.8 | 19100                   | 22                      |
| 49     | bedrock                    | 410        | 60             | HVa                  | 10.8                     | 113              | 7.2                 | 11  | 5700                    | 27                      |
| 50     | bedrock                    | 97         | 60             | HVa                  | 10.0                     | 98               | 5.7                 | 11  | 4700                    | 20                      |
| 51     | bedrock                    | 71         | 18             | Sg                   | 9.0                      | 131              | 5.3                 | 0.4 | 39700                   | 26                      |
| 52     | bedrock                    | 425        | 130            | HVa                  | 10.3                     | 110              | 7.2                 | 3.8 | 5900                    | 25                      |
| 53     | bedrock                    | 140        | 120            | HVa                  | 9.0                      | 60               | 7.2                 | 7.1 | 17300                   | 18                      |
| 54     | bedrock                    | 106        | 60             | HVa                  | 9.7                      | 107              | 5.4                 | 8.5 | 27300                   | 20                      |
| 55     | bedrock                    | 325        | 70             | HVa                  | 10.0                     | 104              | 5.4                 | 5.8 | 17800                   | 32                      |
| 56     | sand and gravel surf-deep  | 35         | 30             | HVa                  | 10.0                     | 75               | 7.1                 | 7.4 | 10000                   | 17                      |
| 57     | till                       | 14         | 20             | HVa                  | 13.0                     | 57               | 5.3                 | 8.3 | 1800                    | 11                      |
| 58     | till                       | 20         | 20             | Sg                   | 12.0                     | 84               | 4.4                 | 11  | 14000                   | 4.0                      |

<sup>*</sup>Sg- granite of the Scituate Igneous Suite; HVa- alaskite gneiss of the Sterling Plutonic Group.
Table 2 continued. Well data for the Upper Wood ground-water sampling sites (in mg/L except as noted).

| well | uranium (ppb)
|------|-----------------|
| 22   | 0.5             |
| 23   | 0.3             |
| 24   | 0.3             |
| 25   | 0.3             |
| 26   | 0.3             |
| 27   | 0.3             |
| 28   | 0.6             |
| 30   | 0.3             |
| 31   | 0.3             |
| 32   | 0.4             |
| 33   | 0.3             |
| 34   | 0.5             |
| 35   | 0.4             |
| 36   | 0.3             |
| 37   | 0.6             |
| 38   | 0.3             |
| 39   | 0.3             |
| 40   | 0.3             |
| 41   | 0.2             |
| 42   | 0.3             |
| 43   | 0.3             |
| 44   | 0.3             |
| 45   | 0.3             |
| 46   | 0.8             |
| 47   | 0.3             |
| 48   | 0.3             |
| 49   | 0.3             |
| 50   | 0.3             |
| 51   | 0.6             |
| 52   | 13.0            |
| 53   | 2.3             |
| 54   | 12              |
| 55   | 4.8             |
| 56   | 0.9             |
| 57   | 0.3             |
| 58   | 0.3             |

| F   | Cl  | Br  | NO₃ | PO₄ | SO₄ | Na  | K   | Mg  | Ca  | Fe  | Mn  | SiO₂ | chrg. bal. error (%) | samples not incl. |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|----------------------|--------------------|
| 20  | <1  | 6   | nd  | 7   | 11  | 1.1 | 1.1 | 4   | nd  | nd  | 11  | -3.3                |                    |
| 35  | <1  | 6   | nd  | 6   | 21  | 1.0 | 0.6 | 6   | <1  | nd  | 8   | -1.2                |                    |
| 17  | <1  | 3   | nd  | 7   | 10  | 0.8 | 1.0 | 4   | <1  | nd  | 9   | -5.0                |                    |
| 35  | <1  | 0.1 | 7   | <1  | 8   | 25  | 5   | 2.4 | 30  | nd  | 13  | -3.3                |                    |
| 22  | <1  | 0.1 | 22  | <1  | 5   | 10  | 1.0 | 4   | <1  | nd  | 0.3 | 15  | 0.8                 |                    |
| 9   | <1  | 13  | nd  | 7   | 6   | 1.3 | 0.9 | 5   | <1  | nd  | 9   | -6.5                |                    |
| 7   | <1  | 0.1 | 6   | <1  | 6   | 5   | 0.7 | 0.9 | 4   | <1  | nd  | 10  | -7.0                |                    |
| 6   | <1  | 0.1 | 10  | <1  | 9   | 40  | 1.1 | 1.5 | 9   | nd  | 15  | -0.4                |                    |
| 5   | <1  | 0.2 | 9   | <1  | 5   | 6   | 0.8 | 0.4 | 3   | 0.5 | 1   | 10  | -3.6                |                    |
| 45  | <1  | 0.2 | 45  | <1  | 6   | 23  | 1.6 | 1.1 | 7   | 0.3 | 1   | 12  | -3.8                |                    |
| 4   | <1  | 0.2 | 4   | <1  | 6   | 5   | 0.9 | 0.4 | 2   | 2   | 0.1 | 19  | 5.7                 |                    |
| 31  | 0.1 | 71  | <1  | 8   | nd  | 14  | 2.0 | 0.9 | 3   | nd  | nd  | 12  | -2.9                |                    |
| 12  | 0.2 | 38  | <1  | 3   | nd  | 6   | 2.1 | 2.3 | 7   | nd  | nd  | 14  | -5.3                |                    |
| 7   | <1  | 3   | nd  | 7   | 4   | 0.7 | 0.9 | 4   | nd  | nd  | 13  | -6.4                |                    |
| 17  | <1  | 8   | nd  | 9   | 5   | 0.8 | 1.1 | 5   | nd  | nd  | 11  | -6.3                |                    |
| 0.2 | <1  | 3   | nd  | 9   | 9   | 0.0 | 0.8 | 3   | 4   | 2   | 8   | 4.8                 |                    |
| 30  | <1  | 30  | nd  | 12  | 12  | 1.2 | 1.8 | 9   | <1  | nd  | 16  | -3.6                |                    |
| 9   | <1  | 25  | 0.2 | 9   | nd  | 10  | 1.5 | 0.6 | 3   | 14  | 0.4 | 22  | 5.7                 |                    |
| 7   | <1  | 17  | nd  | 5   | 40  | 0.3 | 0.4 | 2   | 3   | 0.5 | 7   | 2.2                 |                    |
| 8   | <1  | 15  | nd  | 8   | 8   | 1.0 | 0.7 | 3   | 0.1 | nd  | 8   | -5.1                |                    |
| 11  | <1  | 53  | nd  | 20  | 21  | 1.3 | 1.2 | 15  | nd  | 0.1 | 17  | -3.0                |                    |
| 3   | <1  | 6   | nd  | 1.1 | 0.4 | 4   | 0.1 | nd  | 23  | -7.4|                |                    |
| 24  | <1  | 3   | nd  | 3   | 5   | 1.1 | 0.4 | 4   | 0.1 | nd  | 24  | -2.5                |                    |
| 19  | <1  | 3   | nd  | 0.1 | 6   | 10  | 2.4 | 1.4 | 14  | <1  | nd  | 24  | -3.7                |                    |
| 11  | <1  | 9   | nd  | 9   | 9   | 1.1 | 0.9 | 9   | <1  | nd  | 12  | -3.6                |                    |
| 12  | <1  | 5   | nd  | 5   | 8   | 0.9 | 0.8 | 7   | <1  | nd  | 22  | -5.3                |                    |
| 10  | <1  | 15  | nd  | 10  | 12  | 0.6 | 0.6 | 6   | <1  | 0.2 | 24  | -3.0                |                    |
| 6   | <1  | 2   | nd  | 2   | 6   | 0.6 | 0.3 | 4   | 0.1 | nd  | 21  | -6.9                |                    |
| 12  | <1  | 6   | nd  | 2   | 10  | 1.0 | 0.8 | 8   | <1  | nd  | 26  | -3.6                |                    |
| 7   | <1  | 9   | nd  | 9   | 9   | 1.1 | 0.9 | 9   | <1  | nd  | 19  | -6.5                |                    |
| 3   | <1  | 4   | nd  | 5   | 6   | 0.9 | 0.9 | 4   | <1  | nd  | 19  | -9.5                |                    |
| 12  | <1  | 13  | nd  | 7   | 7   | 2.1 | 0.9 | 3   | 0.4 | 0.1 | 12  | -4.2                |                    |

* measured in the form of the uranyl ion.
* total dissolved.
* charge balance error (in %).
* samples not included in chemical analysis (*).
* non detect.
### Table 3. Well data for the Chipuxet ground-water sampling sites (in mg/L, except as noted).

| Well # | screened material | yield (gallon/min.) | well type | well depth (ft) | depth to bedrock (ft) | bedrock type | temperature (°C) | conductivity (µS/cm) | pH | dissolved oxygen | radon | alkalinity (as CaCO₃) |
|--------|-------------------|---------------------|-----------|----------------|----------------------|--------------|------------------|---------------------|-----|-----------------|-------|---------------------|
| 59     | sand              | surf-shal           | 6.1       | 90             | Eag                  | 7.0          | 132              | 5.4                 | 4.5 | 1000           | 11    | 11                  |
| 60     | sand and gravel   | surf-shal           | 18        | 190            | Eag                  | 11.1         | 222              | 5.1                 | 4.2 | 1200           | 3.3   |                     |
| 61     | sand              | surf-shal           | 19        | 180            | Eag                  | 9.3          | 53               | 4.5                 | 7.1 | 1200           | 6.6   |                     |
| 62     | sand              | surf-shal           | 22        | 190            | Eag                  | 10.2         | 123              | 5.1                 | 3.6 | 1200           | 7.7   |                     |
| 63     | sand and gravel   | surf-shal           | 20        | 200            | Eag                  | 11.6         | 128              | 4.2                 | 8.3 | 900             | 0.2   |                     |
| 64     | sand and gravel   | surf-shal           | 20        | 100            | Eag                  | 11.1         | 134              | 4.4                 | 3.5 | 900             | 3.7   |                     |
| 65     | sand and gravel   | surf-shal           | 20        | 190            | Eag                  | 11.4         | 158              | 4.8                 | 0.9 | 600             | 5.7   |                     |
| 66     | sand and gravel   | surf-shal           | 19        | 180            | Eag                  | 11.2         | 141              | 4.3                 | 2.9 | 1100           | 7.5    |                     |
| 67     | sand and gravel   | surf-shal           | 18        | 190            | Eag                  | 8.4          | 103              | 4.1                 | 8.2 | 500             | 5.3    |                     |
| 68     | sand and gravel   | surf-shal           | 14        | 190            | Eag                  | 11.0         | 93               | 4.5                 | 8.8 | 1000           | 2.6    |                     |
| 69     | sand and gravel   | surf-shal           | 20        | 210            | Eag                  | 10.4         | 269              | 4.0                 | 8.2 | 500             | 1.1    |                     |
| 70     | sand and gravel   | surf-shal           | 22        | 200            | Eag                  | 10.0         | 175              | 5.3                 | 9.2 | 1900           | 0.4    |                     |
| 71     | sand and gravel   | surf-shal           | 14        | 190            | Eag                  | 9.5          | 104              | 5.9                 | 3.0 | 900             | 4.8    |                     |
| 72     | sand and gravel   | surf-deep           | 150       | 150            | Eag                  | 13.0         | 122              | 4.5                 | 8.5 | 1100           | 6.4    |                     |
| 73     | sand              | surf-deep           | 150       | 150            | Eag                  | 10.8         | 172              | 4.8                 | 4.7 | 1400           | 3.3    |                     |
| 74     | sand              | surf-deep           | 37        | 190            | Eag                  | 12.2         | 89               | 4.4                 | 4.8 | 1400           | 1.1    |                     |
| 75     | sand              | surf-deep           | 35        | 190            | Eag                  | 9.4          | 54               | 4.6                 | 9.1 | 1400           | 4.0    |                     |
| 76     | sand and gravel   | surf-deep           | 75        | 100            | Eag                  | 9.4          | 135              | 4.6                 | 8.8 | 2000           | 13     |                     |
| 77     | sand              | surf-deep           | 33        | 190            | Eag                  | 11.0         | 87               | 4.3                 | 0.8 | 1800           | 8.4    |                     |
| 78     | sand              | surf-deep           | 30        | 80             | Eag                  | 10.0         | 93               | 4.2                 | 8.9 | 900             | 4.6    |                     |
| 79     | sand              | surf-deep           | 30        | 80             | Eag                  | 9.1          | 107              | 4.1                 | 8.8 | 600             | 4.4    |                     |
| 80     | sand              | surf-deep           | 28        | 190            | Eag                  | 10.0         | 135              | 6.7                 | 6.1 | 2000           | 50     |                     |
| 81     | sand              | surf-deep           | 65        | 180            | Eag                  | 10.0         | 135              | 6.7                 | 6.1 | 2000           | 50     |                     |
| 82     | bedrock           | bedrock             | 435       | 80             | Eag                  | 10.0         | 121              | 6.8                 | 8.6 | 3200           | 41     |                     |
| 83     | bedrock           | bedrock             | 500       | 95             | Eag                  | 11.0         | 87               | 7.0                 | 0.8 | 13600          | 41     |                     |
| 84     | bedrock           | bedrock             | 125       | 70             | Eag                  | 9.1          | 62               | 5.2                 | 11  | 9500           | 20     |                     |
| 85     | bedrock           | bedrock             | 200       | 30             | Eag                  | 8.0          | 64               | 4.9                 | 12  | 4800           | 3.5     |                     |
| 86     | bedrock           | bedrock             | 150       | 18             | Eag                  | 9.4          | 106              | 5.4                 | 6.4 | 7400           | 22     |                     |
| 87     | bedrock           | bedrock             | 150       | 100            | Eag                  | 10.0         | 321              | 5.6                 | 3.8 | 4600           | 17     |                     |
| 88     | bedrock           | bedrock             | 200       | 190            | Eag                  | 9.5          | 95               | 5.5                 | 0.7  | 1200           | 18     |                     |
| 89     | bedrock           | bedrock             | 350       | 100            | Eag                  | 10.0         | 75               | 6.7                 | 2.8  | 30400          | 24     |                     |
| 90     | bedrock           | bedrock             | 360       | 30             | Eag                  | 10.2         | 147              | 5.8                 | 8.5  | 3700           | 47     |                     |
| 91     | bedrock           | bedrock             | 152       | 18             | Eag                  | 9.2          | 103              | 5.3                 | 6.6  | 1500           | 11     |                     |
| 92     | bedrock           | bedrock             | 120       | 70             | Eag                  | 8.8          | 55               | 5.1                 | 11  | 3700           | 4.0     |                     |
| 93     | bedrock           | bedrock             | 500       | 190            | Eag                  | 11.0         | 132              | 7.0                 | 0.4  | 6000           | 37     |                     |
| 94     | till              | till                | 90        | 90             | Eag                  | 8.5          | 54               | 4.7                 | 12  | 3800           | 13     |                     |
| 95     | till              | till                | 12        | 20             | Eag                  | 9.7          | 41               | 3.9                 | 8.7  | 3000           | 2.0     |                     |

1) Eag- augen granite gneiss of the Esmond Igneous Suite.
Table 3 continued. Well data for the Chipxuel ground-water sampling sites (in mg/L, except as noted).

