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Investigation of Ground Water Level Fluctuations at the Savannah River Site  
(Under the direction of Dr. TODD C. RASMUSSEN)

A primary concern at many waste sites is the ability to correctly predict the migration pathways of contaminants. We wish to determine the conditions that would result in erroneous predictions of contaminant trajectories. Ignoring the effects of barometric pressure can cause large errors in predicted trajectories in confined and watertable aquifers. We find the prediction error is largest in watertable aquifers because of barometric efficiencies near 100 percent. We propose to reduce this error by using total heads (water levels plus barometric pressure) to calculate the hydraulic gradient. An improved hydraulic gradient can be calculated even when water levels are measured at different times. Another proposal is to avoid using measurements following large precipitation events because these water level measurements could corrupt calculated hydraulic gradients for some wells. Water levels in wells near streams rise quickly following large precipitation events but usually return to normal once stormflows have subsided.

INDEX WORDS: Barometric Efficiencies, Barometric Pressure, Contaminant Trajectories, Hydraulic Gradient, Migration Pathways, Prediction Error, Total Head, Water Level Measurements.

INVESTIGATION OF GROUND WATER LEVEL FLUCTUATIONS  
AT THE SAVANNAH RIVER SITE

by

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B.S., University of Idaho, 1980

A Thesis Submitted to the Graduate Faculty  
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## **CHAPTER 1**

### **INTRODUCTION**

The Savannah River Site (SRS) is owned and managed by the U. S. Department of Energy (DOE). The site began operating in the early 1950s to produce special nuclear materials for national defense. The facilities process inventories of radioactive materials for deep space probes, recycling and reloading of tritium to maintain nuclear weapons readiness, and processing liquid radioactive waste into solid form for permanent disposal. The development of environmental restoration techniques and transfer of these techniques to other facilities is another important SRS objective. The Department of Energy owns the Savannah River Site (SRS) and operates it through its prime contractor, Westinghouse Savannah River Company (WSRC) under regulatory supervision of the South Carolina Department of Health and Environmental Control (DHEC) and the U.S. Environmental Protection Agency (EPA).

SRS was placed on the National Priorities List in 1989, and is permitted under the Resource Conservation and Recovery Act (RCRA) as administered by the South Carolina Hazardous Waste Management Regulations (R.61-79). As a part of the general site permit, specific facilities are permitted for closure and post-closure care. Post-closure care activities at the Administration and Materials Area and the General Separations Area center on ground-water monitoring and remediation. The resulting ground-water program is large, with almost 1700 wells sampled for approximately 200,000 analyses per year. Additional ground-water monitoring takes place under the Federal Facility Agreement for SRS, and in compliance with Department of Energy

orders and best management practices. The EPA has delegated authority to DHEC all aspects of RCRA except the 1984 Hazardous and Solid Waste Amendments to RCRA.

### **1.1 Statement of the Problem**

From five to ten percent of the SRS land area may have been contaminated by industrial solvents, tritium, metals, or other contaminants generated by operations there (WSRC, 1993b). The ground water beneath the site flows slowly, from inches per year to several hundred feet per year, towards streams, swamps, springs, or pumped wells. The Savannah River Site is required by DOE and the EPA, as a result of passing the Resource Conservation Recovery Act of 1976, to monitor the environmental effects of on-site activities.

Seepage basins were used until 1985 to hold non-radioactive effluent of construction waste products, cleansers, solvents, etc. Wastes discharged into these basins were allowed to seep into the soil (Eddy et al., 1991). Subsequent to RCRA/CERCLA legislation many contaminant plumes beneath SRS, have been identified and mapped. These plumes contain both chemical waste products and radionuclides. The radionuclides resulted from allowable releases of these contaminants at a rate considered safe by the U.S. Government Department of Energy (DOE) and also from unplanned releases of these contaminants.

Past waste disposal operations from seepage basins have resulted in ground-water contamination. Two sets of seepage basins (F-Area and H-Area) within the General Separations Area have been closed, and are currently undergoing post-closure care under a RCRA Corrective Action Plan that includes extraction of contaminated ground-water, treatment, and re-injection upgradient. Plumes, primarily of metals and radionuclides, are present in unconfined, semi-confined, and confined aquifers. These facilities are monitored by more than two hundred wells in three different aquifer zones. Numerous additional wells in the General Separations Area (GSA) supply supporting

information about aquifer flow paths. Because of the need to provide accurate predictions of contaminant migration, knowledge of the gradient is important when attempting to predict the travel time, direction and velocity of contaminants in the groundwater.

## **1.2 Regulatory Concerns**

Environmental monitoring at the SRS is regulated by the Resource Conservation and Recovery Act as administered by the South Carolina Department of Health and Environmental Control (DHEC) under the South Carolina Hazardous Waste Management Regulations. DHEC requirements have been that all monitored wells be sampled quarterly over a two-week period. A 48-hour sampling period is now required at some of the monitored wells. The desired effect of the new, shorter period is to more accurately estimate the groundwater flow gradients in aquifers potentially affected by releases of contaminants from regulated facilities. Increased accuracy due to water level measurements taken during a 48-hour time period has not been proven. However, DHEC feels that the water level measurements would be more accurate if the time period is short, thereby providing a more accurate estimate of groundwater gradients.

Specification of general monitoring requirements adds significant costs to the ground-water monitoring program because of the magnitude of the program. Unnecessary requirements added by regulations written for generic situations, and not specifically tailored to the needs of SRS, can and do impose cost inefficiencies. This innate conservatism of the regulations is sometimes relieved by flexibility of regulatory staff familiar with site-specific conditions. However, in situations where supporting data are absent or insufficient, regulatory staff often must default to a conservative position on specific issues.

### **1.2.1 Well Sampling Frequency**

Currently, post-closure permits for groundwater remediation at the F- and H-Areas Seepage Basins require quarterly water level measurements in all F-Area monitoring wells within a specified time period ranging from 48 hours to two weeks. Our concern is whether short-term fluctuation due to barometric pressure, earth tides, moon tides, evapotranspiration, etc., in groundwater levels during 48-hour sampling intervals may affect the interpreted groundwater gradient as much as longer-term fluctuations such as seasonal discharge/recharge, regional pumping, etc. If this concern is proven, the 48-hour sampling period for some wells may not provide data with sufficient accuracy to accurately predict contaminant migration trajectories.

### **1.2.2 Well Density and Placement**

SRS has an extensive inventory of wells (over 3000) which can be used for taking water level measurements. Horizontal gradient within one hydrostatic unit can be estimated using data from a minimum of three wells. The piezometric surface of the watertable can be estimated by assuming the plane of the piezometric surface passes through the three points. The Three Point Planar Method is based on the assumption that the local piezometric surface between the three wells is planar, i.e., the gradients are uniform everywhere. In the Three Point Planar Method, there exists three data points,  $H_0$ ,  $H_1$ , and  $H_2$ , corresponding to total head elevation observations obtained from three wells. Taking the difference in elevations divided by the distance between the respective wells results in the gradient.

A literature review failed to locate a procedure for monitoring well or piezometer placement. Although a strategy for well placement is needed, because of the costs involved in drilling wells both in terms of manpower and equipment expenses, it is imperative that a strategy be adopted for the optimal placement of wells when locating a contaminate plume, mapping the watertable, etc. Using water levels in four wells would

allow construction of four different planes, thereby providing additional confidence, as long as the four planes agree.

### **1.3 Thesis Objective**

This study examines the nature and magnitude of water level fluctuations in measured wells. The objective is to determine the influence of these fluctuations on the magnitude and direction of hydraulic gradients related to groundwater contaminant migration. The fluctuations of concern include those related to barometric pressure, precipitation (amounts and rates), stream influences, and aquifer properties. Of specific concern is the influence of water level fluctuations on the optimum well sampling frequency used to predict hydraulic gradient.

### **1.4 Thesis Organization**

This first chapter has been an introduction to the SRS mission with a brief statement of a current problem facing SRS and a summary of the thesis objectives. Chapter 2 contains a field site description of the Savannah River Site with an overview of the geology, surface hydrology, and subsurface hydrology, aquifer properties, and site geometry. The third chapter describes the methods and materials used for data collection, site set-up and analysis procedures. Chapter 4 discusses temporal influences affecting the observed data, methods of data characterization and compensation strategies. Chapter 5 summarizes the findings of this thesis and provides recommendations for improved water level monitoring strategies.

## **CHAPTER 2**

### **SRS SITE DESCRIPTION**

SRS is located in South Carolina along the Savannah River (Figure 2.1) and occupies an area of approximately 300 square miles on the Upper Atlantic Coastal Plain, approximately 20 miles southeast of the Fall Line. The Savannah River forms the southwestern boundary of SRS and the Congaree River is approximately 60 miles northeast of SRS.

SRS lies predominantly on the Aiken Plateau which generally slopes southeastward approximately 5 feet per mile. The Aiken Plateau is bounded to the north by the Piedmont Province at the Fall Line, the Savannah River to the west, the Congaree River to the east and the Lower Coastal Plain to the south. The surface of the Aiken Plateau is highly dissected by numerous small streams that drain into the Savannah River, characterized by broad interfluvial areas with narrow steep-sided valleys. Local relief is as much as 300 feet.

#### **2.1 Regional Setting**

Three hydrogeologic regimes are recognized at SRS (Aadland and Bledsoe, 1990). One regime comprises Paleozoic metamorphic and igneous basement rocks; another consists of Triassic-age lignified mudstones, sandstones, and conglomerates within the Dunbarton Basin; the third regime consists of consolidated to unconsolidated Coastal Plain sediments of Late Cretaceous and Tertiary ages. Paleozoic rocks are predominantly gneisses and schists with lesser amounts of quartzite (Klitgord and Behrendt, 1979). These metamorphic rocks are intruded by younger Paleozoic granitic plutons.

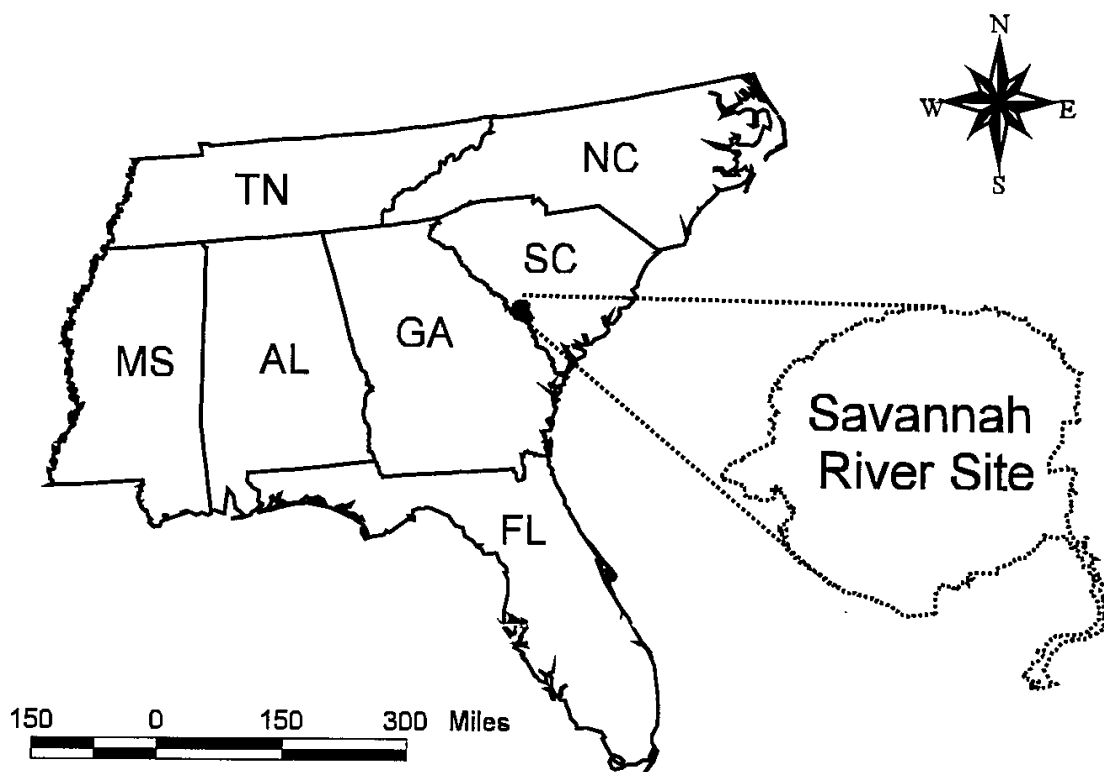


Figure 2.1: Location of the Savannah River Site, South Carolina.

The Triassic sediments consist of poorly sorted, consolidated gravel, sand, silt, and clay. The poor sorting results in extremely low primary porosity in the Triassic rocks. Both the Paleozoic and Triassic rocks were leveled by erosion and are unconformably overlain by unconsolidated to consolidated Coastal Plain sediments. These three regimes have recently been grouped by Aadland et al. (1992) into two hydrogeologic provinces: the Piedmont and Southeastern Coastal Plain.

### **2.1.1 Southeastern Piedmont Province**

The hydrology of the buried Paleozoic and Triassic basement hydrologic system has been studied intensively to assess the safety and feasibility of the disposal of radioactive waste in these rocks. (Marine, 1974). Representative hydraulic conductivity values of  $4.01 \times 10^{-6}$  feet/day to 1.04 feet/day have been estimated for the basement rocks of varying fracture permeability. The rock of highest hydraulic conductivity was found to have a 0.08 percent fracture permeability. A two-well tracer test was used to determine the fracture porosity. Water is not pumped from the Paleozoic or Triassic bedrock because of the poor water quality and low permeability of the rocks. Therefore, the hydrologic regime of the Piedmont Hydrogeologic Province at the SRS is unlikely to change appreciably for many decades.

### **2.1.2 Southeastern Coastal Plain Province**

The sediments of the Atlantic Coastal Plain in South Carolina consist of stratified deposits of sand, silt, clay, calcareous sand and clay, limestone, and gravel that dip gently seaward and range in age from Late Cretaceous to Holocene. The sedimentary sequence is absent at the Fall Line and thickens to more than 4,000 feet at the Atlantic coast. Regional dip is to the southeast, although beds dip and thicken locally in other directions because of locally variable depositional regimes.

In the vicinity of the SRS sediments consist predominantly of sandy clays and clayey sands, although occasional beds of clean sand or clay also occur. Two bioclastic limestone zones occur intermittently within the Eocene strata. These calcareous zones, where present, vary in thickness from about 1 foot to approximately 80 feet. They appear to be lens-like bodies that pinch out laterally into sand or clay facies. This erosional surface dips approximately 35 feet per mile to the southeast (WSRC, 1993b). Collectively, these sediments form a multilayered hydrologic sequence of aquifers and confining layers. Water flow is governed by the lithologic character, hydraulic properties, and geometry of the particular unit.

There are two major aquifer systems, the Dublin-Midville aquifer system, of Late Cretaceous origin, which sits above the Appleton Confining System above the basement rocks. Formations of the Late Cretaceous include from bottom to top the Cape Fear, Middendorf, Black Creek, Peedee and the Steel Creek member. The Floridan aquifer system of Eocene to Miocene origin, lies above the Dublin-Midville aquifer system. The two aquifers are separated by the Meyers Branch Confining System and the Crouch Branch aquitard of Paleocene to Early Eocene age. Groups, from bottom to top of this confining unit/aquifer system include the Black Mingo, Orangeburg, Barnwell and Upland Unit. These are divided into formations. The Black Mingo includes the Ellenton, Williamsburg, and Fishgurne formations (bottom to top). The Orangeburg includes the Congaree, Warley Hill and Santee Limestone formations and the Barnwell Group includes the Clinchfield, Dry Branch and Tobacco Road Sandstone formations.

## **2.2 Surface Water Hydrology**

Surface water is an integral component of the overall hydrologic system (Figure 2.2). If a contaminant travels through the ground water towards a stream and is discharged into the stream, then the transport time of that contaminant to the Savannah River and to populated areas will be much quicker from that point than if the contaminant re-

mained in the subsurface. The lakes and ponds on the SRS are man-made reservoirs mainly used as cooling ponds for the reactors on site. However, because these ponds are there, the natural flow of water to the Savannah River is altered. Additionally, the Carolina Bays of the SRS play a role in the characterization of the watertable, as will be explained later in this chapter. Floodplains have been altered since the beginning of operations at the SRS due to the large amounts of water that have been used for cooling of the reactors and construction of the cooling ponds/lakes.

The major tributaries that occur on the SRS are Upper Three Runs Creek, Fourmile Branch, Beaver Dam Creek, Tinker Creek, Tims Branch, Pen Branch, Indian Grave Branch, Steel Creek, and Lower Three Runs Creek. The interstream upland area is flat to gently rolling and characterized by gently dipping units of sand, silt, sandy clay, and clayey sand. The Savannah River cuts a broad valley approximately 250 feet deep through the Aiken Plateau. The Savannah River Swamp lies in the floodplain along the Savannah River for a distance for about 10 miles on the SRS and averages about 1.5 miles in width. A small natural levee has formed along the river. Three breaches have occurred in this levee at the confluences of Beaver Dam Creek, Fourmile Branch, and Steel Creek.

### **2.2.1 Upper Three Runs Creek**

The Upper Three Runs Creek watershed drains about 200 square miles of the Upper Coastal Plain northeast of the Savannah River. Significant tributaries to Upper Three Runs Creek are Tinker Creek, and Tims Branch. Tims Branch receives industrial wastes and waste water from the F-area Fabrication facility (M Area) and the Savannah River Technology Center (SRTC). The drainage basin consists principally of forested land and farmland and has no significant lakes or flow control structures.

The average flow for Upper Three Runs Creek near its entrance to the SRS for the period 1966 to 1986 was 106 cfs. This represents a water yield of about 1 cubic foot per

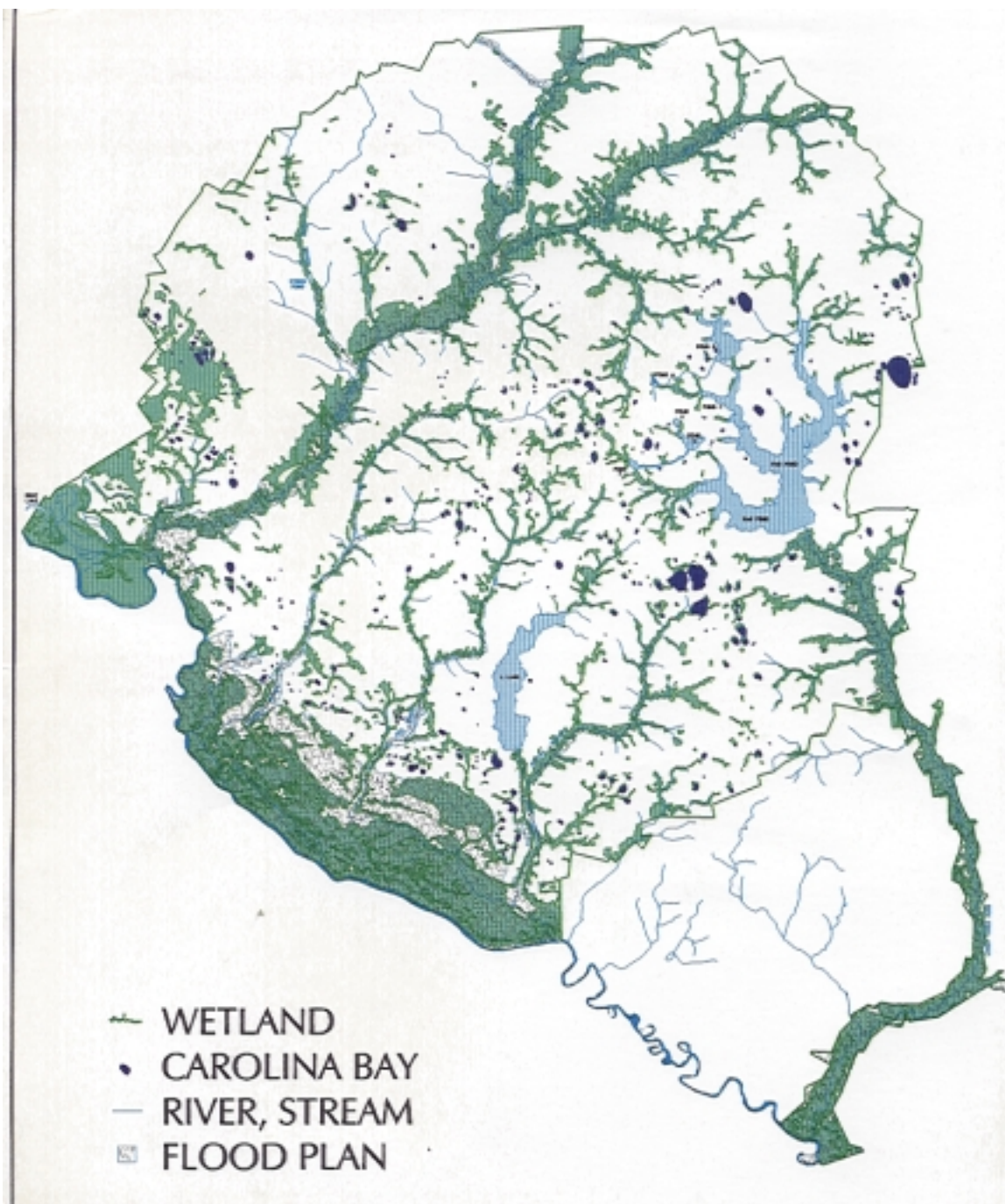


Figure 2.2: Hydrologic features of the Savannah River Site.

square mile or 16.55 inches per year from the drainage basin (WSRC, 1993a). Thus, in the upper reaches of Upper Three Runs Creek, approximately 35 percent of the rainfall appears as stream discharge.

