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**COMPLETION REPORT (PROJECT #50448)**

**ESTIMATING THE SPATIAL DISTRIBUTION OF  
GROUNDWATER RECHARGE RATES USING HYDROLOGIC,  
HYDROGEOLOGIC, AND GEOCHEMICAL METHODS**

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**MOTIVATION AND OBJECTIVES**

Groundwater quality and quantity are affected by a number of activities on the land surface, including application of agricultural chemicals, disposal of solid wastes in landfills, operation of septic systems, pumping of groundwater, and land development. Efficient and effective management of these activities requires information on the spatial and temporal distribution of groundwater recharge. While there exist a variety of operational tools for estimating potential and actual recharge in space, they are not particularly reliable. One of the principal problems is that in most landscapes we have no methods for confirming the results of applying these tools. The purpose of our research was to use measurements and models of surface and ground water flows, levels and chemistry to estimate the spatial distribution of recharge in a watershed in southern Wisconsin, to aid in the development of concepts and methods which could be used in similar watersheds. In particular, the research objectives were to : (1) understand the spatial distribution of groundwater recharge in the Black Earth Creek watershed; and (2) generalize the results for use in similar landscapes

**DESCRIPTION OF STUDY AREA**

Black Earth Creek, located in southwest Dane County, WI (Figure 1) was chosen for this

study for several reasons: (1) groundwater discharge is responsible for much of the base flow of Black Earth Creek; (2) increased demands by urban expansion threaten the groundwater resources; and (3) abundant hydrologic information of the area already exists. Initial field investigations concentrated on locating and measuring groundwater discharge. The discovery of many springs in the Garfoot Creek watershed focused our attention on this sub-watershed, for several reasons: (1) the basin is relatively small and has a U. S. Geological Survey gage at its mouth; (2) the land use is mostly agricultural; (3) the area is entirely within Wisconsin's Driftless Area; and (4) the area is representative of other small watersheds so that conclusions made here could be applied on a larger scale within Black Earth Creek watershed and other watersheds in Wisconsin's Driftless Area.

Black Earth Creek occupies an outwash valley cut and filled during the Wisconsin Ice Age which ended approximately 10,000-12,000 years ago (Cline, 1963). The northeast portion of the watershed is covered with glacial till whereas the south and western portions, including all of Garfoot Creek, lie in Wisconsin's Driftless Area. The main valley of Black Earth Creek contains glacial outwash consisting of sand and gravel interbedded with discontinuous lacustrine sediments of silt and clay. The Johnstown terminal moraine lies within the northeast boundary of the watershed; the other boundaries are formed by bedrock highlands (Cline, 1963). Black Earth Creek lies along the southern flexure of the Wisconsin Arch, marked by gently southward dipping lower Paleozoic sedimentary rocks overlying crystalline Precambrian basement (Cline, 1963). The rocks dip south at about 10 to 15 feet per mile (2 to 3 meters per km). The upper surface of the crystalline bedrock, a low-permeability hydrogeologic boundary, occurs at about 150 feet (46 meters) above sea level at the village of Middleton, directly east of Black Earth Creek watershed (Cline, 1963). Cambrian sandstones of the Elk Mound Group, Tunnel City Group, and Trempealeau Group successively overlie the crystalline bedrock (Figure 2). Ordovician rocks of the Prairie du Chien Group, St. Peter Sandstone and Sinnipee Group overly the Cambrian units.

Garfoot Creek is a man-made channel created around the turn of the century to drain the wetland which occupied the valley bottom. It joins the main channel of Black Earth Creek about one mile west of the village of Cross Plains (Figure 1), draining an area of approximately 5.4 square miles that consists of rolling uplands, steep hillslopes, and heavily cultivated valleys. The relatively steep north facing slopes are covered by deciduous forest. The area is entirely within Wisconsin's Driftless Area. Dolomite of the Sinnipee Group is found only along the southern and topographically highest boundary of the watershed. Sandstone of the St. Peter Sandstone crops out on hilltops in the basin, and below the Sinnipee Group. The sandstone unconformably overlies the dolomite of the Prairie du Chien Group which forms a resistant cap over most of the hills in this area. Cambrian sandstones and siltstones of the Jordan, St. Lawrence and Tunnel City Formations form the valley walls and bottom. Alluvium

of Pleistocene and Recent age fills the valley of Garfoot Creek. Drilling has revealed deposits of silty sand and sandy silt that are more than 60 feet thick. Clay and silt deposits overlie the alluvial sand in the valley and serve to confine the unconsolidated sediments.

Black Earth Creek is in the continental humid temporal climate zone with an annual average air temperature of 46.7 °F (8.2 °C). Average monthly temperatures range from 16.8 °F (-8.4 °C) in January to 72.0 °F (22.2 °C) in July (Figure 2). The average annual precipitation from 1948 through 1991 is 31.12 inches (79 cm). About 60% of the precipitation falls as rain from April through September; the remainder occurs as snow in the winter months.

Although most of the precipitation occurs in the summer, these rains are utilized by transpiring plants or evaporated. During the summer soil moisture is usually deficient because evapotranspiration exceeds precipitation. Fall rains replenish soil moisture first and any excess may infiltrate to recharge the aquifer.

Year-to-year variance in winter climatic conditions probably has the greatest effect on the spatial and temporal distribution of groundwater recharge. Usually the ground is frozen or covered with snow from December to March inhibiting infiltration. As the temperature increases in the spring, snow melt and spring rains infiltrate to recharge the aquifer (Cline, 1963). Soil moisture is at a maximum at this time and evapotranspiration is at a minimum. It is thought that late autumn rains, spring rains and snow melt are responsible for recharging the aquifer (Cline, 1963).

## **SUMMARY OF METHODOLOGY**

As previously noted, there are no proven techniques for estimating the spatial distribution of groundwater recharge at small scales. Furthermore, the surface and ground water hydrology of southern Wisconsin is complex. The following strategy was used to overcome these difficulties:

- A hydrogeological and hydrogeochemical investigation was conducted to develop an understanding of the hydrogeology of the watershed.
- The dominant spring in the watershed was gaged to quantify the amount of recharge and to provide information about the temporal distribution of recharge.
- A conceptual model of recharge was developed for the watershed based on the results of the hydrogeological and hydrogeochemical investigation.
- Additional monitoring capability was developed to test and quantify the conceptual

model.

The first three components of the research have been completed; the results are summarized below. (For a more detailed discussion of this work, see Amman (1993).) The fourth component of the research has been partially completed; completion of this work is being accomplished in a followup research investigation.

## **HYDROGEOLOGICAL AND GEOCHEMICAL INVESTIGATION**

### **Methods**

Field work in Black Earth Creek watershed began in July 1991. Land owners were interviewed in the initial investigation to obtain information on land use history, location of springs and flooding events. Because in a steady-state system groundwater discharge is equal to groundwater recharge, field work focused on locating and measuring discharge to use a water budget method to calculate recharge. Garfoot Creek watershed was chosen for intensive study for reasons listed previously. Figure 5 shows the location of the primary measurement and sampling sites.

The preliminary hydrologic investigation included direct measurements of three spring flows and estimates at three others. A calibrated weir was designed and installed on Spring FF001. The flows of springs FF003 and Herrling Spring were measured with a calibrated bucket. The flows of springs FF002, FF004 and FF005 were estimated by a crude method using channel morphology and flow rate of the stream measured by a float.

Four sets of mini-piezometers were installed in Garfoot Creek to determine the direction and magnitude of the vertical gradients beneath the creek bottom. To determine vertical hydraulic gradients in the alluvium, two sets of nested piezometers (FF006/FF007 and FF014/FF015) were installed in Garfoot Valley in April and June of 1992 using a solid stem auger drill rig owned by the Dept. of Geology and Geophysics. Determination of valley stratigraphy and characterization of alluvial sediments was accomplished during the drilling of the piezometers. A set of monitoring wells (FF012/FF013) was installed in bedrock in January 1993 by Environmental Technologies Inc. Horizontal gradients were determined from a 7.5 minute quadrangle water table map produced by Muldoon (1992) and modified with measurements collected during this study.

Sampling waters for major ion chemistry started in September 1991 and continued on a monthly basis through October 1992. Waters from 12 springs were collected and analyzed in

fall of 1991. Thereafter water samples were collected monthly at five springs in Garfoot Creek watershed to observe temporal differences in spring chemistry. The two alluvial piezometer nests (FF006/FF007 and FF014/FF015) were sampled from June 1992 through October 1992. Eight private wells and two springs outside the field area were also sampled in October 1992 to gain an understanding of the spatial distribution of groundwater chemistry. Groundwater samples from the bedrock piezometer nest (FF012/FF013) were collected in April 1993.

An Instrumentation Specialties Company (ISCO) model 1640 automatic sampler, was installed at the major spring in the basin (FF001) in March 1992, to conduct high frequency sampling. Samples were taken at 1 to 12 hour intervals for a period of four months and then during and after major storm events in an attempt to record chemical differences in discharge as a response to recharge events. Samples were analyzed for chloride using an Orion Research single junction chloride specific ion electrode. If a significant difference in chloride concentrations was noted, the sample would be further analyzed for other constituents.

A Ryan model D-30 automatic temperature gage was installed at FF001 to record variations of temperature through the year and in response to recharge events.

With the exception of the high frequency samples all field samples were filtered in the field using a 0.45 micron membrane filter and refrigerated in the dark until analyzed. High frequency samples were transferred to 100 milliliter polyethylene bottles and refrigerated until analyzed. Nitrate samples were stored frozen and thawed 24 hours before analysis. Field blanks consisted of distilled, de-ionized water (milliQ water) which underwent the same analytical procedure as groundwater samples.

The alluvial piezometers were bailed dry and allowed to recover at least 8 hours before collecting a sample. Private well samples were taken from the house or barn faucet after water ran at least 5 minutes to allow for water in the pressure tank to discharge.

All sample bottles were filled and rinsed with sample water 3 times before collecting the sample. Two 100 milliliter polyethylene bottles were filled for major cation and anion ion analysis. After filtering the field samples one ml Ultrex hydrochloric acid (HCl) was added to preserve the cation samples. Four 20 milliliter polyethylene bottles were filled for nitrate, lab pH, alkalinity and dissolved organic carbon.

Field measurements included water temperature, pH, conductivity and dissolved oxygen. Specific conductance and temperature were measured with a YSI model 33 conductivity meter. DO was measured with a YSI model 51B meter and a polarizing DO specific electrode. The electrode was calibrated against the oxygen content of air near groundwater temperatures in a calibration chamber. The measurements were accomplished by immersing the probe directly

into the springs or, in the case of wells, a beaker which was overflowing with sample water. Samples for pH were collected into a beaker immediately before measurements were taken. A Sargent-Welch Model PBX pH/millivolt meter was used to measure pH and temperature. The pH meter was calibrated with pH 4 and pH 10 buffers and checked with a pH 7 buffer.

Major ion chemistry was determined in the geochemistry lab at the UW Dept. of Geology and Geophysics with the exception of samples from April 1993 (FF012 and FF013) which were analyzed at the Wisconsin State Laboratory of Hygiene. Major ion samples were diluted by weight 10:1 (milliQ water to sample) to remain within the linear analytical range of the laboratory equipment used. All major ion samples were diluted according to this procedure.

Alkalinity samples, unfiltered and undiluted, were run within one week of collection on a Brinkman 636 Titroprocessor using the Gran titration procedure (Stumm and Morgan, 1981) with HCl as the titrant. Cation concentrations were determined by atomic absorption spectrophotometry using a Perkin-Elmer Model 503. Calcium and magnesium concentrations were analyzed using a dual-catheter flow splitter which mixes the sample with a 0.8% lanthanum solution to reduce matrix interference. Potassium concentrations were analyzed using lithium chloride (0.9% lithium) as an ionization suppressant. Sodium concentrations were analyzed without an anion suppressant. The burner angle was adjusted to a 30° angle to increase the linear range of the calcium and magnesium analysis at the sacrifice of some sensitivity.

Anion analysis for chloride and sulfate was performed using a Dionex Model 10 Ion Chromatograph. Silica and nitrate were analyzed with a Technicon Autoanalyzer II by colorimetric method. Silica was analyzed using the molybdosilicate method (Strickland, 1952). Nitrate was analyzed by the automated cadmium reduction method (Armstrong et al., 1967). Dissolved organic and inorganic carbon were analyzed on a OI Model 700 TOC Analyzer using H<sub>3</sub>PO<sub>4</sub> and Na-persulfate to extract the DIC and DOC as CO<sub>2</sub>.

Aliquots and duplicates were run using the same procedure to calculate error involved in dilution techniques and analytical instruments. Percent error in major ion analysis was determined by dividing the range in duplicate values by the mean and multiplying by 100. The replicate error for cation and anion analysis was less than 1%. The error for aliquots was calculated using the same procedure and averaged 5%. Another check on the quality of the chemical analysis was done by performing an ion balance. Most of the samples had less than 10% difference in the cations and anions. This is an acceptable error range for most laboratory wet chemistry. The difference was consistently due to a deficiency in cations.

Five samples in the area were collected for analysis of tritium. The goal of tritium dating in this

study is to differentiate between relatively younger and older waters, determine residence time and gain a better understanding of the groundwater system. The samples were sent to the University of Waterloo, Ontario for analysis by direct scintillation counting.

Radon samples were taken from five springs and six wells in the area as part of a Wisconsin Geologic and Natural History Survey (WGNHS) statewide radon survey. The samples were analyzed at the Wisconsin State Laboratory of Hygiene Radiation Protection Unit.