| well | uranium (ppb) | F | Cl | Br | NO₃ | PO₄ | SO₄ | Na | K | Mg | Ca | Fe* | Mn | SiO₂ | chrg. Bal. error (%) | samples not incl.* |
|------|---------------|---|----|----|-----|-----|-----|----|---|----|----|-----|----|------|------------------|------------------|
| 59   | 0.1           | nd | 13 | <1 | 3   | nd  | 23  | 5  | 2.3| 2.4| 11 | nd  | nd  | nd  | 16  | -5.5             |                   |
| 60   | 0.2           | nd | 33 | 0.1| 25  | nd  | 19  | 21 | 3.9| 2.7| 8  | <1  | 0.1 | 12  | -5.2            |                   |
| 61   | 2.8           | 0.1| 7  | <1 | <1  | 6   | 5   | 0.6| 0.5| 8  | <1  | nd  | 15  | 0               |                   |
| 62   | 0.3           | nd | 12 | <1 | 10  | nd  | 20  | 7  | 2.2| 1.8| 3  | nd  | nd  | 7    | -5.1             |                   |
| 63   | 0.2           | 0.1| 22 | <1 | 17  | nd  | 9   | 15 | 2.7| 0.6| 4  | nd  | <1  | 10   | -5.2             |                   |
| 64   | 0.2           | 0.1| 15 | 0.1| 10  | nd  | 18  | 6  | 1.9| 0.2| 4  | <1  | 0.1 | 15   | -5.1             |                   |
| 65   | 0.6           | 0.1| 26 | 0.1| 15  | nd  | 19  | 12 | 3.3| 2.1| 10 | <1  | 0.1 | 15   | -4.0             |                   |
| 66   | 0.3           | nd | 13 | 0.1| 21  | nd  | 16  | 9  | 3.5| 1.4| 10 | nd  | nd  | 8    | -4.0             |                   |
| 67   | 0.3           | nd | 20 | 0.1| 9   | nd  | 15  | 9  | 3.0| 1.2| 8  | nd  | nd  | 12   | -4.0             |                   |
| 68   | 0.2           | nd | 35 | <1 | 30  | nd  | 18  | 30 | 5.9| 0.8| 4  | nd  | 0.3 | 10   | -4.0             |                   |
| 69   | 0.3           | 0.1| 17 | <1 | 3   | nd  | 9   | 9  | 1.9| 0.5| 4  | nd  | nd  | 9    | -4.0             |                   |
| 70   | 0.4           | 0.1| 49 | 0.1| 33  | nd  | 12  | 30 | 3.5| 1.2| 9  | <1  | 0.1 | 9    | -0.9             |                   |
| 71   | 0.2           | nd | 18 | 0.1| 16  | nd  | 27  | 8  | 5.7| 3.4| 9  | nd  | nd  | 13   | -4.3             |                   |
| 72   | 0.2           | nd | 12 | <1 | 22  | nd  | 12  | 7  | 2.8| 2.0| 9  | 0.1 | nd  | 18   | -5.0             |                   |
| 73   | 0.3           | nd | 8  | <1 | 8   | nd  | 24  | 5  | 0.7| 2.1| 9  | 0.1 | nd  | 14   | -4.7             |                   |
| 74   | 0.3           | nd | 22 | 0.1| 14  | nd  | 22  | 14 | 3.9| 2.4| 7  | <1  | nd  | 15   | -5.1             |                   |
| 75   | 0.2           | nd | 9  | <1 | 12  | nd  | 12  | 4  | 1.8| 0.9| 4  | nd  | nd  | 11   | -7.4             |                   |
| 76   | 0.3           | nd | 9  | <1 | <1  | nd  | 7   | 6  | 0.6| 0.6| 2  | <1  | nd  | 12   | -5.7             |                   |
| 77   | 0.5           | 0.1| 9  | 0.1| 12  | <1  | 17  | 7  | 1.6| 2.4| 7  | <1  | nd  | 16   | -2.7             |                   |
| 78   | 1.4           | 0.1| 13 | <1 | <1  | 7   | 9   | 9  | 1.4| 0.9| 3  | <1  | nd  | 12   | -1.9             |                   |
| 79   | 0.7           | nd | 7  | <1 | 3   | nd  | 15  | 8  | 1.7| 1.9| 5  | 0.1 | 0.1 | 10   | -5.0             |                   |
| 80   | 0.2           | nd | 15 | <1 | 7   | nd  | 14  | 8  | 3.9| 1.0| 5  | 0.1 | 0.1 | 10   | -4.1             |                   |
| 81   | 3.7           | 0.8| 9  | <1 | 3   | nd  | 7   | 9  | 1.7| 7.0| 13 | <1  | <1  | 15   | 5.4              |                   |
| 82   | 15.0          | 0.4| 5  | <1 | <1  | nd  | 6   | 8  | 1.5| 1.7| 11 | nd  | nd  | 15   | -2.7             |                   |
| 83   | 2.5           | 1.3| 5  | <1 | <1  | 3   | 12  | 0.6| 0.6| 8  | nd  | nd  | 16   | -4.1             |                   |
| 84   | 0.3           | 0.3| 5  | <1 | <1  | 1   | 7   | 0.5| 0.9| 3  | <1  | nd  | 18   | -3.0             |                   |
| 85   | 0.9           | 0.1| 9  | <1 | <1  | nd  | 8   | 6  | 1.0| 0.7| 2  | <1  | nd  | 17   | -4.6             |                   |
| 86   | 17.8          | 0.9| 12 | <1 | 2   | nd  | 11  | 10 | 0.9| 0.7| 10 | <1  | nd  | 13   | -4.1             |                   |
| 87   | 3.2           | 0.2| 25 | 0.1| 30  | nd  | 60  | 14 | 2.7| 6  | 30  | 0.2 | nd  | 23   | -5.2             |                   |
| 88   | 0.2           | 0.1| 9  | <1 | <1  | nd  | 9   | 7  | 1.1| 0.5| 4  | 8   | 0.1 | 25   | 5.9              |                   |
| 89   | 3.3           | 0.5| 5  | <1 | nd  | 0.2 | 1   | 8  | 1.1| 1.1| 3  | 0.2 | nd  | 17   | -5.8             |                   |
| 90   | 4.0           | 1.0| 8  | <1 | <1  | nd  | 8   | 12 | 1.0| 1.3| 13 | nd  | 0.6 | 17   | -1.6             |                   |
| 91   | 0.3           | 0.1| 13 | <1 | 5   | <1  | 11  | 14 | 0.8| 1.1| 5  | 0.2 | 0.2 | 14   | 3.9              |                   |
| 92   | 0.3           | nd | 18 | <1 | <1  | nd  | 8   | 5  | 0.7| 0.6| 2  | <1  | nd  | 13   | -9.2             |                   |
| 93   | 7.3           | 0.6| 9  | <1 | <1  | nd  | 10  | 11 | 1.3| 1.6| 11 | 1   | 0.2 | 13   | -0.3             |                   |
| 94   | 0.4           | 0.1| 4  | <1 | nd  | <1  | 6   | 6  | 0.3| 0.5| 2  | <1  | nd  | 22   | -2.7             |                   |
| 95   | 0.3           | nd | 5  | nd | <1  | nd  | 7   | 4  | 0.4| 0.4| 1  | nd  | nd  | 8    | 8.1              |                   |

* measured in the form of the uranyl ion.
+ total dissolved.
* charge balance error (in %).
* samples not included in chemical analysis (*).
(these wells are identified in Tables 1, 2, and 3). Concentrations above these levels show excessive contamination from road-salt runoff, fertilizers, and/or septic leachate. Charge balance errors were calculated for the analyses, and samples with errors of 10% or more were excluded.

There exist distinct chemical differences between the surficial-materials ground water and the bedrock ground water within the three aquifers; bedrock well water has higher pH, fluoride, and silica values than the surficial-materials well water. Median concentrations of selected constituents in the Upper Pawcatuck aquifers are included in Table 4. When the samples are plotted on trilinear diagrams, the chemical differences between bedrock and surficial wells are readily apparent (Figures 5, 6, and 7). The bedrock wells are dominated by HCO₃ (most greater than 40% of anions) and Ca (most greater than 40% of cations) and fall in the Ca+ HCO₃ field. The surficial wells are dominated by higher chloride (most greater than 40% of anions) and Na and K (most greater than 40% of cations) values. However, there is a good deal of overlap between the surficial and bedrock wells in the cation field. The deep surficial wells that plot in the bedrock field show evidence of greater chemical evolution and possible mixing with bedrock ground water.

The water chemistry of the Queen-Usquepaugh aquifer shows considerable water-rock interaction and geochemical evolution. Alkalinity, pH, calcium, silica, magnesium, and conductivity increase with depth into the surficial material, and then further into bedrock.

In the Upper Wood River aquifer, the alkalinity, silica, and conductivity values increase with depth from shallow surficial wells to deep surficial wells, and into the bedrock aquifer. The shallow and deep surficial materials ground water shows very similar pH, calcium, fluoride, magnesium, and sodium values, however they are less than those seen in the bedrock ground water (except magnesium). The geochemical evolution with depth in the Upper Wood River aquifer can only be considered when comparing all surficial material ground water to bedrock ground water.

The Chipuxet aquifer does not exhibit this relationship. Alkalinity, calcium, and conductivity decrease with depth in surficial wells. The bedrock wells are higher in pH, alkalinity, silica, fluoride, and sodium than the surficial-materials wells.
Table 4. Concentrations of selected constituents in Upper Pawcatuck aquifers.

| Median Values          | Chemical Parameters (mg/L) | pH | alkalinity<sup>19</sup> | Ca | SiO<sub>2</sub> | F | Mg | Na<sup>20</sup> | cond<sup>21</sup> |
|------------------------|-----------------------------|----|-------------------------|----|---------------|---|----|----------------|-----------------|
| Queen-USquepaugh       |                             |    |                        |    |               |   |     |                |                 |
| shallow surficial      | 4.7                         | 2.0| 2                       | 10 | 0.3           | 0.5| 4  | 44             |                 |
| (n=4)                  |                             |    |                        |    |               |   |     |                |                 |
| deep surficial         | 5.3                         | 7.4| 4                       | 11 | 0.1           | 0.5| 6  | 78             |                 |
| (n=6)                  |                             |    |                        |    |               |   |     |                |                 |
| all surficial          | 5.2                         | 3.5| 2                       | 10 | 0.1           | 0.5| 5  | 62             |                 |
| (n=10)                 |                             |    |                        |    |               |   |     |                |                 |
| bedrock                | 6.3                         | 40 | 11                      | 17 | 1.3           | 1.2| 8  | 137            |                 |
| (n=7)                  |                             |    |                        |    |               |   |     |                |                 |
| Upper Wood             |                             |    |                        |    |               |   |     |                |                 |
| shallow surficial      | 5.0                         | 6.2| 4                       | 10 | 0.1           | 0.9| 6  | 71             |                 |
| (n=7)                  |                             |    |                        |    |               |   |     |                |                 |
| deep surficial         | 5.0                         | 7.9| 4                       | 12 | 0.1           | 0.8| 6  | 94             |                 |
| (n=8)                  |                             |    |                        |    |               |   |     |                |                 |
| all surficial          | 5.0                         | 7.7| 4                       | 11 | 0.1           | 0.9| 6  | 85             |                 |
| (n=15)                 |                             |    |                        |    |               |   |     |                |                 |
| bedrock                | 6.8                         | 24 | 8                       | 22 | 1.6           | 0.9| 8  | 110            |                 |
| (n=9)                  |                             |    |                        |    |               |   |     |                |                 |
| Chipuxet               |                             |    |                        |    |               |   |     |                |                 |
| shallow surficial      | 4.5                         | 5.3| 8                       | 13 | 0.1           | 1.8| 6  | 128            |                 |
| (n=9)                  |                             |    |                        |    |               |   |     |                |                 |
| deep surficial         | 4.5                         | 4.6| 5                       | 12 | 0.1           | 1.9| 7  | 107            |                 |
| (n=9)                  |                             |    |                        |    |               |   |     |                |                 |
| all surficial          | 4.5                         | 5.0| 6                       | 12 | 0.1           | 1.8| 6  | 123            |                 |
| (n=18)                 |                             |    |                        |    |               |   |     |                |                 |
| bedrock                | 5.5                         | 22 | 5                       | 15 | 0.4           | 0.9| 8  | 95             |                 |
| (n=11)                 |                             |    |                        |    |               |   |     |                |                 |

<sup>19</sup> mg/L CaCO<sub>3</sub>
<sup>20</sup> corrected for anthropogenic contamination by eliminating equivalent Na moles where Cl is in excess of 15 mg/L.
<sup>21</sup> conductivity (µS/cm).
<sup>22</sup> n= total number of samples.
Figure 3. Trilinear diagram of ground water in the Queen-Usquepaugh aquifer.
Figure 4. Trilinear diagram of ground water in the Upper Wood aquifer.
Figure 5. Trilinear diagram of the ground water in the Chipuxet aquifer.
Distinctive chemical characteristics of the aquifers include lower fluoride values in both bedrock and surficial wells in the Chipuxet than in the other two aquifers. The Queen-Usquepaugh aquifer is distinguished by higher calcium and alkalinity in its bedrock aquifer relative to the other two aquifers. These parameters show greater chemical evolution in the Queen-Usquepaugh bedrock aquifer. The Upper Wood, on the other hand, has higher alkalinity in its surficial materials aquifer, and higher silica and fluoride values in its bedrock aquifer than the Chipuxet and Queen-Usquepaugh aquifers. The Upper Wood surficial materials wells are more chemically evolved than the other two aquifers.

Dissolved uranium concentrations were greater in ground water from the bedrock aquifers than the surficial-materials aquifers. Median uranium concentrations in ground water from the surficial and bedrock wells were 0.33 ppb (n=10) and 1.7 ppb (n=7) in the Queen-Usquepaugh, 0.32 ppb (n=15) and 2.32 ppb (n=9) in the Upper Wood, and 0.27 ppb (n=18) and 2.45 ppb (n=11) in the Chipuxet. The Queen-Usquepaugh had slightly lower uranium concentrations in its bedrock aquifer than the other two bedrock aquifers.

**Radon Distribution**

Radon concentrations in the study area ground water were highly variable, ranging from 500 to 83,000 pCi/L. Median radon levels by aquifer are included in Table 5 and a bar diagram of radon distribution by aquifer is included in Figure 8. The single-factor Anova statistical analysis method (at the 95% confidence level) was used to determine whether radon concentrations were drawn from populations with the same mean (Ott, 1993). Statistical analysis is included in Appendix F. In the Queen-Usquepaugh aquifer, the Anova test showed that despite very different medians the radon concentrations in the shallow and deep surficial wells do not represent statistically different waters. Therefore, the surficial wells were pooled together and compared to the bedrock ground-water radon readings. The Queen-Usquepaugh surficial ground-water radon concentrations are significantly lower than the radon concentrations in the bedrock wells.
Table 5. Median radon levels (pCi/L) by aquifer.

| Aquifer         | Well type         | superficial       | surficial close to bedrock | all surficial | bedrock       |
|-----------------|-------------------|-------------------|---------------------------|---------------|---------------|
|                 | shallow           | surficial bedrock |                           |               |               |
| Queen-Usquepaugh| 2800 (n=6)        | 4700 (n=6)        | 3200 (n=12)               | 16500 (n=9)   | range 8,000 to 82,900 |
|                 | range 400 to 15,400 | range 700 to 10,700 |                           |               |               |
| Upper Wood River| 1900 (n=11)       | 1100 (n=14)       | 1200 (n=25)               | 17300 (n=9)   | range 3,000 to 39,700 |
|                 | range 700 to 3,000 | range 800 to 3,200 |                           |               |               |
| Chipuxet        | 1000 (n=14)       | 1400 (n=9)        | 1100 (n=23)               | 4700 (n=12)   | range 1,200 to 30,400 |
|                 | 500 to 1,900      | range 600 to 2,000 |                           |               |               |

Figure 6. Bar diagram of study area radon distribution by aquifer.

Statistical analysis on the Upper Wood River aquifer show that shallow and deep surficial ground-water radon concentrations are not significantly different, and thus they too were pooled together and compared to the bedrock wells. Bedrock ground-water radon levels are again significantly greater than surficial wells.

\(^{23}\text{n= total number of samples.}\)
The Chipuxet aquifer surficial wells exhibit the same relationship. Deep surficial wells have significantly greater radon concentrations than the shallow surficial wells. The bedrock ground-water radon concentrations are significantly greater than both the shallow and deep surficial-well radon concentrations.