### **2.2.2 Fourmile Branch**

Fourmile Branch drains about 23 square miles within the SRS, including much of the F, H, and C Areas. The creek flows to the southwest into the Savannah River Swamp and then into the Savannah River. The sides of the valley vary from gently sloping to steep. The floodplain is up to 1,000 feet wide. Fourmile Branch receives effluent from F and H Areas. The creek valley has been modified by the cooling water discharge, which has created a delta into the Savannah River Swamp. Mean monthly flows range from 88 cfs to 17 cfs (WSRC, 1993a).

### **2.2.3 Lakes and Ponds**

Surface water is held in artificial impoundments and natural wetlands on the Aiken Plateau. Par Pond is the largest impoundment on the SRS and covers approximately 2,700 acres when filled. Par Pond is an artificial lake located in the eastern part of the site. L Lake lies in the southern portion of the SRS and covers approximately 1,000 acres when filled. Water from these impoundments flows south through Lower Three Runs Creek and Steel Creek to the Savannah River.

Water is intermittently retained in natural lowland and upland marshes and natural basins, some of which are Carolina bay depressions (Prouty, 1952; Schalles et al., 1989). The source of most surface water at the SRS is from precipitation which averages 48 inches annually. Also, water is pumped from the Savannah River to cooling plant facilities and is eventually returned to the streams after cooling. Another surface water source is from ground water discharging to the surface streams.

#### **2.2.4 Carolina Bays**

Carolina Bays are shallow, closed depressions (Lide, et al., 1995) of uncertain origin located on the Atlantic Coastal Plain. Estimates range from 10,000 to 500,000 bays in the Southeastern Coastal Plain. Most Carolina Bays contain wetlands and some function as intermittent ponds. A few bays contain permanent open water but that is the exception rather than the rule. It has been suggested that these bays contain perched ground water (Lide et al., 1995). In the early 1930s a hypothesis was proposed that the origin of the numerous Carolina Bays was due to the impact of meteor showers (Melton and Schriever, 1933). Additional hypotheses as to bay origins range from fish nests formed by the fanning of schooling fish waving their fins in unison, to artesian, lacustrine, dissolution, or aeolian causes, as well as some combination of these.

There is significant lack of evidence in support of and evidence contrary to this theory of bay formation. The area of the Piedmont province, where there are known meteor impact areas, has no Carolina Bay formations (Johnson, 1942). There is a lack of meteoric material in the bay areas. Other meteor impact areas have meteor debris. The shallowness of the bays is also contrary to known meteor craters. The insignificant rim size and the irregular outline, leads to a reasonable conclusion that the bays were formed through some other means.

Douglas Johnson (1942) examined the hypotheses presented up to that time and discussed their relative merit. The drowned valley method of bay formation did not take into account the sand ridges surrounding the bays which are distinct from and independent of the sandy ridges of the beach plain. The aeolian hypothesis was discounted by Melton and Schriever (1933) when they noticed that the formation of such regular and smooth depressions is not characteristic of wind scour plus the fact that some of the bays had sand ridges completely surrounded them, which would not be explained by the prevailing winds.

### **2.2.5 Floodplains**

The built-up areas of SRS are above the 100-year flood level so there is little concern that the functional facilities at SRS would be in danger during a 100-year flood. However, if water levels were to rise to the 100-year flood level, it would affect the gradient and would also affect contaminant delivery to the discharge points, i.e. the streams. Travel distance to the stream would be decreased, thereby hastening the time for contaminant delivery. Because of the distances involved from the current contaminant plume to the projected 100 year flood level, and the relatively short time that the waters would be at those levels, a flood of the 100 year variety is not expected to cause any serious threats to contaminant plume expansion.

### **2.3 Ground Water Hydrology**

The average annual precipitation at SRS is 48 inches (WSRC, 1993a). Of this, approximately 15 inches becomes ground-water recharge. Potentiometric surface maps show the vertical gradient relationship beneath the site between the Congaree-Fourmile (Orangeburg Group) and the Cretaceous age sediments. Ground-water data show two areas of downward gradient from the surficial aquifer to the lower aquifers. The remainder of the site generally shows an upwards gradient. The downward gradient areas are recharge zones for the lower aquifers.

Few aquitards are continuous across SRS (WSRC, 1993b). In the northwestern portion of the SRS, the aquitards are less continuous and permit vertical flow of ground water. The aquitards of the southeastern portion of the SRS are more continuous, resulting in a more horizontal flow of the ground water. At the fault zones, where the aquitard is discontinuous, vertical exchange of water from one aquifer to another is quite possible. Across much of the SRS, hydraulic head decreases with depth, indicating that vertical ground-water flow is downward.

At SRS, the horizontal movement of ground water is generally governed by the depths of incision of the streams where water is discharged to the surface. Valleys of smaller streams allow for discharge from the upper saturated formations. The major tributaries to the Savannah drain formations of intermediate depth of Eocene age while the Savannah River drains deep formations of Cretaceous origin. In general, Eocene ground water (which includes the Orangeburg Group through the Barnwell Group) discharges to the valleys of Upper Three Runs Creek and the Savannah River.

Ground water in the upper saturated zone may flow toward discharge points along either Four Mile Branch or Upper Three Runs Creek or downward into the Congaree-Fourmile zone. Once the ground water is in the Congaree-Fourmile zone, the flow is horizontal towards discharge points along Upper Three Runs Creek. The remainder of this section will concentrate on a general description of the Floridan aquifer system and the confining layer beneath it, the Meyers Branch Confining System.

### **2.3.1 Meyers Branch Confining System**

The Meyers Branch Confining System is composed of the clays, silts, and sands of the Paleocene Black Mingo Group and the clayey beds of the upper Peedee Formation (Aadland and Bledsoe, 1990; Aadland et al., 1992). The thickness and lateral continuity of these beds form an effective confining unit separating the overlying Tertiary sediments from the underlying Cretaceous sediments. Both the Williamsburg and Ellenton Formations of the Black Mingo Group contain sand units that are capable of producing significant quantities of water; however, these are relatively thin and discontinuous and do not constitute major aquifers.

### **2.3.2 Floridan Aquifer System**

The Floridan aquifer system overlies the Meyers Branch Confining System throughout the lower two-thirds of the SRS from Upper Three Runs Creek to the southern SRS

boundary. Stratigraphically, the Floridan aquifer system includes all the sediments of the Orangeburg and Barnwell Groups up to the watertable. The Floridan aquifer system is further divided into two aquifers, the Gordon aquifer and the Upper Three Runs aquifer, separated by the Gordon aquitard. Stratigraphically, the Gordon aquifer includes the sands of the Congaree Formation, the Fourmile Member of the Fishburne Formation, and locally, sands in the Warley Hill Formation (Aadland and Bledsoe, 1990; Aadland et al., 1992). The Upper Three Runs aquifer consists of the sedimentary sequences in the upper Orangeburg and Barnwell Groups. The Gordon aquitard consists of the clay beds of the Warley Hill Formation and the Caw Caw Member of the Santee Limestone Formation.

#### **2.4 Study Area Description**

F-area Separations Facility and Hazardous Waste Management Facility (HWMF) and the Burial Grounds Complex are part of the larger General Separations Area (GSA). The GSA is located in the central portion of the SRS, and occupies approximately 15 square miles. In addition to F-area and the Burial Grounds, the GSA also includes H-Area Separation Facility and HWMF. For the purpose of this study, the geologic and hydrologic characteristics of the different hydrogeologic units underlying the GSA will be limited to the Upper Three Runs aquifer down to and including the Meyers Branch Confining System.

Table 2.1 presents a summary of the lithostratigraphic and hydrostratigraphic profiles at the Savannah River Site. Table 2.2 presents a summary of hydrogeologic characterization parameters relevant to the site. Representative hydrogeologic properties are summarized in Table 2.3. Figure 2.3 provides a location map showing monitoring wells used in this study

#### **2.4.1 Surface Morphology**

The GSA is located between Upper Three Runs Creek and Fourmile Branch. Upper Three Runs Creek is located approximately 5,600 feet north and northwest, and Four-mile Branch is located approximately 2,000 feet south of the center of the study area. The interstream topography is relatively flat, but the slope increases near the streams. The primary natural drainage in the vicinity of F-area is to the southeast toward Fourmile Branch.

Upper Three Runs Creek exerts a dominant influence on the ground-water regime in the GSA as a result of the relatively deep incision into the Tertiary section. All runoff from the GSA is conveyed via tributaries toward the Savannah River 9-10 miles to the southwest. Of the approximately 48 inches of precipitation that falls at the GSA, it has been estimated that approximately 70 percent of available precipitation discharges via tributaries to the Savannah River or evaporates (Cahill, 1982). The remaining 30 percent, or approximately 15 inches, is available for ground-water recharge.

#### **2.4.2 Surface-Water Hydrology**

The GSA is bounded by the Upper Three Runs to the north and the Fourmile Branch to the south. The Burial Ground Complex (BGC) portion of the study area is at a local elevation high and encompasses a ground-water divide. The ground water flows to the north or south (generally) towards one of the two rivers from the BGC.

It is our belief that a single hydrologic model may not be appropriate for every site. Each site will exhibit different behavior as a function of local and regional variations in hydrogeologic conditions. The conceptual model for the sites includes, but is not limited to variability in the: 1) barometric efficiency in space and time; 2) rate of recharge from direct precipitation and streamflow; 3) rate of ground-water discharge to surface water; 4) degree of confinement, from watertable to fully confined; 5) water specific weight due to changes in gravity, temperature, dissolved and suspended solids concentrations, or

Table 2.1: Lithohydrostratigraphic Units at the Savannah River Site

Age	Lithostratigraphy		Hydrostratigraphy					
Miocene	Hawthorn	Altamaha (Upland Unit)	Surficial Aquifer	Upper Three Runs Aquifer	Floridan Aquifer System			
Eocene	Barnwell	Tobacco Road						
		Dry Branch	Irwinton Sand					
			Twiggs Clay			Tan Clay Aquitard		
			Griffins Landing			Barnwell-McBean Aquifer		
		Clinchfield						
	Orangeburg	Tinker/Santee						
		Warley Hill	Green Clay Aquitard					
		Congaree	Gordon Aquifer					
	Black Mingo	Fishburne/Fourmile						
	Paleocene	Black Mingo	Snapp/Williamsburg	Crouch Branch Aquitard		Meyers Branch Confining System		
Ellenton								
Cretaceous	Lumbee	Steel Creek/Peedee	Crouch Branch Aquifer		Dublin-Midville Aquifer System			
		Black Creek						

Table 2.2: Hydrogeologic Characterization Parameters

---

Physical Parameters

- b Thickness
- n Porosity,  $n = n_e + n_i$
- $n_e$  effective porosity
- $n_i$  immobile zone porosity
- $\rho_b$  Bulk density,  $\rho_b = (1 - n) \rho_s$
- $\rho_s$  Skeletal density,  $\rho_s = 2.65 \text{ g/cm}^3$

## Conductance Parameters

- K Hydraulic conductivity
- $K_h$  horizontal component for aquifers
- $K_v$  vertical component for aquitards
- $\alpha$  anisotropy ratio,  $\alpha = K_h / K_v$
- T Aquifer transmissivity,  $T = K_h b$
- L Aquitard leakance,  $L = K_v / b$

## Storage Parameters

- $S_s$  Specific storage coefficient, or aquifer compressibility,  $S_s = \epsilon + n \beta$
- $\epsilon$  skeletal compressibility
- $\beta$  water compressibility,  $\beta \approx 5 \text{ e-6 m}^{-1}$
- BE Barometric Efficiency,  $BE = n \beta / S_s$
- TE Tidal (or loading) Efficiency,  $TE = 1 - BE = \epsilon / S_s$
- S Storage coefficient (or storativity),  $S = S_s b$

## Transport Parameters

- $D_s$  Solute Dispersion Coefficient,  $D_s = D_o + \alpha v$
- $D_o$  molecular diffusion coefficient
- $\alpha$  diffusivity coefficient
- $v$  average pore velocity
- R Retardation Factor,  $R = 1 + (\rho_b/n) K_d$
- $K_d$  Distribution Coefficient
- CEC Cation Exchange Capacity
- AEC Anion Exchange Capacity
- OC Organic Carbon content
- $S_a$  Specific surface area
- $\beta$  Sorption kinetic parameters

## Miscellaneous Parameters

- $D_h$  Hydraulic Diffusivity,  $D_h = K / S_s = T / S$
  - $C_p$  Specific Capacity,  $C_p = Q / s$
  - Q steady state pumping rate
  - s steady state drawdown
  - R Recharge rate
  - DP Deep Percolation rate
-

Table 2.3: Representative GSA Hydrogeologic Properties

Hydrogeologic Zone	Thickness <i>b</i> (ft)	Hydraulic Conductivity		Specific Storage Coefficient
		Horizontal $K_h$ (ft/s)	Vertical $K_v$ (ft/s)	$S_s$ (1/ft)
Surficial Aquifer	10 to 39	3.28 E-4	-	2.01 E-4
Tan Clay Aquitard	5 to 26	-	6.92 E-9	-
Barnwell-McBean Aquifer	39 to 131	9.84 E-5	-	2.47 E-6
Green Clay Aquitard	2 to 10	-	20.99 E-10	-
Gordon Aquifer	66 to 98	5.25 E-4	-	0.31 E-5
Crouch Branch Aquitard	59	-	3.28 E-9	-
Crouch Branch Aquifer	246	13.45 E-4	-	1.62 E-6

Hydrogeologic Zone	Transmissivity	Storage Coefficient	Hydraulic Diffusivity	Hydraulic Leakance
	$T = K_h b$ (ft <sup>2</sup> /s)	$S = S_s b$	$D = T/S$ (ft <sup>2</sup> /s)	$L = K_v / b$ (s <sup>-1</sup> )
Surficial Aquifer	86.0 E-4	1.2 E-2	0.75	-
Tan Clay Aquitard	-	-	-	3.0 E-10
Barnwell-McBean Aquifer	64.6 E-4	1.6 E-4	43	-
Green Clay Aquitard	-	-	-	3.2 E-10
Gordon Aquifer	26.9 E-3	2.5 E-4	107.6	-
Crouch Branch Aquitard	-	-	-	5.8 E-11
Crouch Branch Aquifer	33.4 E-2	4.0 E-4	839	-

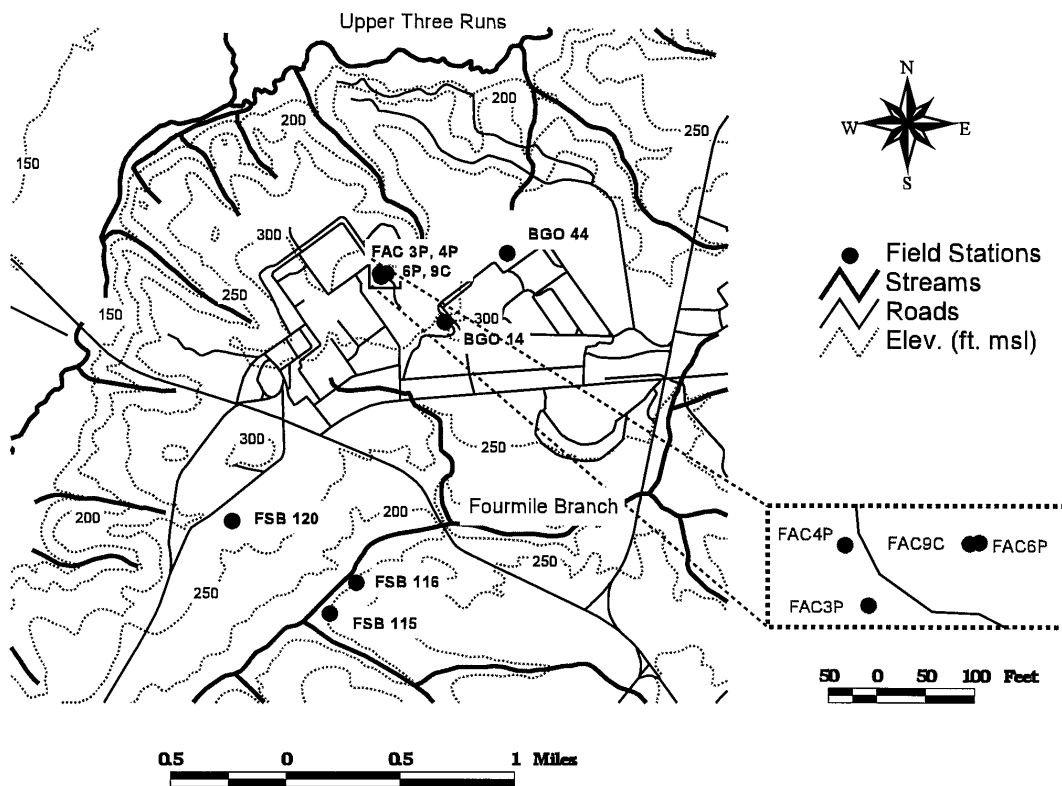


Figure 2.3: Location of GSA monitoring wells used in this study.

dissolved gases; 6) subsurface geological conditions such as permeability, mineralogy, grain size and shape, and degree of induration; and 7) topographic position. A summary of many of these factors can be found in Spane and Mercer (1985), Crawford (1994) and Rasmussen and Crawford (1997a, 1997b). An objective of this project is to provide a preliminary assessment of the relative importance of these factors on the calculated hydraulic gradient.

### **2.4.3 Stratigraphy**

The sedimentary sequence of the GSA is composed of consolidated to unconsolidated sediments of sand, silt, clay and calcareous materials. The sequence is approximately 1000 feet thick and is underlain by Paleozoic crystalline basement rocks (Nystrom et al., 1992). The sedimentary sequence forms a wedge that dips and thickens towards the southeast. The major confining system of concern to this study is the Meyers Branch confining system ( the Ellenton Clays) of Upper Cretaceous to Paleocene origin. The predominant clay material is kaolinite.

Above the Meyers Branch is the Congaree aquifer which ranges from 48 to 98 feet thick within the GSA. The Congaree aquifer consists of sand and clayey sand beds with thin interbeds of sandy clay, clay and calcareous sand. The confining bed above this is commonly referred to as the Green Clay. Lithologically, it is equivalent to the Warley Hill Member of the Santee Formation. The confining unit consists of clay, sandy clay and clayey sand beds with local areas of calcareous mud which contribute significantly to the thickness of the unit. The clay minerals of this formation are illite and smectite.