## **HYDROGEOLOGICAL RESULTS**

The major source of perennial flow of Garfoot Creek is spring discharge. The locations of springs FF001-FF005 are shown in Figure 5. The average flow of spring FF001 from August 6, 1992 through April 30, 1993 was 0.889 cfs (25.2 liters/sec). This is the largest spring in the basin and contributes about 22% of the concurrent baseflow of Garfoot Creek flow measured at the bridge on Observatory Road.

The mini-piezometers installed in the Garfoot Creek streambed show an upward vertical gradient which averages 0.26 (ft/ft). Head data collected at the piezometer nests indicate upward flow exists at all three locations. The alluvial piezometers FF014 and FF015 show an average upward vertical hydraulic gradient of 0.18. The alluvial piezometers FF006 and FF007 show an average upward vertical gradient of 0.23. The bedrock piezometer nest (FF012 and FF013) shows a smaller upward gradient which averages 0.035.

The water table contour map, produced by Muldoon (1992), suggests a 10 foot change in the water level per 1000 feet horizontal distance or a horizontal hydraulic gradient of 0.01 (ft/ft). Figure 6 shows the elevation of the water table in the area based on her data and modified with measurements made during this study. The water table generally follows topography. Flow is from south to north. A local groundwater divide coincides with the surface water divide which is marked by the highest topography in the area.

Sediments collected from the auger stem during the drilling of the alluvial piezometers revealed the presence of a clayey-silt layer approximately 5 feet below the surface at both well nest locations. The unit was encountered in both alluvial piezometer nests and averages about 3 feet in thickness. This unit is assumed to be continuous over Garfoot Valley because it was encountered in both alluvial piezometer nests and because strong upward gradients are present in the valley. Water was encountered within the clay during drilling at a depth of 5 feet at both locations.

Based on slug tests, McGrath (1991) determined the hydraulic conductivity of the Prairie du

Chien Group to range from  $1.2 \times 10^{-3}$  to  $1.2 \times 10^{-7}$  cm/sec. Based on slug tests in piezometers FF012 (screened in dolomite of the St. Lawrence Formation) and FF013 (screened in Jordan Sandstone) we determined the hydraulic conductivities of these units to be  $6.9 \times 10^{-4}$  and  $2.2 \times 10^{-5}$  cm/sec respectively. Using a method developed by Bradbury and Rothschild (1985) the conductivity of the bedrock aquifer was estimated from 11 well logs in the study area (Table 1). The average conductivity determined by this method is  $6.9 \times 10^{-3}$  cm/sec; the range is from  $2.0 \times 10^{-4}$  to  $1.7 \times 10^{-2}$  cm/sec. Conductivity values calculated by this method may be higher than actual values as the wells are usually screened in the most productive unit. The values fall within the range reported by McGrath (1991). The hydraulic conductivity from the alluvial piezometer FF006 was calculated from a slug test to be  $2.0 \times 10^{-5}$  cm/sec. This value falls in the range of  $1.0 \times 10^{-7}$  to  $2.0 \times 10^{-5}$  cm/sec for loess deposits reported by Domenico and Schwartz (1990).

Seepage meters installed in sandy and silty sediments of Garfoot Creek measured groundwater flux into the creek at three different sites. Using mini-piezometers for vertical gradients and applying Darcy's Law, hydraulic conductivities were calculated for these sediments; estimates ranged from  $6.6 \times 10^{-5}$  to  $1.3 \times 10^{-3}$  cm/sec. The high value is interpreted to be an error due to leakage into the collection bag.

## **HYDROGEOCHEMICAL RESULTS**

The average chemical analyses of springs, piezometers and private wells are shown in Table 2. Locations of sampling points are shown on Figure 5. Groundwater in the Garfoot Creek basin is a calcium-magnesium-bicarbonate type. Sulfate and chloride are minor constituents of waters in the Garfoot Creek watershed followed by silica, sodium and potassium. Nitrate is present in most but not all waters sampled.

The major chemical characteristics of the spring discharge are nearly constant over time. Figures 7 and 8 show the variations of the major and minor elements in springs in the area. The coefficient of variation (CV) in calcium and magnesium concentrations at each spring is less than 7% over the year but the CV in minor constituents, nitrate and chloride, is from 5 to 61%.

Although the temporal chemical variability between monthly analyses is small for each spring, the variability between springs is large. Spring FF002 has less total dissolved solids (TDS), lower alkalinity, and higher pH than the other springs in the area (FF001, FF003, FF004, FF005). Figure 9 shows the variation of calcium concentration between springs. FF001 has the highest concentration of calcium, FF002 has the lowest. All other major ions follow the

same trend.

The analyses from all piezometers (FF006, FF007, FF012, FF013, FF014, FF015) show lower TDS in the groundwater in the valley colluvium and in the bedrock than in the springs (with the exception of spring FF002). Wells in the recharge area also show very different compositions. Wells FF009 and FF017 have high TDS whereas wells FF018 and FF016 have low TDS. The ratios of calcium to magnesium in sampled groundwaters range from 1:1 in FF019 to 1.14:1 in FF009.

The results of the high frequency sampling revealed that waters from FF001 did not vary significantly in chloride concentrations over a sampling period however there was slight variation between sampling periods. There was generally less than 1 ppm difference between samples within a sampling period.

Wells in the upland recharge area have higher nitrate and chloride concentrations than waters in the lowland or discharge area (Figure 10). On the basis of the chemical analyses, the waters in Garfoot Creek watershed can be divided into two groups. Group I waters are those with lower TDS, low nitrate (<1 ppm) and high pH (>7.5). Waters with high TDS and relatively high concentrations of nitrate and lower pH are Group 2 waters. Group I waters include waters from spring FF002, piezometers FF006, FF007, FF012, FF013, FF014 and FF015 and private well FF008 (Figure 11a). The Group I waters occur in the discharge area (not all discharge waters are Group I) and are believed to have long flow paths.

Waters from FF009 and FF017 (Group 2) have higher TDS than all other waters analyzed in the area and these occur in the recharge area. Other waters in Group 2 (springs FF001, FF003, FF004, FF005; wells FF010, FF011, FF016, FF019; Figure 11b) have less TDS but similar amounts of nitrate. Figure 12 shows the spatial distribution of TDS in waters sampled in the Garfoot Creek watershed.

#### Temperature

The average temperature of all groundwaters analyzed was less than 11° C. Temperature of the springs varied less than 2° C over the annual cycle. The average temperature of all springs is 9.7° C. This is 1° C higher than the average annual air temperature. The groundwater temperatures measured in the piezometers is warmer than water in bedrock wells or springs.

Results from the automatic temperature gage did not show any variation during or after high flow events. There was not any fluctuation during the 6 months it recorded data. This could be due to a lack of instrument precision, although measurements made monthly with digital

meters were consistent with the data from the automatic temperature gage.

## pH

The pH of a water has been termed the master variable in hydrogeochemical studies because protons are involved in so many reactions. Most natural waters in carbonate terrain have pH values between 7 and 8. The pH values of groundwaters in Garfoot Creek basin range from 7.0 to 7.8 excluding the water from FF016 where a pH value of 6.3 was measured. This well is located in the recharge area and is screened in the St. Peter Sandstone. Field pH values are listed in Table 5.

## Dissolved Oxygen (DO)

The ability of a water to support aquatic life depends heavily on the dissolved oxygen concentration. Cold water is able to contain more dissolved oxygen (DO) than warm water. At 10 ° C fresh water can contain as much as 12.55 mg/L oxygen. The content of DO in springs in the area ranges from 8.4 to 9.8 mg/L which is 67 to 78% saturated. Dissolved oxygen usually decreases along a flow line, however high DO found in the springs which are discharge points may be attributed to the waters mixing with air during discharge. Table 5 contains the average field measured values of DO. The lowest concentration of all waters sampled was measured in wells FF016 (7.5 ppm) and FF007 (7.6 ppm).

## Specific Conductance

Specific conductance is a measure of the ability of an aqueous solution to carry an electrical current. This ability depends on the concentration of ions, their mobility, valence and the temperature of the solution. Ionic strength is directly related to specific conductance. High ionic strength waters have high specific conductance; low ionic strength water has low specific conductance. Values for conductivity ranged from 300 to 610 micromhos/liter (Table 5). The highest values correspond to wells with the highest concentrations of calcium and magnesium, located near the groundwater divide in the recharge area.

## Total Dissolved Solids (TDS)

TDS values were calculated from the chemical analysis by summing the major cation and anion concentrations. The distribution is similar to the specific conductance values in that water with high specific conductance also have high TDS. A spatial distribution of TDS is shown in Figure 12. The highest TDS occurred in well FF009 which occurs in the recharge area near the local groundwater divide. The lowest TDS occur in wells FF016 and FF018, also in the recharge area.

## Calcium-Magnesium

Carbonate rocks, dolomite in particular, control the major ion chemistry of the waters observed in Garfoot Creek watershed. Dissolution of carbonate rocks is dependent on the dissolved CO<sub>2</sub> in the water. The control of partial pressure of CO<sub>2</sub> gas on the dissolution of carbonate rocks is documented by Garrels and Christ (1965), Stumm and Morgan (1981), Drever (1982), and Morse and Mackenzie (1990) among others.

The concentration of calcium ranges from 36 ppm in well FF018 to 85 ppm in well FF017. These two wells are both screened in the siltstone of the St. Lawrence Formation and occur in the upland recharge area (see Figure 5). In the discharge area calcium concentrations are lowest in spring FF002 and in the bedrock piezometers, FF012 and FF013 (Table 2).

The slope of the line drawn between calcium and magnesium is very close to one (0.96). The deviation from 1 (<5%) is not considered significant because of the error in laboratory analysis (5%). Therefore the graph indicates that dissolution of dolomite is the main source of both calcium and magnesium ions. The non-zero intercept may indicate that additional calcium comes from dissolution of calcite cement.

## Alkalinity

Alkalinity is defined as the capacity of a water to neutralize a strong acid. In most natural waters alkalinity is produced by dissolved carbon dioxide species, bicarbonate (HCO<sub>3</sub><sup>-</sup>), and carbonate (CO<sub>3</sub><sup>2-</sup>) (Hem, 1985).

Because TDS consist mostly of calcium and magnesium, area waters which have high alkalinity values also have high TDS. At the pH of the waters in this area, the major ion contributing to alkalinity is the bicarbonate ion (HCO<sub>3</sub><sup>-</sup>), (Stumm and Morgan, 1981).

## Sodium and Potassium

Sodium is naturally present in groundwater of the Garfoot Creek basin in concentrations usually less than 10 mg/L (Table 2). Sodium can be derived from shale units within the Cambrian and Ordovician Formations or from anthropogenic sources such as road salting and chemical fertilizers. Most waters sampled in the study area have low concentrations of sodium (< 7 mg/L). Waters from FF009, FF017 and FF016 have elevated levels of sodium, 17, 15 and 19 mg/L respectively.

Potassium is present in the groundwater in small amounts, less than 1 ppm, in the study area (Table 2). The source for most naturally occurring potassium is the mineral potassium feldspar. Feldspar may be present in minor amounts in the Cambrian sandstone, mainly the Tunnel City Group. Potassium is also applied as an agricultural nutrient (KCl or Sul-Po-Mag™, a source of sulfur, potassium and magnesium). The highest concentration of potassium, 25 ppm, occurs in FF016 and is most likely due to the application of crop nutrients.

#### Chloride

Chloride is naturally present in small amounts, < 10 ppm, within the aquifer (Table 2). Chloride may come from natural sources, such as the weathering of igneous rocks, or from anthropogenic sources such as septic systems, water softeners and road salting. Elevated chloride concentrations occur in the private wells FF009 and FF016. Although chloride is harmless, its presence indicates the land use and may be helpful in delineating recharge areas and catchment areas for springs. Chloride concentrations range from 3 ppm in spring FF020 to 29 ppm in well FF016. Generally Group I waters have less than 10 ppm chloride while Group 2 waters have greater than 10 ppm chloride. Temporal variation in chloride concentration occurs in all springs sampled. The CV for chloride ranges from 22% in FF005 to 123% in FF002. The highest concentrations of chloride, 23 ppm in FF009 and 29 ppm in FF016, indicate an anthropogenic source such as road salt or agricultural nutrients. The high levels of sodium in these wells indicate the source as road salt.

#### Sulfate

Sulfate is naturally present in the groundwater systems in southwestern Wisconsin. Sulfate results from the oxidation of sulfides (mainly pyrite,  $\text{FeS}_2$ ), in sedimentary and crystalline rocks. Additionally sulfur is applied to crops as an agricultural fertilizer. The use of sulfate of potash ( $\text{K}_2\text{SO}_4$ ) as an agricultural nutrient has increased substantially in the last five years (H. Schultz, pers.comm). Sulfate concentrations range from 8 ppm in spring FF002 to 28 ppm in well FF016 (Table 2). The high value may be from agricultural nutrient application. High values of sulfate in piezometer FF013 may be due to the injection of a lubricating foam used during drilling to release the drill rods.

#### Nitrate

Nitrate is present in most of the springs and wells sampled. Nitrate is applied to the fields in the form of manure or chemical compounds such as potassium nitrate (KCl) and sulfate of ammonia ( $(\text{NH}_4)_2\text{SO}_4$ ). Nitrate levels in well FF016 exceed the state drinking water standard of 10 ppm nitrate as nitrogen (Table 2). Group 1 waters have less than 1 ppm nitrate. Group 2 waters contain higher concentrations of nitrate which are variable throughout the year. The

absolute concentrations and the variations in the amount of nitrate help to distinguish local groundwaters from regional groundwaters.

### Silica

Dissolved silica results from the weathering of silicate minerals such as feldspars and quartz, both of which are abundant in the study area. With the exception of FF014, the waters sampled have silica concentrations of about 6 mg/L (Table 2). FF014 contains 11 ppm silica. Silica is more soluble in low pH waters (less than 4) but the pH of this water is over 7.