Radon levels between aquifers were then compared. Shallow and deep surficial wells from each aquifer were pooled to compare radon concentrations between aquifers. Radon levels in Queen-Usquepaugh surficial wells are significantly greater than Upper Wood River surficial wells which in turn are significantly greater than Chipuxet surficial wells. Even though median values in bedrock aquifers show radon levels in the Queen-Usquepaugh bedrock aquifer are greater than the Upper Wood River bedrock aquifer, which in turn are greater than the Chipuxet bedrock aquifer, statistical analysis does not support this. Only radon levels in the Queen-Usquepaugh bedrock ground water are significantly greater than the Chipuxet bedrock ground water.

The Anova statistical analysis test was also used to evaluate radon data on the basis of the underlying bedrock. Median radon levels are included in Table 6 and a bar diagram of radon distribution by underlying bedrock is included in Figure 9. Surficial wells in areas underlain by granite of the Scituate Igneous Suite showed no significant difference between shallow and deep surficial radon concentrations. Therefore, these wells were pooled together and compared to the bedrock wells in the granite of the Scituate Suite. Bedrock ground water has significantly higher radon concentrations than the surficial materials ground water. Wells underlain by gneisses of both the Esmond and Sterling Suites also exhibit the same patterns.

Median radon levels of bedrock ground water show that the granite of the Scituate Suite is greater than the gneiss of the Sterling Suite, which is greater than the gneiss of the Esmond Suite. A statistical comparison of radon concentrations in bedrock wells between granite of the Scituate Suite and gneiss of the Sterling Suite shows no significant difference. A statistical comparison of radon concentrations in bedrock wells between gneiss of the Esmond Suite and gneiss of the Sterling Suite also reveals no significant difference. However, bedrock ground water from granite of the Scituate Suite is significantly higher in radon than bedrock ground water from gneiss of the Esmond Plutonic Suite. Among surficial
wells, the wells underlain by gneisses of the Sterling and Esmond Suites show similar radon concentrations. Surficial wells above granites of the Scituate Igneous Suite exhibit significantly greater radon concentrations than surficial wells overlying gneisses of both the Esmond and Sterling Suites.

Table 6. Median radon levels (pCi/L) by underlying bedrock geology.

| Underlying Bedrock (average uranium content-ppm) | Well Type | Shallow surficial | Surficial close to bedrock | All surficial | Bedrock | All wells |
|-------------------------------------------------|-----------|-------------------|---------------------------|--------------|---------|----------|
| Scituate (4.1)                                  | 2500 (n=9) | 3600 (n=5)        | 3000                      | 19100 (n=9)  | 5900    |          |
|                                                 | range 400 to 15,400 | range 2,400 to 10,700 | (n=14)                    | range 8,000 to 82,900 | (n=23)  |          |
| Sterling (3.3)                                  | 1800 (n=7) | 1100 (n=13)       | 1100                      | 5900 (n=7)   | 1600    |          |
|                                                 | range 700 to 2,800 | range 700 to 2,500   | (n=20)                    | range 3,000 to 27,300 | (n=27)  |          |
| Esmond (1.9)                                    | 1000 (n=15) | 1400 (n=11)      | 1100                      | 5400 (n=14)  | 1400    |          |
|                                                 | range 500 to 2,600 | range 600 to 6,800  | (n=26)                    | range 1,200 to 30,400 | (n=40)  |          |

Figure 7. Bar diagram of study area radon distribution by underlying bedrock.

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24 data from Nevins, 1991.
25 granite of the Scituate Igneous Suite.
26 total number of samples taken.
27 gneiss of the Sterling Plutonic Suite.
28 gneiss of the Esmond Plutonic Suite.
Ground-water radon concentrations for surficial and bedrock wells in the three aquifers are shown in Figures 10, 11, 12, and 13. Bedrock wells show a dramatic increase in radon concentration across the Scituate Igneous Suite/Sterling Suite contact (Figure 10). In the Upper Wood River aquifer, the six bedrock wells in the Sterling Plutonic group south of the Scituate/Sterling contact have a median of 11,600 pCi/L (range 4,700 to 27,300 pCi/L) radon. However, north of the contact, in the Scituate Igneous Suite bedrock, radon concentrations in the three wells have a median of 19,100 pCi/L (range 3,000 to 39,700 pCi/L). There were not enough data to do a comparison across the Scituate/Esmond contact in the Queen-Usquepaugh bedrock aquifer (Figure 11).

The Chipuxet aquifer was used to analyze radon distribution in surficial materials ground water down the axis of an aquifer, the other two aquifers do not have enough samples in the basin or have varying underlying bedrock (Figure 13). There is no systematic variation in radon concentrations from the northern portion of the aquifer down to the southern portion.

**Gamma-ray Data**

The data for the gamma-ray emissions in the stratified sediment deposits are included in Table 7. Only slight differences were found between the measured eU and eTh concentrations of the regolith of the three aquifers.

**Discussion**

Radon levels within the three aquifers are highly variable. This variability is caused by either chemical or physical processes. In order to evaluate which processes have the most effect on the level of radon in a well, radon concentrations must be compared to both the chemical and physical properties of each aquifer.
Figure 8. Radon concentrations in Upper Wood River aquifer bedrock wells (geology from Hermes et al, 1994).
Figure 9. Radon concentrations in Queen-Usquepaugh aquifer and Chipuxet aquifer bedrock wells (geology from Hermes et al, 1994).
Figure 10. Radon concentrations in Upper Wood River aquifer surficial wells (geology from Hermes et al, 1994).
Figure 11. Radon concentrations in Queen-Usquepaugh aquifer and Chipuxet aquifer surficial wells (geology from Hermes et al, 1994).
Table 7. Gamma-ray data of regolith material in the Pawcatuck River Basin.\textsuperscript{29}

| Aquifer            | sample # | eU ppm | eTh ppm | median eU | median eTh |
|--------------------|----------|--------|---------|-----------|------------|
| Queen-Usquepaugh   | Q5       | 2.57   | 11.7    |           |            |
|                    | Q8       | 3.03   | 14.34   | 2.16      | 9.15       |
|                    | Q9       | 1.48   | 7.79    |           |            |
|                    | Q10      | 2.16   | 7.21    |           |            |
|                    | Q11      | 1.43   | 5.97    |           |            |
|                    | Q13      | 1.63   | 9.15    |           |            |
|                    | Q14      | 2.68   | 9.88    |           |            |
| Upper Wood River   | W1       | 2.37   | 10.25   |           |            |
|                    | W2       | 2.55   | 8.88    | 1.87      | 9.15       |
|                    | W3       | 1.77   | 10.64   |           |            |
|                    | W4       | 1.55   | 9.67    |           |            |
|                    | W5       | 1.87   | 8.03    |           |            |
|                    | W6       | 1.73   | 9.15    |           |            |
|                    | W11      | 1.77   | 9.06    |           |            |
|                    | W16      | 2.43   | 11.94   |           |            |
|                    | W17      | 1.9    | 8.31    |           |            |
| Chipuxet           | C1       | 2.35   | 9.37    | 2.35      | 9.37       |
|                    | C4       | 2.28   | 8.73    |           |            |
|                    | C5       | 2.04   | 9.7     |           |            |
|                    | C6       | 1.72   | 6.34    |           |            |
|                    | C7       | 1.74   | 11.31   |           |            |
|                    | C10      | 2.37   | 9.25    |           |            |
|                    | C11      | 2.76   | 11.22   |           |            |
|                    | C12      | 2.73   | 11.19   |           |            |
|                    | C13      | 3.00   | 9.34    |           |            |

The chemistry of ground water in the Pawcatuck river basin is affected by several chemical processes: mineral dissolution, hydrolysis, redox reactions, and ion exchange. Furthermore, anthropogenic input can also influence the chemistry of ground water (fertilizer for instance). As recharge water percolates downward through the aquifer materials, organic acids (from plant decay) react with the material in the aquifer (water-rock reactions), and chemical weathering takes place. Figure 14 shows a correlation between alkalinity represented as % meq of the major anions (bicarbonate, chloride and sulfate) and radon. Because the relationship between alkalinity and radon is not predictive, a rank comparison

\textsuperscript{29} Gamma readings in regolith underestimate actual regolith concentrations because of bulk density variations.
(Spearman's rank test) was used to compare the two parameters. The Spearman's rank test (Appendix F) indicated that there is a statistically significant correlation between radon and alkalinity, with radon levels greater than 10,000 pCi/L usually found in bedrock ground water with alkalinity accounting for more than 40% of the meq. The radon concentration is attributable to local contact with the water because radon has such a short half-life, so long residence time does not produce higher radon concentrations. This is not a causative relationship between elevated radon and alkalinity. Surficial materials aquifers are more or less being continuously replenished by precipitation percolating downward through the surficial material. Bedrock aquifers do not have this direct infiltration, therefore, as a result of bedrock weathering and longer residence time, the ground water is more chemically evolved and has a higher alkalinity than surficial materials ground water.

*not including well #20

Figure 12. Radon concentration versus alkalinity in % milliequivalents of anions.
There is also a general relationship between radon and fluoride concentrations (Figure 15). The Spearman’s rank test was also performed on these data (Appendix F), and indicated a statistically significant correlation between radon and fluoride in ground water. As ground-water fluoride values increase, ground-water radon concentrations increase. Ground water with fluoride concentrations greater than 1 mg/L is likely to have radon concentrations above 10,000 pCi/L. The single-factor Anova statistical analysis method (at the 95% confidence level) was used to determine whether fluoride concentrations were drawn from populations with the same mean (Appendix F) (Ott, 1993). All bedrock fluoride concentrations were statistically greater than surficial well fluoride concentrations. Furthermore, surficial materials and bedrock ground-water fluoride concentrations in the Queen-Usquepaugh and Upper Wood Rivers Aquifers were statistically greater than fluoride concentrations in the Chipuxet aquifer. The Queen-Usquepaugh and Upper Wood River ground-water fluoride concentrations were not statistically different.

Figure 13. Radon versus fluoride concentrations.
The rock in this study that contains fluorite (a fluoride-bearing mineral) is the granite of the Scituate Suite. The granite of the Scituate Igneous Suite is an A-type granite (Hennes and Zartman, 1992), an anhydrous granite formed from high temperature melts in stable fold belts and tensional regimes in continental crust (Collins et al, 1982). Both gneisses of the Sterling and Esmond Suites are considered I-type granites. However, the primary mineralogy of the gneiss of the Sterling Suite is not preserved, thus making it difficult to do a diagnostic characterization of the parental material. The gneiss of the Sterling Suite exhibits some of the chemical features of an A-type granite as well as its I-type characteristics (O. Don Hermes, 1995, University of Rhode Island, Geology Department, written communication). These I-type granites do not contain fluorite, and are formed from more hydrous melts on continental plate edges in Andean kinds of plate boundaries (Collins et al, 1982). The fluorine is associated with the precipitation of U-bearing minerals and thus higher radon levels are found in A-type granites (fluoride complexes will be discussed later). The A-type granite of the Scituate Igneous Suite underlies the Upper Wood River and Queen-Usquepaugh aquifers. The Chipuxet (the aquifer with the lowest radon concentrations) is underlain solely by the gneiss (I-type) of the Esmond Suite, which does not contain fluorite.

The single-factor Anova statistical analysis method (at the 95% confidence level) was also used to determine whether uranium concentrations were drawn from populations with the same mean (Ott, 1993). Bedrock ground water samples have statistically greater dissolved uranium concentrations (median 2.4 ppb) than surficial wells (median .3 ppb), but there was no difference between aquifers (Appendix F). No statistical relationship was found between radon levels and uranium concentrations in the ground-water samples. The solubility of uranium is a function of oxidation-reduction conditions in the aquifer. The effect of redox conditions on uranium solubility is illustrated through a comparison of dissolved uranium and dissolved iron concentrations (Figure 16). Because uranium is mobile in oxidizing conditions and iron is mobile only under reducing conditions, high levels of uranium (greater than 2 ppb) are found only in waters with less than 2 mg/L iron. In addition, wells in the area underlain by the Scituate Granite, the bedrock with the highest uranium content, have, on average, the highest radon levels. The source of radon in ground water therefore, is the uranium in the solid phase, not dissolved uranium. Previous studies have also demonstrated this relationship (Gundersen, 1989, Wanty and Nordstrom, 1993; and Gall et al, 1995).
Previous investigations of radon in ground water have found that radon levels are affected by physical processes and not chemical processes (Wanty and Nordstrom, 1993). In this study of Rhode Island ground water, different radon levels are seen in waters with very similar chemical signatures, the Upper Wood and Queen-Usquepaugh deep surficial materials wells for example. The Queen-Usquepaugh deep surficial-materials wells have much higher radon levels (4,700 pCi/L as compared to 1,100 pCi/L in the Upper Wood), even though the alkalinity, calcium, silica, fluoride, and sodium median values are almost equal. This suggests textural advantages in the Queen-Usquepaugh aquifer material such as the favorable siting of uranium or differences in flow rate (volume of ground water) influencing radon levels. On the other hand, the deep surficial-materials wells in the Upper Wood and Chipuxet are producing similar radon levels (1,100 pCi/L and 1,400 pCi/L, respectively) but have very different alkalinity, calcium,
magnesium, and sodium values. This implies that residence time and water evolution are factors in water chemistry but not on radon levels of ground water. Instead, physical properties such as ground-water flow rate or uranium-siting are more likely the controlling factors.

In an attempt to understand the radon variability within the three-dimensional framework of the aquifer, radon versus depth within the aquifers and radon along the axis of the aquifers was analyzed. When comparing radon with depth to bedrock in the surficial materials wells, the greatest radon levels (greater than 2,000 pCi/L) are found in wells underlain by the Scituate Igneous Suite, all of which are within 20 feet of the bedrock surface (Figure 17). However, when radon values are compared to depth, there is no correlation between radon and depth from the well bottom to bedrock in the three aquifers. The Upper Wood River and Chipuxet surficial aquifers showed no variation in radon concentration over a wide range of proximity to bedrock surface values.

The trilinear diagrams suggest vertical mixing between the bedrock and surficial materials aquifers in the Queen-Usquepaugh and Upper Wood River aquifers (Figures 5 and 6). Several of the deep surficial wells just above the bedrock surface, plot in the bedrock ground-water field. Although it appears that there is mixing between surficial and bedrock aquifers in the trilinear diagrams, chemical data do not support this. Therefore, some of the higher radon values seen in surficial materials wells are a result of in-situ conditions (uranium siting for example) in the lower portions of these aquifers.

There is no spatial variability of radon in surficial wells along the axes of the aquifers (Figures 12 and 13). However, spatial variation is seen in bedrock wells in the study area (Figures 10 and 11). There is an increase in radon concentrations in bedrock ground waters from wells south of the Scituate/Sterling contact (in the Sterling Suite) to wells north of the contact (in the Scituate Suite).

The factors controlling radon concentration seem to be the uranium in the underlying bedrock and the physical properties of the aquifer. Uranium is found in accessory minerals in the crystalline bedrock of the study area. This uranium is either disseminated within the mineral grain, or has been mobilized to the
edges of the mineral grains, resulting in concentrated uranium around the mineral grains. As radium (radon’s parent) decays, alpha recoil is responsible for moving radon that is close enough to the surface of the grains into the adjacent ground water (Wanty and Nordstrom, 1993). Therefore, the siting of the uranium within the mineral is very important in radon mobility. A limitation of this study is that the

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30 Well #22 was no included because well depth is unknown.
physical characteristics of the bedrock (degree of fracturing and possibility of secondary uranium mineralization along the walls of the fracture) where these wells are located are unknown.

Based on the limited sample size used here and unpublished data from Veeger and Hermes (1994), there is no relationship between radon levels in the surficial-materials aquifers and the $^{232}$Th and $^{238}$U concentrations in the regolith. The median uranium content of the three surficial materials aquifers was less than 2.5 ppm.