Above the confining unit is the Barnwell-McBean aquifer. This aquifer consists mostly of sand and clayey sand beds with local occurrences of calcareous sand, sandy and muddy limestone, and limestone interbeds. Thickness of this zone is from 39 to 84 feet. The sand is fine to coarse grained and moderately well sorted. Above the Barnwell-McBean aquifer is the Tan Clay aquitard. This zone is lithostratigraphically equivalent to

the Twiggs Clay Member of the Dry Branch Formation. Thickness of this formation ranges from 0 to 26 feet. The Tan Clay zone consists predominantly of clay and sandy clay beds with interbeds of clayey sand and sand with less common calcareous sand beds.

Above the Tan Clay aquitard is the surficial aquifer. The surficial aquifer ranges in thickness from 1 foot near Fourmile Branch to 60 feet in the HSB area. The vadose zone above the watertable ranges from 4 feet to 80 feet thick (Nystrom, et al. ,1992). Stratigraphically, the combination of the surficial aquifer and the vadose zone correlate with the Tobacco Road Formation and the Upland Unit. Figure 2.4 presents a hydrostratigraphic illustration for the General Separations Area.

#### 2.4.4 Ground-Water Hydrology

The ground-water hydrology beneath the study area is important because of the nature of the activities there. During the earlier years of the site there were numerous seepage basins constructed to allow waste chemicals to soak into the ground. Also, because of the separations facilities and the burial ground complex, this area in particular, is critical to have accurate watertable and potentiometric surface representation so that movement of ground-water contaminants can be predicted with some accuracy. Many factors affect this prediction of contaminant movement and in the case of this study, accurate representation of water levels in the monitored wells is critical to developing a useful gradient from point to point and between aquifers.

A downward gradient dominates from the Upper Three Runs aquifer to the underlying Gordon aquifer. From the potentiometric lines, the general flow direction of the aquifers is northerly and southwesterly from a ridge under the BGC/MWMF area. In the lower Gordon aquifer, this split flow path is not evident and the ground-water flow direction is northwesterly.

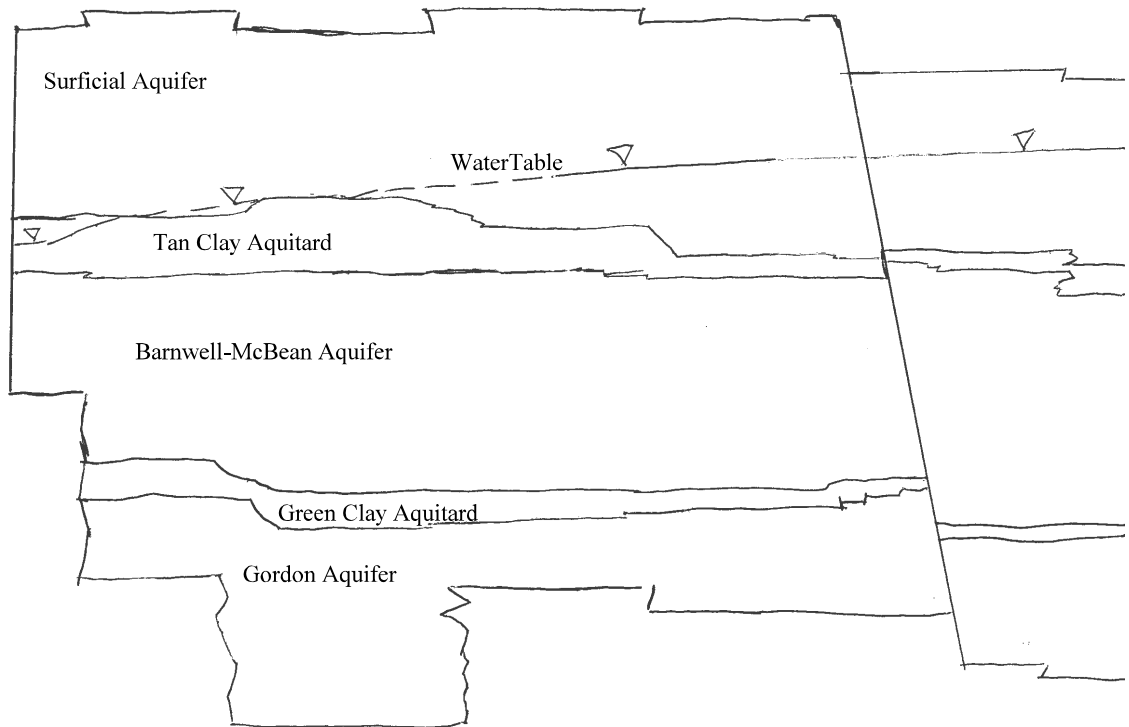


Figure 2.4: Observed GSA stratigraphic section.

The Meyers Branch confining system is the principal confining unit for this area and attains a thickness of over 100 feet in the GSA, below which are the Cretaceous and older sediments. The Floridan aquifer system overlies the Meyers Branch confining system. The aquifer is divided, from bottom to top, into the Gordon aquifer, the Gordon aquitard and the Upper Three Runs aquifer. The upper Three Runs aquifer is further divided into the Barnwell-McBean aquifer, the Tan Clay confining zone and the surficial aquifer. This system effectively separates the Dublin-Midville aquifer system from the Floridan aquifer system. The regional dip of the Meyers Branch Confining System is to the south and southwest. Under F-Area the confining unit slopes uniformly to the south and southwest. This system is an effective hydraulic barrier based on consistent thickness, continuous areal extent, consistent low hydraulic conductivity, and an upward flow potential across the unit from the underlying confined aquifer. The lateral continuity of the Meyers Branch aquitard has been verified by geophysical and lithological data.

GSA ground-water levels in the Dublin-Midville aquifer system are under higher pressure than in the Gordon aquifer, which overlies the Meyers Branch Confining System. Within the GSA, these head reversals range from 0 to greater than 20 feet. In the vicinity of F-area, a cluster of 12 wells (P-28 Cluster) have been monitored monthly since 1987 and have shown consistent head reversals of 25 to 30 feet over the years. The Meyers Branch confining system has consistently low hydraulic conductivity values in both vertical and horizontal directions. These facts, plus the knowledge that the Gordon aquifer is incised by and discharges into Upper Three Runs Creek while flow in the underlying Peedee aquifer is unaffected, provides further evidence of the hydraulic separation provided by the Meyers Branch aquitard.

In the GSA, the Floridan aquifer is divided from bottom to top into the Gordon aquifer, the Gordon aquitard, and the Upper Three Runs aquifer. The Upper Three Runs aquifer is subdivided into the Barnwell-McBean aquifer, the Tan Clay aquitard, and the surficial aquifer. The Gordon aquifer is from 60-128 feet thick within the GSA and consists

mainly of sands and clayey sands with small interbeds of sandy clays, clays and calcareous sands. Sands and clayey sands range in thickness from 2 to 84 feet. Sandy clays and clays range in thickness from 1 to 9 feet. Calcareous sediments occur locally and range in thickness from less than 1 foot to 15 feet. Sands and clayey sands of the Gordon aquifer vary from well to poorly sorted, and consist of fine- to coarse-grained, subangular to subrounded quartz.

Upper Three Runs Creek incises the Gordon aquifer creating a discharge area for the aquifer at the SRS. Fourmile Branch to the south does not incise the Gordon aquitard and therefore, does not influence flow in the underlying Gordon aquifer. Ground-water flow in the Gordon aquifer is northwest toward Upper Three Runs Creek. Recharge into the Gordon aquifer at the SRS is primarily from leakage through the Gordon aquitard. In places where the confining unit is breached by faults, this recharge may be locally increased. An example of this is the marked decrease in head beneath the H-area. This decrease in head parallels the fault trace in this area and also coincides with the presence of calcareous sediments in the Gordon aquitard, suggesting that calcareous sections have different hydraulic properties than siliclastic clays. An upward flow potential exists between the lower Dublin aquifer system and the Gordon aquifer. Therefore, contaminant migration from the Gordon aquifer across the Meyers Branch Confining System is unlikely due to this upward potential and the competency of the Meyers Branch Confining System.

The Gordon aquifer is characterized as a semi-confined aquifer, based on the following site-specific observations:

1. The Gordon aquifer is incised by Upper Three Runs Creek and the Gordon aquitard is discontinuous in some areas. The Gordon aquifer is hydrologically connected to the surface stream and upper aquifer zones.
2. There is vertical leakage across the Gordon aquitard, which infers a hydrologic connection between the Upper Three Runs aquifer and the Gordon aquifer.

3. Head differences between the Gordon aquifer and the overlying Upper Three Runs aquifer are variable. These differences may be due to the variable thickness and the discontinuous nature of the Gordon aquitard.
4. Pumping tests in the Gordon aquifer indicate a low storage coefficient typical of confined aquifers.

The Gordon aquitard, which separates the overlying Upper Three Runs aquifer from the Gordon aquifer has historically been treated as a single horizontally continuous clay bed. Recent studies have revealed that actually consists of several lenses of clay that thicken, thin, and pinch out abruptly (WSRC, 1993a). Locally, beds of calcareous mud add to the thickness of the unit. Minor interbeds of sand are also present. Clay and sandy clay lenses range in thickness from 2 to 12 feet and average 5.3 feet beneath F-Area.

Head differences across the Gordon aquitard in F-Area range from 39.39 to 58.47 feet and average 52.98 feet. Head differences of this magnitude are evidence of the continuity of the clay under the F-Area. Clayey sand beds range in thickness from 3 to 11 feet, and the sand beds range in thickness from 1 foot to 6 feet. The formation has a southern dip with localized lows at the H-area. These lows tend to correspond with the thickest accumulation of the overlying carbonates. Laboratory analyses to determine physical characteristics, including horizontal and vertical hydraulic conductivity, were performed on undisturbed samples of the clayey portions of the Gordon aquitard (WSRC, 1991a, 1991b, 1992).

Vertical hydraulic conductivity estimates from 11 samples taken from the GSA ranged from  $1.13 \times 10^{-6}$  to  $3.40 \times 10^{-3}$  ft/day. Horizontal hydraulic conductivity estimates from 10 samples ranged from  $5.39 \times 10^{-6}$  to  $5.67 \times 10^{-3}$  ft/day. Vertical hydraulic conductivity estimated from ground-water modeling data (WSRC, 1992) was  $1.79 \times 10^{-4}$  ft/day.

Wells used to measure heads were located in the same stratigraphic units as the P-28 Cluster wells, but were not necessarily at the same elevations, due to dip, etc. There is a ridge of maximum head difference across the GSA trending in an east-west direction. The distinct decrease in head values in H-area coincides with the presence of calcareous sediments in the Gordon aquitard, suggesting that these sediments may be more permeable than the surrounding siliclastic clays.

The Upper Three Runs aquifer is divided into two aquifer zones: the Barnwell-McBean aquifer and the surficial aquifer, separated by the Tan Clay aquitard. The Barnwell-McBean aquifer consists of the strata below the Tan Clay aquitard and above the Gordon aquitard. The zone is poorly confined and receives recharge by downward flow from the surficial aquifer. The Barnwell-McBean aquifer consists predominantly of sand and clayey sand beds with locally abundant calcareous sediments.

Thicknesses of this aquifer range from 39 feet to 69 feet and average 56.3 feet at F-Area. Ground-water flow is to the south-southeast. Minor interbeds of clay and sandy clay are also present. The sand and clayey sand beds are generally yellow to tan, but occasionally greenish brown to light brown. The sand is fine to coarse grained, moderately to well sorted and generally subangular.

Numerous faults affect the Barnwell-McBean aquifer. Offsets of sediments range from 3 to 20 feet. They do not correspond directly to the thickness of the entire zone, but appear related to the thickness of the underlying calcareous sediments. The calcareous sediments vary widely in thickness from 1 foot to 42 feet. The thickest carbonate sediments are adjacent to the MWMF. Variations in thickness of these sediments may be due in part, or wholly, to post-depositional carbonate dissolution.

Sieve analyses were conducted on 10 sediment samples of the Barnwell-McBean aquifer in the F-Area using the method of Beard and Weyl (1973). Hydraulic conductivities ranged from 48.6 to 243.3 ft/day with an average of 113.6 ft/day. These hydraulic conductivities are high when compared to estimates based on field tests. Hydraulic

conductivities obtained from representative slug tests ranged from 0.14 to 5.27 ft/day and averaged 1.74 ft/day.

Values derived from the slug tests provide information to calculate transmissivity and flow velocity of the ground water in the Barnwell-McBean aquifer. A ground-water flow model for the entire GSA yielded a calculated hydraulic conductivity of 4.25 ft/day for the Barnwell-McBean aquifer. This value was determined as part of the calibration of the ground-water flow model for the GSA (WSRC, 1992).

The vertical component of flow in this aquifer is downward across the Gordon aquitard into the Gordon aquifer. The Gordon aquitard is considered to be more competent than the Tan Clay aquitard, but there is evidence of leakage and fault offset. Head differences between the surficial aquifer and the Barnwell-McBean aquifer suggest there is communication through the Tan Clay aquitard. The Tan Clay aquitard separates the surficial aquifer from the Barnwell-McBean aquifer. It consists of multiple lenses of clays and sandy clays that thicken, thin, and pinch out abruptly. Dip is southward from a high located beneath the HW/MWMF. A linear depression is associated with possible faulting in the vicinity of the F-area HWMF. There are also localized depressions beneath the BGC and H-area HWMF. The zone thickness is from 0 to 26 feet and averages 11.5 feet thick in F-area.

Two faults near the F-area HWMF result in downward displacement beneath that facility. Three faults are beneath the H-area HWMF and two of them appear to converge and offset the sediments beneath the facility. Six faults are present in the BGC. These features offset the sediments from 3 to 20 feet in the Tan Clay aquitard. Vertical hydraulic conductivity in the GSA is from  $3.4 \times 10^{-6}$  ft/day to  $1.2 \times 10^{-1}$  ft/day, obtained from laboratory tests (WSRC 1991a, 1991b, 1992; Bledsoe et al., 1990). Horizontal hydraulic conductivities, obtained from these tests, ranged from  $1.7 \times 10^{-6}$  to  $1.5 \times 10^{-1}$  ft/day. Modeling data (WSRC, 1992a) estimated vertical hydraulic conductivity to be  $3.89 \times 10^{-3}$  ft/day throughout the GSA.

Vertical hydraulic conductivity in F-area ranges from  $1.86 \times 10^{-5}$  to  $1.15 \times 10^{-4}$  ft/day and averages  $6.88 \times 10^{-5}$  ft/day (Bledsoe et al., 1990). These values indicate a low conductivity zone, suggesting that this zone impedes the downward flow of ground water on a local basis (where it is present and has sufficient thickness). Samples for the test described above were selected from ideal sections of the confining zone containing clays with a very limited sand fraction.

Sections of the confining zone containing sandy clays and some clayey sands would significantly increase the measured hydraulic conductivity of the unit. Head differences across the confining zone are relatively small, indicating extensive vertical flow component across the zone. There is an area of very low head difference southeast of the H-area Seepage Basins where the Tan Clay aquitard is absent. Faults in the Tan Clay may act as preferential vertical flow pathways.

The surficial aquifer includes the vadose and saturated zones above the Tan Clay aquitard. The aquifer varies in thickness from approximately 0 to 127 feet across the site. Beneath F-area this zone varies from 10.6 feet to 46.8 feet thick. The depth to the watertable from the land surface varies from approximately 4 to 80 feet in the GSA. The surficial aquifer consists predominantly of variegated sands and clayey sand with interbedded clay and sandy clay. Sands are fine to very coarse grained, subangular to angular, and moderately to poorly sorted. Gravel and pebble layers occur locally.

The saturated thickness of the surficial aquifer decreases over localized highs and increases over lows in the Tan Clay aquitard. The saturated thickness of the aquifer also decreased adjacent to stream valleys and towards the north as the Tan Clay aquitard elevation increases. Along the northern boundary of the MWMF, the watertable abuts the Tan Clay aquitard and the thickness of the aquifer zone decreases to zero. The zone has a general downward potential into lower units.

A poorly defined ground-water divide occurs at the westerly trending topographic high crossing the MWMF. Ground water to the north of the divide flows toward Upper Three

Runs Creek. To the south of the divide, ground water flows south toward Fourmile Branch and discharges at a seepage line creating a wetlands area. The wetlands discharge directly into Fourmile Branch. Watertable elevations in the GSA range from approximately 190 feet above msl to 240 feet above msl.

Natural recharge to the watertable is from percolation of precipitation. The steepest hydraulic gradients in the watertable are observed between H-area HWMF and Fourmile Branch. The vertical component for the flow of water in the watertable is downward across the Tan Clay aquitard into the Barnwell-McBean aquifer. The degree of leakage across the Tan Clay aquitard is variable and depends on the hydraulic gradient across the zone, vertical hydraulic conductivity, effective porosity, and the local competency of the confining zone.

Offset from faulting breaches the confining unit at the F- and H-areas and the BGC, providing potential pathways for vertical migration of water chemical constituents. Hydraulic conductivity estimates for this aquifer zone are based on slug test, sieve analyses, and pumping tests. Approximately 38 single-well pumping tests have been performed in the vicinity of the GSA. Hydraulic conductivity values calculated from these tests range from 0.30 ft/day to 3.6 ft/day, with a median value of 0.61 ft/day. A more recent series of tests produced values from 0.42 ft/day to 23.50 ft/day and average 3.73 ft/day.

Modeling data (WSRC, 1992) estimated hydraulic conductivity in the surficial aquifer to be 3.40 ft/day beneath the GSA. Sieve tests performed on 16 sediment samples from the Surficial aquifer in F-Area produced hydraulic conductivity estimates from 26.0 to 479.0 ft/day with an average of 162.3 ft/day. The sieve tests were considered not to be representative of the true aquifer properties. Single-well pump tests at the BGC in the vicinity of F-Area yielded hydraulic conductivity estimates for the surficial aquifer ranging from 0.18 ft/day to 40.42 ft/day and averaged 1.22 ft/day (WSRC, 1991a). The average linear velocity of ground water within the surficial aquifer can be estimated using Darcy's

law and the effective porosity of the aquifer. Using a hydraulic gradient of 0.0047, average horizontal hydraulic conductivity of 1.22 ft/day, and an effective porosity of 0.20, the linear ground-water velocity in the surficial aquifer is estimated to be 0.028 ft/day or 10.46 ft/yr.

## CHAPTER 3

### MATERIALS AND METHODS

#### 3.1 Field Equipment

Data were gathered using fixed and portable field stations that monitored water levels, barometric pressure, air temperature, and precipitation. Data collection was undertaken to assure over sampling for future comparison between short-term and long-term water level fluctuation behavior. Difficulties associated with collecting water level data include occasional lightning strikes that disable both sensors and dataloggers, below-freezing temperatures which cause precipitation monitoring equipment to fail, falling water levels that cause pressure transducers to rise above the water surface, and gaps in recorded water levels due to data storage limits and power supply problems.

Once all peripheral sensing devices were installed and connected to the datalogger, and the datalogger was connected to the power supply, then the system was ready and the datalogger program was downloaded to the datalogger via the use of a serial port of a laptop computer.

