1.3.3 Meteorology

Climatology information is based on *Climatography of the United States No. 60, Climate of South Carolina* (DOC [U.S. Department of Commerce] 1977) published by the National Climatic Data Center and Section 1.4.1 of the SRS GSAR (WSRC 1999c). It is also based on long-term meteorological data collected by the National Weather Service at Bush Field in Augusta, Georgia (Bush Field is located approximately 12 mi [19.3 km] northwest of SRS), as summarized by the National Climatic Data Center. Normals, means, and extremes of temperature, precipitation, and wind speed are taken from the National Oceanic and Atmospheric Administration (NOAA). Data on tornado occurrences and hurricanes are derived from *Significant Tornadoes 1680 – 1991, Tornado Project of Environmental Films* (Grazulis 1993) and *Natural Phenomena Hazards Design Criteria and Other Characterization Information for the Mixed Oxide (MOX) Fuel Fabrication Facility at Savannah River Site (U)* (WSRC 2000b).

1.3.3.1 Local Wind Patterns and Average and Maximum Wind Speeds

Winds in the SRS region are generally light to moderate with the highest speeds occurring during spring, with an average of approximately 7 mph (11.3 km/hr) for those months at Bush Field. The lightest winds occur in the summer and fall, with the lowest monthly average wind speed of 5.1 mph (8.2 km/hr) occurring in August. The highest monthly average wind speed of 7.7 mph (12.4 km/hr) occurs in March, and the long-term average wind speed for the year is 6.2 mph (10 km/hr) measured at Bush Field. The prevailing wind direction at Augusta is generally from the northwest during the winter months, from the southeast during the late spring and early autumn, and from the southwest in the summer. There is no overall prevailing wind direction because it is variable throughout the year.

A meteorological database, comprised of data from the eight SRS meteorological towers at SRS, for the 10-year period 1987 to 1996 is currently used for the safety analysis. As indicated by this database, there is no strongly prevailing wind direction at SRS. Northeasterly winds occurred approximately 10% of the time, and west to southwest winds occurred about 8% of the time. Annual average wind speeds at each of the towers ranged from 9.4 mph (15.1 km/hr) to 8.0 mph (12.9 km/hr). The maximum one-minute wind since 1950 was 83 mph (134 km/hr) measured on May 28, 1950. The observed annual fastest one-minute wind speeds for SRS are listed in Table 1.3.3-1.

The peak wind gust at Augusta is 60 mph (96.5 km/hr) from the northwest based on 10 years of observations.

1.3.3.2 Annual Amounts and Forms of Precipitation

Annual average precipitation for SRS over the 30-year period 1967 to 1996 is 49.5 in (126 cm), and the average precipitation for Augusta is slightly less (44.7 in [114 cm]) (Table 1.3.3-2).

Monthly precipitation extremes for SRS range from a maximum of 19.62 in (50 cm), recorded in October 1990, to a trace observed in October 1963. The greatest observed rainfall for a 24-hour period was 7.5 in (19 cm) in October 1990. Hourly observations at Augusta indicate that rainfall rates are usually less than 0.5 in/hr (1.3 cm/hr), although rainfall rates of up to 2 in/hr (5.1 cm/hr) can occur during summer thunderstorms.

Snowfall statistics for Augusta (1951 to 1995) are summarized in Table 1.3.3-3. The average annual snowfall for the SRS area (Augusta) for the period 1951 to 1995 was 1.1 in/yr (2.8 cm/yr), and the average number of days per year with snow was 0.6 day.

An average of about 54 thunderstorm days per year was observed in the SRS area during the period 1951 to 1995. Average thunderstorm days per month are listed in Table 1.3.3-4.

The occurrence of hail with thunderstorms is infrequent. Based on observations in a 1-degree square of latitude and longitude that includes SRS, hail occurs an average of once every two years.

1.3.3.3 Snow and Ice

Snow and ice storms in the region occur very infrequently. Snowfalls of 1 in (2.5 cm) or greater occur once every three years on the average. Furthermore, any accumulation of snow rarely lasts for more than three days.

The greatest single snowfall recorded in the SRS area (Augusta) during the period 1951 to 1995 occurred in February 1973. This storm produced a total of 14.0 in (35.6 cm) of accumulation, including 13.7 in (34.8 cm) in a 24-hour period. Maximum total snowfalls for 24-hour and monthly periods, observed at the National Weather Service office at Augusta, Georgia, are summarized in Table 1.3.3-3. The maximum ground snow load for the SRS area for a 100-year recurrence period is estimated to be 6 psf.

Ice accumulates on exposed surfaces in the SRS area an average of about once every two years. Average ice accumulations for various recurrence intervals for a region that includes SRS and consists of the Gulf Coast states are given in Table 1.3.3-5. The 100-year recurrence ice storm is estimated to produce an accumulation of approximately 0.67 in (1.7 cm), which is equivalent to 3 psf.

Based on the values above, the combined snow and ice design basis load for the SRS area for a 100-year recurrence period is 10 psf. This load is considered as a normal design live load in the design of buildings and structures. The ice and snow load is bounded by the allowance specified in Section 11.1 for general live loading effects, and therefore snow and ice do not control the design of MFFF SSCs.

It is also possible to estimate the magnitude of snow and ice loads with a larger interval. The ice accumulation values shown in Table 1.3.3-5 can be extrapolated to higher recurrence intervals. Using the return period conversions shown in ASCE-7-98, snow loading at higher recurrence intervals can also be extrapolated. With this method, it is estimated that the design basis snow or ice load for a recurrence period of 10,000 years would be approximately twice that for 100 years. Even if the design basis snow and ice loading were increased by this factor to represent a highly unlikely (extreme) snow and ice loading, its magnitude would still be bounded by the allowance for general live loadings and would not control the design of MFFF SSCs. Such highly unlikely snow and ice roof loads are not combined with roof live loads from other sources in the structural evaluations described in Section 11.1.

1.3.3.4 Type, Frequency, and Magnitude of Severe Weather

The SRS region occasionally experiences severe weather in the form of violent thunderstorms, tornadoes, and hurricanes. Although thunderstorms are common in the summer months, the more violent storms are commonly associated with squall lines and active cold fronts in the spring. Augusta averages 54 thunderstorm days per year with the highest number of days (9 to 12 days per month) occurring in June, July, and August. The occurrence of hail with thunderstorms is infrequent.