### Tritium

Tritium is a naturally occurring isotope of hydrogen created by cosmic bombardment in the atmosphere. Atmospheric testing of nuclear weapons in the early 1950's has increased the concentration of tritium in our environment. Because tritium has a short half life (12.3 years) and is widespread in the environment it has been used for dating waters less than 35 years old. Bradbury (1992) has calibrated tritium curves for Dane County. In this study tritium is used to determine groundwater ages in order to distinguish groundwater flow paths.

Tritium concentrations range from 3.4 tritium units (TU) in well FF008 to 21.5 TU in well FV-322 (Table 3). The results fall into two groups, those with tritium concentrations greater than 10 and less than 10 tritium units. Piezometer FF007 and well FF008 have low concentrations of tritium (9.6 and 3.4 respectively) whereas springs FF001, FF004 and well FV-322 each have greater than 15 tritium units.

Ages were determined according to the tritium input curve developed by Bradbury, 1992 (Figure 13). The USGS stopped sampling precipitation for tritium content in 1986. Waters with less than 10 TU are believed to be more than 35 years old, although very young waters, less than 6 years old may also have less than 10 TU. Because of the location of the sampling points along the flow line and the fact that the groundwater flows through bedrock rather than colluvium, the residence time for these waters is thought to be greater than 6 years. By plotting the concentration of tritium on Figure 13, the time of recharge can be determined. As the figure shows, there is not always a unique date for each tritium concentration. The ages of waters with tritium concentrations greater than 15 are more difficult to ascertain. Waters from springs FF001 and FF004 could be 10, 13 or 36 years old.

### Radon

Radon 222 is a product of radioactive decay of uranium and thorium. These elements occur

primarily in accessory minerals such as zircon, apatite and sphene which are minor constituents in granite (Faure, 1986). The resistance of these minerals allows them to be cycled into sedimentary clastic rocks without alteration. The lowest concentration (105 picocuries/Liter (pc/L)) occurred in well FF009; the highest (1248 pc/L) occurred in well FF008 (Table 4.)

### Saturation Indices

Calculated saturation indices (SI) were used to determine which mineral phases present in the aquifer may be controlling the chemical evolution of the groundwater. SI is equal to zero when the mineral is at equilibrium with an aqueous solution and positive when the solution is oversaturated with respect to the mineral in question. When SI is negative the solution is undersaturated with respect to the mineral in question and therefore has the capability of dissolving the mineral. Saturation indices were calculated using the chemical equilibrium model PHREEQE (Parkhurst et al., 1980). The saturation indices for calcite and dolomite in waters of Upper Garfoot Creek Watershed are shown in Table 6. Generally my model assumes that dolomite can only be dissolved whereas calcite, where present, can be dissolved or precipitated.

In principle, young waters with a short flow path would be expected to be undersaturated with respect to dolomite and calcite in contrast to older or more evolved waters which we may expect to be closer to saturation with respect to these mineral phases.

A sensitivity analysis was done to evaluate the possible variation in saturation indices due to measurement/instrument error. The SI is not very sensitive to slight differences in temperature, alkalinity or molar concentration but is very sensitive to errors in pH. A small difference of + 0.1 pH units results in a difference of + 0.1 units in the SI calculated. In this study both field and lab pH were measured. Measurements of field pH are only accurate to 0.1 pH units but the lab pH values are accurate to 0.05 pH units. Lab pH and field measurements agree closely however. Uncertainties in determining major ion concentrations due to laboratory error may increase the uncertainty in SI so that it is reasonable to assume that SI values have an uncertainty of + 0.1 units. Even with this uncertainty, waters saturated with respect to dolomite and calcite can be distinguished from undersaturated waters (Table 6.). Waters with a SI(calcite/dolomite) less than -0.11 are considered to be undersaturated; waters with a SI(calcite/dolomite) greater than 0.11 are considered saturated. Waters that fall between this range are at equilibrium with respect to calcite and dolomite.

The results of the calculations in this area indicate that some waters near the beginning of local flow paths (wells FF009, FF017) are saturated with respect to calcite and dolomite whereas some waters which have longer flow paths are understaturated (springs FF003 - FF005).

Because of higher pH, waters from the alluvial piezometer nest (FF007, FF008 & FF014, FF015) are saturated at lower concentrations of calcium and magnesium than waters from springs FF003 - FF005 which are undersaturated.

Saturation indices of some waters also appear to change over time. The variation observed may be due to temporal changes of recharge to the aquifer. A supersaturated water may indicate a time when little or no recharge to the water table occurs and discharging water consists mostly of water that has been in prolonged contact with the aquifer.

## **DISCUSSION OF RESULTS**

Published research on groundwater systems in southwestern Wisconsin identify upland areas as important recharge areas and lowland regions as areas of discharge (Drescher, 1956; Cline, 1963). Although highlands are areas of recharge, it would be incorrect to assume that recharge is evenly distributed over these areas. The spatial variation over small areas may be important where differences in geology, soil type, slope aspect and land use exist. Agricultural areas and forested hillslopes have different recharge characteristics (see Sartz (1961), Sartz (1969), Sartz (1973); Sartz et al. (1977) and Whipkey and Kirkby, (1978)). The differences in the hydrologic properties of dolomite and sandstone can also affect the recharge process. Urbanization of the landscape may reduce the quantity of recharge by paving roads and driveways.

During the summer months the uplands in Garfoot Creek watershed are covered with crops such as corn and alfalfa. Except during major rainfall events, it is unlikely that rainwaters are able to escape evapotranspiration and infiltrate to the water table even though the region receives most of its annual precipitation during this time. In severe winters the hilltops are frozen and under snow. During the spring snowmelt the frozen soil forms an impermeable barrier preventing meltwaters and spring rains from infiltrating to the bedrock. In mild winters a frozen impermeable layer does not form and recharge then occurs unimpeded.

The role forested hillslopes play in groundwater recharge has been documented by many researchers. Sartz et al. (1977) conducted studies in Minnesota on sites which are similar to the Black Earth Creek watershed. They demonstrated that infiltration rates on wooded areas are significantly higher than on cropped areas. This is due to the fact that tilled soils are compacted by farm equipment. Because most of the hillslopes in the study area are forested, the hillslope soils are generally not compact as compared to farmed soils. When these soils are frozen they still maintain a porosity and permeability that is lost in frozen cultivated soils. Therefore melt water and spring rains should be able to percolate through hillslope soils more easily than the farmed upland soils.

The geology of the recharge area is also important in determining the temporal distribution of groundwater recharge rates. The St. Peter Sandstone crops out on the southern hilltop near the local groundwater divide. This porous medium is extremely well drained and promotes rapid infiltration of rainwater and snow melt. Land use on the St. Peter Sandstone is usually limited to grazing because of thin soils and low moisture holding capacity. Prickly pear cactuses, which require well drained soils, exist on the St. Peter Sandstone and further illustrate the hydraulic characteristics of this formation. Precipitation may infiltrate to the water table throughout the year on this unit.

The conceptual model of the area incorporates field observations, geochemical analysis of groundwaters and hydrogeologic measurements made over the year. During the two years of observation in Garfoot Creek watershed, two very different winters occurred, neither of which was "typical.". The winter of 1991-1992 was a mild winter with little snowfall or major melt events. Daytime temperatures remained above freezing during most of the winter months. Recharge in the highlands and forested slopes occurred as precipitation in the form of rain infiltrated through the unfrozen ground. Snow melted within two weeks of accumulation preventing large spring runoff events. Recharge proceeded throughout the winter months and was not concentrated in space or time.

The winter of 1992-1993 consisted of many freeze and thaw events which created an impermeable frozen layer on farmed fields. Rain on snow produced large runoff events in the spring. Recharge occurred in the highlands and on the forested hillslopes and was concentrated in the spring months, when snowmelt and spring rains were abundant. Forested hillslopes may be important recharge areas because rainwater runoff rapidly from the farmed fields, forest soils are loose, and there is evidence of large fractures on the hillslopes. There was no runoff observed from the forested hillslopes with the exception of water flowing down gullies draining the uplands. Observations in the uplands indicated that snowmelt and rains did not infiltrate through the frozen barrier present on the fields but ponded and ran off down gullies in the hillslopes. Some portion of these runoff waters may have infiltrated through fractures in the hillslope and recharge the aquifer.

The strong upward vertical gradient present in the valley bottom prevents significant recharge from occurring in this area and indicates the lowlands are areas of discharge. The clayey-silt layer is believed to be an extensive confining unit preventing groundwater from discharging rapidly to Garfoot Creek. This unit helps maintain the upward gradients thus enhancing spring flow. The upward gradient present at the bedrock piezometer nest indicates that infiltrating waters are not recharging the aquifer at this point.

In the Garfoot Creek watershed both regional and local flow systems occur. The regional flow system begins approximately nine miles (15 km), south of the surface water divide. The local water table divide coincides with the topographic surface water divide and delineates the southern boundary of the local groundwater flow. Water flows from south to north across the watershed (Figure 6). The eastern and western boundaries are delineated on the basis of groundwater flow lines drawn from the water table contour map. The northern boundary is defined by Garfoot Creek. Springs and seeps issue forth at the base of the hillslopes. Among the hypothesis suggested to explain the occurrence of springs are (1) they are controlled by topography, part of a local flow system corresponding to Toth's (Toth, 1962, 1963, 1966, 1984) idea of different groundwater flow systems (Figures 3 and 4) and (2) they are affected by geologic heterogeneity within the flow system.

The lower hydraulic conductivity of the siltstone of the St. Lawrence Formation could restrict downward flow of groundwater forcing it out at the contact between the Jordan Sandstone and the underlying siltstone of the St. Lawrence Formation resulting in contact springs. Although this may explain the occurrence of Herrling Spring, many of the springs emanate through the St. Lawrence Formation and may be caused by other less apparent reasons. Springs FF001, FF002, FF003, FF004 and FF005 discharge from the base of a large hillslope. These springs may correspond to the discharge of a local flow system.

Groundwater equals groundwater recharge in a steady state system (Freeze and Cherry, 1979, Fetter, 1980). In this area a recharge value of 7 to 10 inches/year is generally accepted (Cline, 1963). For the period August 20 through April 30, the largest spring in the basin had a flow of approximately 0.89 cfs (400 gal/min.; 25.2 liters/sec). A catchment area for this spring was delineated based on topographic and water table contour maps. Flow lines were drawn assuming an isotropic medium. Although it is unlikely that the aquifer is isotropic and homogeneous this method gives a general estimate and a starting point for further investigation. Using a planimeter, a catchment area for spring FF001 was measured to be 285 acres (Figure 14). If this is the total area contributing to the spring flow, a recharge rate of 27 inches/year would be necessary to maintain the flow at 0.89 cfs for 9-month period. Accounting for the change in storage in the aquifer during the 9-month period, the recharge rate would have to be about 38 inches/year. These are much higher than the commonly accepted value of 7-10 inches/year for the region. Other catchment area estimates were used (Table 7) to obtain a more reasonable recharge rate. A generous catchment area of 640 acres would require 12 inches of recharge annually to maintain the flow of just spring FF001 and 17 inches accounting for the change in storage. This is an indication that inflow from other sources may be occurring in the area. This inflow may be brought in by fractures or from a deeper, regional flow system. The upward gradient present at the bedrock piezometer nest (FF012, FF013) indicates that this may be a regional (or deep) groundwater discharge area.

The hypothesis that regional discharge occurs in the area is also supported by tritium data. Tritium ages of well FF008 and piezometer FF007 indicate that these waters recharged over 35 years ago. These waters have similar chemical compositions to those of the bedrock piezometers, FF012 and FF013.

Knowledge of the velocity of groundwater flow helps to establish the residence time during which a water is in contact with the aquifer and thus aids in determining the time and place of recharge. The velocity of groundwater depends on the hydraulic conductivity, gradient and the effective porosity. Effective porosity is one of the most difficult parameters to estimate and usually a range is considered. Estimates of effective porosity range from 0.05 to 0.5% in limestone, 5 to 50% in karst limestone and 0.5 to 10% in sandstone (Domenico and Schwartz, 1990). This large range shows the difficulty in obtaining an accurate value for this parameter. Values of 1 to 10% were used in calculations of velocity in Table 10. These values were chosen because even though the dolomite bedrock is fractured, the aquifer is mainly in the sandstone units which consist of poorly cemented to well cemented grains.

Using the hydraulic parameters described above, velocity and residence times of groundwater were calculated using Darcy's Law. Reasonable velocities range from 2 to 250 ft/yr (0.6 to 75 m/yr) (Table 10). Ignoring flow through the unsaturated zone, travel times for waters originating near the local groundwater divide (Figure 6) and discharging as springs and seeps into Garfoot Creek were calculated. Travel times for waters FF001, FF004 and FF008 range from 33 to 1400 years. Using the highest velocity (234 ft/yr), a minimum travel time for well FF008 waters is 33 years; the maximum travel time is 1100 years.

Tritium data for well FF008 indicate that this water is over 35 years old (Table 3, Figure 13). Well FF008 also contains the highest concentration of radon-222 (1248 pc/L) which further suggests a long residence time for this water. The age estimates, based on tritium data, for FF001 are 10, 13, 17 or 38 years (Table 3). If these waters recharged 10 or 13 years ago, they must have short flow paths. The farthest spring FF001 waters could travel in 10 years at the highest velocity is about 2000 feet (710 meters). This would result in a small catchment area that would require over 30 inches of recharge a year. Using the older residence time of 38 years, the waters could have traveled about 8000 feet. This corresponds closely with the local groundwater divide and the measured catchment area but still does not supply enough water to maintain the flow of this spring.