##### 3.1.1 Instrument Shelter

A shelter was constructed of  $\frac{1}{2}$  inch (sides and top) and  $\frac{3}{4}$  inch (bottom) nominal thickness, external grade plywood (Figure 3.1). The shelter provided housing for the datalogger, power supply, barometric pressure sensor, plastic enclosure and desiccant. At each well cluster used for this study, there was a series of steel well protection posts  $4\frac{1}{2}$  inch outside diameter surrounding the cluster to protect the wells from vehicle damage. The shelter was placed on top of one of the well protection posts and was

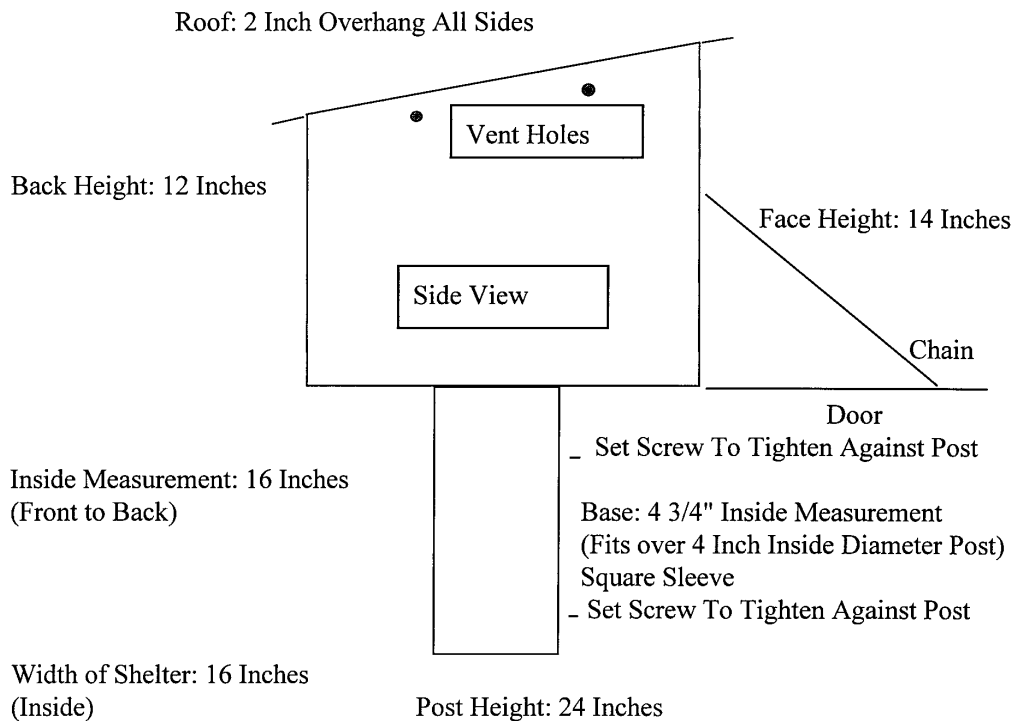


Figure 3.1: Instrument shelter detail.

fastened to the post via a system of two sets of opposable bolts through the base sleeve that fitted around the post.

### **3.1.2 Water Levels**

Pressure transducers monitor target aquifer zones in well clusters for the purpose of comparing water level variations in wells screened within watertable, semi-confined, and confined aquifer systems. Water levels are collected at a rate of once per second, averaged every ten minutes, and stored in dataloggers for periodic retrieval using a portable computer. The well water levels were obtained using Druck (Druck Inc., New Fairfield CT) PDCR 830 series, gage-type pressure transducers ( $\pm 1\%$  linearity and hysteresis). One pressure transducer was used per well water level being monitored and the well clusters varied from two to three wells being monitored for water fluctuations. Fourteen of these pressure transducers operated in the 0-5 pound per square inch (psi) range which equates to 11.5 feet of water, while one pressure transducer operated in the 0-50 psi range.

Depth to water readings were occasionally taken using a Powers Well Sounder (Powers Electric Product Co., Inc., Fresno CA), marked each five feet. Distances between the five foot markings were obtained using a standard metal tape measure, graduated in sixteenths of an inch. Measurements of distance to water were made from the top of the standpipe of each well utilized for this study.

A pressure transducer was placed approximately 3-10 feet below the water surface. A rubber stopper with a hole through the center and split from the hole to one side of the stopper was attached around the pressure transducer cable at the top of the standpipe. A standard hose clamp was attached around the stopper and tightened. This ensured that the pressure transducer inside the well was returned to the same depth each time data were collected or maintenance performed at the site and the pressure transducer was moved.

### **3.1.3 Barometric Pressure**

Barometric pressure was monitored at the same rate as water levels and stored on the datalogger. Data from monitoring well clusters have been collected and analyzed from summer 1994 to the present. Two Vaisala (Vaisala, Inc., Boston MA) PTB100A analog barometers (range 800 - 1060 hPa,  $\pm 0.3$  hPa accuracy) were used to record the barometric pressure at two sites on the SRS. One barometric pressure sensor was located at the FSB120 well cluster and the other was located at the FAC1 equipment site (in the vicinity of FAC3P). The barometric pressure sensor was mounted on the inside wall of the shelter. The sensor was attached to the appropriate port on the datalogger.

### **3.1.4 Precipitation**

Rainfall intensity was concurrently measured using tipping bucket raingages, and recorded by the datalogger. Rainfall depths were measured using standard raingages. A Rainwise (RainWise, Inc. Bar Harbor, ME) tipping bucket electronic recording raingage capable of measuring to 0.01 inches was mounted at each equipment site. A Tru-Chek (Tru-Chek, Inc., Albert Lee, MN) direct-reading raingage was also mounted at each equipment site as a physical check to ensure the automatic raingage was operating. Readings were made in inches to the nearest 0.01 inch.

Because the tipping bucket raingage automatically recorded in increments of 0.01 inches, the side of the direct-reading raingage graduated in inches was used for this project. The raingages were mounted on opposing sides of the shelter on wood brackets approximately one inch thick by four inches wide of enough length to make the tops of the raingages approximately 24 inches above the roof of the shelter. This height was needed to get the top of the gages above the splash zone. The wire from the tipping bucket raingage was attached to the wood bracket and entered the shelter through a small hole drilled through the side of the shelter just below the roof.

### **3.1.5 Datalogger**

All peripheral devices were wired into Campbell Scientific CR-10 Measurement and Control Modules (Figure 3.2) for data storage (Campbell Scientific, Inc., Logan, UT). Power for the peripherals and dataloggers was provided by a 12-volt automotive or marine type battery, with supplementary power provided by a Solarex Mega MSX-10 photovoltaic module (BP Solarex, Inc., Linthicum, MD). Datalogger internal temperature measurements were recorded at each site. The shelter alone did not provide adequate environmental protection for the datalogger nor the pressure transducer cable ends which included the barometric pressure vent tube.

A 2.2 gallon Rubbermaid container (Rubbermaid Home Products, Inc., Wooster OH) was placed inside the shelter and the datalogger was set inside that along with a cotton bag filled with approximately ½ pound of desiccant. A 6-gage solid copper grounding wire was attached to the datalogger through the plastic enclosure, continuing through the bottom of the shelter and attaching to the grounding rod imbedded in one of the concrete well pads that were present at each site. Sensor wires were inserted through the side of the plastic container using holes drilled just large enough for the cable or wire. Holes in the plastic container were as small as possible to reduce the amount of moisture that would contact the datalogger.

The programs used in the dataloggers located at each site were written using the PC208 software package developed by Campbell Scientific (Campbell Scientific, Inc., Logan, UT) for use with their CR-10 dataloggers. The steps described below relate to a representative datalogger program (shown in Table 3.1) that was used in the collection of data for this project that encompasses all the peripheral sensors used in the course of this study. Each program starts with the designation of the Mode. In this study, the Mode used was always Mode 1. This designates that the data acquisition and processing functions will be in Program Table 1. The data acquisition and processing functions constitute the program that controls the data being collected by the peripherals and

Table 3.1: Campbell Scientific CR-10 Datalogger Program

<i>Step</i>	<i>Command</i>	<i>Purpose</i>	<i>Step</i>	<i>Command</i>	<i>Purpose</i>
1	P10	Battery Voltage	8	P71	Average
	1	Memory Location		1	Repetitions
2	P17	Internal Temperature		2	Start Location
	2	Memory Location	9	P71	Average
3	P3	Tipping Bucket		2	Repetitions
	1	One Sensor		4	Start Location
	1		10	P72	Totalize
	2			1	Repetition
	3	Memory Location		3	Start Location
	1	Multiplier	11	P92	If Time
	0	Offset		0	Time into interval
4	P6	Water Levels		1,440	Interval
	2	Two sensors		10	Set out flag high
	23	Medium Range - 60 Hz Re- ject	12	P77	Record Time
	1	Ex location		100	Day
	1	In location	13	P74	Minimum
	2,500	Ex voltage		1	Repetitions
	4	Memory Location		0	Time
	1	Multiplier		1	Location
	0	Offset	14	P72	Totalize
5	P92	If Time		1	Repetitions
	0	Time into interval		3	Location
	10	Interval			
	10	Set Output Flag			
6	P77	Record Time			
	10	Hour and Minute			
7	78	Set Resolution			
	1	High			

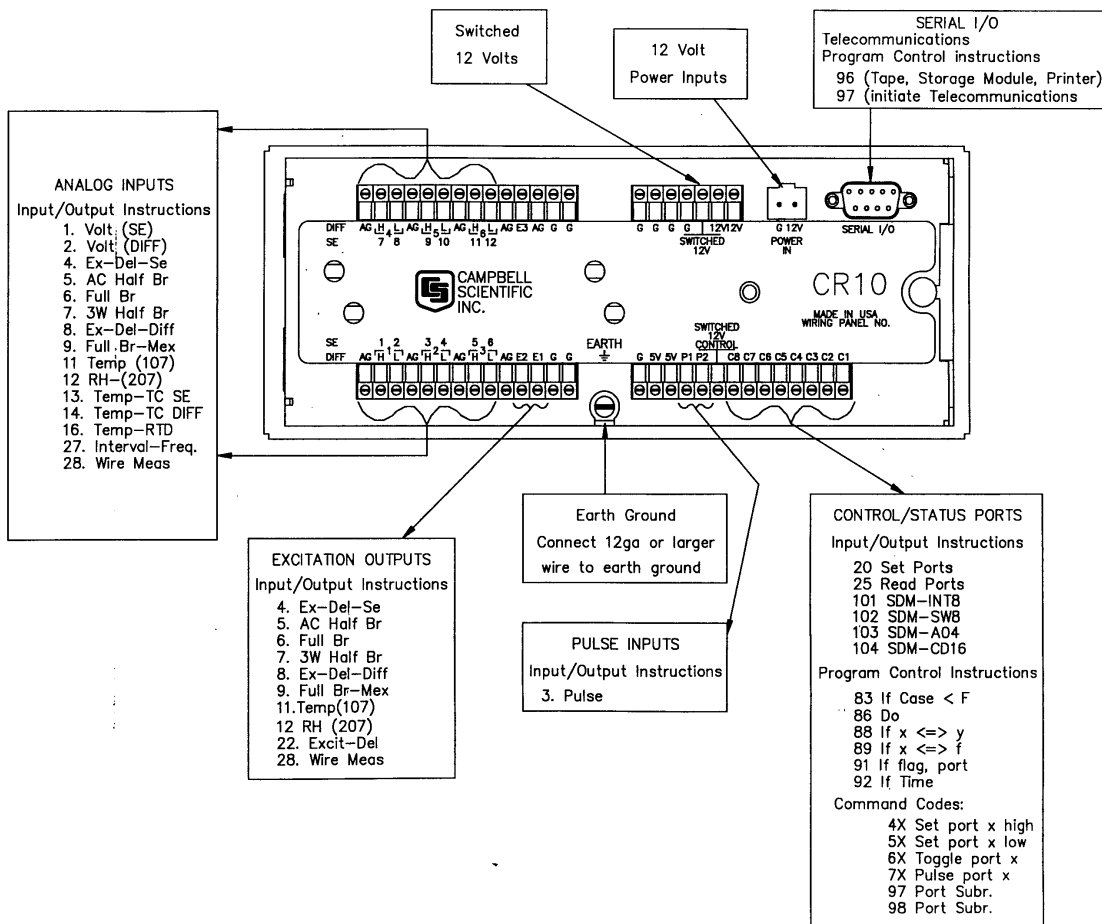


Figure 3.2: Campbell Scientific CR-10 datalogger.

stored by the datalogger. The program steps, or instructions, are controlled by the user. Following the Mode, is the Scan Rate. A short Scan Rate of one second was chosen because it was not known at the beginning of the study exactly what quantity of data would be needed. One of the proposed outcomes of this study was to determine optimal data acquisition sampling rates.

The Program Instructions begin with Program Instruction one. At all sites used for this study, Program Instruction one was "P10". This monitored the power supply voltage. This command made it relatively easy to guard against losing data due to low supply voltage. Because the voltage drain was relatively slow, a replacement battery could be charged and the low battery replaced when the voltage of the battery used as a power supply would get too low. Twelve volts was the point used as the indicating voltage level required before exchanging power supplies.

The second Program Instruction in each program developed was "P17" which monitored datalogger internal temperature.

The third Program Instruction was always "P3". The P3 command is used to count pulses. In this case the pulse being counted was the tipping bucket raingage. Each time the tipping bucket raingage collects .01 inches of precipitation, the small internal "bucket" tips, dumping the water and causing a switch closure, thereby registering as one count in the datalogger data file.

The fourth Program Instruction varied according to the peripherals attached to the datalogger at each site. In this case, the fourth Program Instruction was "P2" which measures single-ended voltage differential. Barometric pressure sensors were controlled using this command.

The next command in this program was "P6" which measured "full bridge" voltage differential. This command was used to monitor a multiple of pressure transducers. In this case, two pressure transducers were controlled with this one command. The first

instruction within the command controls the number of “repetitions” or devices that will be wired to the datalogger. The resulting readings are in millivolts.

The Program Instructions mentioned to this point control the peripheral devices wired to the datalogger or are a portion of the datalogger itself. The following commands control the timing, data handling instructions and Final Storage information. A “P92” command, or a Program control Instruction is next which sets the time interval for the commands that follow it. In this case the time interval was set at ten minutes. This meant that each ten minutes, some information would be written to Final Storage. The command instructions following the P92 command that direct exactly which data are averaged, totaled, minimized, etc.

To know exactly what time of day the data were being collected, a “P77” command was entered which, because of the P92 command, will log into Final Storage, the hour and minute. There are several options that can be used within the P77 command including seconds, day, and year but only hour and minute were chosen to be logged since the day is already scheduled to be logged into Final Storage once daily and to log in seconds would take up too much storage space.

The eighth Program Instruction, the “P78” command sets the resolution. The resolution was set to the high setting. This option takes more storage space than does the low resolution setting but because it was not known at the beginning of the project the exact data requirements, it was felt that setting the resolution high would be better than finding out at a later time that a higher resolution was needed.

Next, the internal temperature, originally collected at Program Instruction step two with the P17 command, was averaged over the ten minute time interval set with the P92 command. It was felt that an average for the 600 measurements taken during the ten minute time interval would be most useful than a minimum or maximum. Another P71 command was used to average the barometric pressure measurements taken over the same ten minute time interval. However, where precipitation is involved, it was desired

to know the total precipitation that had fallen in the previous ten minutes so a "P72" command was used.

The datalogger processed the Final Storage sequence each ten minutes. In addition to the information logged into Final Storage each ten minutes, some information was desired to be logged daily. Program Instruction twelve was a P92 command to set the time interval to 1440 minutes, or once daily. The P77 command following that sets the program to write out the day. Julian dates were used which assigns January 1 as day one and the last day of December as day 365 in a non-leap year.

The only information that was desired to be logged into Final Storage on a daily basis was minimum battery voltage and the total precipitation that fell the previous day, which was accomplished by using the P74 and P72 commands, respectively. This completes the data being put into Final Storage. Of the seven sites set up during this project, there were some variations to the program described above but the program above does have all the peripherals used during this project and all the program steps involved in Final Storage.

### **3.2 Analysis Techniques**

The central problem of system analysis is the determination of the response of a system to a specified input. There are a number of ways that such a determination can be completed. Solution of the differential equations that characterize the system is one way, use of integral transformations, and analysis based on the response to given input and the principle of superposition. The principle of superposition applies only to systems that are linear. Convolution and deconvolution are based on the principle of superposition and are used in the analysis of the data for this study. Additional methods of analysis used to examine the data include cross-correlation and Fast Fourier Transform (FFT).

Through the use of these analyses, it is hoped to identify unit input, unit response, periodicity of fluctuations, and what correlation, if any, the individual processes have with each other. These analyses will be used to predict responses of varying levels of inputs. Adding the knowledge of cyclic fluctuations obtained through use of the FFT, will give us the capability to better predict gradient and with that knowledge, better predictions of contaminant travel times and path can be made. These analyses will be used for the surficial aquifer and confined aquifers of varying depths to determine responses with changing subsurface conditions.

Collected data are examined using a variety of tools. Table 3.2 summarizes the types of anticipated effects and the measurement tools required. Because barometric pressure varies continuously, a spectral analysis is performed to identify the relative magnitude of the barometric pressure variability as a function of period. Rainfall, on the other hand, is an episodic, discontinuous process, alternating between long periods of dry weather with brief periods of high and low intensity precipitation. The relationship between environmental factors and water levels in wells is reflected in their different behaviors. A cross-spectral analysis is appropriate for the continuous behavior of barometric pressure, while deconvolution is more appropriate for the discontinuous (i.e., episodic) behavior of precipitation. Auto- and cross-correlation analysis are also appropriate for investigating transient effects of perturbations of finite duration.

### **3.2.1 Cross-Correlation Analysis**

Cross-correlation is used to determine the correlation between variables. In the case of this study those processes may be precipitation, barometric pressure changes, well water level changes or precipitation, or any combination of processes being monitored. The processes being analyzed may seem to be related or may not appear to be related, that is unimportant before the analysis is made. The covariance and cross-correlation

Table 3.2: Effects of Environmental Conditions on Water Level Fluctuations

<i>Environmental Stress</i>	<i>Type of Effect</i>	<i>Magnitude</i>	<i>Method of Analysis</i>
Barometric Pressure	Continuous	Large	Spectral Analysis
Precipitation	Discontinuous	Locally Large	Deconvolution
Topographic Variation	Continuous	Locally Large	Cross-Correlation
Fluid Specific Weight	Continuous	Locally Moderate	Unknown
Geologic Media	Mixed	Locally Large	Cross-Correlation
Confinement	Mixed	Unknown	Cross-Correlation

measure the degree of dependence between variables. The cross-covariance matrix,  $C$ , is the covariance between multiple observation vectors. For two vectors, this is:

$$C_{xy} = \sum_{i=1}^n \frac{(x_i - \bar{x})(y_i - \bar{y})}{n - 1} \quad (3.1)$$

where  $n$  is the number of observations, and the mean is estimated using:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (3.2)$$

The correlation matrix,  $R$ , can be estimated between individual vectors using:

$$R_{xy} = \frac{C_{xy}}{\sqrt{V_x V_y}} \quad (3.3)$$

where the variance,  $V$ , is estimated using:

$$V_x = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2 \quad (3.4)$$

### **3.2.2 Convolution and Regression Deconvolution**

Convolution is used to relate an input parameter, e.g. precipitation, barometric pressure, to an output. The purpose of using convolution is to determine the response function given a known input and if a lagged response is expected. Using this knowledge, then the impulse function can be used to obtain the response of the system to any input signal. This, of course, assumes the system is linear and will react accordingly to varying inputs. Deconvolution uses the measured response, e.g. ground-water levels in monitored wells, to determine what the input was in order to produce that response.

Convolution can be represented by:

$$y_i = \sum_{j=0}^m x_{i-j} u_j \quad (3.5)$$

where  $u_j$  is the impulse response function. This can also be written in terms of changes in the input,  $\Delta x$ , using:

$$y_i = \sum_{j=0}^{\infty} \Delta x_{i-j} U_j \quad (3.6)$$

where  $U_j$  is the step response function. Equation (3.5) uses observed input values,  $x$ , and a known impulse response function,  $u$ , to predict outputs. Equation (3.6) uses changes in observed input values,  $\Delta x$ , and a known step response function,  $U$ , to predict outputs.

The unknown response function can be estimated using deconvolution. Given the observed inputs,  $X$ , and outputs,  $Y$ , the regression convolution equation (in matrix notation) is:

$$Y = u X \quad (3.7)$$

Because  $u$  is the desired output, we post-multiply each side by the transpose of  $X$  which yields:

$$Y X^T = u X X^T \quad (3.8)$$

The unknown response function is estimated by post-multiplying both sides by the inverse of  $(X X^T)$ :

$$u = (Y X^T) (X X^T)^{-1} \quad (3.9)$$

### **3.2.3 Fourier Transform**

Fourier analysis is closely related to some aspects of spectral analysis, where the objective of the analysis is to discover the frequencies and amplitudes of the individual cycles that make up the periodic phenomenon. By using Fourier Analysis on the data presented here, it is hoped that periodic fluctuations in the barometric pressure measurements as Crawford (1994) saw, will be able to be identified and mapped into their individual components. This analysis will explain much of the variation in water levels observed in the monitored wells used for this study.

The fluctuations in the well water levels can be corrected easily for the fluctuations due to barometric pressure. Additionally, this data set represents approximately one year of data collection. As mentioned in Crawford (1994), this should allow for determination of some periodicities that she was unable to determine due to her data collection period of 39 days as compared to the data set in this study of one year.