1.3.3.4.1 Tornadoes

A total of 165 tornadoes occurring within a 2-degree square of latitude and longitude centered on SRS over a 30-year period from 1967 have been identified. The tornado occurrences by month and Fujita (F)-scale intensity category since 1951 are summarized in Table 1.3.3-6.

Nine tornadoes have occurred on or in close proximity to SRS since operations began in the 1950s. A tornado that occurred on October 1, 1989, knocked down several thousand trees over a 16-mi (26-km) path across the southern and eastern portions of the site. Wind speeds produced by this F2 tornado were estimated to be as high as 150 mph (241 km/hr). Four F2 tornadoes struck forested areas of SRS on three separate days during March 1991. Considerable damage to trees was observed in the affected area. The other four confirmed tornadoes were classified as F1 and produced relative minor damage. None of the nine tornadoes caused damage to buildings.

Estimates of the expected tornado wind speeds that are exceeded at SRS for various return frequencies are summarized in Table 1.3.3-7. These estimates were determined from a tornado wind hazard model developed by Lawrence Livermore National Laboratory (LLNL). The estimated wind speed for each of the return intervals summarized in Table 1.3.3-7 represents a mean of the resulting set of wind speed values.

Design basis tornado speeds for DOE moderate hazard (performance category or PC-3) and high hazard (PC-4) facilities are shown in Table 1.3.3-8. The PC-3 and PC-4 design basis atmospheric pressure change and the rate thereof, shown in Table 1.3.3-8, are taken as the rounded values corresponding to the tornado speeds of 180 and 240 mph (290 and 386 km/hr), respectively. MFFF principal SSCs are evaluated for a recurrence interval of 2×10^{-6} for a design basis tornado with a three-second tornado speed of 240 mph (386 km/hr).

1.3.3.4.2 Extreme Winds

Extreme winds in the SRS area, excluding tornado winds, are associated with tropical weather systems, thunderstorms, or strong winter storms. Extreme fastest one-minute wind speeds for the 30-year period 1967 to 1996 are summarized in Table 1.3.3-1.

Estimates of an expected maximum "straight-line" (nontornadic) wind speed (three-second gust) for any point on the site for return periods from 100 to 100,000 years are summarized in Table

1.3.3-7. These estimates were generated from a Fisher-Tippet Type I extreme value distribution function using historical wind speed (gust) data from the SRS meteorological database and from nearby National Weather Service stations (Columbia in South Carolina and Augusta, Macon, and Athens in Georgia).

Design basis wind speeds for DOE moderate hazard (PC-3) and high hazard (PC-4) facilities are given in Table 1.3.3-8. MFFF principal SSCs are evaluated for a recurrence interval of 1×10^{-4} for design basis wind with a three-second wind speed of 130 mph (209 km/hr).

1.3.3.4.3 Hurricanes

A total of 36 hurricanes have caused damage in South Carolina over the 293-year period from 1700 to 1992. The average frequency of occurrence of a hurricane in the state is once every eight years; however, the observed interval between hurricane occurrences has ranged from two months to 27 years. The percentages of hurricane occurrences by month in South Carolina are given in Table 1.3.3-9.

Because SRS is approximately 100 mi (160 km) inland, winds associated with tropical weather systems usually diminish below hurricane force (sustained speeds of 75 mph [120 km/hr] or greater) before reaching SRS. However, winds associated with Hurricane Gracie, which passed to the north of SRS on September 29, 1959, were measured as high as 75 mph (120 km/hr) on an anemometer located in F Area. No other hurricane-force wind has been measured on the site. On September 22, 1989, the center of Hurricane Hugo passed about 100 mi (160 km) northeast of SRS. The maximum 15-minute average wind speed observed onsite during this hurricane was 38 mph (61 km/hr). The highest observed instantaneous wind speed was 62 mph (100 km/hr).

1.3.3.4.4 Extreme Precipitation

Maximum observed rainfall recorded at Augusta's Bush Field and the Columbia, South Carolina, airport for various accumulation periods is summarized in Table 1.3.3-10. These data were based on a 48-year period of record (1948 to 1995).

Estimates of expected maximum rainfall at SRS for rainfall durations of 15 minutes to 24 hours and return periods from 10 years to 100,000 years are shown in Table 1.3.3-11. These estimates were based on a statistical analysis of hourly rainfall from eight National Weather Service first-order and cooperative stations (Augusta, Macon, Athens, Sylvania, and Louisville in Georgia and Columbia, Wagener, and Clark Hill in South Carolina), 15-minute rainfall from three of the cooperative stations (Sylvania, Louisville, and Wagener), and daily rainfall from four rain gages at SRS. Stations were selected based on proximity to and geographic similarity with SRS. For each station (as appropriate to the data set), the annual maximum observed rainfall for each of the six duration intervals of interest over the available period of record was determined. The period of record ranged from 25 to 47 years.

Several significant rainfall events occurred at SRS in the summer and fall of 1990. Table 1.3.3-11 includes the observed rainfall totals from those storms that exceeded the predicted extreme rainfall values. Short duration extreme rainfalls are generally produced by spring and summer thunderstorms. Longer duration extreme rains are usually produced by the remnants of tropical weather systems. MFFF principal SSCs are evaluated for an annual recurrence frequency of 1×10^{-5} for extreme precipitation values shown in Table 1.3.3-11.

1.3.3.4.5 Lightning

The frequency of cloud-to-ground lightning strikes has been estimated using conservative input values. The number of flashes to earth per square kilometer was estimated to be 10 per year. Measurements of cloud-to-ground lightning strikes recorded from the National Lightning Detection Network over the five-year period 1989 to 1993 show an average of four strikes per square kilometer per year in the SRS area.

1.3.3.5 Temperature

Monthly and annual average temperatures for SRS for the 30-year period 1967 to 1996 are included in Table 1.3.3-12. At SRS, the annual average temperature is 64.7°F. July is the warmest month with an average daily high temperature of 92.1°F and an average daily low temperature of 71.5°F. January is the coldest month with an average daily high temperature of 55.9°F and an average daily low temperature of 36.0°F. Observed temperature extremes for SRS over the period 1961 to 1996 ranged from 107°F to -3°F.