Several hypotheses are discussed to explain the geochemical trends observed over the sampling period. A simple explanation for the lower TDS waters occurring in the discharge area would be dilution along the flow path by pure rain water. If dilution occurs then discharge chemistry would be variable throughout the year depending on the magnitude of recharge events. The

compositional consistency of these waters indicates that dilution by recharge waters is not rapid. Moreover, the upward vertical gradient in Garfoot Creek Valley also prevents rain waters from mixing with waters sampled in the piezometer nests.

Data from wells FF009 and FF017 indicate that some young recharge waters are saturated with respect to both calcite and dolomite yet waters which have longer flow paths (springs FF003, FF004, FF005) are undersaturated with respect to these minerals (Figure 26). Even though these waters have lower concentrations of calcium and magnesium, they have higher pH's and are, thus, saturated with respect to both dolomite and calcite.

The groundwaters which have longer flow paths and lower TDS yet are saturated with respect to calcite and dolomite can be explained by the geology and soils of the recharge area or related to the season of major recharge. Thin soils with low organic carbon content generate lower  $pCO_2$  and therefore water passing through them has a lower dissolution capability at the water table leading to lower concentrations of calcium and magnesium in the subsequent groundwaters. As discussed above, recharge through frozen forested hillslopes may be an important process. The lack of photosynthetic activity during this time could lead to lower  $pCO_2$  levels of the infiltrating waters.

The near constancy of the major ion concentrations over time indicates that the spring discharge waters have long residence time within the aquifer. Therefore I believe diffuse flow, rather than fracture flow, accounts for most of the spring discharge.

The elevated levels of nitrate can be directly related to land use in the recharge areas. Manure applications proceed throughout the year with the exception of the growing season from May to September. Monthly variations in nitrate are observed in the springs sampled (Figure 7). These fluctuations could be the result of the variation in the amount of local groundwater discharge relative to regional groundwater discharge. The absence of nitrate in the bedrock piezometer nest suggests that regional groundwater is being sampled at this point; the upward gradient at this location prevents local groundwater from recharging the regional flow system in this immediate area.

Though the relative constancy of the spring flow volume and chemical composition suggests the springs are points of regional discharge, some chemical constituents such as nitrate and chloride, vary throughout the year suggesting a component of a more local groundwater system. Most of the springs are undersaturated with respect to calcite and dolomite and contain nitrate. Discharge waters from piezometer FF007 are saturated with respect to calcite and dolomite. A tritium age for this water is over 30 years. These observations suggest that spring discharge is a mix of a local groundwater flow system and an older, deeper groundwater system.

The mixing of local and regional waters further complicates ascertaining an age for these waters. The mixing of the two systems may occur in a dissolution plane between hydrogeologic units. The Black Earth Member of the St. Lawrence Formation may occur at or near the elevation of the springs and could perform as such a channel. The possibility of mixing of local and regional water was tested using a geochemical model, as described below.

### **GEOCHEMICAL MODELING**

The model PHREEQE (Parkhurst et al., 1980) was used to determine the chemistry of a mixture of local and regional waters. A mass balance method was also applied to particular constituents when mixing two end-member waters according to the equation:

$$m_{i,mix} = xm_{i,1} + (1-x)m_{i,2}$$

where  $m_{i,mix}$  is the molality of a conservative constituent,  $i$ , in the mixture of two end-member waters,  $m_{i,1}$  and  $m_{i,2}$  are the molalities of  $i$  in the end-members 1 and 2, and  $x$  is the mixing fraction of water 1 in the mixture. The fraction of water 1 in the mixture is then given by:

$$x = (m_{i,mix} - m_{i,2}) / (m_{i,1} - m_{i,2})$$

(after Plummer and Back, 1980).

Because some waters in the recharge area (Group 2), are already saturated with respect to calcite and dolomite it was reasonable to use a water saturated with these minerals in the modeling attempts. A rainwater saturated with calcite and dolomite at various  $pCO_2$  was mixed with a regional groundwater to produce the observed chemistry of the major spring in the area, Spring FF001. A  $\log pCO_2$  of -1.5 was used because the dolomite and calcite of the resulting water closely matched the amount of calcite and dolomite measured in wells in the recharge area (FF009 and FF017).

The water chosen to represent regional groundwater chemistry is that from piezometer FF007. This water has an old tritium age, high pH, and is believed to have a long flow path. Modeling results indicate that observed spring chemistry can be obtained with a mixture of 58 to 70% regional groundwater and 30 to 42% local groundwater. Table 8 compares results of two mixing ratios. Both mixing ratios work for calcium, magnesium, alkalinity, pH and saturation indices. Because of the monthly variability of the hydrogeochemistry and the uncertainty in analysis, a range of 12% is a reasonable constraint.

The tritium concentrations were also mixed in the above ratios. Assuming that regional groundwater has zero tritium units, a local groundwater would need 50 or 65 tritium units to produce the tritium concentration of spring FF001 (19.9 TU). A water that recharged in 1958-1959, 1961, 1966, or 1968-1971 would have 50 to 65 tritium units today (Figure 13). Waters recharged in 1958-59 and 1961 have residence times of over 34 and 31 years respectively. Thirty-six years is the minimum travel time calculated for waters recharged near the local groundwater divide and discharged as spring flow. At this time there are insufficient tritium data to confirm the conceptual model, but these calculations are in close agreement with the major ion mixing model.

## CONCLUSIONS

The goal of this study was to define the groundwater flow system operating in the Garfoot Creek watershed and identify important recharge areas using a geochemical approach. This was accomplished by sampling of springs, piezometers and private wells in the study area. Preliminary conclusions made from this study are generalized due to an atypical sampling year. During the winter of 1992, the Black Earth Creek watershed did not receive much snowfall and there was not a big recharge event as compared with the 1993 spring. Although the time frame of this research may not have been long enough to accurately quantify the controlling recharge processes, many important characteristics of the groundwater flow system have been identified.

Groundwaters in the Garfoot Creek watershed consist of calcium-magnesium-bicarbonate water reflecting the dolomite bedrock in the area. The chemistry of the waters suggest that there are two distinct flow systems operating in the watershed. One system contains nitrate and high TDS, the other has low nitrate, lower TDS and higher pH. The springs seem to be a mixture of the two systems, a conclusion supported by the geochemical modeling effort.

The flow of Garfoot Creek is supported mainly by spring discharge. Groundwater seepage into the creek is negligible compared to the large flow of springs. Based on catchment areas delineated from maps, spring discharge exceeds the generally accepted recharge rate (7 to 10 in/yr) for this area.

Recharge occurs in the uplands and forested slopes. Absence of runoff from the St. Peter Sandstone leads to the conclusion that waters may infiltrate through thin soils covering sandstone bedrock throughout the year. Forested hillslopes may be important recharge areas during the winter because they have large macropores and maintain a permeability even when frozen. Recharge does not occur through frozen tilled fields in the winter nor does recharge occur in the lowlands where there are strong upward vertical gradients.

Land use occurring in the recharge area influences the groundwater chemistry observed in private wells beneath upland fields. High levels of nitrate and, in some cases, chloride and sulfate have affected local wells. The lower concentration of these constituents further downgradient indicates that they are either diluted along the way or have not had sufficient time to reach the discharge area. Groundwater beneath cropped fields in the lowland discharge area is not affected by the agricultural nutrients applied to the overlying lands.

The groundwater system active in Garfoot Creek watershed appears to be influenced by a regional groundwater flow system. Regional discharge is evidenced by the consistency of spring discharge volume and chemistry and the strong upward vertical gradients in the lowlands. The conclusion that regional discharge occurs in this area has significant implications with respect to defining recharge areas. Regional groundwater discharge means that the recharge area is larger than the local topographic basin. Therefore land use that occurs 5 or 10 miles south of the study area may influence groundwater presently discharged as springs in the Garfoot Creek watershed. Because springs supply a major portion of flow in Garfoot Creek, regional recharge has the potential to diminish or sustain the ecological health of the creek. A regional flow system could provide a continuous supply of groundwater discharge thereby buffering the effects of local urbanization. Land management decisions on the protection of critical recharge areas need to be extended to include areas outside the immediate watershed. Whether the land use is agricultural or urban development, the effect will be noticed in the quantity and/or quality of the future groundwater.

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DANE COUNTY	WISCONSIN	HYDRAULIC	
WELL ID	UNIQUE WELL	CONDUCTIVITY	
		(ft/sec)	(cm/sec)
130771049	FF010	3.6E-04	1.1E-02
130771050	FF008	2.9E-04	8.8E-03
130771052	FF011	1.6E-04	4.9E-03
130771076		1.8E-05	5.4E-04
130771078		2.1E-04	6.5E-03
130771079		2.4E-04	7.3E-03
130771080		5.5E-04	1.7E-02
130771100	FF018	2.3E-04	6.9E-03
130771177		3.6E-04	1.1E-02
130771181	FF0017	7.4E-05	2.3E-03
	FV-322	6.7E-06	2.0E-04
<b>AVERAGE</b>		<b>2.3E-04</b>	<b>6.9E-03</b>

Table 1. Hydraulic conductivities calculated from specific capacity of wells in Upper Garfoot Creek watershed using the method described by Bradbury and Rothschild (1987). Aquifer thickness was calculated as the saturated open interval plus 50 feet. See Figure 5.

		Calcium (ppm)	Magnesium (ppm)	Sodium (ppm)	Potassium (ppm)	Silica (ppm)	Chloride (ppm)	Sulfate (ppm)	Nitrate-N (ppm)	ALK (meq)	FIELD PH
FF001	AVERAGE	67.9	37.8	3.6	0.6	5.9	14.0	15.3	4.1	6.0	7.3
NUMBER	ANALYSIS	10.0	10.0	10.0	10.0	10.0	10.0	10.0	7.0	10.0	10.0
FF001	STDEV	3.5	2.2	1.2	0.2	0.4	6.5	2.0	1.3	0.2	0.1
FF002	AVERAGE	49.2	26.9	1.6	0.5	5.1	5.2	2.8	0.6	4.8	7.6
NUMBER	ANALYSIS	10.0	10.0	10.0	10.0	10.0	10.0	10.0	8.0	10.0	10.0
FF002	STDEV	2.4	1.2	0.6	0.3	0.5	6.4	1.7	0.2	0.2	0.1
FF003	AVERAGE	61.0	34.2	4.7	0.5	5.7	16.9	17.5	5.6	4.6	7.3
NUMBER	ANALYSIS	10.0	10.0	10.0	10.0	10.0	10.0	10.0	8.0	10.0	10.0
FF003	STDEV	3.2	2.1	1.7	0.3	0.3	3.5	1.4	1.6	1.6	0.2
FF004	AVERAGE	67.1	37.8	6.0	0.5	5.5	20.8	16.4	2.9	5.9	7.3
NUMBER	ANALYSIS	10.0	10.0	10.0	10.0	10.0	10.0	10.0	7.0	10.0	10.0
FF004	STDEV	3.5	3.6	2.2	0.3	0.3	8.8	1.5	1.2	0.2	0.0
FF005	AVERAGE	59.4	34.7	4.9	0.7	5.6	14.7	16.4	3.2	5.3	7.2
NUMBER	ANALYSIS	10.0	10.0	10.0	10.0	10.0	10.0	10.0	7.0	10.0	10.0
FF005	STDEV	3.5	2.2	1.7	0.3	0.2	3.2	0.9	1.1	0.2	0.1
FF014	AVERAGE	62.3	29.6	5.1	1.2	11.2	4.9	16.1	0.5	5.3	7.7
NUMBER	ANALYSIS	4.0	4.0	3.0	3.0	4.0	4.0	4.0	4.0	4.0	4.0
FF014	STDEV	4.4	1.2	2.7	0.1	0.5	1.9	1.6	0.7	0.0	0.1
FF006	AVERAGE	59.6	30.4	2.7	0.9	6.6	8.1	19.6	3.1	4.8	7.6
NUMBER	ANALYSIS	5.0	5.0	3.0	3.0	5.0	5.0	5.0	4.0	5.0	5.0
FF006	STDEV	6.3	0.9	0.6	0.3	0.2	6.3	1.3	1.5	0.1	0.1
FF015	AVERAGE	63.6	30.9	2.5	1.1	8.2	5.0	21.3	0.4	5.2	7.7
NUMBER	ANALYSIS	4.0	4.0	3.0	3.0	4.0	4.0	4.0	4.0	4.0	4.0
FF015	STDEV	3.6	0.6	0.2	0.5	1.6	2.0	1.8	0.2	0.0	0.2
FF007	AVERAGE	55.6	29.1	2.9	2.4	6.5	5.9	10.6	2.7	4.7	7.6
NUMBER	ANALYSIS	5.0	5.0	4.0	4.0	5.0	5.0	5.0	4.0	5.0	5.0
FF007	STDEV	6.0	1.2	0.4	2.7	0.8	3.6	0.8	0.2	0.1	0.0

Table 2. Chemical analysis of springs, piezometers and private wells. The analyses of FF001 - FF005 are averages of 1 monthly samples; analyses FF006, FF007, FF014 and FF015 are averages of 4 samples; the remaining values are from single sampling event in October 1992.