Fourier transform of the impulse response function,  $u(t)$ , is given by:

$$F(h) = \int_{-\infty}^{\infty} u(t) \exp(-i\omega t) dt \quad (3.10)$$

The estimate of the unit response function can be found by noting that

$$F(h) = \frac{F(Y) F(X)}{F(X) \overline{F(x)}} \quad (3.11)$$

where  $F(Y)$  is the Fourier transform of  $Y$ , and  $\overline{F(x)}$  is the complex complement of  $F(x)$ .

### 3.3 Hydrologic Variables

Four variables are of most concern in this analysis; the barometric efficiency which relates the water level in a well to barometric pressure, the total head which determines the fluid potential at every point, the hydraulic gradient which determines the direction in which the total head changes, and the fluid trajectory which determines the magnitude and direction of fluid flow. These variables are described in the next four sections of this chapter.

#### 3.3.1 Barometric Efficiency

The barometric efficiency,  $\alpha$ , is a measure of how sensitive water levels in a well are to barometric pressure. For short-term changes in barometric pressure, we can define a short-term barometric efficiency,  $\alpha_s$ , using:

$$\alpha_s = - \frac{\Delta w}{\Delta b} \quad (3.12)$$

where  $\Delta w$  is the change in water levels in an open well, and  $\Delta b$  is the change in barometric pressure. A regression relationship between  $\Delta w$  and  $\Delta b$  is used to estimate the barometric efficiency:

$$\Delta w = \alpha_s (-\Delta b) \quad (3.13)$$

Clark's method can also be employed (see, e.g., Davis and Rasmussen, 1993; Rasmussen and Crawford, 1997a, 1997b). Alternatively, the barometric efficiency can also be found using long-term changes in barometric pressure:

$$\alpha_L = - \frac{(w - \bar{w})}{(b - \bar{b})} \quad (3.14)$$

The equivalent regression equation is:

$$w = \bar{w} - \alpha_L (b - \bar{b}) \quad (3.15)$$

The tidal, or loading, efficiency,  $\beta$ , is related to the barometric efficiency by:

$$(\alpha + \beta) = 1 \quad (3.16)$$

The tidal efficiency accounts for changes in total head within a hydrostratigraphic unit due to a disturbance.

### **3.3.2 Total Head**

The total head,  $h$ , is the sum of the water level,  $w$ , plus the pressure head at the surface of the watertable within the formation,  $b$ , or:

$$h = w + b \quad (3.17)$$

We use this relationship to understand how barometric pressure changes affect water levels. The change in total head with changes in water level and barometric pressure is:

$$\Delta h = \Delta [w + b] = \Delta w + \Delta b \quad (3.18)$$

Substituting the barometric efficiency,  $\alpha_S = -\Delta w/\Delta b$ , we have:

$$\Delta h = -\alpha_S \Delta b + \Delta b = (1 - \alpha_S) \Delta b \quad (3.19)$$

We define the tidal efficiency,  $\beta$ , as one minus the barometric efficiency, so that:

$$\Delta h = \beta \Delta b \quad (3.20)$$

### 3.3.3 Hydraulic Gradient

The hydraulic gradient,  $G$ , is defined as:

$$G = \nabla h \quad (3.21)$$

where  $h$  is the total head:

$$h = \frac{p}{\gamma} + z \quad (3.22)$$

where  $p$  is the fluid pressure at the elevation of measurement,  $z$ , and  $\gamma$  is the fluid specific weight above the point of measurement. We assume a standard specific weight of water for these analyses of 2.307 feet per psi. The gradient operator,  $\nabla$ , applies only to scalar fields, and is defined as:

$$\nabla \cdot = \left[ \frac{\partial \cdot}{\partial x}, \frac{\partial \cdot}{\partial y}, \frac{\partial \cdot}{\partial z} \right] \quad (3.23)$$

The gradient can be written in vector notation using:

$$G = \left[ \frac{\partial h}{\partial x}, \frac{\partial h}{\partial y}, \frac{\partial h}{\partial z} \right] = [G_x, G_y, G_z] \quad (3.24)$$

where  $G_x = \partial h / \partial x$ , etc. The magnitude of the gradient is:

$$|G| = \sqrt{G_x^2 + G_y^2 + G_z^2} \quad (3.25)$$

$G_z$  is the magnitude of the vertical component of the gradient,  $G_v$  is:

$$G_v = G_z \quad (3.26)$$

The magnitude of the horizontal component of the gradient,  $G_H$ , is:

$$G_H = \sqrt{G_x^2 + G_y^2} = \sqrt{|G|^2 - G_z^2} \quad (3.27)$$

### **3.3.4 Fluid Trajectory**

Darcy's law relates the ground-water flow trajectory,  $q$ , to the hydraulic gradient,  $G$ , using:

$$q = K \cdot G \quad (3.28)$$

where  $K$  is the hydraulic conductivity tensor. The direction of fluid flow is generally not the same as the direction of the hydraulic gradient. The two are aligned only if the hydraulic conductivity is the same in all directions (i.e., isotropic).

## CHAPTER 4

### OBSERVED WATER LEVEL FLUCTUATIONS

Our objective is to evaluate the possible errors in determining the hydraulic gradient due to temporal variability in water levels. This is important because the magnitude and direction of subsurface fluid movement is controlled, at least in part, by the total head gradient. The total head gradient, or hydraulic gradient, is largely determined by recharge and discharge conditions and the geologic stratigraphy. The purpose of this chapter is to explore and explain the temporal variability of the hydraulic gradient. If an acceptable gradient calculation error can be quantified, then small errors introduced by water level measurements may, at a given facility, prove to be irrelevant to compliance strategies. The analysis must use comparison with local conditions of flow, local monitoring network configurations, and the resulting increased potential (if any) for a failure to detect contamination migration.

Data collected in the F-Area Seepage Basins (FSB) are presented in Figure 4.1. These data are used to first assess the magnitude of water level variability with the GSA. Table 4.1 summarizes average water level fluctuations in seven FSB wells (FSB-115C, FSB-115D, FSB-116C, FSB-116D, FSB-120A, FSB-120C, and FSB-120D), located in three well clusters (FSB-115, FSB-116, and FSB-120), spanning three aquifers (A = Congaree, C = Barnwell-McBean, D = surficial).

Note that the average magnitude of water level fluctuation increases with the delay between the sampling time; very little error is introduced if a water level is sampled within ten minutes (less than 0.01 foot), while larger errors of 0.149 to 0.308 feet are

Table 4.1: Average Water Level Variations (feet) in FSB Wells

<i>Interval</i>	<i>FSB Wells</i>						
	<i>115C</i>	<i>115D</i>	<i>116C</i>	<i>116D</i>	<i>120A</i>	<i>120C</i>	<i>120D</i>
10 minutes	0.002	0.001	0.002	0.006	0.004	0.005	0.003
30 minutes	0.006	0.002	0.003	0.010	0.005	0.007	0.007
1 hour	0.011	0.003	0.005	0.012	0.007	0.009	0.007
6 hours	0.048	0.013	0.020	0.033	0.022	0.024	0.052
12 hours	0.072	0.020	0.029	0.047	0.034	0.034	0.067
1 day	0.095	0.033	0.041	0.068	0.055	0.051	0.080
2 days	0.117	0.052	0.057	0.098	0.083	0.071	0.099
1 week	0.158	0.105	0.088	0.158	0.126	0.089	0.118
2 weeks	0.173	0.153	0.109	0.188	0.151	0.132	0.170
1 month	0.170	0.257	0.149	0.234	0.201	0.234	0.308

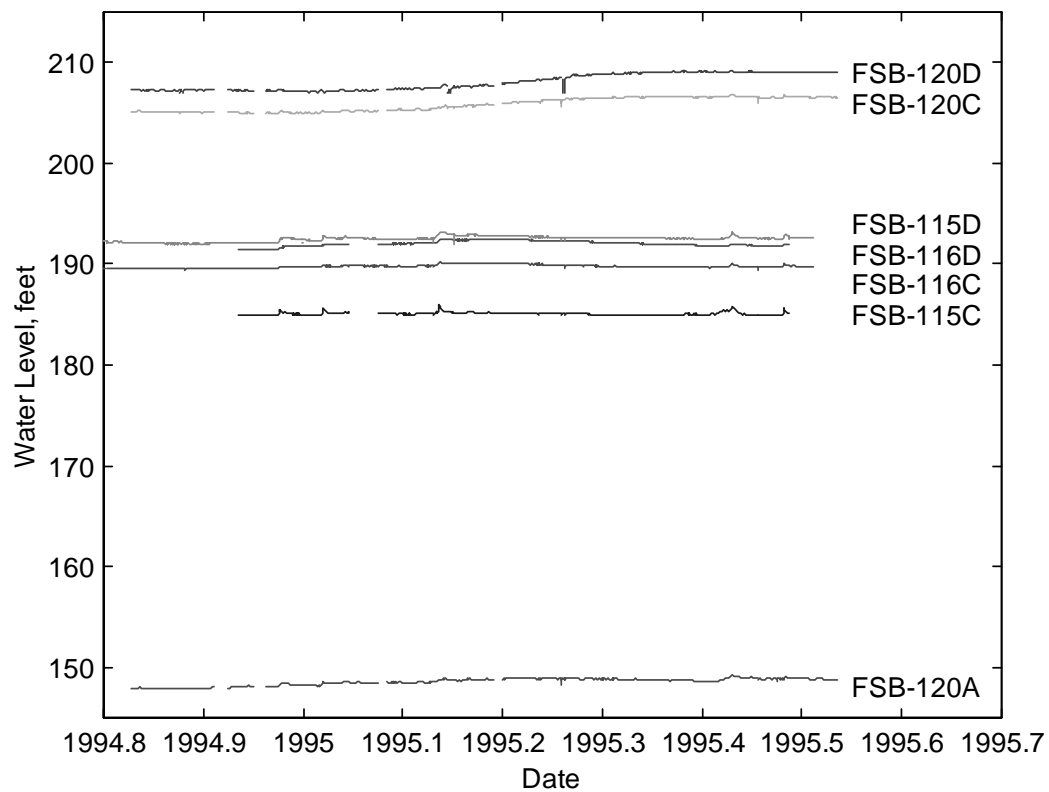


Figure 4.1 Water levels in FSB wells

observed when the same well is sampled at an interval of one-month. These errors are actually measurements of water levels that have changed over time. But if those measurements taken at different times are to be used to determine the water table or gradient without adjustment, then it is treated as an error.

Of greater interest is the variation in total head, which is the variable used to calculate the hydraulic gradient. Barometric pressure was monitored at the site and recorded. Variations of these measurements over time are treated as errors if they are to be used as representing synchronous measurements, as in the case of the required quarterly measurements at SRS. Table 4.2 summarizes average total head variation in the same wells presented in Table 4.1. Note that the mean error is still low for ten-minute sampling frequencies, while larger errors, 0.273 to 0.366 feet, are again observed at one-month sampling intervals. Average water level errors are greater than average total head errors.

Also of interest is the relative correlation between water levels in wells. Table 4.3 summarizes cross-correlations in water levels between the seven FSB wells. High correlations indicate similarity in long-term behavior. Note that FSB-115C is better correlated ( $r = .680$ ) with water levels in the same aquifer at a more distant well (FSB-116C) than it is ( $r = 0.387$ ) with a well in a different aquifer within the same well cluster (FSB-115D). This is not true, however, with FSB-120C which is poorly correlated ( $r = -0.068$  and  $0.034$ ) with water levels in the same aquifer (FSB-115C and FSB-116C) than with water levels ( $r = 0.827$  and  $0.981$ ) in different aquifers at the same well cluster (FSB-120A and FSB-120D).

The four wells monitored in the FAC area (FAC-3P, FAC-4P, FAC-6P, and FAC-9C) are presented in Figure 4.2. Water levels in these wells are all highly correlated with one another (Table 4.4). These piezometers are all less than 100 feet from each other and are screened in the surficial aquifer. The high correlation implies strong homogeneity of the subsurface at this scale. Well FAC-9C, which is physically located approximately five

Table 4.2: Average Total Head Variations (feet) in FSB Wells

<i>Interval</i>	<i>FSB Wells</i>						
	<i>115C</i>	<i>115D</i>	<i>116C</i>	<i>116D</i>	<i>120A</i>	<i>120C</i>	<i>120D</i>
10 minutes	0.005	0.004	0.005	0.007	0.006	0.007	0.005
30 minutes	0.012	0.010	0.011	0.014	0.011	0.012	0.010
1 hour	0.021	0.018	0.019	0.021	0.018	0.018	0.016
6 hours	0.087	0.073	0.075	0.075	0.065	0.062	0.063
12 hours	0.123	0.109	0.106	0.107	0.089	0.085	0.093
1 day	0.176	0.168	0.159	0.160	0.132	0.127	0.144
2 days	0.239	0.233	0.223	0.223	0.182	0.176	0.203
1 week	0.253	0.239	0.224	0.241	0.190	0.191	0.220
2 weeks	0.289	0.296	0.250	0.280	0.215	0.222	0.255
1 month	0.331	0.366	0.308	0.353	0.273	0.291	0.356

Table 4.3: Simple Correlation Coefficients (r) for FSB Water Levels

<i>FSB Wells</i>							
	<i>115C</i>	<i>115D</i>	<i>116C</i>	<i>116D</i>	<i>120A</i>	<i>120C</i>	<i>120D</i>
<i>115C</i>	1						
<i>115D</i>	0.367	1					
<i>116C</i>	0.680	0.885	1				
<i>116D</i>	0.674	0.814	0.900	1			
<i>120A</i>	0.283	0.634	0.536	0.737	1		
<i>120C</i>	-0.068	0.245	0.034	0.349	0.827	1	
<i>120D</i>	-0.163	0.078	-0.132	0.207	0.723	0.981	1

Table 4.4: Simple Correlation Coefficients (r) for FAC Water Levels

<i>FAC Wells</i>				
	<i>3P</i>	<i>4P</i>	<i>6P</i>	<i>9D</i>
<i>3P</i>	1			
<i>4P</i>	0.968	1		
<i>6P</i>	0.958	0.967	1	
<i>9C</i>	0.909	0.882	0.923	1

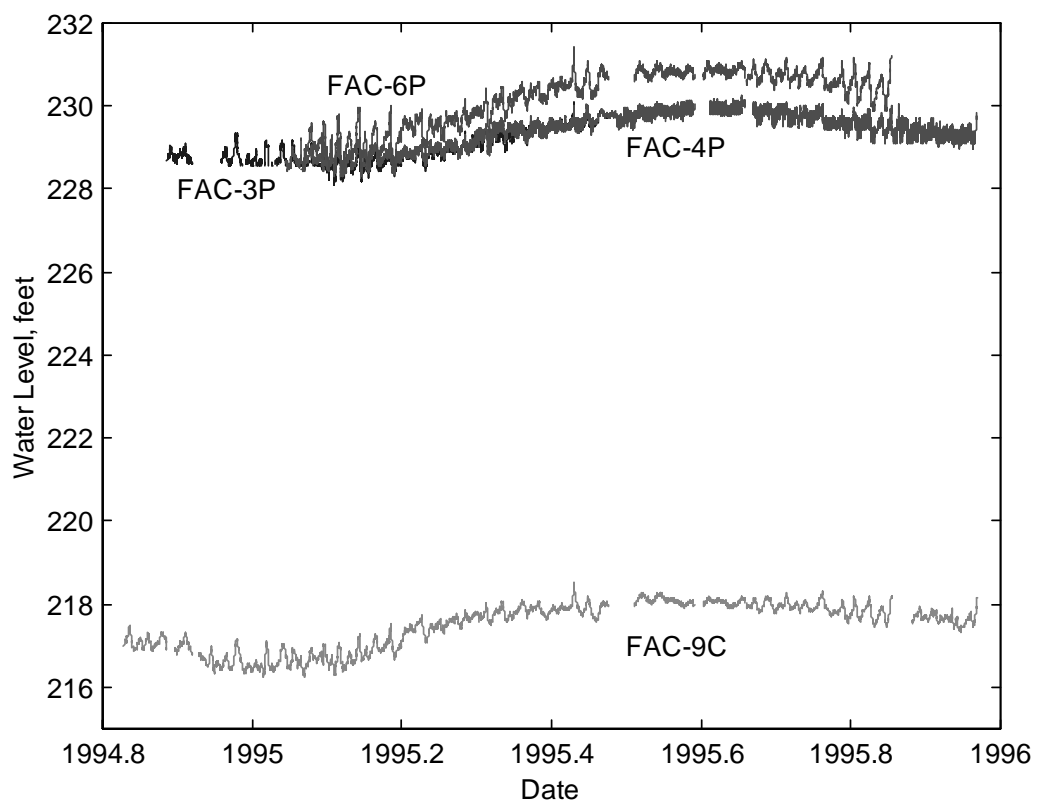


Figure 4.2 Water levels in FAC wells

feet from FAC-6P, is screened in the Barnwell-McBean aquifer but shows extremely high correlation with the wells screened in the surficial aquifer. There are several plausible explanations for the observed correlation. The well screen of FAC-9C could be in an improper level, or the bentonite seal around the well could have failed. If the seal had failed, water monitoring activities would reveal extremely high levels of calcium, which has not happened. If the screen was improperly placed above the clay separation layer, then FAC-9C and FAC-6P should have similar water levels, which is not the case. A review of the well level data shows consistent elevation differences of approximately 30 feet. The only plausible explanation is a leaky confining layer between the surficial and the Barnwell-McBean aquifers in the FAC area and a large vertical hydraulic gradient.

Another means of examining water level fluctuations is to perform a first-difference test which allows changes in water levels to be examined. Tables 4.5 and 4.6 summarize cross-correlations in differenced water levels for FSB and FAC well clusters, respectively. These correlations provide an indication of how small perturbations, or changes, are correlated, rather than long-term trends. Note that FSB-115C is now just as well correlated with FSB-115D ( $r = 0.328$ ) as with FSB-116C ( $r = 0.326$ ). This indicates that short-term influences affect these wells similarly. Correlations within the FAC area decline substantially, however, indicating that trend components dominate over short term fluctuations.

#### **4.1 Types of Water Level Fluctuations**

We now evaluate potential changes in environmental conditions on water levels. Environmental conditions change, thus inducing dynamic water level changes over time. For example, temperature changes every day, being warmer during the early afternoon and lower (normally) during the pre-dawn hours. This change in temperature can affect evapotranspiration rates, thus affecting water levels and recharge. Precipitation rates

Table 4.5: Simple Correlation Coefficients (r) for Differenced FSB Water Levels

<i>FSB Wells</i>							
	<i>115C</i>	<i>115D</i>	<i>116C</i>	<i>116D</i>	<i>120A</i>	<i>120C</i>	<i>120D</i>
<i>115C</i>	1						
<i>115D</i>	0.328	1					
<i>116C</i>	0.326	0.106	1				
<i>116D</i>	0.270	0.250	0.389	1			
<i>120A</i>	0.066	0.051	0.073	0.089	1		
<i>120C</i>	0.044	0.050	0.064	0.061	0.964	1	
<i>120D</i>	0.014	0.084	0.105	0.082	0.055	0.067	1

Table 4.6: Simple Correlation Coefficients (r) for FAC Differenced Water Levels

<i>FAC Wells</i>				
	<i>3P</i>	<i>4P</i>	<i>6P</i>	<i>9D</i>
<i>3P</i>	1			
<i>4P</i>	0.124	1		
<i>6P</i>	0.414	0.207	1	
<i>9C</i>	0.417	0.190	0.676	1

and amounts change with time as a storm moves through an area. Also, soil moisture changes seasonally, depending on both temperature and precipitation.

Stream discharges fluctuate in response to precipitation inputs. Streamflow can change immediately due to channel precipitation, as well as in response to overland flow and increased subsurface flow. The amount of precipitation, as well as its intensity and duration are critical elements. Barometric pressure changes with approaching frontal systems and can have a marked response in measured well water levels as shown in Crawford(1994) and Rasmussen and Crawford (1997a, 1997b). Identification of the time lag of measured well water fluctuations from when the precipitation is received, barometric pressure changes, or temperature fluctuates, is of particular interest to this study.