Data for Augusta, Georgia, indicate that prolonged periods of cold weather seldom occur. Daytime high temperatures during the winter months are rarely below 32°F. Conversely, high temperatures in the summer months are above 90°F on more than half of all days. The average dates of the first and last freeze are November 12 and March 16, respectively.

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Tables

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Table 1.3.3-1. Observed Annual Fastest One-Minute Wind Speeds for SRS [a, b, c]

Year	Wind Speed (mph) [d]	Direction	Date
1967	52	W	5/8
1968	43	NW	7/16
1969	43	NE	7/8
1970	52	NW	7/16
1971	34	SW	7/11
1972	56	SW	3/2
1973	37	NW	11/21
1974	49	W	3/21
1975	37	W	7/6
1976	32	NW	3/9
1977	43	S	10/2
1978	39	SW	1/26
1979	30	W	5/12
1980	32	S	7/9
1981	33	NW	3/16
1982	40	NW	2/16
1983	32	NW	12/31
1984	32	SW	3/28
1985	35	W	2/11
1986	32	NW	7/2
1987	35	NNW	7/24
1988	32	WNW	5/24
1989	39	NW	6/22
1990	28	WSW	1/29
1991	29	NW	2/15
1992	29	SW	7/1
1993	33	W	3/13
1994	34	SE	7/10
1995	38	W	11/11
1996	35	W	2/12

[a] Maximum 1-minute wind since 1950: 83 mph on 5/28/50

[b] Data for 1967-1994 from National Weather Service Office, Bush Field, Augusta, Georgia.
Source: *Local Climatological Data, Annual Summary with Comparative Data, 1995, Augusta, Georgia* (DOC 1996)

[c] Data for 1995-1996 from SRS Central Climatology Facility.
Source: "Updated Meteorological Data for Revision 4 of the SRS Generic Safety Analysis Report" (Hunter 1999)

[d] Values interpolated to a 10-m anemometer height.

Data from WSRC 2000b

Table 1.3.3-2. Average and Extreme Precipitation at SRS (Water Equivalent), in Inches

Month	Average[a]	Maximum (Year)[b]	Minimum (Year)[b]
January	4.44	10.02 (1978)	0.89 (1981)
February	4.25	7.97 (1995)	0.94 (1968)
March	4.83	10.96 (1980)	0.91 (1995)
April	3.02	8.20 (1961)	0.57 (1972)
May	3.86	10.90 (1976)	1.33 (1965)
June	4.53	10.98 (1973)	0.89 (1990)
July	5.57	11.48 (1982)	0.90 (1980)
August	5.44	12.34 (1964)	1.04 (1963)
September	3.63	8.71 (1959)	0.49 (1985)
October	3.40	19.62 (1990)	0.00 (1963)
November	2.89	7.78 (1992)	0.21 (1958)
December	3.59	9.55 (1981)	0.46 (1955)
Year	49.46	73.47 (1964)	28.82 (1954)

[a] Period of record: 1967-1996.
[b] Period of record: 1952-1996.

Augusta[a] Climatological Summary – Precipitation (inches)

Month	Normal Monthly	Maximum Monthly	Year Occurred	Minimum Monthly	Year Occurred	24-Hour Maximum	Year Occurred
January	4.05	8.91	1987	0.75	1981	3.61	1960
February	4.27	7.67	1961	0.69	1968	3.69	1985
March	4.65	11.92	1980	0.88	1968	5.31	1967
April	3.31	8.43	1961	0.60	1970	3.96	1955
May	3.77	9.61	1979	0.48	1951	4.44	1981
June	4.13	8.84	1989	0.68	1984	5.08	1981
July	4.24	11.43	1967	1.02	1987	3.71	1979
August	4.50	11.34	1986	0.65	1980	5.98	1964
September	3.02	9.51	1975	0.31	1984	7.30	1998
October	2.84	14.82	1990	T	1953	8.57	1990
November	2.48	7.76	1985	0.09	1960	3.82	1985
December	3.40	8.65	1981	0.32	1955	3.12	1970
Year	44.66	14.82	1990	T	1953	8.57	1990

Source: *Local Climatological Data, Annual Summary with Comparative Data, 1991* (DOC 1991)
T – Trace
[a] Taken at Bush Field, Augusta, Georgia, national weather station
Data from WSRC 2000b

Table 1.3.3-3. Maximum Snow, Ice Pellets - Augusta, Georgia, in Inches

Month	Average	Maximum (Year)	24-Hr Maximum (Year)
January	0.3	2.6 (1992)	2.6 (1992)
February	0.7	14.0 (1973)	13.7 (1973)
March	<0.1	1.1 (1980)	1.1 (1980)
April	0.0	0.0	0.0
May	0.0	0.0	0.0
June	0.0	0.0	0.0
July	0.0	0.0	0.0
August	0.0	0.0	0.0
September	0.0	0.0	0.0
October	0.0	0.0	0.0
November	<0.1	Trace (1968)	Trace (1968)
December	0.1	1.0 (1993)	1.0 (1993)
Year	1.1	14.0 (1973)	13.7 (1973)

Period of record, 1951-1995.

Data from WSRC 2000b

Table 1.3.3-4. Average Number of Thunderstorm Days, Augusta, Georgia, 1951-1995

Month	Thunderstorm Days
January	0.8
February	1.7
March	2.6
April	3.9
May	6.3
June	9.7
July	13.1
August	10.0
September	3.5
October	1.3
November	0.8
December	0.7
Annual	54.4

Data from WSRC 2000b

Table 1.3.3-5. Estimated Ice Accumulation for Various Recurrence Intervals for the Gulf Coast States

Recurrence Interval (yr)	Accumulation (inches)
2	0
5	0.24
10	0.39
25	0.51
50	0.59
100	0.66

Data from WSRC 2000b

Table 1.3.3-6. Number of Tornadoes Reported Between 1951 and 1996 by Month and F-Scale in a Two-Degree Square Centered at SRS