<b>Wisconsin</b>											
<b>unique well #</b>	<b>Date</b>	<b>Calcium</b>	<b>Magnesium</b>	<b>Sodium</b>	<b>Potassium</b>	<b>Silica</b>	<b>Chloride</b>	<b>Sulfate</b>	<b>Nitrate-N</b>	<b>ALK</b>	<b>FIELD PH</b>
		(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(meq)	
<b>FF008</b>	<b>10/24/92</b>	59.0	33.3	3.8	0.6	6.2	8.1	10.4	0.9	5.8	7.4
<b>FF009</b>	<b>10/24/92</b>	81.8	43.6	16.5	0.3	4.8	23.4	10.3	6.4	6.5	7.3
<b>FF010</b>	<b>10/24/92</b>	58.9	32.9	5.3	0.7	5.8	15.4	17.2	9.5	5.3	7.3
<b>FF011</b>	<b>10/24/92</b>	63.9	38.4	4.7	0.7	5.1	10.2	15.8	2.5	6.2	7.4
<b>FF012</b>	<b>4/30/93</b>	48.3	27.4	2.9	0.6	ND	1.0	0.4	0.5	3.9	7.5
<b>FF013</b>	<b>4/30/93</b>	56.6	40.9	6.2	3.9	ND	7.5	20.2	0.5	4.7	7.4
<b>FF017</b>	<b>10/24/92</b>	85.0	50.6	14.7	0.5	6.4	3.7	17.3	7.9	7.1	7.6
<b>FF016</b>	<b>10/24/92</b>	27.8	13.6	18.8	25.1	4.9	28.7	28.0	11.3	1.5	6.3
<b>FF018</b>	<b>10/24/92</b>	36.4	20.2	6.1	0.8	5.7	20.4	18.1	3.3	2.8	7.0
<b>FF019</b>	<b>10/24/92</b>	64.3	38.9	4.4	2.2	5.0	11.8	14.2	7.5	5.7	7.5
<b>FF020</b>	<b>10/24/92</b>	58.8	35.4	1.1	0.6	6.4	3.1	17.2	0.7	5.8	7.6
<b>PAUL 9</b>	<b>10/24/92</b>	51.3	28.3	2.4	8.9	6.2	7.5	20.5	10.7	4.3	7.5

Table 2 cont.

<b>Sample ID</b>	<b>Tritium Units</b>	<b>Estimated Age</b>
FF-001	19.9	10, 13, 17 or 37 years
FF-004	16.1	9, 34, or 37 years
FF-008	3.4	>37 years
FF-007	9.6	>35 years
FV-322	21.5	10, 18 or 34 years

Table 3. Tritium units and estimated ages for sampled waters.

WI unique#	RADON 222 (picocuries/liter)
FF001	788
FF002	422
FF003	742
FF004	331
FF005	580
FF006	678
FF007	393
FF008	1248
FF009	105
FF010	566
FF011	301

Table 4 . Activities of radon 222 measured in selected wells and springs.

SAMPLE ID	DATE	TEMPERATURE degrees Celsius	FIELD pH	CONDUCTIVITY (microohms/liter)	DISSOLVED OXYGEN (mg/liter)
FF001	8/17/92	11.0	7.2	355	9.2
FF002	8/17/92	13.0	7.6	320	10.0
FF003	8/17/92	14.0	7.3	400	9.3
FF004	8/17/92	13.0	7.2	430	9.1
FF005	8/17/92	14.5	7.1	400	9.1
FF014	8/17/92	15.0	7.7	370	ND
FF006	8/17/92	14.1	7.6	375	15.2
FF015	8/17/92	13.0	8.0	360	12.2
FF007	8/17/92	15.0	7.6	365	15.2
FF008	10/25/92	9.0	6.7	380	9.2
FF011	10/22/92	11.5	7.1	425	11.4
FF009	10/22/92	11.0	7.1	610	10.5
FF017	10/22/92	11.0	6.8	600	8.5
FF016	10/22/92	11.0	6.3	340	7.5
FF012	4/30/93	12.0	7.5	432	13.8
FF013	4/30/93	15.0	7.4	300	10.0

Figure 5. Field chemical measurements of springs, piezometers and private wells.

WELL ID	SI CALCITE	SI DOLOMITE	PCO2	PERCENT SATURATED WITH RESPECT TO CALCITE	PERCENT SATURATED WITH RESPECT TO DOLOMITE
FF001	-0.03	-0.15	-1.81	93	71
FF002	0.03	-0.03	-2.23	108	94
FF003	-0.17	-0.42	-1.91	67	38
FF004	-0.18	-0.44	-1.74	65	36
FF005	-0.27	-0.61	-1.79	54	25
FF014	0.29	0.41	-2.28	194	256
FF015	0.27	0.39	-2.28	187	248
FF006	0.09	0.06	-2.25	123	115
FF007	0.24	0.33	-2.32	172	215
FF008	-0.05	-0.18	-1.98	89	67
FF009	0.06	0.01	-1.80	114	102
FF010	-0.16	-0.02	-1.88	70	94
FF011	0.04	0.03	-1.91	109	107
FF016	-1.97	-4.07	-1.40	1	0
FF017	0.39	0.73	-2.06	247	540
FF018	-0.89	-1.87	-1.84	13	1
FF019	0.11	0.17	-2.05	129	149

Table 6. Values of calcite and dolomite saturation indices (SI), and  $pCO_2$  calculated using PHREEQ (Parkhurst et al., 1980). Negative SI indicates a water is undersaturated with respect to the mineral phase; positive SI indicates over saturation with respect to the mineral phase.

Catchment area (acres)	Recharge (in/yr)	FF001 discharge (Ac/ft/yr)	Percent spring flow provided
285	7	644	26
285	10	644	37
285	27	644	100
360	7	644	33
360	10	644	47
360	21.5	644	100
468	7	644	42
468	10	644	61
468	16.5	644	100
640	7	644	58
640	10	644	83
640	12	644	99

Table 7. Recharge needed to provide base flow of Spring FF001. Catchment area is measured using the water table contour map and topographic map and assuming flow is perpendicular to equipotential lines (isotropic conditions).

RAIN WATER  
saturated w/dolomite @  
log PCO2=-1.5

calcium	2.17
magnesium	2.17
alkalinity	8.67
pH	7.13
SI calcite	0
SI dol	0.024
log PCO2	-1.5

REGIONAL WATER  
WELL FF007

calcium	1.26
magnesium	1.15
alkalinity	7.6
pH	4.64
SI calcite	0.0399
SI dol	-0.0041
log PCO2	-2.2321

DISCHARGE WATER  
MODELED FF001  
MIX OCT. 1992

1.54	calcium	1.54
1.47	magnesium	1.47
5.85	alkalinity	5.8
7.33	pH	7.35
-0.0561	SI calcite	-0.0471
-0.1801	SI dol	-0.1594
-1.869	log PCO2	-1.889

30% + 70% → 100%

MODELED FF001  
MIX MAR. 1992

calcium	2.17
magnesium	2.17
alkalinity	8.67
pH	7.13
SI calcite	0
SI dol	0.024
log PCO2	-1.5

calcium	1.26
magnesium	1.15
alkalinity	7.6
pH	4.64
SI calcite	0.0399
SI dol	-0.0041
log PCO2	-2.2321

1.64	calcium	1.66
1.58	magnesium	1.57
6.34	alkalinity	6.31
7.28	pH	7.37
-0.0547	SI calcite	0.0363
-0.1724	SI dol	-0.0227
-1.7796	log PCO2	-1.8959

42% + 58% → 100%

Table 8. Modeling results from mixing regional and local waters. A local water is produced by saturating pure rainwater with dolomite at a log pCO2 of -1.5. The local water is then mixed with a water representing the regional groundwater chemistry in a ratio of 30:70 and 42:58 to produce the chemistry of the major spring (FF001) in the basin.

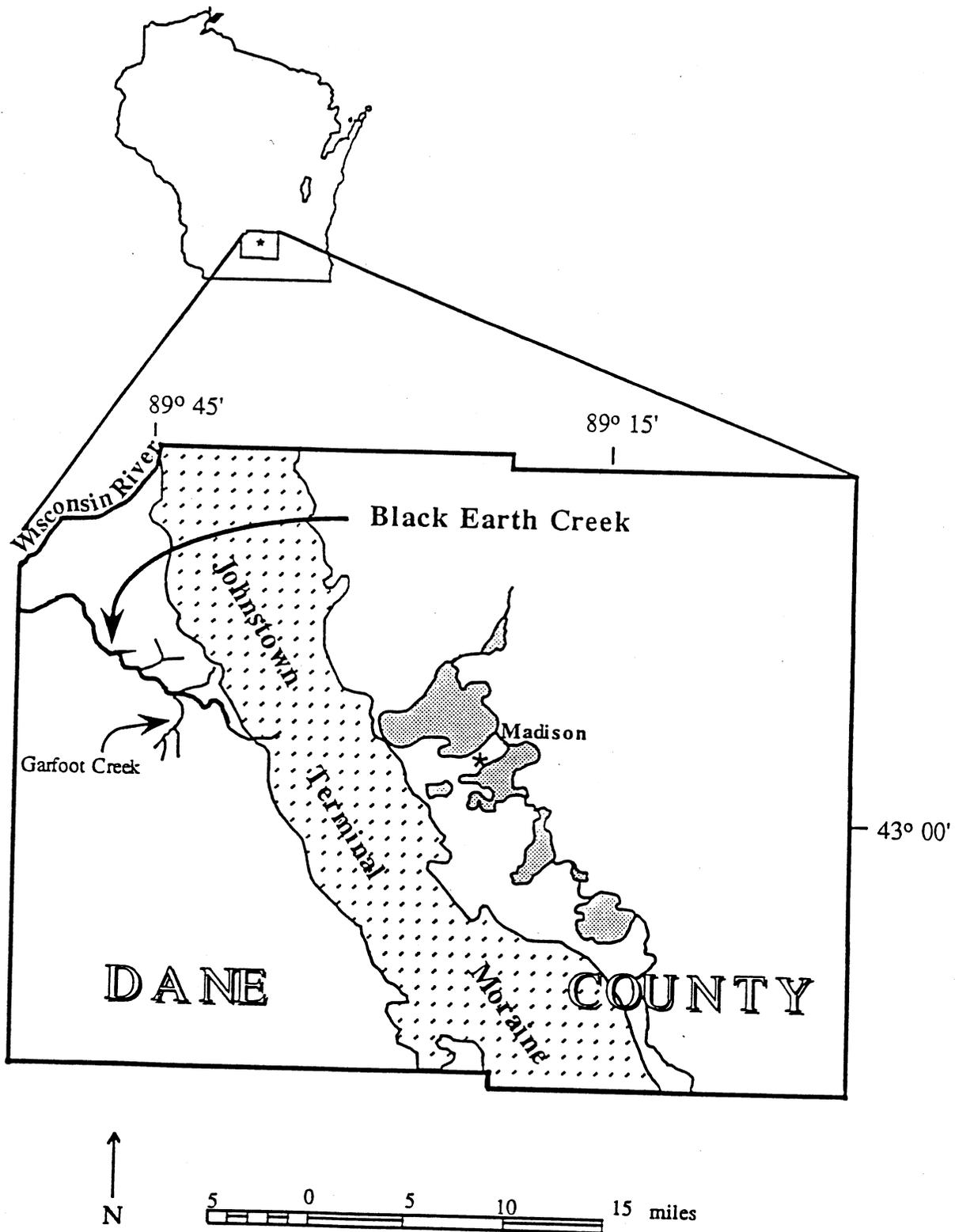


Figure 1. Location of Black Earth Creek and Garfoot Creek in Dane County, Wisconsin.

	SYSTEM	GROUP	FORMATION	ROCK TYPE	K ft/sec
ORDOVICIAN	SINNIPEE		Galena	Carbonate (dolomite)	
			Decorah	Shale	
			Platteville	Dolomite	
			St. Peter	Shale	3.2e-5
	PRAIRIE DU CHIEN		Shakopee	Quartz Sandstone	7.9e-5
			Oneota	Dolomite	
UPPER CAMBRIAN	TREMPEALEAU		Jordan	Quartz Sandstone	1.9e-4
			St. Lawrence	Carbonate	2.3e-4
	TUNNEL CITY		Lone Rock	Feldspathic Sandstone	1.4e-5
			Mazomanie		
	ELK MOUND		Wonewoc	Quartz Sandstone	3.6e-5
			Eau Claire	Shaley Sandstone	2.7e-5
			Mount Simon	Arkosic Sandstone	1.5e-5

Figure 2. Stratigraphic column showing Paleozoic stratigraphy in the Driftless Area and the hydraulic conductivity of formations as determined by Young (1992).

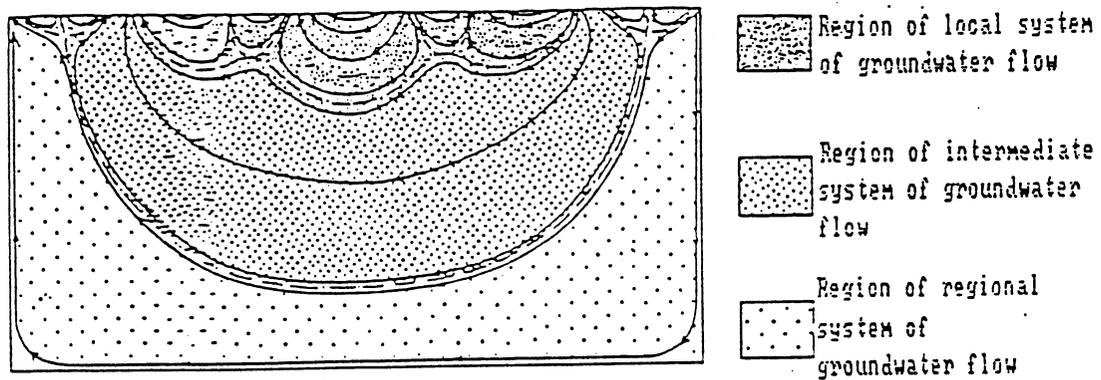


Figure 3. Schematic representation of local, intermediate and regional systems of groundwater flow. (after Toth, 1963, and Freeze and Cherry, 1979).