Because well yields were available for only one third of the wells, and most of them were qualitative estimates by the well drillers, well-yield data were insufficient to create a quantitative comparison between the amount of flow through an aquifer and radon levels. In previous studies of radon and hydraulic aperture, differences in radon concentration within well pairs were attributed to differences in hydraulic aperture alone (Peter Folger, 1994, Colorado School of Mines, written communication) and inverse correlations were seen between dissolved radon and well yield (Wanty and Nordstrom, 1993). A larger fracture aperture allows a greater volume of water to pass through, thus the $^{222}$Rn produced in the rock is in essence diluted by the greater volume of water transmitted through the fracture. In this study, evidence of this relationship is also seen. Two of the bedrock wells sampled in this study, numbers 17 and 20, were located in the same bedrock material but yielded ground water with very different radon concentrations. Well 20 (well depth 85 feet) has a reported yield of 0.25 gallons per minute and radon concentration of 82,900 pCi/L, whereas well 17 (well depth 360 feet) has a reported yield of 20 gallons per minute and a radon concentration of 11,300 pCi/L. The radon in well 17 was probably diluted by a greater volume of water in the fracture resulting in a dramatically lower radon concentration.

Nevins (1991) found that the siting of uranium in the Scituate and Esmond rocks is within the accessory minerals and not along grain boundaries. She did not analyze a sample from the Sterling alaskite gneiss. Nevins' samples were from a fresh outcrop and not from a well boring. Water-bearing fractures are weathered as a result of water-rock interactions. This weathering process could redistribute uranium from within the lattices to the grain surfaces. Zielinski et al (1987) found that although uranium was held within the allanite grain in unaltered samples, weathered samples indicated that the uranium remobilized and adsorbed onto nearby biotite and microfractures.
This study has found that there is a statistically significant relationship between ground-water fluoride and radon concentrations. Previous studies have discovered that the presence of fluoride, phosphate, hydroxide, sulfate, and carbonate in natural waters increase the solubility of uranium minerals and thus mobility of uranium in ground waters (Langmuir, 1978). The most important uranyl complexes in the acidic waters of this study are formed with fluorides (because of water pH and species concentrations). When redox conditions are conducive to uranium complexing in the solid phase, the fluoride species remains in the liquid phase as a marker. Uranyl complexing with fluoride is another reason why there is a statistically significant relationship between ground-water fluoride and radon concentrations (Figure 15).

Further evidence of uranium remobilization is found in studies conducted on $^{226}$Ra, the parent of radon. Radon concentrations are generally several orders of magnitude greater than the radium concentrations (Wanty et al, 1992; Wanty and Nordstrom, 1995; Walters, 1995). Therefore, the radium must be concentrated near enough to the water-rock interface (adsorbed onto mineral surfaces) to produce these high dissolved radon concentrations.

Metamictization (the destruction of mineral structure as a result of radiation) may also influence the mobility of uranium. Studies have found that with increased metamictization, uranium-bearing minerals like zircon become amorphous and more easily leached because of the internal radiation damage to the structure of the mineral (Ewing et al, 1982). In some cases, allanite and zircon are metamict minerals. Nevins (1991) found evidence of metamictization in some allanite grains in her Rhode Island bedrock samples.

A further consideration involving uranium siting is the possibility of shear zones in the underlying bedrock surrounding the well. During rock shear, strain is concentrated in narrow fault zones, causing mylonites to develop because of the ductile shear (plastic deformation). A mylonite is a rock that has undergone a change in microstructure, porosity, permeability, and chemical composition from the parent rock. This reorganizing of the parent rock creates a foliation into which the uranium is redistributed by hot oxidizing fluids (Gundersen, 1989). Several studies on shear zones throughout the Appalachian region have found the uranium-bearing minerals concentrated in zones of local melting (Gundersen, 1989). Uranium is a much more effective producer of mobile radon when it is in the mylonite foliation because
this foliation may weather preferentially, exposing the uraniferous surfaces. As a result, the radon in soil
gas and ground water, and the uranium concentration in the bedrock may increase with increasing shear.
Although data from this study were not comprehensive enough to thoroughly investigate this phenomenon,
anomalously high ground-water radon concentrations are seen in wells near the Hope Valley Shear Zone
(39,700 pCi/L in a bedrock well) and in the Queen Usquepaugh aquifer near the Scituate/Esmond bedrock
contact where some shearing might exist (10,700 pCi/L and 15,400 pCi/L in two surficial wells and 82,900
pCi/L in a bedrock well)(Figures 10, 11, 12, and 13). Uranium concentrations in Nevins’ (1991) bedrock
samples also show evidence of this relationship in increased concentrations near the Hope Valley Shear
Zone and contacts of Scituate granite with other bedrock types.

Summary and Conclusions

All wells sampled yielded radon levels above the proposed EPA limit of 300 pCi/L and many
were more than an order of magnitude greater. Although the EPA will probably adopt a standard that is
less rigorous than 300 pCi/L, this study reveals that much of the ground water in southern Rhode Island has
elevated radon levels that may be cause for concern.

Water chemistry does not play an important role in controlling radon concentrations. However,
some chemical parameters can provide clues about the uranium content of the bedrock and the radon
content of the ground water. High radon values correlated with high fluoride in the ground water because
the bedrock suites that contain the mineral fluorite (A-type granites) are likely to be uranium-rich and
fluoride also increases uranium mobility.

Bedrock aquifers yield higher concentrations of radon than surficial materials (derived from local
bedrock) aquifers. This relationship is both related to the lower ground-water flow rate in bedrock aquifers
as compared to permeable surficial materials aquifers, and the availability of uranium-bearing minerals in
both settings. High radon values were discovered in areas where the underlying bedrock contained the
most uranium (Scituate Suite) because the source uranium is the solid phase and not the dissolved species
(there was no correlation between radon concentration and dissolved uranium).
The greatest radon levels among surficial materials wells (greater than 2,000 pCi/L) are found in surficial wells that are underlain by bedrock with high uranium contents (seen in the Queen-Usquepaugh and Upper Wood River surficial materials aquifers). Radon values in the Queen-Usquepaugh surficial materials ground water are much greater than radon values in the surficial materials aquifers of the other two because of the higher uranium content in the underlying bedrock (granite of the Scituate Suite) of the northern portion of the Queen-Usquepaugh aquifer. Radon concentrations in the Upper Wood bedrock aquifer are not significantly different from those in the Queen-Usquepaugh or Chipuxet bedrock aquifers. However, the Chipuxet bedrock aquifer yields much lower radon values than the Queen-Usquepaugh bedrock aquifer. These relationships are seen because radon concentrations in the ground water are dominated by the amount of uranium in the underlying bedrock. Samples taken in the Queen-Usquepaugh aquifer are predominantly underlain by the Scituate Igneous granite (the bedrock with the highest uranium content). The Upper Wood River aquifer is predominantly underlain by the Sterling Plutonic Suite (the bedrock with the second highest uranium content). The Chipuxet aquifer is underlain by the bedrock containing the least amount of uranium, the Esmond Plutonic Suite.

The variability of ground-water radon concentrations between bedrock and surficial materials wells cannot be isolated to one specific reason. The variable with a great deal of influence is ground-water flow rate. Higher ground-water radon levels are seen in bedrock wells because of the lower flow rate of ground water through the bedrock aquifer as opposed to the flow through the surficial material. Furthermore, the more favorable siting of uranium and metamictization in the bedrock aquifer, are also factors in producing higher radon concentrations in bedrock wells as opposed to surficial wells within an aquifer. This study has found that there is a statistically significant relationship between ground-water fluoride and radon concentrations. The presence of fluoride increases the solubility of uranium minerals, the uranium remobilizes to a more favorable siting along the grain boundaries, and the fluoride remains in the ground water as a marker. Differences in radon concentrations between aquifers are caused by uranium-siting and ground-water flow rate as well, but the uranium content of the underlying bedrock and the possibility of influence from a shear zone in the bedrock play the important roles in radon concentrations of the ground water.
Factors controlling radon distribution are so complex that it is impossible to develop a quantitative model to predict radon levels in the ground water with the available data. Information needed to distinguish between these factors would be well yields, fracture size for bedrock wells, and samples of both the bedrock and surficial material to evaluate textural differences (for surficial wells) and the siting of uranium.

This investigation has shown that radon is a concern for ground-water users within the Pawcatuck River Basin, Rhode Island. Although it is not possible to make precise predictions of radon concentrations in ground water, this study shows that bedrock ground-water users in the Queen-Usquepaugh and Upper Wood aquifers, particularly those underlain by the Scituate Igneous Suite, can expect relatively high levels of radon in their ground water (10,000 pCi/L to 85,000 pCi/L), while bedrock ground water users in the Chipuxet can expect relatively low levels (less than 10,000 pCi/L). Those users who withdraw ground water from surficial-materials aquifers are at a lower risk for elevated radon levels in their ground water than bedrock ground water users.
References
Aieta, E.M., Singley, J.E., Trussell, A.R., Thorbjarnarson, K.W., and McGuire, M.J., 1987, Radionuclides in drinking water: an overview: Journal of the American Water Works Association 79, p. 144-152.

Clesceri, L.S., Greenberg, A.E., and Trussel, R.R., 1989, Standard Methods for the Examination of Water and Wastewater: Washington D.C., American Public Health Association, seventeenth edition, 1527p.

Collins, W.J., Beams, S.D., White, A.J.R., and Chappell, B.W., 1982, Nature and origin of A-type granites with particular reference to southeastern Australia: Contributions to Mineralogy and Petrology, v. 80, p. 189-200.

Cothern, C.R., Lappenbusch, W.L., and Michel, J., 1986, Drinking water contribution to natural background radiation: Health Physics, v. 50, p. 33.

Cothern, C.R., 1987, Development of regulations for radionuclides in drinking water, in Graves, B., ed., Radon, Radium, and Other Radioactivity in Ground Water: Chelsea, MI, Lewis Publishers, p. 1-11.

Cothern, C.R., and Smith, J.E. Jr., 1987, Radon in surface waters, in Cothern, C.R., and Smith, J.E. Jr., eds., Environmental Radon: New York, New York, Plenum Press, p. 108-118.

Crawford-Brown, D.J., 1990, Analysis of the health risk from ingested radon, in Cothern, C.R. and Rebers, P.A., eds., Radon, Radium, and Uranium in Drinking Water: Chelsea, MI, Lewis Publishers, p. 17-26.

Dickerman, D.C., and Bell, R.W., 1993, Hydrology, water quality, and ground-water-development alternatives in the Upper Wood River ground-water reservoir, Rhode Island: USGS Water-Resources Investigations Report 92-4119, 87 p.

Ewing, R.C., Haaker, R.F., and Lutze, W., 1982, Leachability of zircon as a function of alpha dose, in Lutze, W., ed., Scientific Basis for Radioactive Waste Management: Elsevier Press, p. 389-397.

Folger, P.F., Nyberg, P., Wanty, R.B., and Poeter, E., 1994, Relationships between $^{222}$Rn dissolved in ground water supplies and indoor $^{222}$Rn concentrations in some Colorado front range houses: Health Physics, v. 67, n. 3, p. 245-153.
Gall, I.K., Ritzl, R.W., Jr., Baldwin, A.D., Jr., Pushkar, P.D., Carney, C.K., and Talnagi, J.F., Jr., 1995, The correlation between bedrock uranium and dissolved radon in ground water of a fractured carbonate aquifer in southwestern Ohio: Ground Water, v. 33, n. 2, p. 197-206.

Gundersen, L.C.S., 1989, Anomalously high radon in shear zones, in Osborne, M.C., and Harrison, J., symposium cochairmen, The 1988 Symposium on Radon and Radon Reduction Technology, Proc., v. 1, Symposium Oral Papers: Research Triangle Park, NC, Radian Corp., U.S. Environmental Protection Agency Pub. EPA/600/9-89/006a [Springfield, Va., NTIS Order No. PB89-167480], p. 5-27 - 5-44.

Hall, F.R., Boudette, E.L., and Olszewski, W.J., 1987, Geologic controls and radon occurrence in New England, in Cothern, C.R., and Smith, J.E., Jr., eds., Environmental radon: New York, New York, Plenium Press, p. 15-27.

Hermes, O.D., Gromet, L.P., Murray, D.P. (compilers), 1994, Bedrock geologic map of Rhode Island: Rhode Island Map Series No.1, University of Rhode Island, Kingston. Scale = 1:100,000.

Hermes, O.D., and Zartman, R.E., 1985, Late Precambrian and Devonian plutonic terrane within the Avalon Zone of Rhode Island: Geological Society of America Bulletin, v. 96, p. 272-282.

Hermes, O.D., and Zartman, R.E., 1992, Late Proterozoic and Silurian alkaline plutons within the southeastern New England Avalon Zone: Journal of Geology, v.100, p. 477-486.

Hess, C.T., Korsah, J.K., and Einloth, C.J., 1985, Radon in houses due to radon in potable water: Land and Water Resources Center, University of Maine Completion Report G846-04, G910-03. 45 p.

Holden, J.B., 1994, The effects of human activities on the quality of ground water in the Chipuxet aquifer, Rhode Island [M.S. thesis]: Kingston, Rhode Island, University of Rhode Island, 84p.

Hollocher, K., and Yuskaitis, A., 1993, Chemical composition of surface and high-uranium well water, Lake Sunapee area, New Hampshire: Northern Geology, v. 15, n. 2, pp.159-169.

Hughes, T.J., 1985, Models of glacial reconstruction and deglaciation applied to Maritime Canada and New England, in Borns et al, eds., Late Pleistocene History of Northeastern New England and Adjacent Quebec, Geological Survey of America Special Paper 197, p.139-150.
Johnston, H.E., and Dickerman, D.C., 1985, Hydrology, water quality, and ground-water-development alternatives in the Chipuxet ground-water reservoir, Rhode Island: USGS Water Resources Investigations Report 84-4254, 100 p.

Krishnaswami, S., and Seidemann, D.E., 1988, Comparative study of 222Rn, 40Ar, 39Ar and 37Ar leakage from rocks and minerals: implications for the role of nanopores in gas transport through natural silicates: Geochimica et Cosmochimica Acta, v. 52, p. 655-658.

Langmuir, D., 1978, Uranium solution-mineral equilibria at low temperatures with application to sedimentary ore deposits: Geochimica et Cosmochimica Acta, v. 42, p. 547-569.

Lawrence, E.P., Wanty, R.B., and Nyberg, P., 1992, Contribution of 222Rn in domestic water supplies to 222Rn in indoor air in Colorado homes: Health Physics, v. 62, n. 2, p. 171-177.

LeGrand, H.E., 1987, Radon and radium emanations from fractured crystalline rocks- a conceptual hydrogeological model: Ground Water, v. 25, n. 1, p. 59-69.

National Research Council, 1988, Health Risks of Radon and other Internally Deposited Alpha-Emitters, BEIR IV: Washington, D.C., National Academy Press.

Nevins, N., 1991, Uranium in Rhode Island bedrock: a primary source of radon-222 in indoor air and ground water [M.S. thesis]: Kingston, Rhode Island, University of Rhode Island, 154 p.

Ott, R.L., 1993, An introduction to statistical methods and data analysis, Duxbury Press, Belmont California, 1051p.

RIDEM, Groundwater Section, 1990, Rhode Island Private Well Survey: Rhode Island Department of Environmental Management, Division of Groundwater and Freshwater Wetlands, Final Report, May 1990, 107 p.

Walters, M.O., 1995, Radium in coastal Sarasota county ground water: Ground Water Monitoring & Remediation, v. 15, n. 4, p. 114-118.

Wanty, R.B., Lawrence, E.P., and Gundersen, L., 1992, A theoretical model for the flux of radon from rock to ground water: Geological Society of America Special Paper 271, p. 73-78.

Wanty, R.B., and Nordstrom, D.K., 1993, Natural radionuclides, in Alley, W.M., ed., Regional Ground-water Quality: New York, New York, Van Nostrand Reinhold, p. 423-441.
Wathen, J.B., 1987, The effect of uranium siting in two-mica granites on uranium concentrations and radon activity in ground water, in Cothern, C.R., and Smith, J.E. Jr., eds., Environmental Radon: New York, New York, Plenum Press, p. 31-45.