Month	F-0	F-1	F-2	F-3	F-4	F-5	Total	Percent
January	3	8	2	1	0	0	14	7.0
February	4	12	1	0	0	0	17	8.5
March	1	10	9	0	1	0	21	10.5
April	4	17	4	1	0	0	26	13.0
May	3	18	6	0	0	0	27	13.5
June	4	10	0	0	0	0	14	7.0
July	2	8	3	0	0	0	13	6.5
August	4	7	5	2	0	0	18	9.0
September	0	5	3	0	0	0	8	4.0
October	1	2	4	0	0	0	7	3.5
November	10	8	7	2	0	0	27	13.5
December	1	2	2	2	1	0	8	4.0
Total	37	107	46	8	2	0	200	100.0

Data from WSRC 2000b

Table 1.3.3-7. Estimated Maximum Three-Second Wind Speeds for Tornadoes and "Straight-Line" Winds

Recurrence Interval, years	Probability events/year	Estimated Maximum 3-Sec Wind Speed, mph	
		Tornadoes	"Straight-Line" Winds
100	1×10^{-2}	---	88
200	5×10^{-3}	---	94
500	2×10^{-3}	---	102
1,000	1×10^{-3}	70	107
5,000	2×10^{-4}	120	120
10,000	1×10^{-4}	135	126
50,000	2×10^{-5}	180	140
100,000	1×10^{-5}	200	145
500,000	2×10^{-6}	240	---
1,000,000	1×10^{-6}	251	---

Data from WSRC 2000b

Table 1.3.3-8. Wind and Tornado Design Criteria for SRS

	Item	PC-3	PC-4
WIND	Annual Hazard Exceedance Probability	$1x10^{-3}$	$1x10^{-4}$
	Three-Second Wind Speed, mph	110 rounded up value	130 rounded up value
	Missile Criteria	2x4 timber plank 15 lb. @50 mph (horizontal); max height 30 ft.	2x4 timber plank 15 lb. @50 mph (horizontal); max height 50 ft.
	ASCE 7-98 [a]		
TORNADO	Annual Hazard Exceedance Probability	$2x10^{-5}$	$2x10^{-6}$
	Three-Second Tornado Speed, mph	180	240
	Atmospheric Pressure Change (APC), psf, at the rate of psf/sec	70 psf at 31 psf/sec	150 psf at 55 psf/sec
	Missile Criteria	2x4 timber plank 15 lb. @100 mph (horizontal); max height 150 ft; 70 mph (vertical) 3 in. diameter standard steel pipe, 75 lb. @50 mph (horizontal); max height 75 ft; 35 mph (vertical) 3000 lb. automobile @19 mph rolls and tumbles	2x4 timber plank 15 lb. @150 mph (horizontal); max height 200 ft; 100 mph (vertical) 3 in. diameter standard steel pipe, 75 lb. @75 mph (horizontal); max height 100 ft; 50 mph (vertical) 3000 lb. automobile @25 mph rolls and tumbles
	ASCE 7-98 [a]		

[a] For determining wind and tornado loads using the ASCE 7-98 procedure, the following definitions apply: I = 1.0, Exposure Category = C, K_{zt} = 1.0, and K_d = 1.0.

Data from WSRC 2000b

Table 1.3.3-9. Total Occurrences of Hurricanes in South Carolina by Month, 1700-1992

Month	Number	Percent of Total
June	1	2.8
July	2	5.6
August	11	30.5
September	18	50.0
October	4	11.1

Data from WSRC 2000b

Table 1.3.3-10. **Extreme Total Rainfall for SRS Region (August 1948-December 1995)**

Period Hours	Period Days	Inches/ Period	Begin Time	Begin Date
Augusta Bush Field				
1		3.14	1300	7/24/86
3		4.25	1900	9/20/75
6		4.50	1900	9/20/75
12		7.62	2100	10/11/90
24		8.57	1300	10/11/90
	3	12.24		10/10/90
	7	12.24		10/10/90
	10	12.24		10/10/90
	14	14.56		10/10/90
	30	15.47		9/30/90
	60	19.84		7/15/64
	90	25.88		7/18/64
Columbia Airport				
1		3.80	2000	8/18/65
3		5.03	1900	8/18/65
6		5.29	1700	6/15/73
12		7.03	2200	8/16/49
24		7.66	1600	8/16/49
	3	8.41		8/14/90
	7	10.22		6/15/73
	10	10.29		6/13/73
	14	14.71		8/14/49
	30	19.30		7/29/49
	60	25.64		6/18/71
	90	33.69		7/18/64

Data from WSRC 2000b

Table 1.3.3-11. Extreme Precipitation Recurrence Estimates by Accumulation Period

Recurrence Interval (years)	15 min	1 hr	3 hr	6 hr	24 hr	48 hr
10	1.5	2.7	3.3	3.6	5.0	6.5 7.39[b]
25	1.8	3.2	4.0	4.4	6.1	7.9
50	2.0	3.5	4.6	5.0	6.9 (7.39)[b]	8.6
100	2.1	3.9	5.1 (5.2)[a]	5.7 (5.8)[b]	7.8	9.4 (10.2)[c] (11.15)[d]
1,000	2.7	5.0	7.4	8.3	11.5	N/A
10,000	3.3	6.2	10.3	11.8	16.3	N/A
100,000	3.9	7.4	14.1	16.7	22.7	N/A

[a] July 25 rainfall at the 700 Area
[b] August 22 rainfall at the Climatology Site
[c] October 11-12 rainfall at the 773-A Area
[d] October 11-12 rainfall at Bush Field

Data from WSRC 2000b

Table 1.3.3-12. Monthly Average and Extreme Temperatures for SRS

	Average Daily Temperature, °F [a]			Extreme Temperature, °F [b]	
Month	Maximum	Minimum	Month	Max(Yr)	Min (Yr)
January	55.9	36.0	45.8	86 (1975)	-3 (1985)
February	60.0	38.3	49.1	86 (1989)	10 (1996)
March	68.6	45.4	57.0	91 (1974)	11 (1980)
April	77.1	52.5	64.8	99 (1986)	29 (1983)
May	83.5	60.7	72.1	102 (1963)	38 (1989)
June	89.6	68.0	78.8	105 (1985)	48 (1984)
July	92.1	71.5	81.7	107 (1986)	56 (1963)
August	90.1	69.6	80.3	107 (1983)	56 (1986)
September	85.4	65.6	75.4	104 (1990)	41 (1967)
October	76.6	54.6	65.6	96 (1986)	28 (1976)
November	67.0	45.2	56.2	89 (1974)	18 (1970)
December	59.3	39.1	49.1	82 (1984)	5 (1962)
Annual	75.5	54.0	64.7	107 (1986)	-3 (1985)

[a] Period of record: 1967-1996.
[b] Period of record: 1961-1996.