#### **4.1.1 Barometric Pressure**

The temporal variation in barometric pressure is presented as Figure 4.3. Note that over the course of a year that the amplitude is at least one foot of water level change. This temporal variability of barometric pressure is summarized in Table 4.7. Spatial fluctuations in barometric pressure are small, primarily due to elevation effects. The elevation effect results from the small change in barometric pressure with altitude, which does not change appreciably with time.

From Table 4.7 we note that mean and maximum differences in barometric pressure measurements increase with the time between measurements. Mean long term differences are on the order of 0.25 feet, and approach an extreme of one foot. Observed barometric pressure fluctuations of up to 0.432 feet over a six-hour period introduce the potential for significant variability of derived gradients.

The effect of barometric pressure can be most readily observed at FAC-9C. At this well, and the three other nearby wells (FAC-3C, FAC-4C, and FAC-6C), the barometric efficiency is approximately 80%. Figure 4.4 presents water level and total head for an

Table 4.7: Observed GSA Barometric Pressure Changes

<i>Time Difference</i>	<i>Variability (feet)</i>	
	<i>Average</i>	<i>Maximum</i>
10 minutes	0.004	0.087
30 minutes	0.011	0.132
1 hour	0.018	0.149
6 hour	0.073	0.437
12 hour	0.104	0.487
1 day	0.164	0.631
2 days	0.232	0.868
1 week	0.234	0.737
2 weeks	0.248	0.906
1 month	0.268	0.816

annual cycle. Note the large amount of short-term variability in water levels, while the total head is reasonably smooth.

Table 4.8 presents the barometric efficiencies for four FAC (FAC-3P, FAC-4P, FAC-6P, and FAC-9C) and seven FSB (FSB-115C, FSB-115D, FSB-116C, FSB-116D, FSB-120A, FSB-120C, and FSB-120D) wells. The FSB-115 and FSB-116 well clusters border the banks of the Fourmile Branch and observed low barometric efficiencies are consistent with shallow water levels. It is interesting to note that barometric efficiencies are also low in all wells at the FSB-120 cluster. The barometric efficiency in the surficial aquifer (FSB-120D) is low, indicating that the system is relatively open to barometric pressure changes. In addition, the barometric efficiency in the deeper, confined Gordon aquifer (FSB-120A) is low, indicative of poorly consolidated media.

Barometric efficiencies in the FAC wells are much higher, and some anomalously high readings greater than 100% are observed. It appears that a barometric efficiency of between 80 and 100% would be reasonable for the FAC area, which is consistent with a deep unsaturated zone.

#### **4.1.2 Riparian Effects**

Two well clusters, FSB-115 and FSB-116, were monitored within the riparian influence of Fourmile Branch. Water levels in these wells in both the surficial (D-wells) and Barnwell-McBean (C-wells) aquifers showed rapid responses to changes in stream stage. Figure 4.5 presents water level records for these wells. Note that perturbations generally rise rapidly to a maximum that is less than a foot above the previous level, recedes over time to a more stable, baseline condition.

#### **4.1.3 Seasonal Effects**

The FSB-120 well cluster is not in the proximity of any riparian zones, and is not immediately affected by stormflows. Water levels (shown in Figure 4.6) for the surficial

Table 4.8 Barometric Efficiencies, % ( $\pm 1$  standard error)

<i>Well</i>	<i>Barometric Efficiency</i>
FSB-115C	2.75 ( $\pm 0.30$ )
FSB-115D	13.4 ( $\pm 0.2$ )
FSB-116C	2.98 ( $\pm 0.24$ )
FSB-116D	19.4 ( $\pm 0.8$ )
FSB-120A	9.85 ( $\pm 0.44$ )
FSB-120C	12.6 ( $\pm 0.63$ )
FSB-120D	22.0 ( $\pm 0.4$ )
FAC-3P	108 ( $\pm 1$ )
FAC-4P	78.6 ( $\pm 2.6$ )
FAC-6P	127 ( $\pm 1$ )
FAC-9C	79.4 ( $\pm 0.2$ )

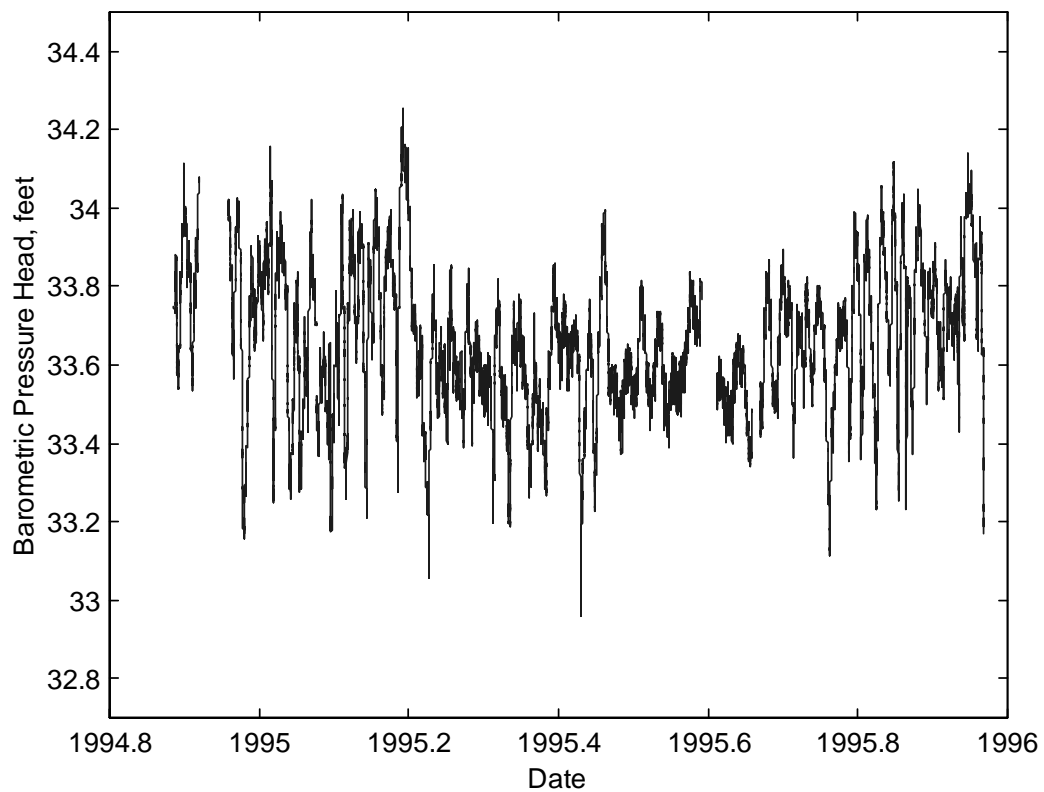


Figure 4.3: Barometric pressure at the FSB-120 well cluster.

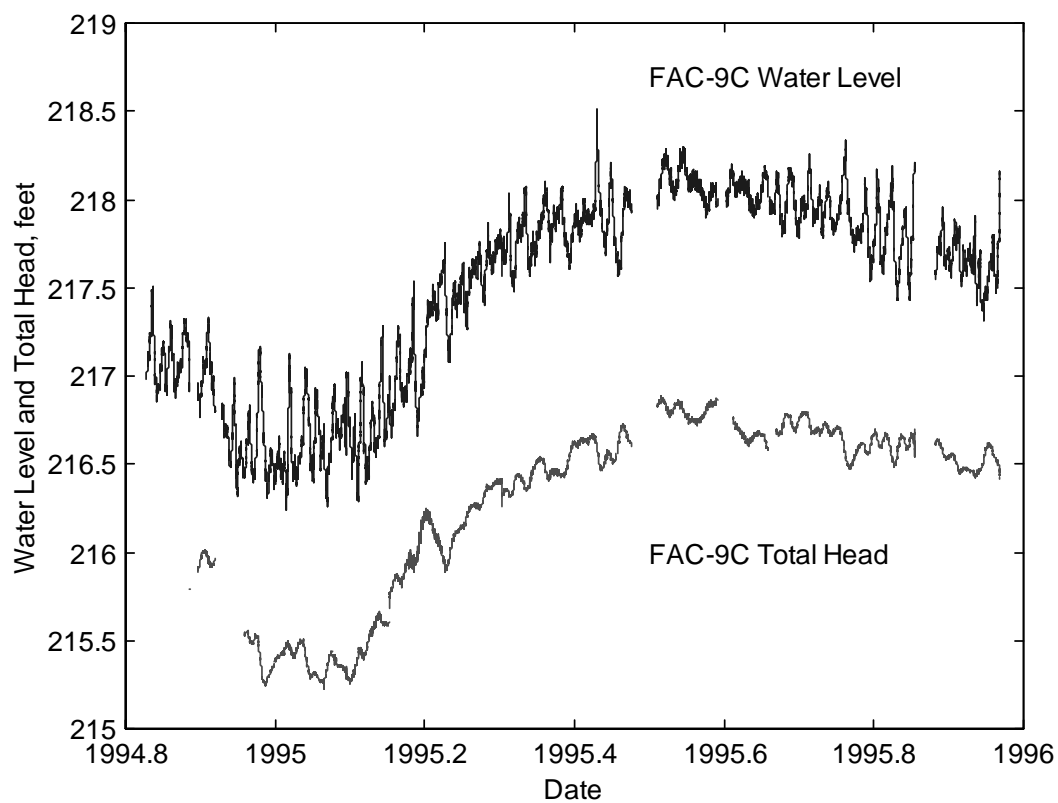


Figure 4.4: Water levels and total heads at well FAC-9C.

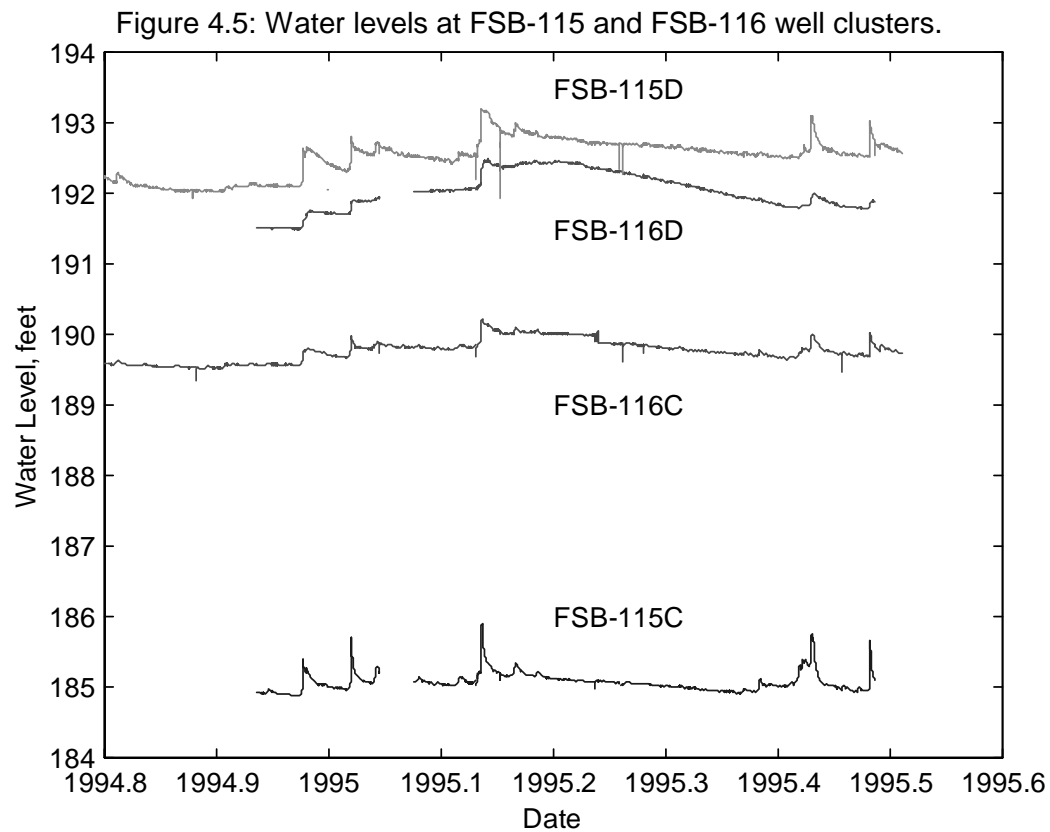


Figure 4.5: Water Levels in Wells FSB-115 and FSB-116 Well Clusters

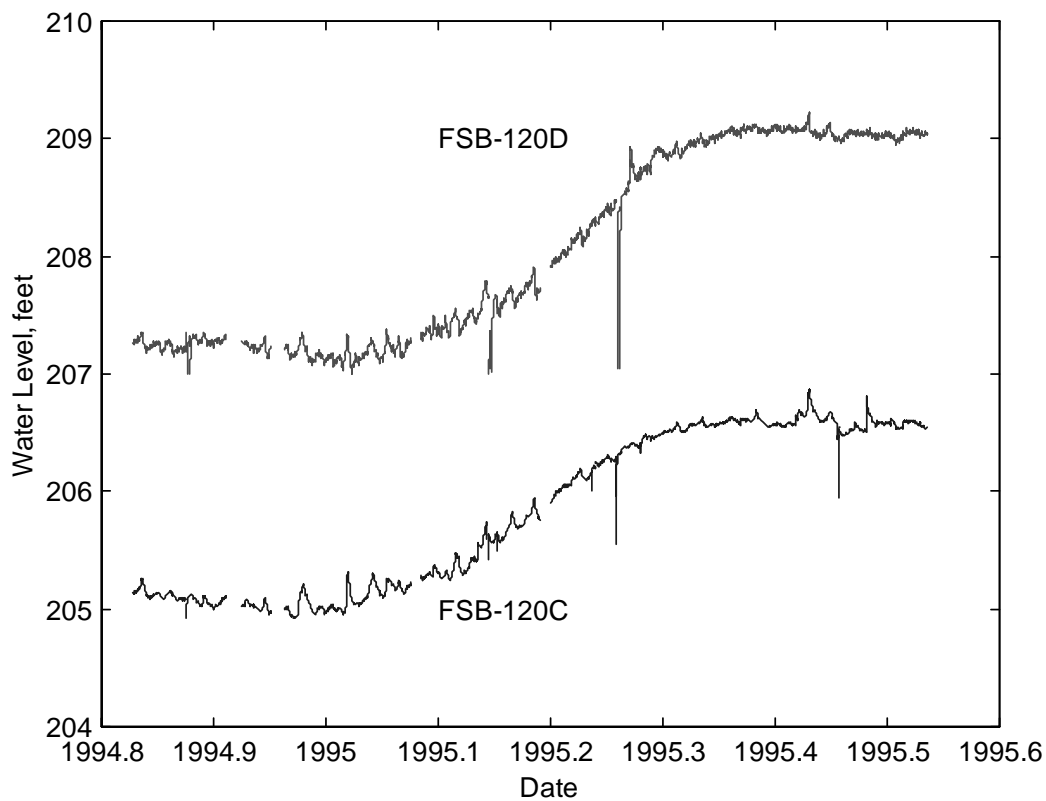


Figure 4.6: Water levels in wells FSB-120C and FSB-120D.

and Barnwell-McBean aquifers demonstrate a slow, seasonal response. This undoubtedly results from seasonal recharge through the unsaturated zone. Additional, less substantial responses are due to barometric effects. Occasional water quality sampling by SRS personnel at the wells also perturbs the water levels, causing declines of approximately one foot that recede within a day or so following the perturbation.

#### **4.1.4 Precipitation Effects**

An additional response only seen in the Congaree aquifer, which is confined above by the Green Clay aquitard, is an immediate response to precipitation. Figure 4.7 presents water levels and corresponding precipitation totals for FSB-120A for a ten-day period in 1995. Note that the water level rise is comparable to the precipitation accumulation on the surface. This response is consistent with a high tidal efficiency and a low barometric efficiency. Precipitation depth correlations were performed for different intervals. These are presented as Table 4.9. Note that ten-minute accumulations are small (<0.01 foot), but can become appreciable (approaching one foot) for monthly intervals.

#### **4.2 Gradient Response**

The gradient in potentiometric head, in conjunction with the aquifer hydraulic conductivity tensor, determine the magnitude and direction of the darcian flux. The darcian flux, in conjunction with aquifer porosity and solute properties determine the direction and magnitude of the solute velocity. Our goal in this section is to evaluate the error in calculated hydraulic gradient induced by dynamic water levels in observation wells at the Savannah River Site

Table 4.9: Observed GSA Precipitation Depths

<i>Time Difference</i>	<i>Variability (feet)</i>	
	<i>Average</i>	<i>Maximum</i>
10 minutes	0.004	0.087
30 minutes	0.011	0.132
1 hour	0.018	0.149
6 hour	0.073	0.437
12 hour	0.104	0.487
1 day	0.164	0.631
2 days	0.232	0.868
1 week	0.234	0.737
2 weeks	0.248	0.906
1 month	0.268	0.816

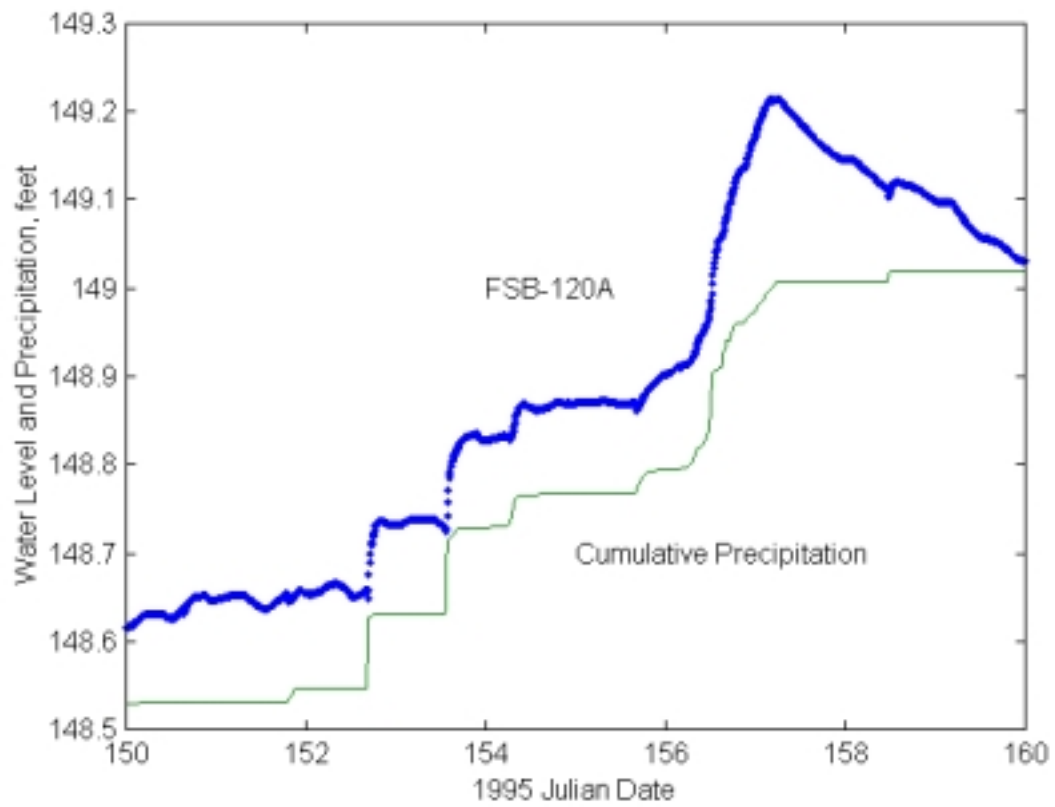


Figure 4.7: Water levels and precipitation at well FSB-120A.

#### **4.2.1 FAC Hydraulic Gradients**

The magnitude of the horizontal and vertical gradients at the FAC site are presented as Figure 4.8. The horizontal gradient was calculated using wells FAC-3P, FAC-4P, and FAC-6P in the surficial aquifer, while the vertical gradient was determined using FAC-6P and FAC-9C. Figure 4.9 is a polar plot of the horizontal hydraulic gradient showing both the magnitude and direction. Note that the general trend is toward the northwest, with occasional flow to the southeast. It is clear that larger gradients are associated with flow toward the west. Figure 4.10 presents the hydraulic gradient direction as a function of time. A steady flow at a bearing of  $280 - 290^\circ$  is clear, with brief changes toward the south and east. This range in directions is also illustrated using a histogram in Figure 4.11. Here we show the strong preference for flow to the west, but with occasional changes in the opposite direction.