Zielinski, R.A., Johnson, S.Y., and Otton, J.K., 1987, The geologic setting of a surficial uranium deposit, northeastern Washington, in Marikos, M.A., and Hansman, R.H., eds., Geologic Causes of Natural Radionuclide Anomalies, p. 43-57.
Appendix A: Well Survey

The University of Rhode Island, Kingston, RI 02881-0807
Department of Geology

Dear Homeowner,

We are conducting a study of the water in the Pawcatuck River Basin. This study is supported by the Rhode Island Water Resources Center. We are investigating the relationship between ground-water quality and geology. As part of this study, a number of private wells in the area will be sampled. We are asking for help from homeowners around the Wood River, to develop a data base for our study. If you have answers to any of the following questions, please return them in the self-addressed, stamped envelope we have provided. If your well is included in the study, you will receive a copy of the laboratory results with the complete chemical analysis.

Is your house served by a well? (YES, NO) (circle one)

Date of well construction? ____________

Type of well construction? (dug, drive point, drilled) (circle one)

Depth of well? ____________

Type of pump? (submersible pump in the well, vacuum pump in your house) (circle one)

The driller’s name? __________________________

Well yield? ____________ Water bearing material? ____________

Do you have any problems with your water? (iron, taste, odor, other)

Do you use your water for drinking purposes? (YES, NO) (circle one)

Do you have a water treatment device? (filter, water softener, iron removal, other)

Has your home or well been tested for radon? __________________________

Please draw us a quick sketch of your house and well location, in the box provided.

Could we have permission to sample your well?

signature: __________________________

name: __________________________

address: __________________________

phone #: __________________________

If we have your permission, we will contact you to set up a convenient time for you, to sample your well. If you have any questions, please contact Dr. Anne Veeger at the University of Rhode Island, 792-2187.

Thank you for your cooperation.

Nicole C. Ruderman

Graduate Student, Univ of R.I.
Using the homeowner's well pump, ground-water samples were collected after 3-well volumes had been evacuated from each well, and the pH, temperature, and electrical conductivity had stabilized. The pumping rate, type of pump (submerged for deep wells or vacuum for shallow wells), water level (if possible to obtain), temperature, electrical conductivity, pH, dissolved oxygen, color, odor, and turbidity were recorded during the time of collection. A field sheet is provided in Appendix C. The samples were stored in a cooler and later stored in the U.R.I. Department of Geology, Hydrogeology laboratory refrigerator to await analysis. Five hundred milliliter samples were collected for anion analysis, 250 milliliter samples were collected for cation analysis, 60 milliliter samples were collected for uranium analysis, and 20 milliliter samples were collected for radon analysis. The cation, anion, and uranium samples were filtered through a 0.45 µm filter in order to remove particulate matter, and stored in high-density polypropylene bottles. Samples collected for cation analysis were treated with hydrochloric acid and samples collected for uranium analysis were treated with nitric acid to maintain the dissolved constituents. Water levels were measured in wells with accessible casings using an electric tape.
Appendix C: Field Sheet

Field Report
RIWRC - FY 92 Project - Geochemical Controls on Ground-Water Chemistry

| Site # | Location |
|--------|----------|
| Owner: |          |
| Date:  | Time:    | Field Personnel: |
| Weather: |          |
| Site type: |          |
| Sampling method: |          |

- bedrock well
- surficial well
- till well
- bailed
- submerged pump
- vacuum pump

Remarks:

On-site measurements:

- Temperature
- Elect. Cond.
- Water level:
- pH
- Diss. Oxy.
- Meas. point
- Turbidity
- Odor
- W.L. method
- Color

Samples collected for laboratory analysis:

- cations sample size sample treatment
- anions sample size sample treatment
- alk/SiO₂ sample size sample treatment
- isotopes sample size sample treatment

Map of field site:
### Appendix D. Summary of Analytical Techniques.

| Chemical Parameter | Analytical Technique |
|--------------------|----------------------|
| Specific Conductance | YSI model 32 conductivity bridge. |
| pH                 | Combination electrode, Accumet model pH/°C/mV meter. |
| Fe                 | 1,10 phenanthroline colorimetric method (Std Method 3500). |
| Alkalinity         | Standard method 2320 (Clesceri et al, 1989), potentiometric titration, alkalinity using Accumet model 925 pH/°C/mV meter. |
| F, Cl, Br, NO₃, SO₄ | Ion chromatography, Dionex Series 4500i with AS4A anion separator column. |
| Na, K, Mg, Ca      | Ion chromatography, Dionex Series 4500i with CS3 cation separator column. |
| SiO₂               | Standard method 4500-Si D, molybdosilicate colorimetric method (Clesceri et al, 1989) using Milton Roy model 1201 spectrophotometer. |
| Mn                 | Atomic absorption air-acetylene flame method. |
| Uranium            | Fluorometric analytical method, laser phosphorimetry with standard addition of sodium hexametaphosphate. |
| Radon              | Liquid scintillation method modified after Prichard and Gesell (1977). |
Appendix E. Ion Chromatography Accuracy.

The ground-water samples were analyzed for anions and cations using the Dionex series 4500i ion chromatograph. The ion chromatograph is calibrated using four levels of standards. Samples with values greater than the standards were diluted. The standards used are included in Tables E1 and E2. These standards were run as samples to determine the accuracy of the ion chromatograph. The ion chromatograph results for the standards were then used to calculate the percent error for each run. Average percent errors for anion and cation analyses are given in Tables E3 and E4.

Table E 1. Concentrations of anion standards used in this study.

| Standard Name | Concentration |
|---------------|---------------|
| Standard 1    | 0.1mg/L F, Br, PO₄ | 1 mg/L Cl, NO₃, SO₄ |
| Standard 2    | 0.4mg/L F, Br, PO₄ | 4 mg/L Cl, NO₃, SO₄ |
| Standard 3    | 1mg/L F, Br, PO₄  | 10 mg/L Cl, NO₃, SO₄ |
| Standard 4    | 2mg/L F, Br, PO₄  | 20 mg/L Cl, NO₃, SO₄ |

Table E 2. Concentrations of cation standards used in this study.

| Standard Name | Concentration |
|---------------|---------------|
| Standard 1    | 1 mg/L Na     | 0.2 mg/L K,Mg | 0.5 mg/L Ca |
| Standard 2    | 4 mg/L Na     | 0.8 mg/L K,Mg | 2 mg/L Ca   |
| Standard 3    | 10 mg/L Na    | 2 mg/L K,Mg   | 5 mg/L Ca   |
| Standard 4    | 20 mg/L Na    | 4 mg/L K,Mg   | 10 mg/L Ca  |

Table E 3. Average errors in anion analyses (mg/L).

| Standard Name | Fluoride | Bromide | Phosphate | Chloride | Nitrate | Sulfate | number of samples |
|---------------|----------|---------|-----------|----------|---------|---------|-----------------|
| Standard 1    | 0.01     | 0.10    | 0.01      | 0.04     | 0.03    | 0.1     | 12              |
| Standard 2    | 0.04     | 0.17    | 0.01      | 0.1      | 0.03    | 0.1     | 4               |
| Standard 3    | 0.02     | 0.13    | 0.02      | 0.2      | 0.02    | 0.2     | 9               |
| Standard 4    | 0.07     | 0.68    | 0.03      | 0.2      | 0.05    | 0.1     | 14              |
Table E 4. Average errors in cation analyses (mg/L).

| Standard Name | Sodium | Potassium | Magnesium | Calcium | number of samples |
|---------------|--------|-----------|-----------|---------|------------------|
| Standard 1    | 0.04   | 0.01      | 0.01      | 0.03    | 6                |
| Standard 2    | 0.2    | 0.03      | 0.03      | 0.1     | 10               |
| Standard 3    | 0.5    | 0.06      | 0.1       | 0.2     | 10               |
| Standard 4    | 0.7    | 0.06      | 0.1       | 0.3     | 10               |
Appendix F. Statistical Analysis.

Analysis of radon data.

Statistical analysis of the radon data was done to test whether two populations were significantly different. First, the Anova (single factor) test was done to statistically analyze the data. The populations were assumed to be distributed normally. In order to make the distribution roughly symmetric (normal) without heavy outliers, anomalously high and low values were discarded on a few of the tests. Then, the F-test was used to test whether the populations were significantly different.

F-test. The hypothesis that the populations are not significantly different is rejected if $F > F_{\text{crit}}$. Both the $F$ and $F_{\text{crit}}$ values are found in the A-nova output.

The data are in log form and are first analyzed by aquifer.

Analysis of radon data by aquifer.

Queen-Usquepaugh

Shallow surficial compared to deep surficial radon levels in wells:

| LOG #S          | Anova: Single Factor |
|-----------------|----------------------|
| **SUMMARY**     | Groups n Sum Average Variance |
| Shallow         | 6 20.46 3.41 0.25 |
| Deep            | 6 21.40 3.57 0.18 |

| ANOVA           | Source of Variation | SS  | df | MS  | F    | P-value | F crit |
|-----------------|---------------------|-----|----|-----|------|---------|--------|
|                 | Between Groups      | 0.07414 | 1  | 0.07414 | 0.34 | 0.57    | 4.96   |
|                 | Within Groups       | 2.153542 | 10 | 0.215354 |     |         |        |
| Total           |                     | 2.227682 | 11 |     |      |         |        |

Queen-Usquepaugh surficial wells continued.
The surficial wells are pooled together and compared to the bedrock radon levels in wells.

**surficial wells compared to bedrock wells:**

Anova: Single Factor

| SUMMARY |
|---------|
| Groups | n | Sum | Average | Variance |
|---------|---|-----|---------|----------|
| surficial | 12 | 41.87 | 3.49 | 0.20 |
| bedrock | 9 | 38.24 | 4.25 | 0.10 |

| ANOVA |
|--------|
| Source of Variation | SS | df | MS | F | P-value | F crit |
|----------------------|----|----|----|---|---------|--------|
| Between Groups | 2.975385 | 1 | 2.975385 | 18.67 | 0.00 | 4.38 |
| Within Groups | 3.028436 | 19 | 0.159391 |
| Total | 6.003821 | 20 |

F = 18.67, $F_{crit} = 4.38$. F > $F_{crit}$ therefore, the bedrock ground-water radon levels are significantly greater than the surficial radon levels.
**Upper Wood River**

shallow surficial compared to deep surficial radon levels in wells:

Anova: Single Factor

| Groups  | n   | Sum   | Average | Variance |
|---------|-----|-------|---------|----------|
| shallow | 11  | 35.51 | 3.23    | 0.04     |
| deep    | 14  | 43.30 | 3.09    | 0.04     |

ANOVA

| Source of Variation | SS    | df | MS    | F      | P-value | F crit |
|---------------------|-------|----|-------|--------|---------|--------|
| Between Groups      | 0.114259 | 1  | 0.114259 | 2.74   | 0.11    | 4.28   |
| Within Groups       | 0.957404 | 23 | 0.041626 |         |         |        |
| Total               | 1.071663 | 24 |        |        |         |        |

F = 2.74, $F_{crit} = 4.28$. $F < F_{crit}$ therefore, the surficial wells ground-water radon levels are not significantly different.

The surficial wells are pooled together and compared to the bedrock wells.

surficial wells compared to bedrock wells radon levels:

Anova: Single Factor

| Groups   | n   | Sum   | Average | Variance |
|----------|-----|-------|---------|----------|
| surficial| 25  | 78.81 | 3.15    | 0.04     |
| bedrock  | 9   | 28.40 | 4.06    | 0.10     |

ANOVA

| Source of Variation | SS    | df | MS    | F      | P-value | F crit |
|---------------------|-------|----|-------|--------|---------|--------|
| Between Groups      | 4.4803 | 1  | 4.4803 | 81.13  | .00     | 4.17   |
| Within Groups       | 1.656628 | 30 | 0.055221 |        |         |        |
| Total               | 6.136928 | 31 |        |        |         |        |

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Upper Wood River surficial compared to bedrock wells continued.

F=81.13, $F_{crit} = 4.17$. $F > F_{crit}$ therefore, the bedrock ground-water radon levels are significantly greater than the surficial wells.

Chipuxet

shallow surficial compared to deep surficial radon levels in wells:

Anova: Single Factor

| SUMMARY |
|---------|
| Groups  | n  | Sum | Average | Variance |
| shallow | 10 | 29.65 | 2.97    | 0.02     |
| deep    | 9  | 28.03 | 3.11    | 0.03     |

| ANOVA    |
|----------|
| Source of | SS   | df | MS   | F     | P-value | F crit |
| Variation|      |    |      |       |         |        |
| Between  | 0.105777 | 1  | 0.105777 | 4.67  | 0.05    | 4.45   |
| Groups   |        |    |       |       |         |        |
| Within   | 0.384701 | 17 | 0.022629 |       |         |        |
| Groups   |        |    |       |       |         |        |
| Total    | 0.490479 | 18 |       |       |         |        |

F=4.67, $F_{crit} = 4.45$. $F > F_{crit}$, therefore, the deep surficial ground-water radon levels are significantly greater than the shallow surficial wells.

The surficial wells are pooled together (to maintain similar analysis techniques) and compared to the bedrock wells.
Chipuxet surficial wells compared to bedrock wells radon levels:

Anova: Single Factor

| Groups     | n  | Sum  | Average | Variance |
|------------|----|------|---------|----------|
| surficial  | 23 | 69.65| 3.03    | 0.03     |
| bedrock    | 8  | 29.60| 3.70    | 0.03     |

ANOVA

| Source of Variation | SS      | df | MS       | F        | P-value | F crit |
|---------------------|---------|----|----------|----------|---------|--------|
| Between Groups      | 2.676544| 1  | 2.676544 | 91.64    | .00     | 4.18   |
| Within Groups       | 0.846976| 29 | 0.029206 |          |         |        |
| Total               | 3.52352 | 30 |          |          |         |        |

F=91.64, \( F_{crit} = 4.18 \). \( F > F_{crit} \) therefore, the bedrock ground-water radon levels are significantly greater than the surficial wells.

Chipuxet surficial wells compared to Upper Wood surficial wells radon levels:

Anova: Single Factor

| Groups      | n  | Sum  | Average | Variance |
|-------------|----|------|---------|----------|
| Upper Wood  | 25 | 78.81| 3.15    | 0.04     |
| Chipuxet    | 23 | 69.65| 3.03    | 0.03     |

ANOVA

| Source of Variation | SS      | df | MS       | F        | P-value | F crit |
|---------------------|---------|----|----------|----------|---------|--------|
| Between Groups      | 0.184984| 1  | 0.184984 | 4.92     | 0.03    | 4.05   |
| Within Groups       | 1.728552| 46 | 0.037577 |          |         |        |
| Total               | 1.913536| 47 |          |          |         |        |

F=4.92, \( F_{crit} = 4.05 \). \( F > F_{crit} \) therefore, the Upper Wood surficial wells ground-water radon levels are significantly greater than the Chipuxet wells.
Chipuxet surficial wells compared to Queen-Usquepaugh surficial wells radon levels:

Anova: Single Factor

SUMMARY

| Groups   | n  | Sum  | Average | Variance |
|----------|----|------|---------|----------|
| queen    | 8  | 28.18| 3.52    | 0.04     |
| chipuxet | 23 | 69.65| 3.03    | 0.03     |

ANOVA

| Source of Variation | SS      | df | MS       | F       | P-value | F crit |
|---------------------|---------|----|----------|---------|---------|--------|
| Between Groups      | 1.448114| 1  | 1.448114 | 44.39   | .00     | 4.18   |
| Within Groups       | 0.946077| 29 | 0.032623 |         |         |        |

F=44.39, F_{crit}= 4.18. F > F_{crit}, therefore, the Queen-Usquepaugh surficial wells ground-water radon levels are significantly greater than the Chipuxet wells.