Data from WSRC 2000b

1.3.4 Hydrology

1.3.4.1 Surface Hydrology

1.3.4.1.1 Hydrologic Description

Much of SRS is located on the Aiken Plateau (Figure 1.3.4-1). The plateau slopes to the southeast approximately 5 ft/mi (1 m/km). The plateau is dissected by streams that drain into the Savannah River. The major tributaries that occur on SRS are Upper Three Runs, Fourmile Branch, Pen Branch, Steel Creek, and Lower Three Runs (Figure 1.3.4-2). Beaver Dam Creek, the smallest of the six SRS tributaries of the Savannah River, is located north of Fourmile Branch, primarily in the floodplain of the Savannah River. Tinker Creek and Tims Branch are tributaries of Upper Three Runs; Indian Grave Branch is a tributary of Pen Branch. Each creek originates on the Aiken Plateau and descends 49 to 200 ft (15 to 61 m) before discharging to the Savannah River. The interstream upland area is flat to gently rolling and is characterized by gently dipping units of sand, sandy clay, and clayey sand.

The Savannah River is the principal surface water system near SRS. The river adjoins the site along its southwestern boundary for a distance of about 17 mi (27.4 km) and is 140 river-mi (225 river-km) from the Atlantic Ocean.

The Savannah River cuts a broad valley approximately 250 ft (76.2 m) deep through the Aiken Plateau (Figure 1.3.4-3). Pleistocene coastal terraces lie between the Savannah River and the Aiken Plateau. The lowest terrace is the Savannah River floodplain, which is covered with a dense swamp forest. Higher terraces rise successively from the river floodplain to the Aiken Plateau and have a level to gently rolling topography.

The Savannah River Swamp lies in the floodplain along the Savannah River for a distance of about 10 mi (16.1 km) and averages about 1.5 mi (2.4 km) wide (Figure 1.3.4-2). A small embankment or natural levee has built up along the north side of the river from sediments deposited during periods of flooding. The top of the natural levee is approximately 3 to 6 ft (0.9 to 1.8 m) above the river during normal flow (river stage 85 ft [25.9 m]) at the SRS boat dock. Three breaches in this levee (at the confluences with Beaver Dam Creek, Fourmile Branch, and Steel Creek) allow discharge of stream water to the river. During periods of high river level (above 88 ft [26.8 m]), river water overflows the levee and stream mouths and floods the entire swamp area. The water from these streams mixes with river water and then flows through the swamp parallel to the river and combines with the Pen Branch flow. The flows of Steel Creek and Pen Branch converge 0.5 mi (0.8 km) above the Steel Creek mouth. However, when the river level is high, the flows are diverted parallel to the river across the offsite Creek Plantation Swamp; ultimately they join the Savannah River flow near Little Hell Landing.

Surface water is held in artificial impoundments and natural wetlands on the Aiken Plateau. Par Pond, the largest impoundment on SRS, is an artificial lake located in the eastern part of the site that covers approximately 2,700 ac (1,093 ha). A second large artificial impoundment, L Lake, lies in the southern portion of SRS and covers approximately 1,000 ac (405 ha). Water from both Par Pond (200 ft [61 m]) and L Lake (190 ft [57.9 m]) drains to the south via Lower Three Runs and Steel Creek, respectively, into the Savannah River. Water is also retained intermittently in natural lowland and upland marshes and natural basins, some of which are Carolina bay depressions.

The source of most of the surface water on SRS is either natural rainfall, which averages 48 in (122 cm) annually, water pumped from the Savannah River and used for cooling site facilities, or groundwater discharging to the surface streams. Cooling water is discharged to streams that flow back to the Savannah River, L Lake, or Par Pond. Small volumes of water are also discharged from other SRS facilities to the streams.

The flow data used for computing statistics for the Savannah River and SRS streams were obtained from U.S. Geological Survey (USGS) stream measurement data. The data set consisted of daily average flows with varying periods of record (from 2 to 81 years) for SRS streams and the Savannah River.

Several flow statistics were derived from this data set over the period of record: daily minimums, maximums, and means; average flow; seven-day low flow, and the seven-day flow with a 10-year recurrence interval (7Q10) flow. The sampling locations are shown in Figure 1.3.4-4. Emphasis was placed on low flow statistics because disposal of wastes and maintenance of conditions for aquatic life are usually based on some type of low flow statistic. The seven-day low flow is widely used and is less likely to be influenced by minor disturbances upstream than is the minimum daily flow. The 7Q10 flow is a measure of the dependability of flow. The 7Q10 flow is derived from the frequency curve of the yearly seven-day low flow statistics over the period of record at that stream or river location. The Log Pearson Type III distribution statistics are normally used for computation of low flows in natural streams. Other distributions may be more appropriate in streams that are not naturally driven (such as those where cooling water may be the dominant component of flow).

The Log Pearson Type III distribution was applied to all SRS stream locations where a 7Q10 flow was computed (a program equivalent to the USGS A193 for computing Log Pearson Type III distributions was used). The climatic year, April 1 to March 31, is used for calculation of low flow statistics. In the United States, this period contains the low flow period for each year. Flow statistics are summarized in Table 1.3.4-1 (average flow, standard deviation, 7Q10 flow, and seven-day low flow).

The Savannah River drainage basin has a total area of 10,600 mi^2 (27,454 km^2) and forms the boundary between Georgia and South Carolina. The total drainage area of the river encompasses all or part of 41 counties in Georgia, South Carolina, and North Carolina. The Savannah River Basin is located in three physiographic regions or provinces: the Mountain, the Piedmont, and the Coastal Plain.

The Mountain Province contains most of the major tributaries of the Savannah River, including the Seneca, Tugaloo, and Chattooga Rivers. The region is characterized by a relatively steep gradient ranging in elevation from about 5,497 to 1,000 ft (1,675 to 305 m) and includes 2,042 mi^2 (5,289 km^2) (19%) of the total drainage basin. The Mountain Province lies in the Blue Ridge Mountains and has bedrock composed of gneisses, granites, schists, and quartzites; the subsoil is composed of brown and red sandy clays. In this region, the Savannah River and its tributaries have the character of mountain streams with shallow riffles, clear creeks, and a fairly steep gradient. The streambed is mainly sand and rubble.