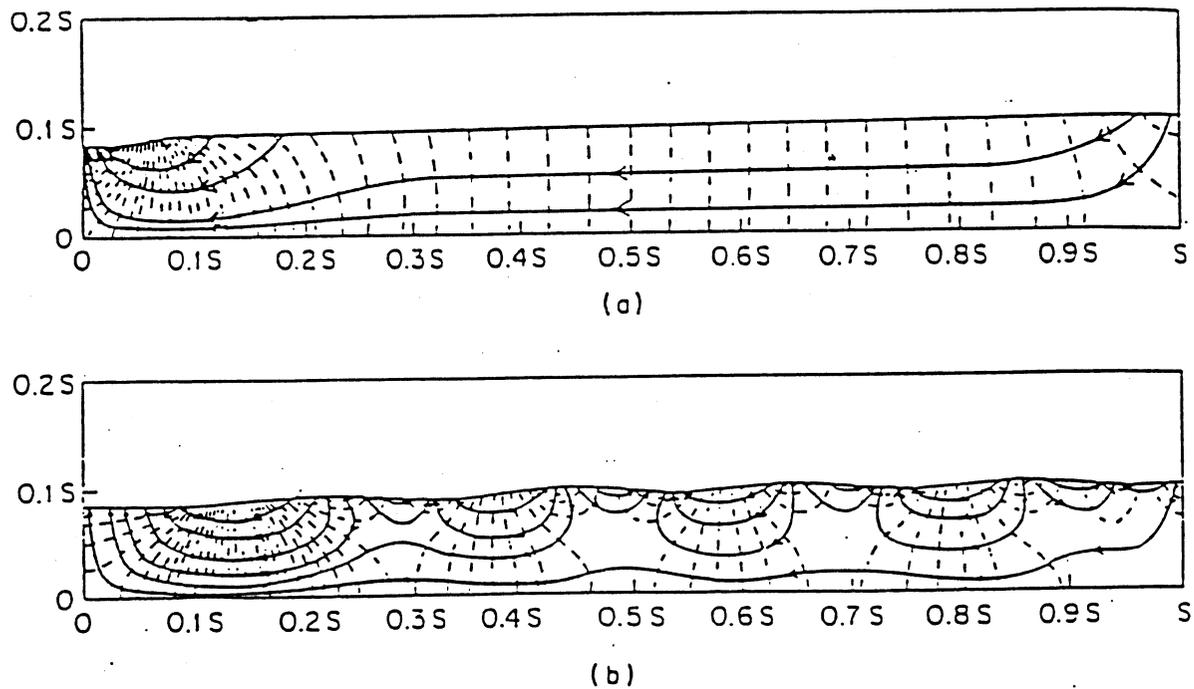


Figure 4. Effect of topography on regional groundwater flow pattern. (after Freeze and Cherry, 1979). The flow system in an area with flat topography is shown in a. The effect of undulating topography similar to that existing in the Garfoot creek area is shown in b.

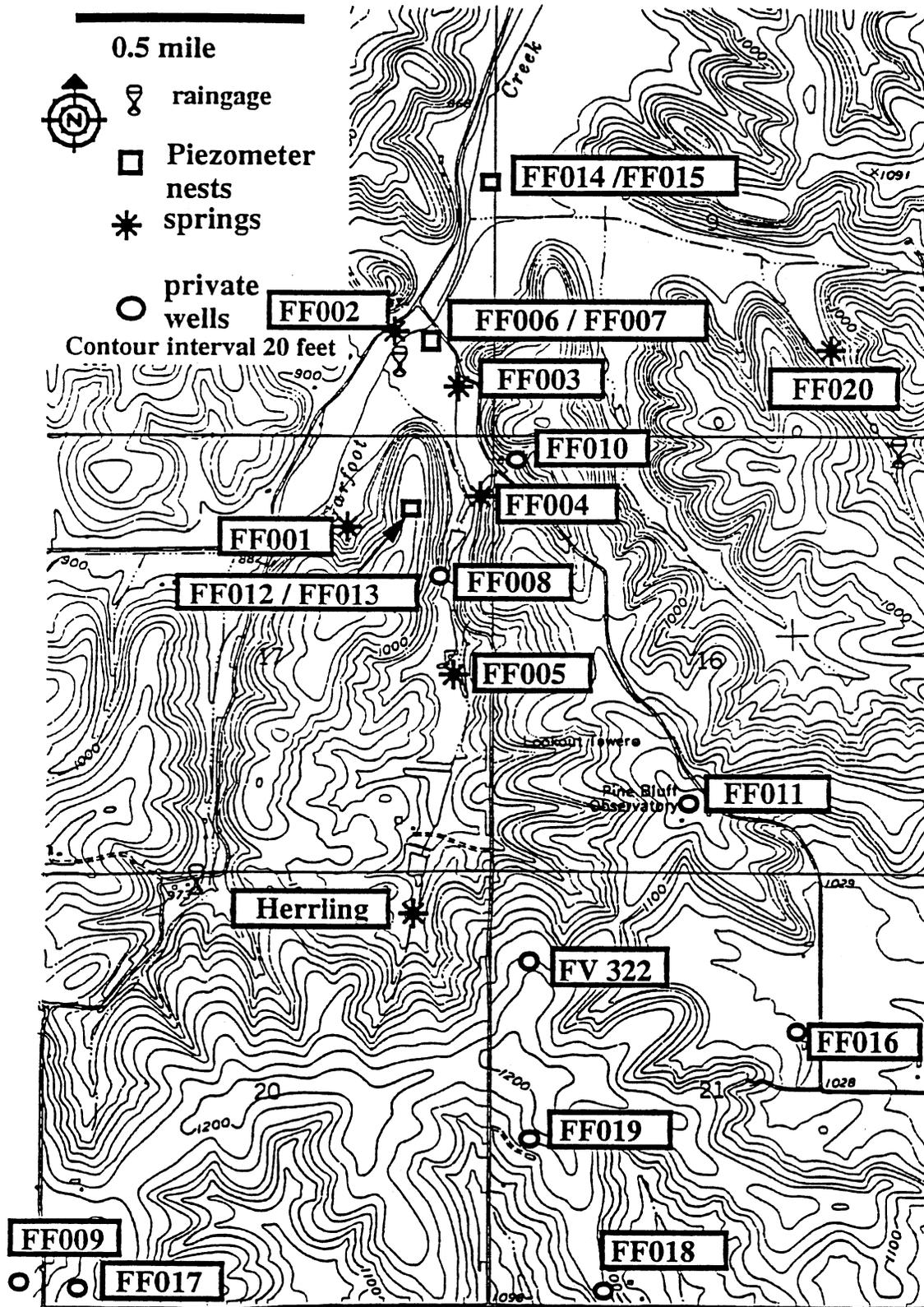


Figure 5. The location of wells, springs, piezometers and raingages in Garfoot Creek watershed shown on a topographic map. The map is a portion of the Cross Plains 7.5 minute quadrangle, T7N, R7W sections 16,17,20 and 21.

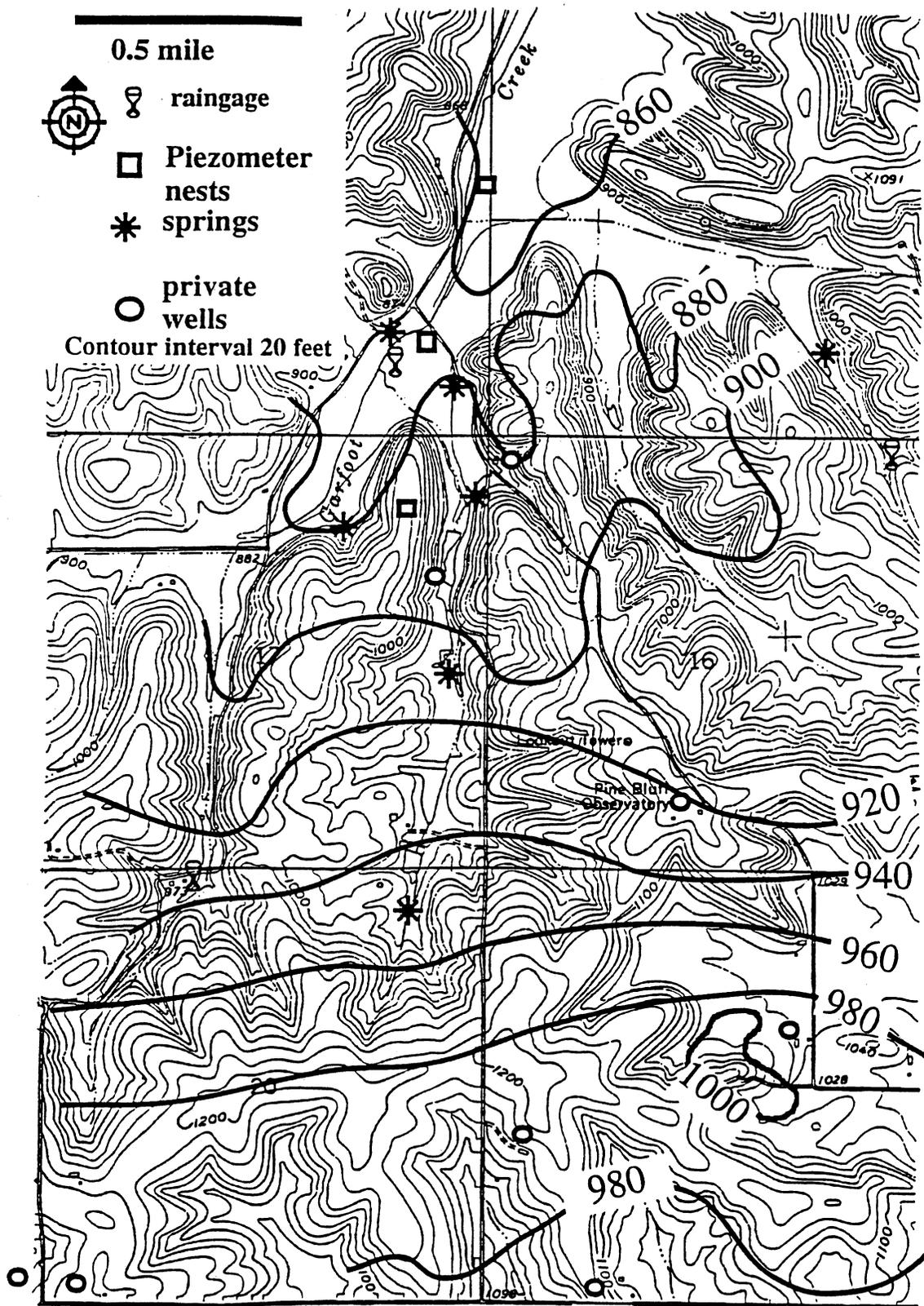


Figure 6. Water table contour map on elevation contours. This map was modified from Muldoon, 1992.

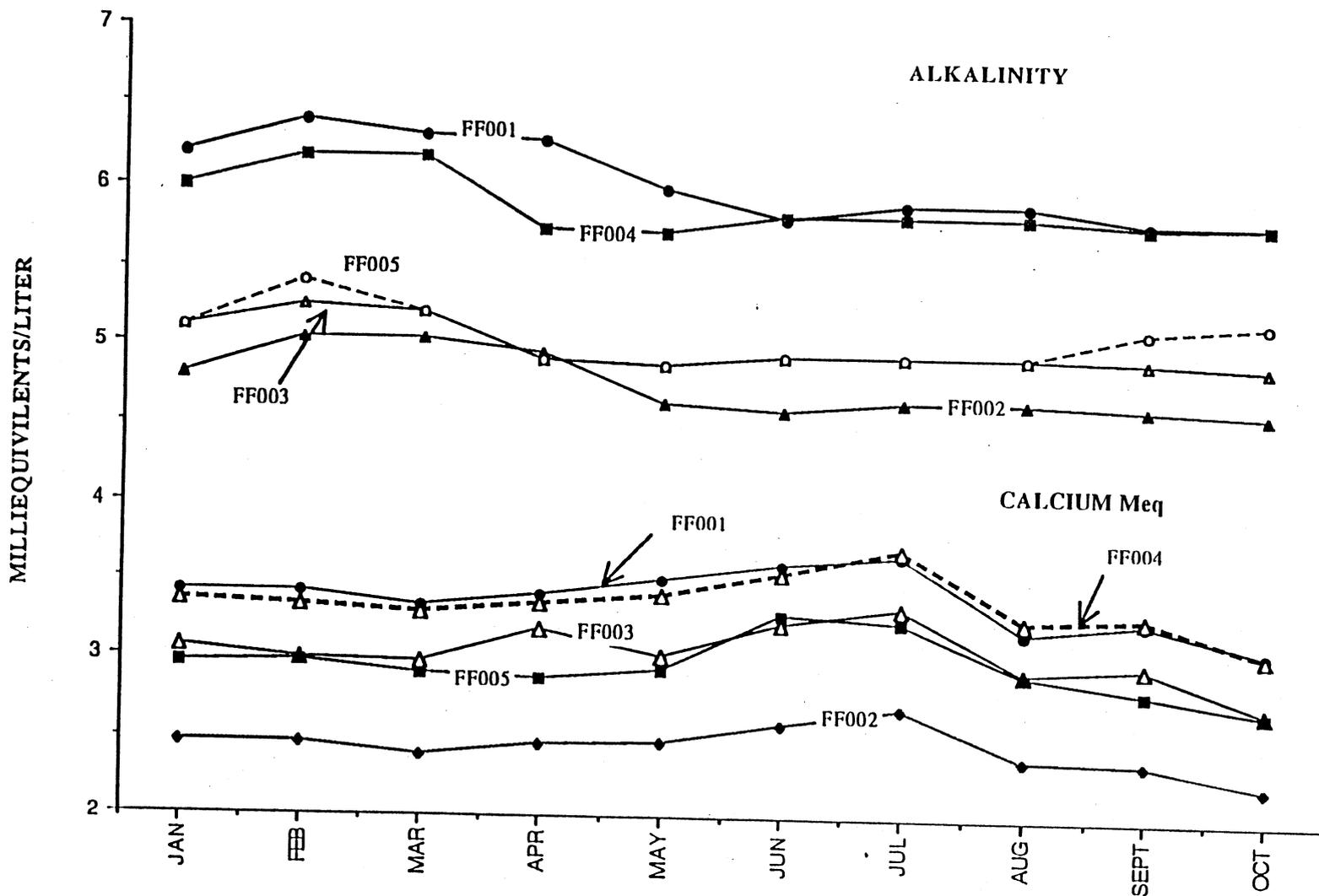


Figure 7. The temporal variation of calcium and alkalinity in springs FF001 through FF005 from January 1992 to October 1992. Concentrations of all constituents is in meq/L.