Upper Wood surficial wells compared to Queen-Usquepaugh surficial wells radon levels:

Anova: Single Factor

SUMMARY

| Groups   | n  | Sum  | Average | Variance |
|----------|----|------|---------|----------|
| Queen    | 8  | 28.18| 3.52    | 0.04     |
| U. Wood  | 25 | 78.81| 3.15    | 0.04     |

ANOVA

| Source of Variation | SS      | df | MS       | F       | P-value | F crit |
|---------------------|---------|----|----------|---------|---------|--------|
| Between Groups      | 0.82823 | 1  | 0.82823  | 18.87   | 0.00    | 4.16   |
| Within Groups       | 1.36085 | 31 | 0.043898 |         |         |        |

Total 2.189081 32

F=18.87, F_{crit}= 4.16. F > F_{crit}, therefore, the Queen-Usquepaugh surficial wells ground-water radon levels are significantly greater than the Upper Wood wells.
Upper Wood bedrock wells compared to Queen-Usquepaugh bedrock wells radon levels:

Anova: Single Factor

SUMMARY

| Groups  | n  | Sum    | Average | Variance |
|---------|----|--------|---------|----------|
| Queen   | 9  | 38.24436 | 4.249373 | 0.100094 |
| U. Wood | 9  | 36.48553 | 4.053947 | 0.150867 |

ANOVA

| Source of Variation | SS    | df | MS        | F    | P-value | F crit |
|---------------------|-------|----|-----------|------|---------|--------|
| Between Groups      | 0.171861 | 1  | 0.171861  | 1.37 | 0.26    | 4.49   |
| Within Groups       | 2.00769 | 16 | 0.125481  |      |         |        |
| Total               | 2.179551 | 17 |           |      |         |        |

F=1.37, F crit= 4.49. F < F crit, therefore, the Queen-Usquepaugh and Upper Wood bedrock wells ground-water radon levels are not significantly different.

Upper Wood bedrock wells compared to Chipuxet bedrock wells radon levels:

Anova: Single Factor

SUMMARY

| Groups | n | Sum | Average | Variance |
|--------|---|-----|---------|----------|
| U. Wood| 9 | 36.49 | 4.05 | 0.15    |
| Chipuxet| 12 | 44.47 | 3.71 | 0.15    |

ANOVA

| Source of Variation | SS    | df | MS        | F    | P-value | F crit |
|---------------------|-------|----|-----------|------|---------|--------|
| Between Groups      | 0.62433 | 1  | 0.62433   | 4.15 | 0.06    | 4.38   |
| Within Groups       | 2.859571 | 19 | 0.150504  |      |         |        |
| Total               | 3.483901 | 20 |           |      |         |        |

F=4.15, F crit= 4.38. F < F crit, therefore, the Chipuxet and Upper Wood bedrock wells ground-water radon levels are not significantly different.
Queen-Usquepaugh bedrock wells compared to Chipuxet bedrock wells radon levels:

Anova: Single Factor

**SUMMARY**

| Groups    | n  | Sum   | Average | Variance |
|-----------|----|-------|---------|----------|
| Queen     | 9  | 38.24 | 4.25    | 0.10     |
| Chipuxet  | 12 | 44.47 | 3.71    | 0.15     |

**ANOVA**

| Source of Variation | SS    | df | MS     | F      | P-value | F crit |
|---------------------|-------|----|--------|--------|---------|--------|
| Between Groups      | 1.521102 | 1  | 1.521102 | 11.78  | 0.00    | 4.38   |
| Within Groups       | 2.453389  | 19 | 0.129126 |        |         |        |
| Total               | 3.974491  | 20 |         |        |         |        |

F=11.78, F_{crit} = 4.38. F > F_{crit}, therefore, the Queen-Usquepaugh bedrock wells ground-water radon levels are significantly greater than the Chipuxet bedrock wells.
Analysis of radon data by underlying bedrock.

Scituate

Shallow surficial compared to deep surficial radon levels in wells:

Anova: Single Factor

| Groups | n  | Sum  | Average | Variance |
|--------|----|------|---------|----------|
| shallow | 9  | 30.42| 3.38    | 0.16     |
| deep   | 5  | 18.25| 3.65    | 0.06     |

ANOVA

| Source of Variation | SS        | df | MS         | F         | P-value | F crit |
|---------------------|-----------|----|------------|-----------|---------|--------|
| Between Groups      | 0.232993  | 1  | 0.232993   | 1.78      | 0.21    | 4.75   |
| Within Groups       | 1.566423  | 12 | 0.130535   |           |         |        |
| Total               | 1.799416  | 13 |            |           |         |        |

F=1.78, F_{crit}=4.75. F < F_{crit} therefore, the Scituate surficial wells ground-water radon levels are not significantly different.

The surficial wells were pooled together and compared to bedrock wells radon levels.

Scituate surficial compared to bedrock radon levels in wells:

Anova: Single Factor

| Groups | n  | Sum  | Average | Variance |
|--------|----|------|---------|----------|
| surficial | 14 | 48.67| 3.48    | 0.14     |
| bedrock | 9  | 38.76| 4.31    | 0.11     |

ANOVA

| Source of Variation | SS        | df | MS         | F         | P-value | F crit |
|---------------------|-----------|----|------------|-----------|---------|--------|
| Between Groups      | 3.776129  | 1  | 3.776129   | 29.57     | .00     | 4.32   |
| Within Groups       | 2.681486  | 21 | 0.12769    |           |         |        |
| Total               | 6.457615  | 22 |            |           |         |        |
Scituate surficial compared to bedrock radon levels in wells continued:

F=29.57, $F_{\text{crit}}=4.32$. $F > F_{\text{crit}}$, therefore, the Scituate bedrock wells ground-water radon levels are significantly greater than the surficial wells.

**Esmond**

shallow surficial compared to deep surficial radon levels in wells:

Anova: Single Factor

**SUMMARY**

| Groups  | n  | Sum  | Average | Variance |
|---------|----|------|---------|----------|
| shallow | 15 | 45.02| 3.00    | 0.03     |
| deep    | 11 | 34.70| 3.15    | 0.08     |

**ANOVA**

| Source of Variation | SS   | df  | MS    | F      | P-value | F crit |
|---------------------|------|-----|-------|--------|---------|--------|
| Between Groups      | 0.14797 | 1   | 0.14797 | 2.74   | 0.11    | 4.26   |
| Within Groups       | 1.298331 | 24  | 0.054097 |        |         |        |
| Total               | 1.446301 | 25  |        |        |         |        |

F=2.74, $F_{\text{crit}}=4.26$. $F < F_{\text{crit}}$, therefore, the Esmond surficial wells ground-water radon levels are not significantly different.

The surficial wells were pooled together and compared to bedrock wells radon levels.
Esmond surficial compared to bedrock radon levels in wells:

Anova: Single Factor

| Groups  | n  | Sum  | Average | Variance |
|---------|----|------|---------|----------|
| surficial | 26 | 79.72 | 3.07    | 0.06     |
| bedrock  | 12 | 45.28 | 3.77    | 0.09     |

ANOVA

| Source of Variation | SS      | df | MS      | F       | P-value | F crit |
|---------------------|---------|----|---------|---------|---------|--------|
| Between Groups      | 4.102655| 1  | 4.102655| 59.34   | .00     | 4.11   |
| Within Groups       | 2.489034| 36 | 0.06914 |         |         |        |
| Total               | 6.591688| 37 |         |         |         |        |

F=59.34, F crit = 4.11. F > F crit, therefore, the Esmond bedrock wells ground-water radon levels are significantly greater than the surficial wells.

Sterling

shallow surficial compared to deep surficial radon levels in wells:

Anova: Single Factor

| Groups | n  | Sum  | Average | Variance |
|--------|----|------|---------|----------|
| shallow| 7  | 22.14| 3.16    | 0.05     |
| deep   | 13 | 39.79| 3.06    | 0.03     |

ANOVA

| Source of Variation | SS      | df | MS      | F       | P-value | F crit |
|---------------------|---------|----|---------|---------|---------|--------|
| Between Groups      | 0.047636| 1  | 0.047636| 1.32    | 0.27    | 4.41   |
| Within Groups       | 0.648078| 18 | 0.036004|         |         |        |
| Total               | 0.695715| 19 |         |         |         |        |

F=1.32, F crit = 4.41. F < F crit, therefore, the Sterling surficial wells ground-water radon levels are not significantly different.

The surficial wells were pooled together and compared to bedrock wells radon levels.
Sterling surficial compared to bedrock radon levels in wells:

Anova: Single Factor

**SUMMARY**

|       | n  | Sum  | Average | Variance |
|-------|----|------|---------|----------|
| surficial | 20 | 61.93 | 3.10    | 0.04     |
| bedrock   | 5  | 19.69 | 3.94    | 0.08     |

**ANOVA**

| Source of Variation | SS      | df | MS       | F      | P-value | F crit |
|---------------------|---------|----|----------|--------|---------|--------|
| Between Groups      | 2.828335| 1  | 2.828335 | 64.08  | .00     | 4.28   |
| Within Groups       | 1.015234| 23 | 0.044141 |        |         |        |
| Total               | 3.84357 | 24 |          |        |         |        |

F=64.08, F<sub>crit</sub> = 4.28. F > F<sub>crit</sub>, therefore, the Sterling bedrock wells ground-water radon levels are significantly greater than the surficial wells.

Scituate bedrock wells compared to Esmond bedrock wells radon levels:

Anova: Single Factor

**SUMMARY**

|       | n  | Sum  | Average | Variance |
|-------|----|------|---------|----------|
| Scituate | 9  | 38.76 | 4.31    | 0.11     |
| Esmond  | 14 | 52.83 | 3.77    | 0.16     |

**ANOVA**

| Source of Variation | SS      | df | MS       | F      | P-value | F crit |
|---------------------|---------|----|----------|--------|---------|--------|
| Between Groups      | 1.558744| 1  | 1.558744 | 11.19  | .00     | 4.32   |
| Within Groups       | 2.92498 | 21 | 0.139285 |        |         |        |
| Total               | 4.483725| 22 |          |        |         |        |

F=11.19, F<sub>crit</sub> = 4.32. F > F<sub>crit</sub>, therefore, the Scituate bedrock wells ground-water radon levels are significantly greater than the Esmond bedrock wells.
Scituate bedrock wells compared to Sterling bedrock wells radon levels:

Anova: Single Factor

| Groups   | n  | Sum  | Average | Variance |
|----------|----|------|---------|----------|
| Scituate | 9  | 38.76| 4.31    | 0.11     |
| Sterling | 7  | 27.61| 3.94    | 0.13     |

ANOVA

| Source of Variation | SS       | df | MS       | F         | P-value | F crit |
|---------------------|----------|----|----------|-----------|---------|--------|
| Between Groups      | 0.519105 | 1  | 0.519105 | 4.39      | 0.05    | 4.60   |
| Within Groups       | 1.655674 | 14 | 0.118262 |           |         |        |
| Total               | 2.174779 | 15 |          |           |         |        |

F=4.39, F_{crit}= 4.6. F < F_{crit}, therefore, the Scituate and the Sterling bedrock wells ground-water radon levels are not significantly different.

Esmond bedrock wells compared to Sterling bedrock wells radon levels:

Anova: Single Factor

| Groups   | n  | Sum  | Average | Variance |
|----------|----|------|---------|----------|
| Esmond   | 14 | 52.83| 3.77    | 0.16     |
| Sterling | 7  | 27.61| 3.94    | 0.13     |

ANOVA

| Source of Variation | SS       | df | MS       | F         | P-value | F crit |
|---------------------|----------|----|----------|-----------|---------|--------|
| Between Groups      | 0.135381 | 1  | 0.135381 | 0.91      | 0.35    | 4.38   |
| Within Groups       | 2.816515 | 19 | 0.148238 |           |         |        |
| Total               | 2.951895 | 20 |          |           |         |        |

F=0.91, F_{crit}= 4.38. F < F_{crit}, therefore, the Esmond and the Sterling bedrock wells ground-water radon levels are not significantly different.
Esmond surficial wells compared to Scituate surficial wells radon levels:

Anova: Single Factor

SUMMARY

| Groups  | n  | Sum   | Average | Variance |
|---------|----|-------|---------|----------|
| Scituate| 12 | 41.85 | 3.49    | 0.05     |
| Esmond  | 26 | 79.72 | 3.07    | 0.06     |

ANOVA

| Source of Variation | SS          | df | MS         | F      | P-value | F crit |
|---------------------|-------------|----|------------|--------|---------|--------|
| Between Groups      | 1.45463     | 1  | 1.45463    | 25.70  | .00     | 4.11   |
| Within Groups       | 2.037388    | 36 | 0.056594   |        |         |        |
| Total               | 3.492018    | 37 |            |        |         |        |

F=25.70, $F_{crit}= 4.11$. $F > F_{crit}$ therefore, the Scituate surficial wells ground-water radon levels are significantly greater than the Esmond wells.

Sterling surficial wells compared to Scituate surficial wells radon levels:

Anova: Single Factor

SUMMARY

| Groups  | n  | Sum   | Average | Variance |
|---------|----|-------|---------|----------|
| Scituate| 12 | 41.85 | 3.49    | 0.05     |
| Sterling| 20 | 61.93 | 3.10    | 0.04     |

ANOVA

| Source of Variation | SS          | df | MS         | F      | P-value | F crit |
|---------------------|-------------|----|------------|--------|---------|--------|
| Between Groups      | 1.145446    | 1  | 1.145446   | 26.70  | .00     | 4.17   |
| Within Groups       | 1.286801    | 30 | 0.042893   |        |         |        |
| Total               | 2.432248    | 31 |            |        |         |        |

F=26.70, $F_{crit}= 4.17$. $F > F_{crit}$ therefore, the Scituate surficial wells ground-water radon levels are significantly greater than the Sterling wells.
Sterling surficial wells compared to Esmond surficial wells radon levels:

Anova: Single Factor

SUMMARY

| Groups   | n  | Sum   | Average | Variance |
|----------|----|-------|---------|----------|
| Sterling | 20 | 61.93 | 3.10    | 0.04     |
| Esmond   | 26 | 79.72 | 3.07    | 0.06     |

ANOVA

| Source of Variation | SS      | df | MS      | F   | P-value | F crit |
|---------------------|---------|----|---------|-----|---------|--------|
| Between Groups      | 0.010248| 1  | 0.010248| 0.21| 0.65    | 4.06   |
| Within Groups       | 2.142016| 44 | 0.048682|     |         |        |
| Total               | 2.152264| 45 |         |     |         |        |

F=0.21, F_{crit}= 4.06. F < F_{crit} therefore, the Sterling and Esmond surficial wells ground-water radon levels are not significantly different.
Analysis of fluoride compared to radon data.

Spearman’s rank correlation coefficient was used to test whether there is a significant correlation between fluoride and radon. Both the radon data and the fluoride data were ranked and the Spearman’s rank correlation coefficient was calculated. This correlation coefficient was then analyzed using the Student’s T-test to determine its significance.

\[
\text{Spearman’s rank } (r_s) = 1 - 6 \sum_{i=1}^{n} d_i^2 \left( \frac{1}{n^2 - n} \right)
\]

where \( n \) (number of samples) = 75, \( \sum_{i=1}^{n} d_i^2 \) (sum of the rank differences, squared) = 22,700.

In the Student’s T-test, the hypothesis that there is no relationship between two variables is rejected if \( t > t_{\text{crit}} \).

\[
t = r_s \times \sqrt{\frac{n-2}{1-r_s^2}}
\]

\( r_s \) is found in the Table of Critical Values of t, where \( \alpha = .05 \) (t.025) and \( df = n-2 \).

\[
r_s = 1 - [(6 \times 22,700) / (75^2 - 75)] = .677.
\]

\[
t = .677 \times \sqrt{[(75 - 2) / (1 - .6772)]} = 7.857.
\]

\( t_{\text{crit}} = 1.96 \).

Since \( t \) is greater than \( t_{\text{crit}} \), the correlation coefficient of the ranks is significant, and therefore there is a significant correlation between radon and fluoride.
Analysis of alkalinity compared to radon data.

Spearman’s rank correlation coefficient was used to test whether there is a significant correlation between alkalinity and radon. Both the radon data and the alkalinity data were ranked and the Spearman’s rank correlation coefficient was calculated. This correlation coefficient was then analyzed using the Student’s T-test to determine its significance.

\[ r_s = 1 - \frac{6 \sum_{i=1}^{n} d_i^2}{n^3 - n} \]

where \( n \) (number of samples) = 75, \( \sum_{i=1}^{n} d_i^2 \) (sum of the rank differences, squared) = 27,277.