The Piedmont Region has an intermediate gradient with elevations ranging from 1,000 to 200 ft (305 to 61 m). This region includes 5,234 mi^2 (13,556 km^2)(50%) of the total drainage basin. Soils in the Piedmont are primarily red, sandy, or silty clays with weathered bedrock consisting of ancient sediments containing granitic intrusions. The Piedmont is bordered by the Fall Line, an area where the sandy soils of the Coastal Plain meet the rocky terrane of the Piedmont foothills. The city of Augusta, Georgia is located near this line. The Savannah River picks up the majority of its silt load in the Piedmont Region, and most of this silt load is deposited in the large reservoirs located in the Piedmont Region.

The Coastal Plain has a negligible gradient ranging from an elevation of 200 ft (61 m) to sea level. The soils of this region are primarily stratified sand, silts, and clays. The Coastal Plain contains 3,366 mi^2 (8,718 km^2) (31%) of the total Savannah River drainage area (10,681 mi^2 [27,664 km^2]) and includes the city of Savannah, Georgia. In the Coastal Plain, the Savannah River is slow moving. Tidal effects may be observed up to 40 mi (65 km) upriver, and a salt front extends upstream along the bottom of the riverbed for about 20 mi (32 km).

Dredging operations on the Savannah River have been conducted by the U.S. Army Corps of Engineers between the cities of Savannah and Augusta, Georgia. This program, initiated in October 1958, was designed to dredge and maintain a 9-ft (2.7-m) navigation channel in the Savannah River from Savannah to Augusta, Georgia. Sixty-one sets of pile dikes were placed to constrict the river flow, thereby increasing flow velocities, and 38,000 linear feet of wood and stone revetment was laid to reduce erosion on banks opposite from the dikes. In addition, the channel was dredged and 31 cutoffs were made, reducing the total river distance from Augusta to Savannah by about 15 river-mi (24.1 river-km). The project was completed in July 1965; periodic dredging was continued to maintain the channel until 1985.

SRS is located in the Coastal Plain Province of the Savannah River, about 25 mi (40.2 km) downstream of Augusta, Georgia. Construction of upriver reservoirs (Strom Thurmond, Richard B. Russell, Hartwell, Keowee, and Jocassee) and the New Savannah River Bluff Lock and Dam have reduced the variability of the river flow. Low flows in the Savannah River typically occur during the autumn months while higher flows occur in late winter and early spring.

Upstream of SRS at Augusta, Georgia, the average flow for the 81-year period of record is 10,027 cfs. The average flow at Augusta since the filling of Thurmond Lake (Clarks Hill) has been 9,571 cfs (Table 1.3.4-1). Flows increase below Augusta to about 12,009 cfs near Clyo, Georgia, about 100 mi (161 km) downriver (Table 1.3.4-1). The 7Q10 flow at Augusta is 3,746 cfs.

The peak historic flow for the 81-year period of record was 350,021 cfs in 1929. Since the construction of the upstream reservoirs, the maximum average monthly flow has been 43,867 cfs for the month of April.

Natural discharge patterns on the Savannah River are cyclic: the highest river levels are recorded in the winter and spring, and lowest levels are recorded in the summer and fall. Stream flow on the Savannah River near the site is regulated by a series of three upstream reservoirs: Thurmond, Russell, and Hartwell. These reservoirs have stabilized average, annual stream flow to 10,200 cfs near Augusta and 10,419 cfs at SRS.

The river overflows its channel and floods the swamps bordering the site when its elevation rises higher than 88.5 ft (27 m) above msl (which corresponds to flows equal to or greater than 15,470 cfs). River elevation measurements made at the SRS Boat Dock indicate that the swamp was flooded approximately 20% of the time (74 days per year on the average) from 1958 through 1967.

The Savannah River forms the boundary between Georgia and South Carolina. Upstream of SRS, the river supplies domestic and industrial water needs for Augusta, Georgia, and North Augusta, South Carolina. The river receives treated wastewater from these municipalities and from Horse Creek Valley (Aiken, South Carolina). The Savannah River Class B waterway is used for commercial and sport fishing and pleasure boating downstream from SRS.

Water withdrawn from the river is used for various SRS activities. The Savannah River downstream from Augusta, Georgia, is classified by the State of South Carolina as a Class B waterway, which is suitable for agricultural and industrial use, the propagation of fish, and after treatment, domestic use. The river upstream from the site supplies municipal water for Augusta, Georgia (river-mi 187 [river-km 301]), and North Augusta, South Carolina (river-mi 201 [river-km 323]). Downstream, the Beaufort-Jasper Water Authority in South Carolina (river mile 39.2) withdraws water to supply a population of about 51,000. The Cherokee Hill Water Treatment Plant at Port Wentworth, Georgia (river-mi 29.0 [river-km 46.7]) withdraws water to supply a business-industrial complex near Savannah, Georgia, that has an estimated consumer population of about 20,000. It is estimated that each individual served by the two water treatment plants consumes an average of 0.34 gal (1.3 L) of water per day. Site expansions for both systems are planned for the future.

SRS was once a major user of water from the Savannah River and withdrew a maximum of 920 cfs from the river. Currently, all SRS reactors are shut down, and river water withdrawals are minimal. Past operations typically removed about 9% of the average annual Savannah River flow, but river water usage averaged 0.133 cfs during the second quarter of 1995.

In 1995, DOE decided to discharge a minimum flow of 10 ft^3 (0.28 m^3) per second to Lower Three Runs and to allow the water level in Par Pond to fluctuate naturally near its operating level (200 ft [61 m] above msl) but not allowing the water level to fall below 195 ft (59.4 m). Additionally it was decided to reduce the flow to L Lake so long as the normal operating level of 190 ft (57.9 m) was maintained and the flow in Steel Creek (downstream of L Lake) was greater than 10 cfs.

Currently, only one of the pumps at pumphouse 3G is operated; it supplies 23,000 gpm (1.5 m^3/sec), which is more than is needed for system uses. The excess water is discharged from reactor areas to Fourmile Branch, Pen Branch, L Lake, and the headwaters of Steel Creek.