Table 4.10 quantifies the effects of average and worst case errors in the magnitude and direction of the water level gradient induced by a delay in measurement. Note that the average error is small for the vertical and horizontal gradients. This indicates that routine sampling, on average, will not result in large errors in the water level gradient estimate. Even at a one-month delay between measurements, the average vertical water level gradient magnitude is affected by only 10‰, the average horizontal water level gradient magnitude by 23‰, and the horizontal water level gradient direction by  $6.7^\circ$ .

Worst case conditions are more troublesome. The vertical gradient can be off by up to 41‰, the horizontal magnitude by 80‰, and the horizontal direction by  $180^\circ$ . This means that sampling for water levels even six hours apart can cause a substantial misinterpretation of the direction of flow. Clearly, sampling even two days apart introduces substantial gradient uncertainties.

Table 4.11 shows how the errors can be reduced by using the hydraulic gradient instead of the water level gradient. The water level gradient introduces substantial errors

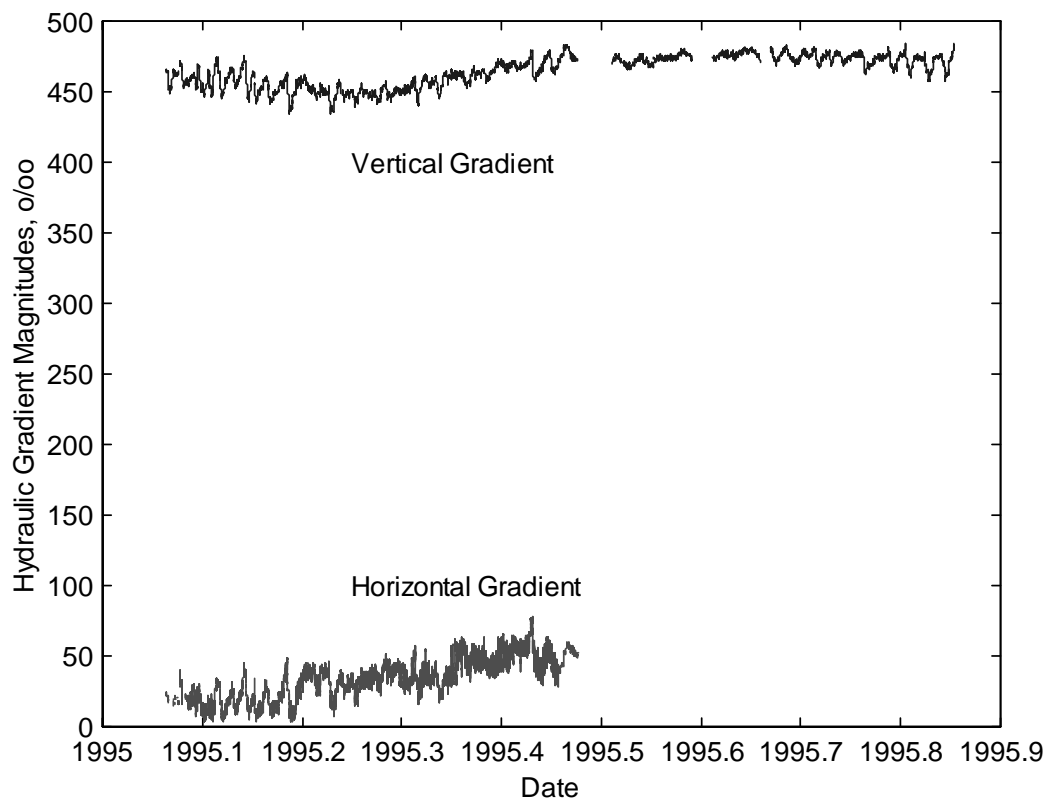


Figure 4.8: FAC Horizontal and vertical hydraulic gradients

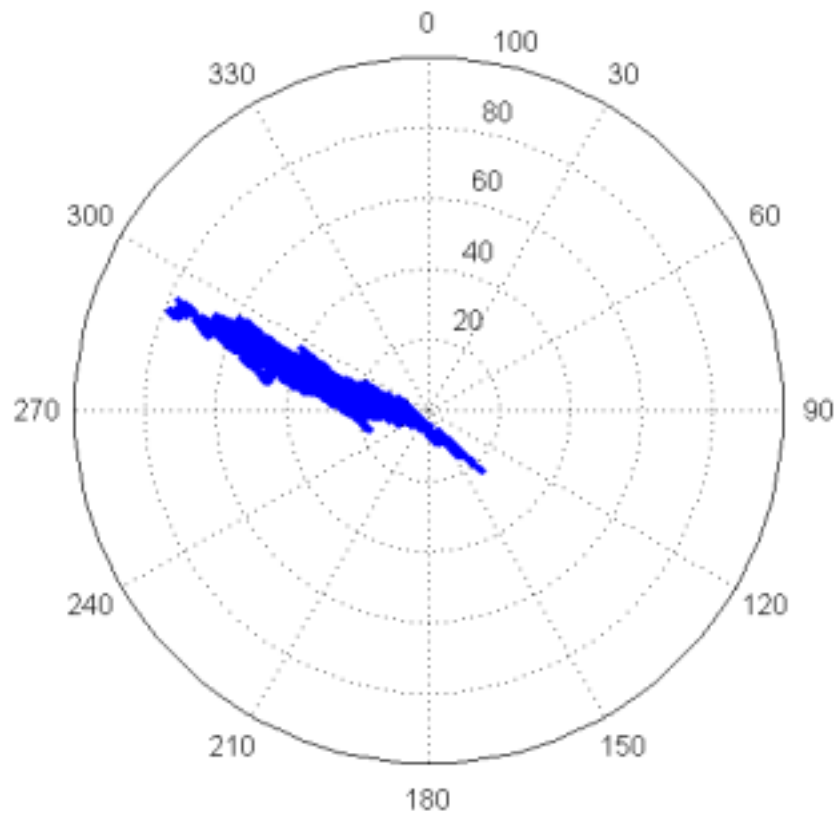


Figure 4.9: FAC horizontal hydraulic gradient direction ( $^{\circ}$ ) and magnitude (‰)

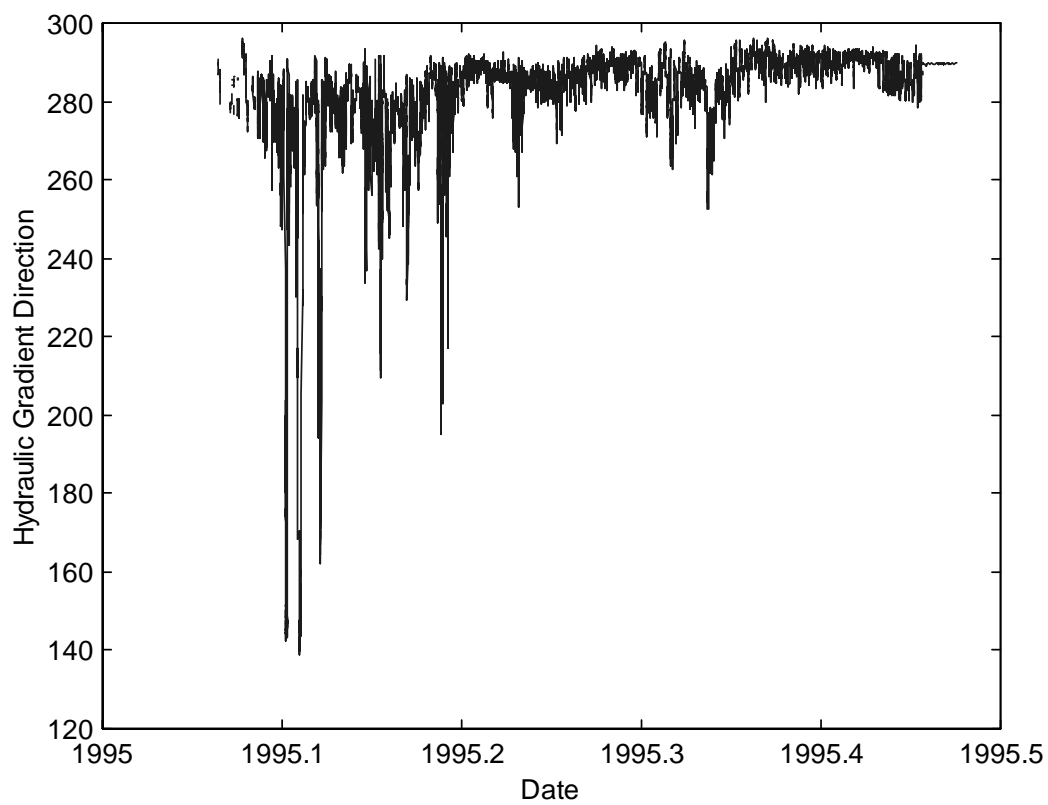


Figure 4.10: Time plot of FAC horizontal hydraulic gradient direction.

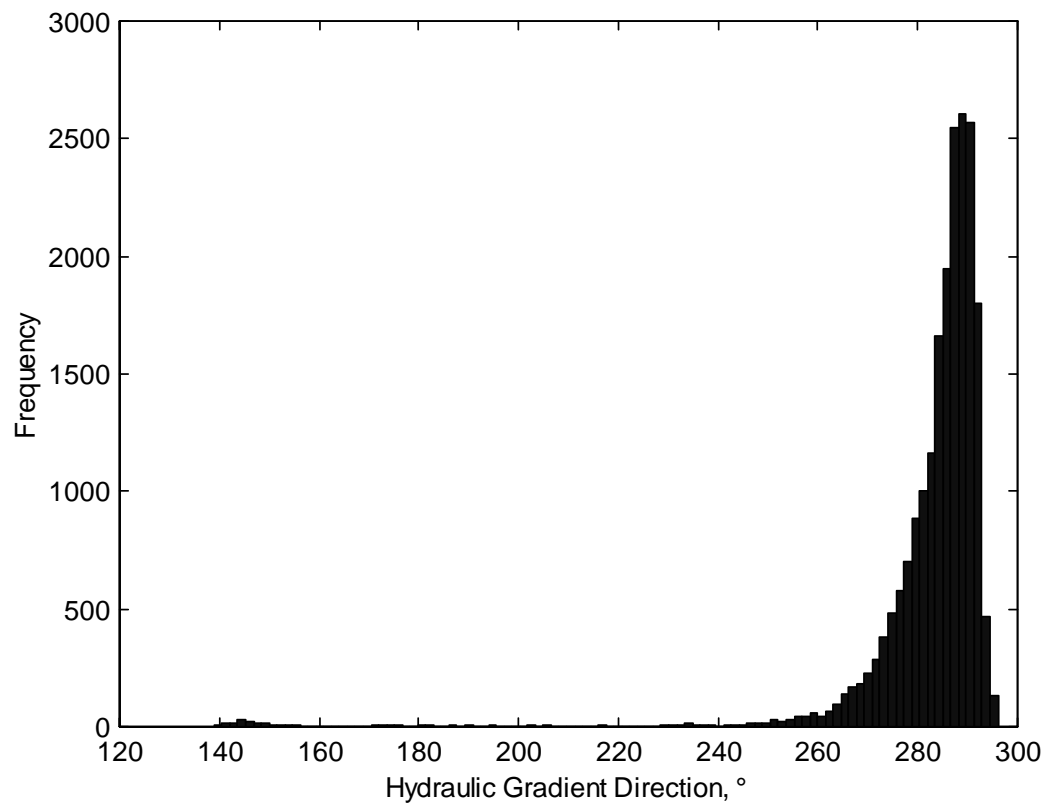


Figure 4.11: Histogram of FAC horizontal hydraulic gradient direction.

Table 4.10: FAC Water Level Gradient Errors

<i>Time Since Initial Water Level Mea- surement</i>	<i>Vertical, ‰</i>		<i>Horizontal</i>			
			<i>Magnitude, ‰</i>		<i>Direction, °</i>	
	<i>Avg</i>	<i>Max</i>	<i>Avg</i>	<i>Max</i>	<i>Avg</i>	<i>Max</i>
10 minutes	0	5	0	6	0.1	14.6
30 minutes	0	5	1	10	0.4	38.7
1 hour	1	6	2	13	0.7	68.9
6 hour	2	11	6	33	4.3	167.9
12 hour	3	16	7	48	8.5	179.8
1 day	4	23	10	52	13.5	179.9
2 days	6	30	14	60	16.4	179.8
1 week	5	31	12	68	11.4	179.8
2 weeks	6	33	15	75	9.7	179.9
1 month	10	41	23	80	6.7	179.6

Table 4.11: FAC Hydraulic Gradient Errors

<i>Time Since Initial Water Level Mea- surement</i>	<i>Vertical, ‰</i>		<i>Horizontal</i>			
			<i>Magnitude, ‰</i>		<i>Direction, °</i>	
	<i>Avg</i>	<i>Max</i>	<i>Avg</i>	<i>Max</i>	<i>Avg</i>	<i>Max</i>
10 minutes	0	5	0	4	0.1	10.4
30 minutes	0	5	0	6	0.2	20.5
1 hour	0	5	0	7	0.4	39.5
6 hour	0	6	0	20	1.8	102.3
12 hour	0	6	0	32	3.1	119.7
1 day	0	7	0	38	5.0	128.1
2 days	1	8	1	39	7.6	156.0
1 week	2	13	4	43	6.1	177.2
2 weeks	4	16	8	50	6.9	179.4
1 month	6	31	17	61	4.7	138.1

FAC-6P in the surficial aquifer, while the vertical gradient was determined using FAC-6P and FAC-9C. Figure 4.9 is a polar plot of the horizontal hydraulic gradient showing both the magnitude and direction. Note that the general trend is toward the northwest, with occasional flow to the southeast. It is clear that larger gradients are associated with flow toward the west. Figure 4.10 presents the hydraulic gradient direction as a function of time. A steady flow at a bearing of  $280 - 290^\circ$  is clear, with brief changes toward the south and east. This range in directions is also illustrated using a histogram in Figure 4.11. Here we show the strong preference for flow to the west, but with occasional changes in the opposite direction.

Table 4.10 quantifies the effects of average and worst case errors in the magnitude and direction of the water level gradient induced by a delay in measurement. Note that the average error is small for the vertical and horizontal gradients. This indicates that routine sampling, on average, will not result in large errors in the water level gradient estimate. Even at a one-month delay between measurements, the average vertical water level gradient magnitude is affected by only 10‰, the average horizontal water level gradient magnitude by 23‰, and the horizontal water level gradient direction by  $6.7^\circ$ .

Worst case conditions are more troublesome. The vertical gradient can be off by up to 41‰, the horizontal magnitude by 80‰, and the horizontal direction by  $180^\circ$ . This means that sampling for water levels even six hours apart can cause a substantial misinterpretation of the direction of flow. Clearly, sampling even two days apart introduces substantial gradient uncertainties.

Table 4.11 shows how the errors can be reduced by using the hydraulic gradient instead of the water level gradient. The water level gradient introduces substantial errors because of barometric pressure effects. Now the two-day error is about equal to the six-hour error associated with water level gradient estimation. Figure 4.12 presents the

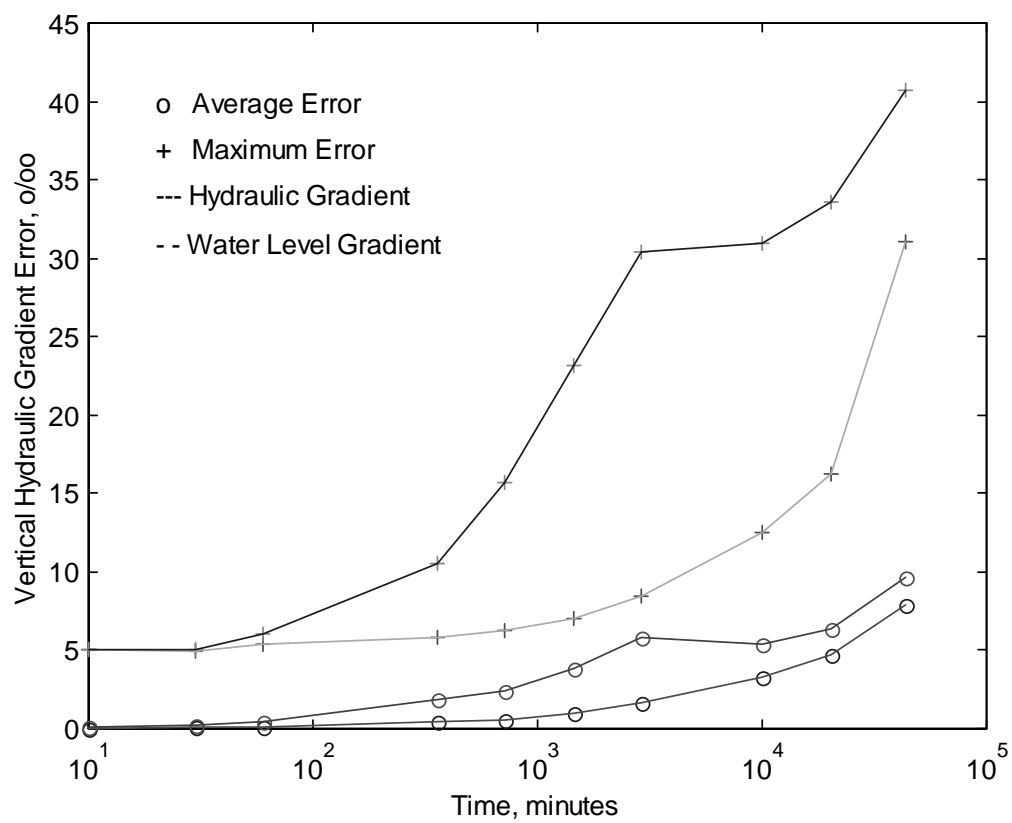


Figure 4.12: FAC average and maximum vertical gradient magnitude errors.

average and worst case vertical hydraulic and water level gradient errors for the period of study. Note the larger errors induced by delayed measurements. Also note that the hydraulic gradient error is smaller for all delays than the water level gradient. Figure 4.13 presents the average and worst case horizontal magnitude errors. Again note that the hydraulic gradient is less prone to error than the water-level gradient calculation. Figure 4.14 presents the average and worst case horizontal direction error. Note that while the average errors are small, the worst-case errors can result in an error of  $180^\circ$ . These large errors indicate the need to obtain synchronous measurements during periods when the water levels are changing rapidly, or to avoid measurements during this period. A strategy that minimizes error would also focus on using total head to determine the hydraulic gradient in this area.

#### **4.2.2 FSB Hydraulic Gradients**

Vertical hydraulic gradients in the F-area vary depending upon location and the intervening confining units. It is clear from Figure 4.15 that the Green Clay aquitard maintains a substantial gradient (greater than unity) across it. The Tan Clay aquitard, however, demonstrates a variable degree of confinement in some areas FSB-115, but a much lower confinement at FSB-120. An inference of confinement is weak, however, because regional flow must be considered.

Horizontal gradients, both magnitude and direction, are much less dynamic. Figures 4.16 through 4.18 present horizontal gradients using the three wells. These wells are separated by greater distances, with much larger water level changes between them. Note that small perturbations in water levels in the riparian wells do not substantially affect the magnitude of the gradient, and insignificantly affect the direction of flow when measured on this scale. Inferences on local perturbations near the riparian zone are weaker, due to the lag of monitoring at a finer scale. When measured on this scale.