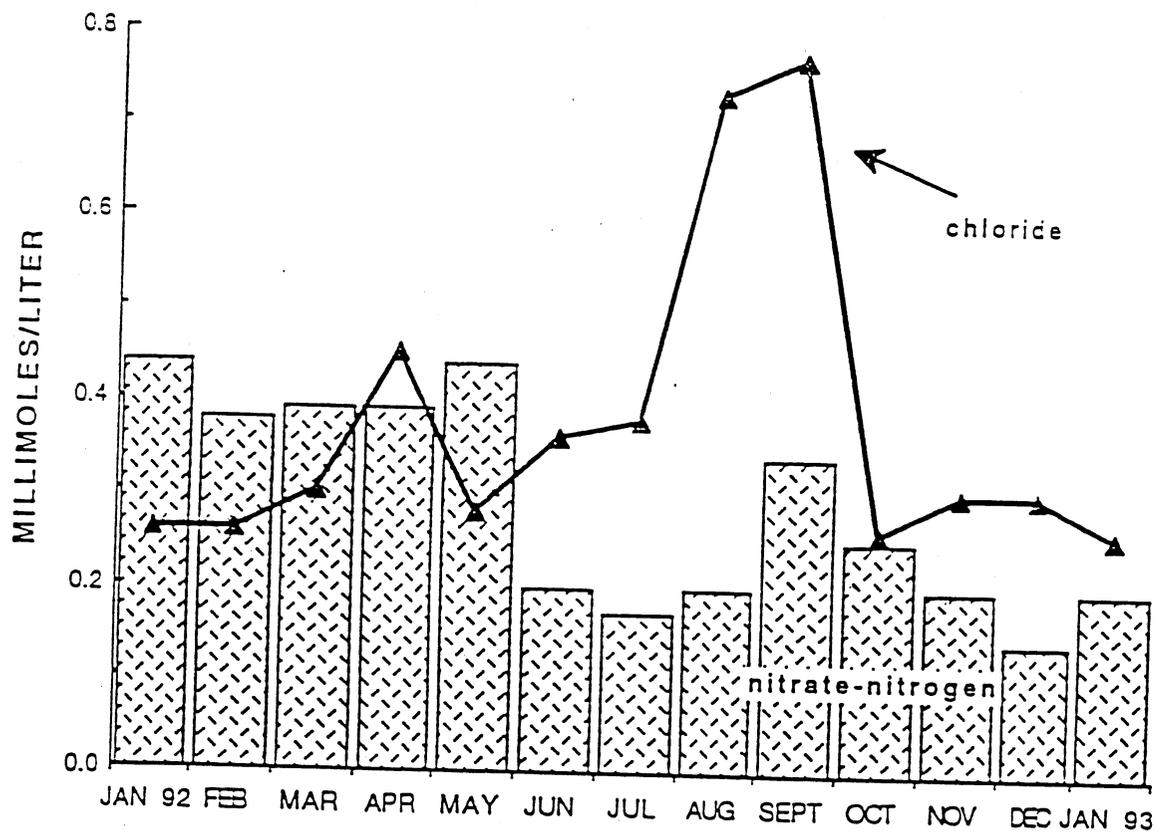


Figure 8. Variation of nitrate and chloride in spring FF001 from January 1992 through October 1992. Concentrations are in meq/L.

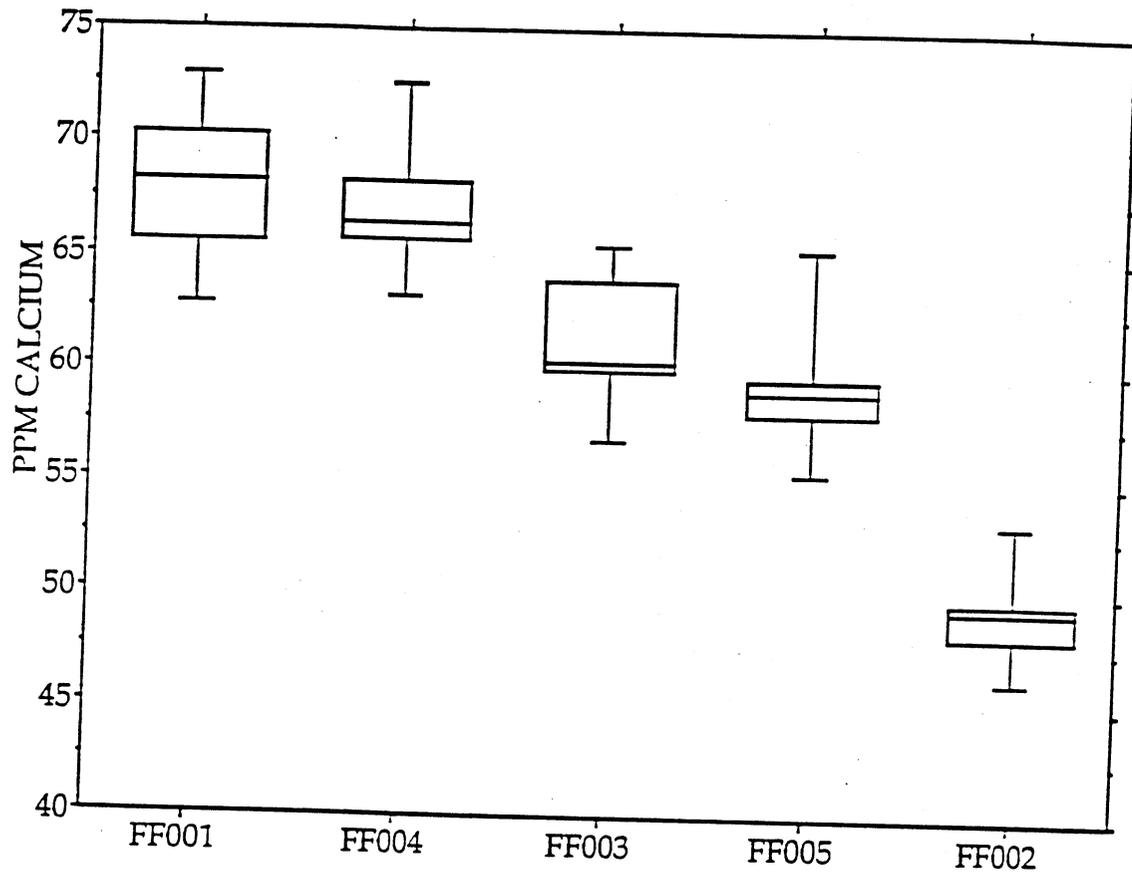
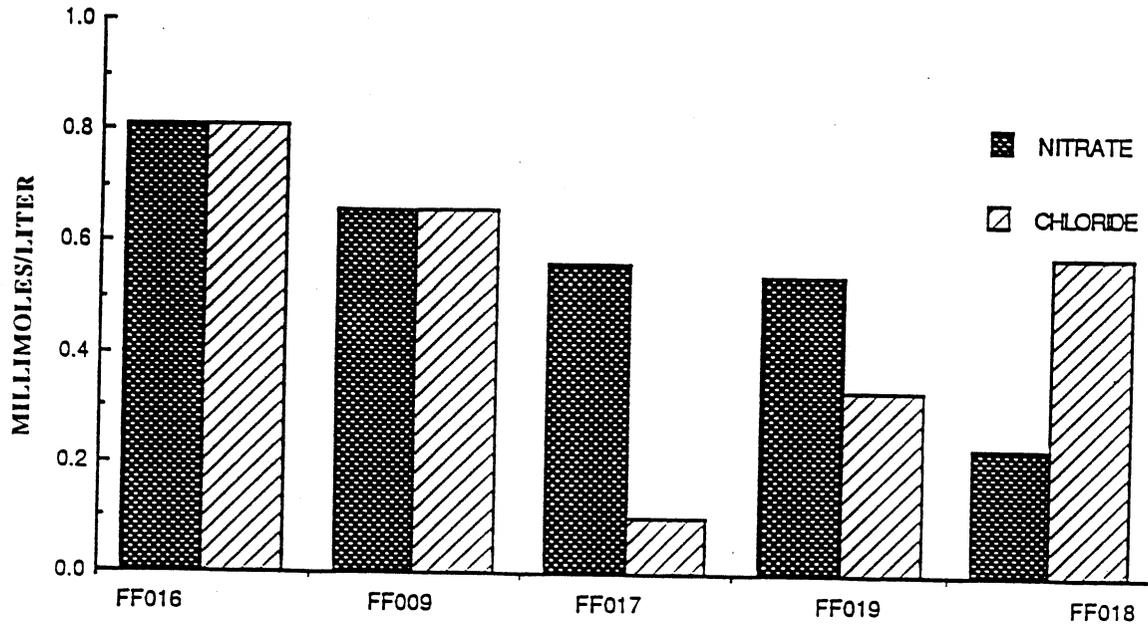


Figure 17.

Figure 9 . Box plots of the calcium concentrations of springs FF001 - FF005 showing the range of concentrations through the sampling period for each spring and the variability between springs.

### NITRATE AND CHLORIDE IN RECHARGE AREA



### CHLORIDE AND NITRATE IN SPRINGS AND LOWLAND WELLS

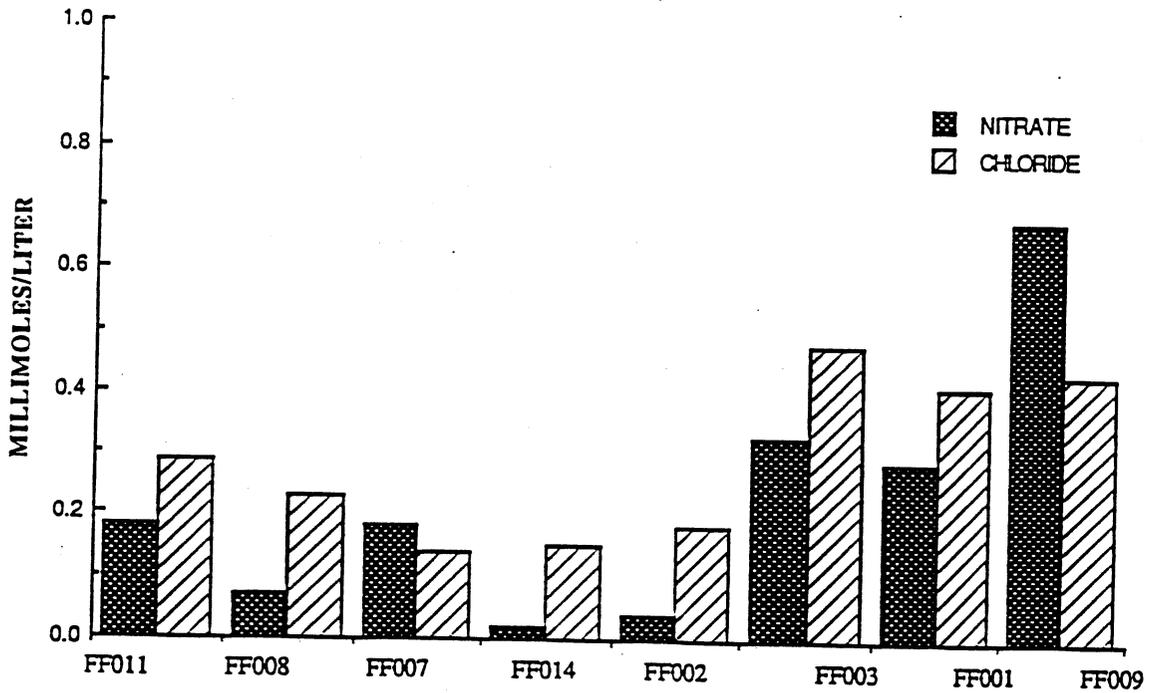


Figure 10. Concentrations of chloride and nitrate in wells in the recharge area and wells and springs in the discharge area. Refer to Figure 5 for location of sampling points.