The river also receives sewage treatment plant effluents from Augusta, Georgia; North Augusta, Aiken, and Horse Creek Valley, South Carolina; and other waste discharges along with the heated SRS cooling water via its tributaries. Vogtle Electric Generating Plant (VEGP) withdraws an average of 92 cfs from the river for cooling and returns an average of 25 cfs. The Urquhart Steam Generating Station at Beech Island withdraws approximately 261 cfs of once-through cooling water. Upstream, recreational use of impoundments on the Savannah River, including water contact recreation, is more extensive than it is near SRS and downstream. No uses of the Savannah River for irrigation have been identified in either South Carolina or Georgia.

The Beaufort-Jasper Water Authority in South Carolina (river-mi 39.2 [river-km 64.1]) withdraws about 8 cfs to supply domestic water for a population of about 51,000. The Cherokee Hill Water Treatment Plant at Port Wentworth, Georgia (river-mi 29.0 [river-km 46.7]) withdraws about 50 cfs from the river to supply a business-industrial complex near Savannah, which has an estimated consumer population of about 20,000.

Based on available information, the following sections describe surface hydrology in reference to specific local facilities.

1.3.4.1.1.1 F Area and MFFF Site

Surface drainage for F Area and surrounding land drains into Upper Three Runs and Fourmile Branch as shown on the topographic map in Figure 1.3.4-5. The MFFF site is adjacent to F Area as shown in Figure 1.3.4-6 and is at an elevation of approximately 270 ft (82.3 m) above msl. The nearest significant stream to F Area and the MFFF site is Upper Three Runs, which is located about 0.7 mi (1.1 km) north and west of F Area. Upper Three Runs flows at elevations below 150 ft (45.7 m) above msl and has a mean annual flow at a gauging station approximately 3 mi (4.8 km) from F Area of 215 cfs and approximately 245 cfs at its mouth. The measured maximum flow for the period 1974 to 1986 was about 950 cfs. Runoff due to precipitation from F Area and the MFFF site is diverted into storm sewers and then discharged into an unnamed tributary of Upper Three Runs, which empties into the Savannah River.

1.3.4.1.2 Hydrosphere – Surface Waters

Surface water includes marine or freshwater bodies that occur above the ground surface, including rivers, streams, lakes, ponds, rainwater catchments, embayments, and oceans.

1.3.4.1.2.1 Savannah River

SRS is bounded on the southwest for approximately 17 mi (27 km) by the Savannah River. Six streams flow through SRS and discharge into the Savannah River: Upper Three Runs, Beaver Dam Creek, Fourmile Branch, Pen Branch, Steel Creek, and Lower Three Runs. Upper Three Runs has two tributaries (Tims Branch and Tinker Creek); Pen Branch has one tributary (Indian Grave Branch); and Steel Creek has one tributary (Meyers Branch).

The Savannah River Basin (Figure 1.3.4-4) is one of the major river basins in the southeastern United States. It has a drainage area of 10,577 mi^2 (27,394 km^2) of which 8,160 mi^2 (21,134 km^2) are upstream of SRS. The headwaters of the Savannah River are in the Blue Ridge Mountains of North Carolina, South Carolina, and Georgia. The river forms at the junction of the Tugaloo and Seneca Rivers approximately 100 mi (161 km) northwest of SRS, now the site of Hartwell Reservoir, and empties into the Atlantic Ocean near Savannah, Georgia, approximately 95 mi (153 km) southeast of SRS. From the Hartwell Reservoir Dam to the Savannah Harbor, the river runs a course of 289 river-mi (465 river-km).

Three large reservoirs on the Savannah River upstream of SRS provide hydroelectric power, flood control, and recreation. Strom Thurmond Reservoir (2.51 million acre-feet), completed in 1952 (Table 1.3.4-2), is approximately 35 mi (56.3 km) upstream of SRS. The Richard B. Russell Reservoir (1.026 million acre-feet), completed in 1984, is approximately 72 mi (116 km) upstream of SRS. Hartwell Reservoir (2.549 million acre-feet), completed in 1961, is approximately 90 mi (145 km) upstream of SRS (Figure 1.3.4-7). These three dams are owned by the U.S. Army Corps of Engineers. The Stevens Creek Dam, also on the Savannah River, is owned by South Carolina Electric and Gas (SCE&G).

Additional dams lie upstream of Hartwell Reservoir and are used primarily for hydroelectric power generation (Figure 1.3.4-7). The Yonah, Tugaloo, Tallulah Falls, Mathis, Nacoochee, and Burton Dams are owned by Georgia Power Company, and the Keowee, Little River, and Jocassee Dams are owned by Duke Power Company. Although many of these dams impound water to depths in excess of 100 ft (30.5 m), only the Jocassee Dam and the combined Little River-Keowee Dams impound significant quantities (approximately 1 million acre-feet each).

Dredging operations on the Savannah River are discussed in section 1.3.4.1.1 above. The Savannah River is gauged above SRS near Augusta, Georgia (station 02197000), 0.5 mi (0.8 km) downstream from Upper Three Runs at Ellenton Landing (station 02197320), at Steel Creek (station 02197357), and below SRS at Burtons Ferry Bridge (station 02197500) and 3 mi (4.8 km) north of Clyo, Georgia (station 02198500) (Figure 1.3.4-4). Since upstream stabilization, the yearly average flow of the Savannah River near SRS has been approximately 10,419 cfs. Flow extremes are discussed in Section 1.3.4.2. The elevation of the river at SRS pumphouses is 80.4 ft (24.5 m) above msl at a flow of 5,800 cfs. The Savannah River has a flow of 5,800 cfs and has an average velocity of approximately 2 mph at VEGP, which is across the river from SRS (Figure 1.3.4-4). The river is about 340 ft (1.4 m) wide and from 9 to 16 ft (2.7 to 4.9 m) deep. The minimum flow that is required for navigation downstream from Strom Thurmond Dam is 5,800 cfs. From SRS, river water usually reaches the coast in approximately five to six days but may take as few as three days.

Three locations below the mouth of Upper Three Runs pump raw water from the Savannah River for drinking water supplies. The Cherokee Hill Water Plant at Port Wentworth, Georgia (Figure 1.3.4-4), can withdraw about 70 cfs for an effective consumer population of about 20,000. The Beaufort-Jasper Water Treatment Plant at Hardeeville, South Carolina (Figure 1.3.4-4), can withdraw about 12 cfs for a consumer population of approximately 51,000. The SRS D Area, downstream of the mouth of Upper Three Runs, removes approximately 0.1 cfs from the river.