In the Student’s T-test, the hypothesis that there is no relationship between two variables is rejected if \( t > t_{crit} \).

\[ t = r_s \times \sqrt{\frac{n-2}{1-r_s^2}} \]

and \( t_{crit} \) is found in the Table of Critical Values of \( t \), where \( \alpha = .05 \) (\( t_{0.05} \)) and df = n-2.

\[ r_s = 1 - \frac{(6 \times 27,277)}{(75^3 - 75)} = .612. \]

\[ t = .612 \times \sqrt{\frac{75-2}{1-.612^2}} = 6.61. \]

\[ t_{crit} = 1.96. \]

Since \( t \) is greater than \( t_{crit} \), the correlation coefficient of the ranks is significant, and therefore there is a significant correlation between radon and alkalinity.
Anova analysis of fluoride data.

Statistical analysis of the fluoride data was done to test whether two populations were significantly different. First, the Anova (single factor) test was done to statistically analyze the data. The populations were assumed to be distributed normally. In order to make the distribution roughly symmetric (normal) without heavy outliers, anomalously high and low values were discarded on a few of the tests. Then, the F-test was used to test whether the populations were significantly different.

F-test. The hypothesis that the populations are not significantly different is rejected if $F > F_{crit}$. Both the $F$ and $F_{crit}$ values are found in the Anova output.

The data are first analyzed by aquifer.

Analysis of fluoride data by aquifer.

Queen-Usquepaugh

Shallow surficial compared to deep surficial fluoride levels in wells:

Anova: Single Factor

| Groups  | $n$ | Sum | Average | Variance |
|---------|-----|-----|---------|----------|
| shallow | 4   | 1.38| 0.34    | 0.10     |
| deep    | 6   | 1.29| 0.21    | 0.07     |

ANOVA

| Source of Variation | SS   | df  | MS    | $F$  | $P$-value | $F_{crit}$ |
|---------------------|------|-----|-------|------|-----------|------------|
| Between Groups      | 0.04056 | 1   | 0.04056 | 0.51 | 0.50      | 5.32       |
| Within Groups       | 0.63605 | 8   | 0.079506 |     |           |            |
| Total               | 0.67661 | 9   |        |      |           |            |

$F = 0.51$, $F_{crit} = 5.32$. $F < F_{crit}$, therefore, the surficial well ground-water fluoride levels are not significantly different.

The surficial wells are pooled together and compared to the bedrock fluoride levels in wells.
Queen-Usquepaugh surficial wells compared to bedrock wells:

Anova: Single Factor

| Groups     | n  | Sum | Average | Variance |
|------------|----|-----|---------|----------|
| surficial  | 10 | 2.67| 0.27    | 0.08     |
| bedrock    | 7  | 13.13| 1.88    | 1.97     |

ANOVA

| Source of Variation | SS      | df | MS          | F       | P-value | F crit |
|---------------------|---------|----|-------------|---------|---------|--------|
| Between Groups      | 10.65631| 1  | 10.65631    | 12.81   | 0.00    | 4.54   |
| Within Groups       | 12.47698| 15 | 0.831799    |         |         |        |

F=12.81, F_{crit}=4.54.  
F > F_{crit}, therefore, the surficial well ground-water fluoride levels are significantly less than the bedrock fluoride levels.

Upper Wood River

Shallow surficial compared to deep surficial fluoride levels in wells:

Anova: Single Factor

| Groups  | n  | Sum | Average | Variance |
|---------|----|-----|---------|----------|
| shallow | 7  | 0.82| 0.12    | 0.01     |
| deep    | 8  | 3.07| 0.38    | 0.49     |

ANOVA

| Source of Variation | SS      | df | MS          | F       | P-value | F crit |
|---------------------|---------|----|-------------|---------|---------|--------|
| Between Groups      | 0.265363| 1  | 0.265363    | 0.99    | 0.34    | 4.67   |
| Within Groups       | 3.48293 | 13 | 0.267918    |         |         |        |

F=.99, F_{crit}=4.67.  
F < F_{crit}, therefore, the surficial well ground-water fluoride levels are not significantly different.
The Upper Wood River surficial wells are pooled together and compared to the bedrock fluoride levels in wells.

**Anova: Single Factor**

### SUMMARY

| Groups       | n  | Sum  | Average | Variance |
|--------------|----|------|---------|----------|
| surficial    | 15 | 3.89 | 0.26    | 0.27     |
| bedrock      | 9  | 14.33| 1.59    | 0.55     |

### ANOVA

| Source of Variation | SS     | df | MS       | F        | P-value | F crit |
|---------------------|--------|----|----------|----------|---------|--------|
| Between Groups      | 9.99334| 1  | 9.99334  | 26.96    | .00     | 4.30   |
| Within Groups       | 8.15449| 22 | 0.370657 |          |         |        |
| Total               | 18.14778| 23 |          |          |         |        |

$F=26.96, F_{crit}=4.30$. $F > F_{crit}$, therefore, the surficial well ground-water fluoride levels are significantly less than the bedrock fluoride levels.

**Chinuxet**

Shallow surficial compared to deep surficial fluoride levels in wells:

**Anova: Single Factor**

### SUMMARY

| Groups | n | Sum  | Average | Variance |
|--------|---|------|---------|----------|
| shallow| 9 | 0.46 | 0.05    | 0.00     |
| deep   | 9 | 1.14 | 0.13    | 0.07     |

### ANOVA

| Source of Variation | SS     | df | MS       | F        | P-value | F crit |
|---------------------|--------|----|----------|----------|---------|--------|
| Between Groups      | 0.025689| 1  | 0.025689 | 0.69     | 0.42    | 4.49   |
| Within Groups       | 0.597489| 16 | 0.037343 |          |         |        |
| Total               | 0.623178| 17 |          |          |         |        |

$F=.69, F_{crit}=4.49$. $F < F_{crit}$, therefore, the surficial well ground-water fluoride levels are not significantly different.
The Chipuxet surficial wells are pooled together and compared to the bedrock fluoride levels in wells.

**Anova: Single Factor**

**SUMMARY**

| Groups   | n  | Sum | Average | Variance |
|----------|----|-----|---------|----------|
| surficial| 18 | 1.5 | 0.09    | 0.04     |
| bedrock  | 11 | 5.2 | 0.47    | 0.17     |

**ANOVA**

| Source of Variation | SS     | df | MS        | F        | P-value | F crit |
|---------------------|--------|----|-----------|----------|---------|--------|
| Between Groups      | 1.005921 | 1  | 1.005921  | 11.75    | 0.00    | 4.21   |
| Within Groups       | 2.312196 | 27 | 0.085637  |          |         |        |
| Total               | 3.318117 | 28 |           |          |         |        |

$F = 11.75, F_{crit} = 4.21$. $F > F_{crit}$, therefore, the surficial well ground-water fluoride levels are significantly less than the bedrock fluoride levels.

Fluoride levels were then compared between aquifers. 
**Surficial wells.**

**Queen-Usguepaugh and Upper Wood River.**

**Anova: Single Factor**

**SUMMARY**

| Groups            | n  | Sum | Average | Variance |
|-------------------|----|-----|---------|----------|
| Queen             | 6  | 0.97| 0.16    | 0.01     |
| Upper Wood        | 13 | 1.79| 0.14    | 0.01     |

**ANOVA**

| Source of Variation | SS     | df | MS        | F        | P-value | F crit |
|---------------------|--------|----|-----------|----------|---------|--------|
| Between Groups      | 0.00236 | 1  | 0.00236   | 0.23     | 0.64    | 4.45   |
| Within Groups       | 0.175114 | 17 | 0.010301  |          |         |        |
| Total               | 0.177474 | 18 |           |          |         |        |

$F = 0.23, F_{crit} = 4.45$. $F < F_{crit}$, therefore, the surficial well ground-water fluoride levels are not significantly different.
Queen-Usquepaugh and Chipuxet.

Anova: Single Factor

SUMMARY

| Groups   | n  | Sum  | Average | Variance |
|----------|----|------|---------|----------|
| Queen    | 8  | 1.82 | 0.23    | 0.06     |
| Chipuxet | 16 | 0.76 | 0.05    | 0.00     |

ANOVA

| Source of Variation | SS       | df | MS      | F        | P-value | F crit |
|---------------------|----------|----|---------|----------|---------|--------|
| Between Groups      | 0.1728   | 1  | 0.1728  | 9.19     | 0.01    | 4.30   |
| Within Groups       | 0.41345  | 22 | 0.018793|          |         |        |
| Total               | 0.58625  | 23 |         |          |         |        |

F=9.19, F crit= 4.30. F > F crit, therefore, the Queen-Usquepaugh ground-water fluoride levels are significantly greater than the Chipuxet fluoride levels.

Upper Wood River and Chipuxet.

Anova: Single Factor

SUMMARY

| Groups   | n  | Sum  | Average | Variance |
|----------|----|------|---------|----------|
| Upper Wood | 13 | 1.79 | 0.14    | 0.01     |
| Chipuxet | 16 | 0.76 | 0.05    | 0.00     |

ANOVA

| Source of Variation | SS       | df | MS      | F        | P-value | F crit |
|---------------------|----------|----|---------|----------|---------|--------|
| Between Groups      | 0.058345 | 1  | 0.058345| 12.67    | 0.00    | 4.21   |
| Within Groups       | 0.124331 | 27 | 0.004605|          |         |        |
| Total               | 0.182676 | 28 |         |          |         |        |

F=12.67, F crit= 4.21. F > F crit, therefore, the Upper Wood River ground-water fluoride levels are significantly greater than the Chipuxet fluoride levels.
**Bedrock wells.**

**Queen-Usquepaugh and Upper Wood River.**

Anova: Single Factor

**SUMMARY**

| Groups   | n  | Sum   | Average | Variance |
|----------|----|-------|---------|----------|
| Queen    | 5  | 9.49  | 1.90    | 1.50     |
| U. Wood  | 9  | 14.33 | 1.59    | 0.55     |

**ANOVA**

| Source of Variation | SS     | df  | MS     | F      | P-value | F crit |
|---------------------|--------|-----|--------|--------|---------|--------|
| Between Groups      | 0.300536 | 1   | 0.300536 | 0.35   | 0.57    | 4.75   |
| Within Groups       | 10.41784 | 12  | 0.868153 |        |         |        |
| Total               | 10.71837 | 13  |         |        |         |        |

\( F = 35, F_{crit} = 4.75 \). \( F < F_{crit} \), therefore, the bedrock well ground-water fluoride levels are not significantly different.

**Queen-Usquepaugh and Chipuxet.**

Anova: Single Factor

**SUMMARY**

| Groups   | n  | Sum   | Average | Variance |
|----------|----|-------|---------|----------|
| Queen    | 5  | 9.49  | 1.90    | 1.50     |
| Chipuxet | 11 | 5.2   | 0.47    | 0.17     |

**ANOVA**

| Source of Variation | SS        | df  | MS       | F      | P-value | F crit |
|---------------------|-----------|-----|----------|--------|---------|--------|
| Between Groups      | 6.982946  | 1   | 6.982946 | 12.70  | 0.00    | 4.60   |
| Within Groups       | 7.700698  | 14  | 0.55005  |        |         |        |
| Total               | 14.68364  | 15  |          |        |         |        |

\( F = 12.70, F_{crit} = 4.60 \). \( F > F_{crit} \), therefore, the Queen-Usquepaugh ground-water fluoride levels are significantly greater than the Chipuxet fluoride levels.
Upper Wood River and Chipuxet.

Anova: Single Factor

| SUMMARY       | Groups | n  | Sum   | Average | Variance |
|---------------|--------|----|-------|---------|----------|
|               | U. Wood| 9  | 14.33 | 1.59    | 0.55     |
|               | Chipuxet| 11 | 5.2   | 0.47    | 0.17     |

ANOVA

| Source of Variation | SS          | df | MS      | F    | P-value | F crit |
|---------------------|-------------|----|---------|------|---------|--------|
| Between Groups      | 6.203681    | 1  | 6.203681| 18.32| 0.00    | 4.41   |
| Within Groups       | 6.095174    | 18 | 0.338621|      |         |        |
| Total               | 12.29886    | 19 |         |      |         |        |

F=18.32, \( F_{\text{crit}} = 4.41 \). F > \( F_{\text{crit}} \) therefore, the Upper Wood River ground-water fluoride levels are significantly greater than the Chipuxet fluoride levels.
Anova analysis of uranium data.

Statistical analysis of the dissolved uranium data was done to test whether two populations were significantly different. First, the Anova (single factor) test was done to statistically analyze the data. The populations were assumed to be distributed normally. In order to make the distribution roughly symmetric (normal) without heavy outliers, anomalously high and low values were discarded on a few of the tests. Then, the F-test was used to test whether the populations were significantly different.

F-test. The hypothesis that the populations are not significantly different is rejected if $F > F_{crit}$.
Both the $F$ and $F_{crit}$ values are found in the A-nova output.

The data are first analyzed by aquifer.

Analysis of dissolved uranium data by aquifer.

Queen-Usguepaugh

Shallow surficial compared to deep surficial uranium levels in wells:

Anova: Single Factor

| Groups | n | Sum | Average | Variance |
|--------|---|-----|---------|----------|
| shallow | 4 | 1.91 | 0.48 | 0.13 |
| deep | 4 | 2.12 | 0.53 | 0.10 |

ANOVA

| Source of Variation | SS     | df | MS     | F   | P-value | $F_{crit}$ |
|---------------------|--------|----|--------|-----|---------|------------|
| Between Groups      | 0.005513 | 1  | 0.005513 | 0.05 | 0.83    | 5.99       |
| Within Groups       | 0.685275 | 6  | 0.114213 |      |         |            |
| Total               | 0.690788 | 7  |         |      |         |            |

$F=0.5, F_{crit}=5.99$. $F < F_{crit}$, therefore, the surficial well ground-water uranium levels are not significantly different.
The Queen-Usquepaugh surficial wells are pooled together and compared to the bedrock uranium levels in wells.

Anova: Single Factor

**SUMMARY**

| Groups     | n | Sum | Average | Variance |
|------------|---|-----|---------|----------|
| surficial  | 8 | 4.03| 0.50    | 0.10     |
| bedrock    | 7 | 23.35| 3.34    | 12.48    |

**ANOVA**

| Source of Variation | SS      | df | MS       | F         | P-value | F crit |
|---------------------|---------|----|----------|-----------|---------|--------|
| Between Groups      | 29.94141| 1  | 29.94141 | 5.15      | 0.04    | 4.67   |
| Within Groups       | 75.55096| 13 | 0.021915 |           |         |        |
| Total               | 105.4924| 14 |          |           |         |        |

F=5.15, $F_{crit}$= 4.67. F > $F_{crit}$, therefore, the bedrock ground-water uranium levels are significantly greater than the surficial uranium levels.

**Upper Wood River**

shallow surficial compared to deep surficial uranium levels in wells:

Anova: Single Factor

**SUMMARY**

| Groups | n | Sum | Average | Variance |
|--------|---|-----|---------|----------|
| shallow| 7 | 2.4 | 0.34    | 0.01     |
| deep   | 8 | 3.54| 0.44    | 0.03     |

**ANOVA**

| Source of Variation | SS      | df | MS       | F         | P-value | F crit |
|---------------------|---------|----|----------|-----------|---------|--------|
| Between Groups      | 0.037067| 1  | 0.037067 | 1.69      | 0.22    | 4.67   |
| Within Groups       | 0.284893| 13 | 0.021915 |           |         |        |
| Total               | 0.32196 | 14 |          |           |         |        |

F=1.69, $F_{crit}$= 4.67. F < $F_{crit}$, therefore, the surficial well ground-water uranium levels are not significantly different.
The Upper Wood River surficial wells are pooled together and compared to the bedrock uranium levels in wells.