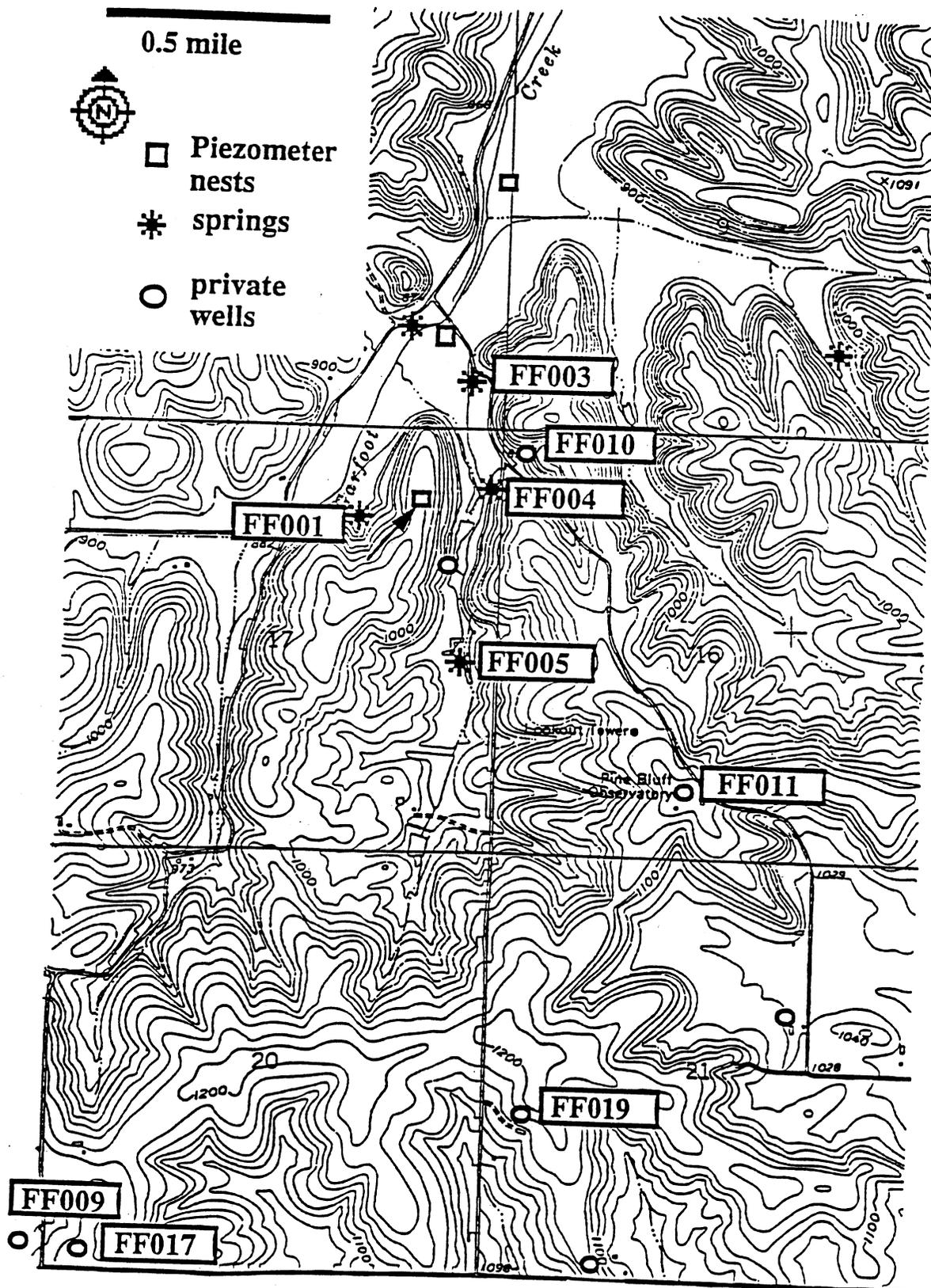


Figure 11b. Location of Group 2 waters.

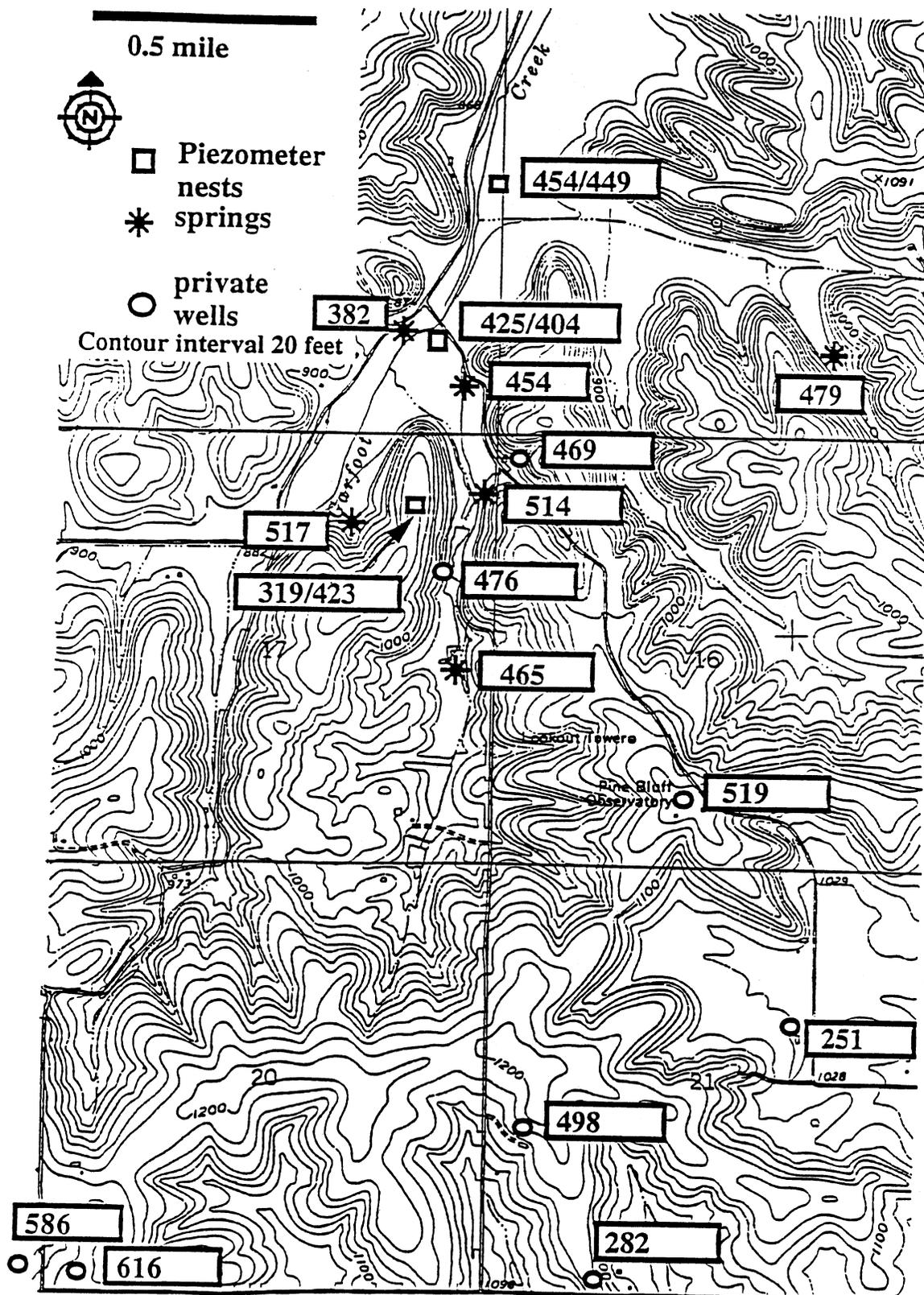


Figure 12. The spatial distribution of total dissolved solids (TDS) of sampled waters in the Garfoot Creek watershed.

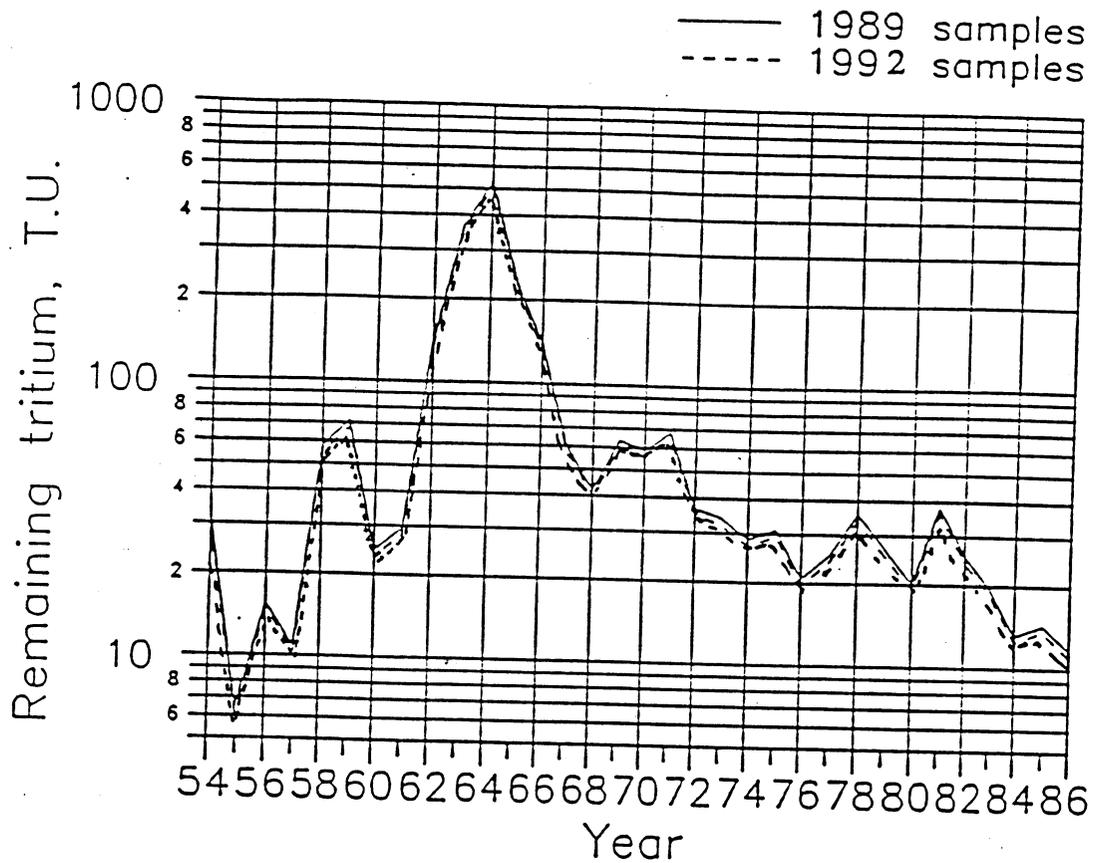


Figure 13. Tritium input curve for tritium in Dane County. Curves indicate tritium remaining in groundwater allowing for radioactive decay prior to the indicated sample date. (from Bradbury, 1992).

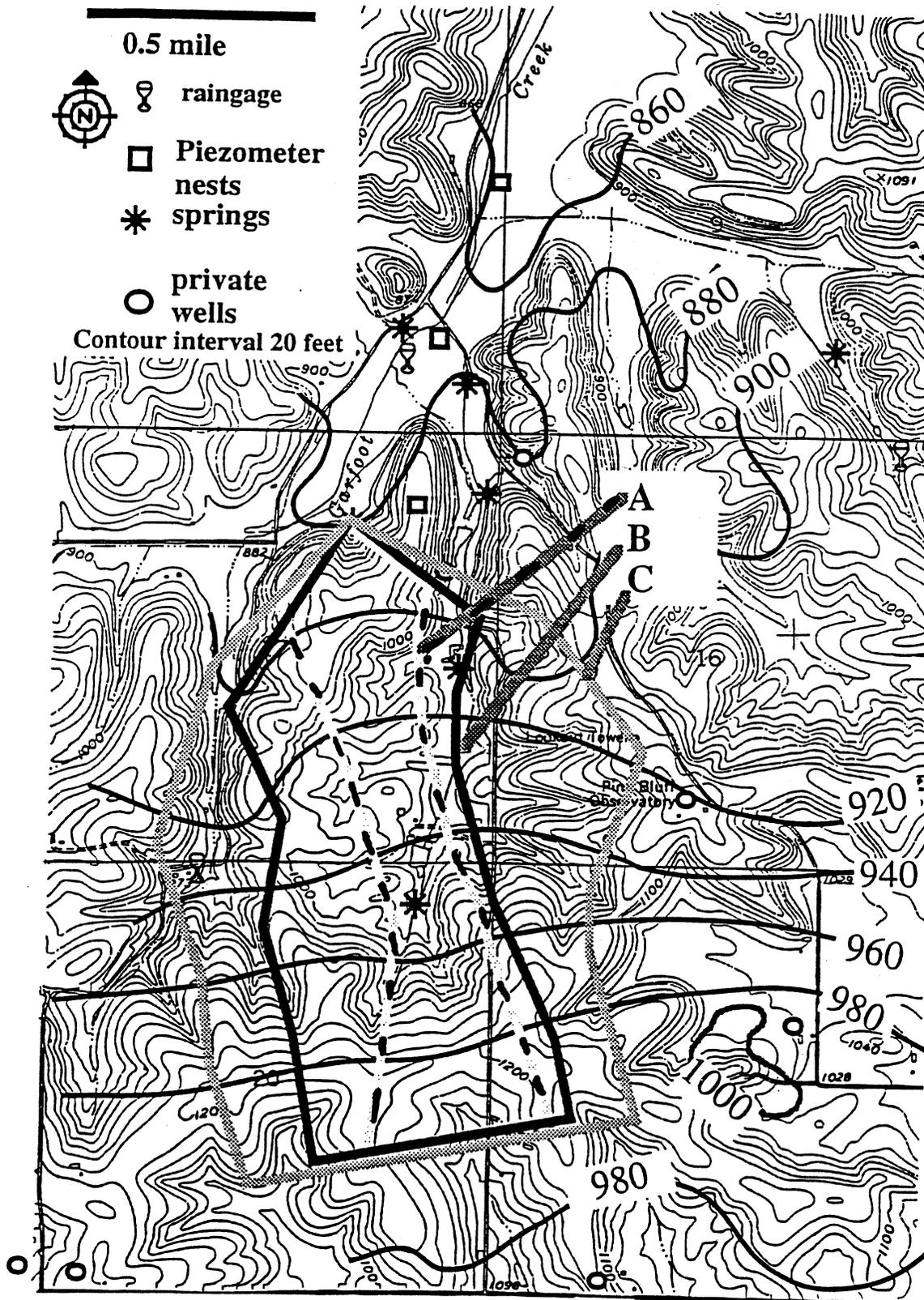


Figure 14. Map of measured catchment areas. The smallest area, A is about 285 acres. The area of B is 360 acres and C is 640 acres.