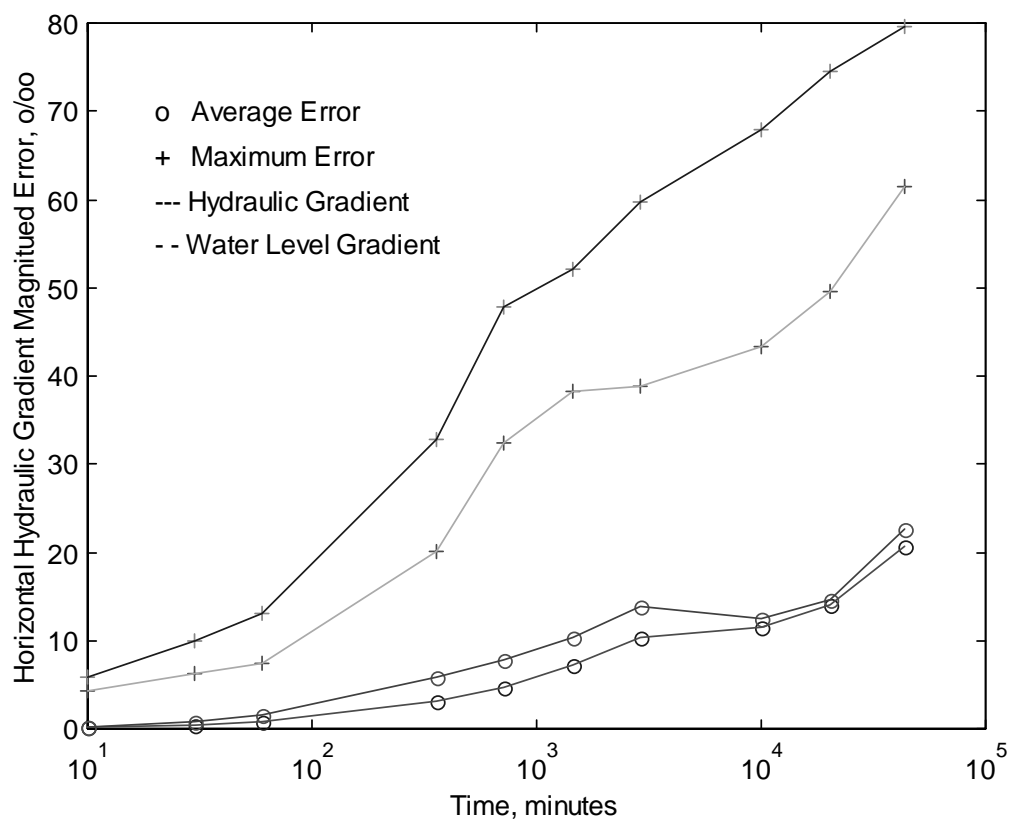


Figure 4.13: FAC average and maximum horizontal gradient magnitude errors.

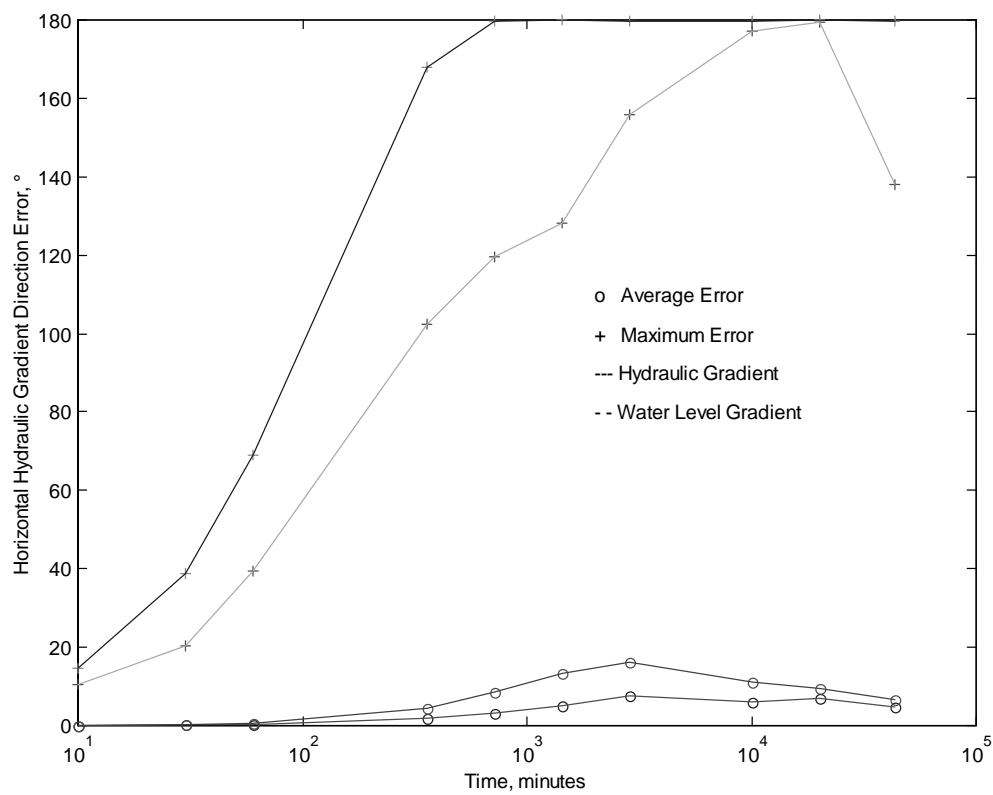


Figure 4.14: FAC average and maximum horizontal gradient direction errors.

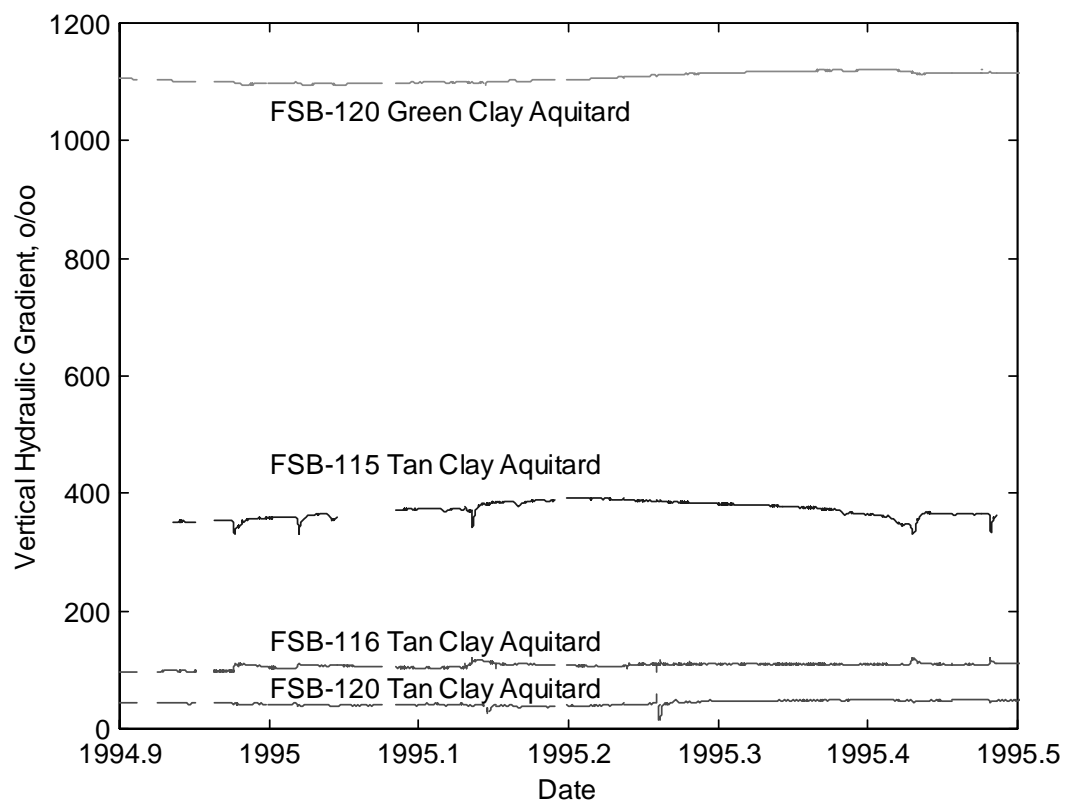


Figure 4.15: FSB vertical hydraulic gradients.

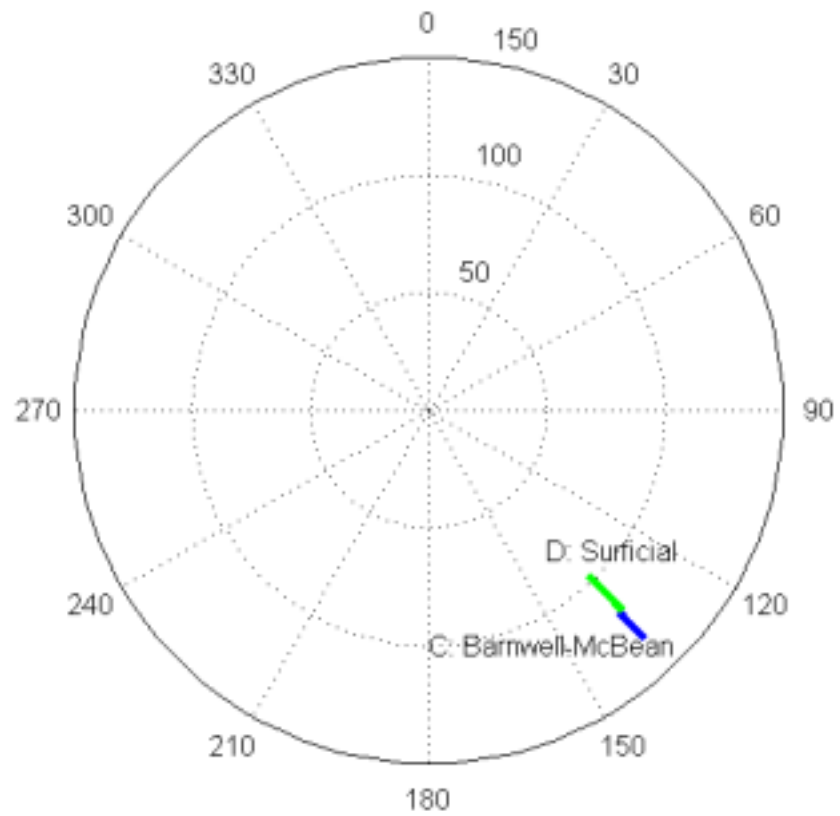


Figure 4.16: FSB Horizontal Hydraulic Gradient Directions ( $^{\circ}$ ) and Magnitudes ( $\%$ )

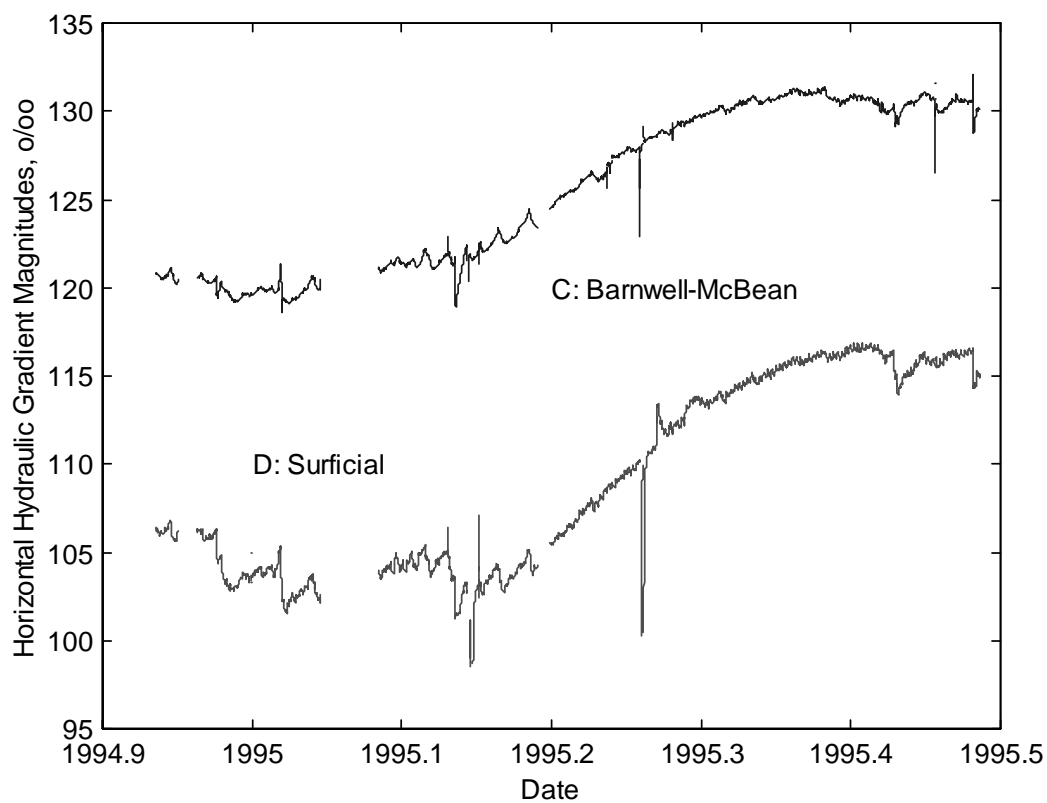


Figure 4.17: FSB Horizontal Hydraulic Gradient Magnitudes

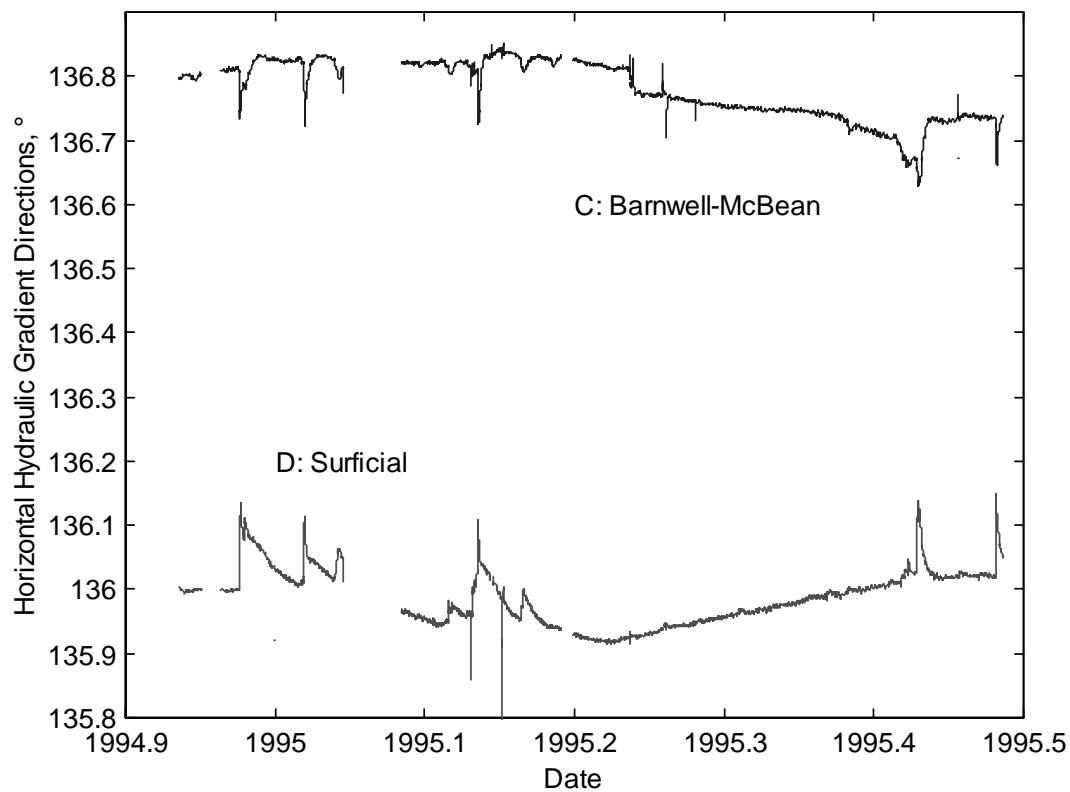


Figure 4.18: FSB Horizontal Hydraulic Gradient Directions

Inferences on local perturbations near the riparian zone are weaker, due to the lag of monitoring at a finer scale.

## CHAPTER 5

### SUMMARY AND RECOMMENDATIONS

This thesis examines the nature of the temporal variability of water levels in wells near the General Separations Area at the Savannah River Site. We find that short-term fluctuations in water levels ( $\Delta t < 48$  hours) can be significant due to natural variations in barometric pressure, rainfall, or streamflow. In many cases, the magnitude of these short-term fluctuations exceed longer-term fluctuations caused by changes in recharge, evapotranspiration or ground-water discharge. Estimates of the direction and magnitude of the hydraulic gradient may be incorrect using a strategy that relies solely on quarterly synchronous measurements. This is because the quarterly measurements focus on long-term changes, and are unable to provide information about short-term fluctuations in water levels and gradients.

We wish to show that improved estimates of the hydraulic gradient can be obtained using a strategy that properly accounts for short-term fluctuations. Accounting for short-term fluctuations permits a reduction in the sampling frequency with no substantial loss in accuracy.

A major source of water level variation in the FAC wells is due to changes in barometric pressure. The barometric efficiency for these wells approach 100 percent, which indicates that a one-foot increase in barometric pressure head will cause a one-foot decline in water levels in the well. We can compensate for this variability by calculating the total head as the sum of the barometric pressure plus the observed water level. In this case, the two terms cancel each other, resulting in an observed hydraulic head that is substantially less variable in time.

Another source of error is derived from intense rainfall events. Rainfall of approximately two inches within a two-day period can result in water level changes in unconfined and semi-confined aquifers near local stream baselines, as measured by wells near local streams. In addition to riparian responses, wells in confined aquifers with low barometric efficiencies show rapid responses to precipitation due to loading responses to the rainfall itself. However, these responses in the water surface are short-term and appear as spikes on hydrographs of the affected wells. A program to examine if there are rainfall thresholds for these responses may be in order so that water level measurements can be delayed during the rainfall period

Water levels in FSB wells are not as sensitive to changes in barometric pressure. In wells where the water level is near the surface, this is because the change in barometric pressure quickly changes the total head within the aquifer. In these wells, which are near Fourmile Branch (FSB-115 and FSB-116), water levels respond rapidly to changes in streamflow. Sampling wells in riparian areas near streams should be avoided when water levels in the stream are changing rapidly following significant precipitation.

In the FAC-area, short-term fluctuations (i.e., < 48 hours) in water levels are large, approximately 0.5 foot. These fluctuations are caused by changes in barometric pressure. Adding the barometric pressure to the water level elevation smooths most of the fluctuations. This is because the total head in the aquifer is not immediately affected by changes in barometric pressure.

An analysis of water level fluctuations and hydraulic gradients reveals that the most effective reduction in error would be by total head conversion rather than synchronous water level measurement as currently defined by the state regulators. In fact, if water levels in a monitoring network's wells are not measured within two hours of each other, the error inherent in the short-term fluctuations caused by barometric pressure changes will exceed the error inherent in a total head measurement caused by longer term

fluctuations (recharge, evapotranspiration, etc.) even if the measurements interval among the monitoring wells is 60 days.

If the objective is to minimize the uncertainty in water level gradients, then the sources of error in gradient estimation should be determined. Sources of error include, but are not limited to: 1) Misspecification of the horizontal distance between wells; 2) Errors in surface casing elevation; 3) Error in the water level measurement; 4) Failure to use the total head for determining the hydraulic gradient; 5) Failure to consider large changes in recharge and/or discharge, and 6) Failure to consider vertical changes in hydraulic head.

It can be shown (see, e.g., Crawford, 1994) that the magnitude of the error in gradient is a function of the magnitude of water level fluctuations over time, and the magnitude of the true gradient. The best case (i.e., the importance of simultaneous measurements is minimized) occurs when water levels fluctuations are small and when the gradient is large. The worst case occurs when water level fluctuations are large and when the gradient is small.

Facility monitoring networks located in a small area or in a region of very low potentiometric relief are affected more severely than those located on strong potentiometric slopes. This source of error can be corrected by developing a total head calculation based on one of two methods. Either the barometric efficiency can be determined for each well (or local collection of wells) and used to calculate total head of each measured water level, or barometric pressure at the ground surface can be measured at the same time the water level is measured and the two pressures summed to generate total head.

Potential methods for reducing uncertainties include the continuous monitoring of water levels at key indicator wells with augmented quarterly measurements from all wells, measurement of water levels at all wells within a narrow sampling interval, or identifying and monitoring the external causes of water level fluctuations (e.g., baromet-

ric pressure, precipitation, earth tides, etc.) at each site and compensate quarterly water level measurements using measured values of the external determinants in conjunction with an analysis that determines the sampling interval needed to reduce the fluctuation error below a specified error.

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