**Anova: Single Factor**

**SUMMARY**

| Groups      | n | Sum | Average | Variance |
|-------------|---|-----|---------|----------|
| surficial   | 15| 5.94| 0.40    | 0.02     |
| bedrock     | 5 | 20.65| 4.13    | 24.27    |

**ANOVA**

| Source of Variation | SS    | df | MS      | F      | P-value | F crit |
|---------------------|-------|----|---------|--------|---------|--------|
| Between Groups      | 52.28534 | 1  | 52.28534 | 9.66   | 0.01    | 4.41   |
| Within Groups       | 97.38596 | 18 | 5.410331 |        |         |        |
| Total               | 149.6713 | 19 |          |        |         |        |

F = 9.66, F crit = 4.41. F > F crit, therefore, the bedrock ground-water uranium levels are significantly greater than the surficial uranium levels.

**Chipuxet**

shallow surficial compared to deep surficial uranium levels in wells:

**Anova: Single Factor**

**SUMMARY**

| Groups   | n | Sum | Average | Variance |
|----------|---|-----|---------|----------|
| shallow  | 9 | 4.9 | 0.54    | 0.72     |
| deep     | 9 | 7.01| 0.78    | 1.32     |

**ANOVA**

| Source of Variation | SS    | df | MS      | F      | P-value | F crit |
|---------------------|-------|----|---------|--------|---------|--------|
| Between Groups      | 0.247339 | 1  | 0.247339 | 0.24   | 0.63    | 4.49   |
| Within Groups       | 16.35931 | 16 | 1.022457 |        |         |        |
| Total               | 16.60665 | 17 |          |        |         |        |

F = 0.24, F crit = 4.49. F < F crit, therefore, the surficial well ground-water uranium levels are not significantly different.
The Chipuxet surficial wells are pooled together and compared to the bedrock uranium levels in wells.

Anova: Single Factor

**SUMMARY**

| Groups   | n  | Sum | Average | Variance |
|----------|----|-----|---------|----------|
| surficial | 18 | 11.91 | 0.661667 | 0.976862 |
| bedrock   | 7  | 18.67 | 2.667143 | 6.348024 |

**ANOVA**

| Source of Variation | SS          | df | MS      | F     | P-value | F crit |
|---------------------|-------------|----|---------|-------|---------|--------|
| Between Groups      | 20.27055    | 1  | 20.27   | 8.52  | 0.01    | 4.28   |
| Within Groups       | 54.69479    | 23 | 2.38    |       |         |        |
| Total               | 74.96534    | 24 |         |       |         |        |

$F=8.52, F_{crit}=4.28$. $F > F_{crit}$, therefore, the bedrock ground-water uranium levels are significantly greater than the surficial uranium levels.

**Uranium levels were then compared between aquifers.**

**Surficial wells.**

**Queen-Usguepaugh and Upper Wood River.**

Anova: Single Factor

**SUMMARY**

| Groups   | n  | Sum | Average | Variance |
|----------|----|-----|---------|----------|
| Queen    | 8  | 4.03 | 0.50    | 0.10     |
| U. Wood  | 15 | 5.94 | 0.40    | 0.02     |

**ANOVA**

| Source of Variation | SS          | df | MS      | F     | P-value | F crit |
|---------------------|-------------|----|---------|-------|---------|--------|
| Between Groups      | 0.060574    | 1  | 0.060574| 1.26  | 0.28    | 4.32   |
| Within Groups       | 1.012748    | 21 | 0.048226|       |         |        |
| Total               | 1.073322    | 22 |         |       |         |        |

$F=1.26, F_{crit}=4.32$. $F < F_{crit}$, therefore, the surficial well ground-water uranium levels are not significantly different.
### Queen-Usguepaugh and Chipuxet

**Anova: Single Factor**

#### SUMMARY

| Groups  | n  | Sum  | Average | Variance |
|---------|----|------|---------|----------|
| Queen   | 8  | 4.03 | 0.50    | 0.10     |
| Chipuxet| 16 | 8.11 | 0.51    | 0.46     |

#### ANOVA

| Source of Variation | SS       | df | MS       | F        | P-value | F crit |
|---------------------|----------|----|----------|----------|---------|--------|
| Between Groups      | 5.21E-05 | 1  | 5.21E-05 | 0.00     | 0.99    | 4.30   |
| Within Groups       | 7.581331 | 22 | 0.344606 |          |         |        |
| Total               | 7.581383 | 23 |          |          |         |        |

F=0.00, F < F crit, therefore, the surficial well ground-water uranium levels are not significantly different.

### Upper Wood River and Chipuxet

**Anova: Single Factor**

#### SUMMARY

| Groups  | n  | Sum  | Average | Variance |
|---------|----|------|---------|----------|
| U Wood  | 12 | 4.66 | 0.39    | 0.12     |
| Chipuxet| 15 | 5.94 | 0.40    | 0.03     |

#### ANOVA

| Source of Variation | SS       | df | MS       | F        | P-value | F crit |
|---------------------|----------|----|----------|----------|---------|--------|
| Between Groups      | 0.000392 | 1  | 0.000392 | 0.01     | 0.94    | 4.24   |
| Within Groups       | 1.626727 | 25 | 0.065069 |          |         |        |
| Total               | 1.627119 | 26 |          |          |         |        |

F=0.01, F < F crit, therefore, the surficial well ground-water uranium levels are not significantly different.
**Bedrock wells.**

**Queen-Usquepaugh and Upper Wood River.**

Anova: Single Factor

| SUMMARY | Groups | n | Sum | Average | Variance |
|---------|--------|---|-----|---------|----------|
| Queen   | 7      | 23.35 | 3.34 | 12.48 |
| U. Wood | 5      | 20.65 | 4.13 | 24.27 |

**ANOVA**

| Source of Variation | SS        | df | MS      | F       | P-value | F crit |
|---------------------|-----------|----|---------|---------|---------|--------|
| Between Groups      | 1.840095  | 1  | 1.840095| 0.11    | 0.75    | 4.96   |
| Within Groups       | 171.9242  | 10 | 17.19242|         |         |        |
| Total               | 173.7643  | 11 |         |         |         |        |

F=0.11, F\text{crit}=4.96. F < F\text{crit} therefore, the bedrock well ground-water uranium levels are not significantly different.

**Queen-Usquepaugh and Chipuxet.**

Anova: Single Factor

| SUMMARY | Groups | n | Sum | Average | Variance |
|---------|--------|---|-----|---------|----------|
| Queen   | 7      | 23.35 | 3.34 | 12.48 |
| Chipuxet| 7      | 18.67 | 2.67 | 6.35  |

**ANOVA**

| Source of Variation | SS         | df | MS       | F      | P-value | F crit |
|---------------------|------------|----|----------|--------|---------|--------|
| Between Groups      | 1.564457   | 1  | 1.564457 | 0.17   | 0.69    | 4.75   |
| Within Groups       | 112.9483   | 12 | 9.41236  |        |         |        |
| Total               | 114.5128   | 13 |          |        |         |        |

F=0.17, F\text{crit}=4.75. F < F\text{crit} therefore, the bedrock well ground-water uranium levels are not significantly different.
Upper Wood River and Chipuxet.

Anova: Single Factor

| Groups     | n  | Sum | Average | Variance |
|------------|----|-----|---------|----------|
| U. Wood    | 5  | 20.65 | 4.13 | 24.27 |
| Chipuxet   | 7  | 18.67 | 2.67 | 6.35 |

ANOVA

| Source of Variation | SS          | df | MS         | F       | P-value | F crit |
|---------------------|-------------|----|------------|---------|---------|--------|
| Between Groups      | 6.241524    | 1  | 6.241524   | 0.46    | 0.51    | 4.96   |
| Within Groups       | 135.1521    | 10 | 13.51521   |         |         |        |
| Total               | 141.3937    | 11 |            |         |         |        |

F = 0.46, F crit = 4.96. F < F crit, therefore, the bedrock well ground-water uranium levels are not significantly different.
Bibliography

Aieta, E.M., Singley, J.E., Trussell, A.R., Thorbjarnarson, K.W., and McGuire, M.J., 1987, Radionuclides in drinking water: an overview: Journal of the American Water Works Association 79, p. 144-152.

Clesceri, L.S., Greenberg, A.E., and Trussel, R.R., 1989, Standard Methods for the Examination of Water and Wastewater: Washington D.C., American Public Health Association, seventeenth edition, 1527p.

Collins, W.J., Beams, S.D., White, A.J.R., and Chappell, B.W., 1982, Nature and origin of A-type granites with particular reference to southeastern Australia: Contributions to Mineralogy and Petrology, v. 80, p. 189-200.

Cothern, C.R., Lappenbusch, W.L., and Michel, J., 1986, Drinking water contribution to natural background radiation: Health Physics, v. 50, p. 33.

Cothern, C.R., 1987, Development of regulations for radionuclides in drinking water, in Graves, B., ed., Radon, Radium, and Other Radioactivity in Ground Water: Chelsea, MI, Lewis Publishers, p. 1-11.

Cothern, C.R., and Smith, J.E. Jr., 1987, Radon in surface waters, in Cothern, C.R., and Smith, J.E. Jr., eds., Environmental Radon: New York, New York, Plenium Press, p. 108-118.

Crawford-Brown, D.J., 1990, Analysis of the health risk from ingested radon, in Cothern, C.R. and Rebers, P.A., eds., Radon, Radium, and Uranium in Drinking Water: Chelsea, MI, Lewis Publishers, p. 17-26.

Dickerman, D.C., and Bell, R.W., 1993, Hydrology, water quality, and ground-water-development alternatives in the Upper Wood River ground-water reservoir, Rhode Island: USGS Water-Resources Investigations Report 92-4119, 87 p.

Drever, J.I., 1988, The geochemistry of natural waters, Prentice Hall, Englewood Cliffs, New Jersey, 437p.
Ewing, R.C., Haaker, R.F., and Lutze, W., 1982, Leachability of zircon as a function of alpha dose, in Lutze, W., ed., Scientific Basis for Radioactive Waste Management: Elsevier Press, p. 389-397.

Folger, P.F., Nyberg, P., Wanty, R.B., and Poeter, E., 1994, Relationships between $^{222}$Rn dissolved in ground water supplies and indoor $^{222}$Rn concentrations in some Colorado front range houses: Health Physics, v. 67, n. 3, p. 245-153.

Gall, I.K., Ritz, R.W. Jr., Baldwin, A.D. Jr., Pushkar, P.D., Carney, C.K., and Talnagi, J.F. Jr., 1995, The correlation between bedrock uranium and dissolved radon in ground water of a fractured carbonate aquifer in southwestern Ohio: Ground Water, v. 33, n. 2, p. 197-206.

Gundersen, L.C.S., 1989, Anomalously high radon in shear zones, in Osborne, M.C., and Harrison, J., symposium cochairmen, The 1988 Symposium on Radon and Radon Reduction Technology, Proc., v. 1, Symposium Oral Papers: Research Triangle Park, NC, Radian Corp., U.S. Environmental Protection Agency Pub. EPA/600/9-89/006a [Springfield, Va., NTIS Order No. PB89-167480], p. 5-27 - 5-44.

Hall, F.R., Boudette, E.L., and Olszewski, W.J., 1987, Geologic controls and radon occurrence in New England, in Cothern, C.R., and Smith, J.E. Jr., eds., Environmental radon: New York, New York, Plenium Press, p. 15-27.

Hem, J.D., 1992, Study and Interpretation of the Chemical Characteristics of Natural Water: United States Geological Survey Water-Supply Paper 2254, 264 p.

Hermes, O.D., Gromet, L.P., Murray, D.P. (compilers), 1994, Bedrock geologic map of Rhode Island: Rhode Island Map Series No.1, University of Rhode Island, Kingston. Scale = 1:100,000.

Hermes, O.D., and Zartman, R.E., 1985, Late Precambrian and Devonian plutonic terrane within the Avalon Zone of Rhode Island: Geological Society of America Bulletin, v. 96, p. 272-282.

Hermes, O.D., and Zartman, R.E., 1992, Late Proterozoic and Silurian alkaline plutons within the southeastern New England Avalon Zone: Journal of Geology, v.100, p. 477-486.

Hess, C.T., Korsah, J.K., and Einloth, C.J., 1985, Radon in houses due to radon in potable water: Land and Water Resources Center, University of Maine Completion Report G846-04. G910-03. 45 p.
Holden, J.B., 1994, The effects of human activities on the quality of ground water in the Chipuxet aquifer, Rhode Island [M.S. thesis]: Kingston, Rhode Island, University of Rhode Island, 84p.

Hollocher, K., and Yuskaitis, A., 1993, Chemical composition of surface and high-uranium well water, Lake Sunapee area, New Hampshire: Northern Geology, v. 15, n. 2, pp.159-169.

Hughes, T.J., 1985, Models of glacial reconstruction and deglaciation applied to Maritime Canada and New England, in Borns et al, eds., Late Pleistocene History of Northeastern New England and Adjacent Quebec, Geological Survey of America Special Paper 197, p.139-150.

Hyndman, D.W., 1985, Petrology of igneous and metamorphic rocks, McGraw-Hill, U.S.A., 786 p.

Johnston, H.E., and Dickerman, D.C., 1985, Hydrology, water quality, and ground-water-development alternatives in the Chipuxet ground-water reservoir, Rhode Island: USGS Water Resources Investigations Report 84-4254, 100 p.

Klein, C., and Hurlbut, C.S. Jr., 1985, Manual of mineralogy. John Wiley & Sons, U.S.A., 596 p.

Krishnaswami, S., and Seidemann, D.E., 1988, Comparative study of 222Rn, 40Ar, 39Ar and 37Ar leakage from rocks and minerals: implications for the role of nanopores in gas transport through natural silicates: Geochimica et Cosmochimica Acta, v. 52, p. 655-658.

Langmuir, D., 1978, Uranium solution-mineral equilibria at low temperatures with application to sedimentary ore deposits: Geochimica et Cosmochimica Acta, v. 42, p. 547-569.

Lawrence, E.P., Wanty, R.B., and Nyberg, P., 1992, Contribution of 222Rn in domestic water supplies to 222Rn in indoor air in Colorado homes: Health Physics, v. 62, n. 2, p. 171-177.

LeGrand, H.E., 1987, Radon and radium emanations from fractured crystalline rocks- a conceptual hydrogeological model: Ground Water, v. 25, n. 1, p. 59-69.

Murray, D.P., 1988, Rhode Island: the last billion years: Kingston, Rhode Island, University of Rhode Island, 96p.

National Research Council, 1988, Health Risks of Radon and other Internally Deposited Alpha-Emitters. BEIR IV: Washington, D.C., National Academy Press.

Nevins, N., 1991, Uranium in Rhode Island bedrock: a primary source of radon-222 in indoor air and ground water [M.S. thesis]: Kingston, Rhode Island, University of Rhode Island, 154 p.
Ott, R.L., 1993, *An introduction to statistical methods and data analysis*, Duxbury Press, Belmont, California, 1051p.

RIDEM, Groundwater Section, 1990, *Rhode Island Private Well Survey*: Rhode Island Department of Environmental Management, Division of Groundwater and Freshwater Wetlands, Final Report, May 1990, 107 p.

Walters, M.O., 1995, Radium in coastal Sarasota county ground water: *Ground Water Monitoring & Remediation*, v. 15, n. 4, p. 114-118.

Wanty, R.B., Lawrence, E.P., and Gundersen, L., 1992, A theoretical model for the flux of radon from rock to ground water: *Geological Society of America Special Paper 271*, p. 73-78.

Wanty, R.B., and Nordstrom, D.K., 1993, Natural radionuclides, in Alley, W.M., ed., *Regional Groundwater Quality*: New York, New York, Van Nostrand Reinhold, p. 423-441.

Wathen, J.B., 1987, The effect of uranium siting in two-mica granites on uranium concentrations and radon activity in ground water, in Cothern, C.R., and Smith, J.E. Jr., eds., *Environmental Radon*: New York, New York, Plenium Press, p. 31-45.

Zielinski, R.A., Johnson, S.Y., and Otton, J.K., 1987, The geologic setting of a surficial uranium deposit, northeastern Washington, in Marikos, M.A., and Hansman, R.H., eds., *Geologic Causes of Natural Radionuclide Anomalies*, p. 43-57.