Savannah River water is also used for industrial water cooling purposes by several facilities. SRS is a major user, with intake points downstream of the confluence of Upper Three Runs with the Savannah River. SRS could remove 1,450 cfs with all pumps in three pumphouses concurrently in use, but it usually withdraws a maximum of 1,320 cfs from the river. The coal-fired power plant in D Area receives about 100 cfs, and Par Pond receives about 20 cfs to compensate for seepage and evaporation. VEGP uses 100 cfs and SCE&G's Urquhart Steam Station, located between Augusta and SRS (Figure 1.3.4-4), uses 260 cfs.

1.3.4.1.2.2 Upper Three Runs

Upper Three Runs is the longest of the onsite streams. It drains an area of over 195 mi^2 (505 km^2) and differs from the other five onsite streams in two respects. It is the only stream with headwaters arising outside the site. It is the only stream that has never received heated discharges of cooling water from the production reactors. Tims Branch receives primarily treated industrial waste waters from M Area, Savannah River Technology Center (SRTC), a small coal-fired plant, and treated sanitary wastewater and remediated groundwater from A and M Areas.

The minimum and maximum flow history for Upper Three Runs is discussed in Section 1.3.4.2. The Upper Three Runs stream channel has a low gradient and is meandering, especially in the lower reaches. Its floodplain ranges in width from 0.25 to 1 mi (0.4 to 1.6 km) and contains extensive stands (about 98% coverage) of bottomland hardwood forest. Within SRS, the Upper Three Runs valley is asymmetrical, having a steep southeastern side and a gently sloping northwestern side.

Upper Three Runs is gauged near Highway 278 (station 02197300 relocated downstream), at SRS Road C (station 02197310), and at SRS Road A about 3 mi (4.8 km) above the confluence of Upper Three Runs with the Savannah River (station 02197315) (Figure 1.3.4-4). The Highway 278 station is a National Hydrologic Benchmark Station. Benchmark streams are measured monthly for water flow, temperature, and quality to provide hydrologic data on river basins governed by natural conditions.

The average Upper Three Runs flow at Highway 278 from 1966 to 1986 was 106 cfs, which represents a water yield of about 1.0 ft^3/mi^2 or 16.55 in/yr from the drainage basin. The average annual precipitation at SRS is 48.3 in (123 cm). Thus, in the upper reaches of Upper Three Runs, about 35% of the rainfall appears as stream discharge. Flow rates are also measured downstream of the Highway 278 site at SRS Road C and at SRS Road A. Average daily flows were calculated to be 102, 203, and 251 cfs, respectively. The minimum daily flow rates recorded at these sites during this period were 45, 117, and 124 cfs, respectively.

1.3.4.1.2.3 Fourmile Branch

Fourmile Branch drains about 23 mi^2 (59.6 km^2) within SRS, including much of F, H, and C Areas (Figure 1.3.4-3). The creek flows to the southwest into the Savannah River Swamp and then into the Savannah River. The valley is V-shaped, with the sides varying from steep to gently sloping. The floodplain is up to 1,000 ft (305 m) wide. No human population resides in the Fourmile Branch drainage.

Fourmile Branch receives effluents from F, H, and C Areas; and a groundwater plume from a radioactive waste burial ground (southeast of F Area), F-Area Seepage Basin (southwest of F Area), and H-Area Seepage Basin (use discontinued in November 1988). Until June 1985, it received large volumes of cooling water from the production reactor in C Area. The creek valley has been modified by the cooling water discharge, which has created a delta into the Savannah River Swamp. Downstream of this delta area, it re-forms into one main channel, and most of the flow discharges into the Savannah River at river-mi 152.1 (river-km 245). When the Savannah River floods, water from Fourmile Branch flows along the northern boundary of the floodplain and joins with other site streams to exit the swamp via Steel Creek instead of flowing directly into the Savannah River. Fourmile Branch also receives tritium and strontium-90 migrating from the F- and H-Area Seepage Basins and the Solid Waste Management Facility (SWMF).

Water flow measurements have been made on Fourmile Branch near SRS Road A-12.2 at SRS (station 02197344) since November 1976. Mean monthly flows for water years 1986 and 1987, after C-Reactor shutdown, ranged from 88 cfs in January 1986 to 17 cfs in August 1987. Extreme flows for this period were 436 cfs (gage height 3.14 ft [0.96 m]) on March 1, 1987, to 13 cfs on August 24-25 and 28-29, 1987. The maximum and minimum discharges for the period of record are 903 cfs (gage height 3.93 ft [1.2 m]) on March 13, 1980, and 13 cfs on August 24-25 and 28-29, 1987, respectively.

1.3.4.1.3 Environmental Acceptance of Effluents

All National Pollutant Discharge Elimination System (NPDES) permitted outfalls within SRS are identified in the annual SRS Environmental Report (WSRC 1997b).

1.3.4.1.4 Chemical and Biological Composition of Adjacent Watercourses

1.3.4.1.4.1 Upper Three Runs

The Upper Three Runs valley is swampy with a meandering and braided channel, especially in the lower reaches. In SRS, the stream has a gradient of approximately 5.3 ft/mi (1 m/km). Upper Three Runs stream channel sediments have sand as the dominant fraction, with silt plus clay fractions increasing to about 40% at SRS Road A.

Upper Three Runs is a slightly dystrophic, large, cool, blackwater stream that flows into the Savannah River. The stream is neutral to somewhat acidic and carries a relatively low load of suspended and dissolved organics compared to other streams of the southeastern Atlantic Coastal Plain. Suspended solid loads are heaviest during periods of highest stream flow, normally late winter to early spring when vegetative cover is reduced. From the upper to lower reaches, the suspended load increases substantially. Although inorganic sediments are preferentially deposited in the floodplains, there is a concurrent input of organics from the floodplains, which causes an increase in total suspended solids (mostly organic matter). This increase is more pronounced in periods when the stream overflows its banks and floods the surrounding swamps. Water quality samples for Upper Three Runs are collected monthly, and the data are presented in the annual SRS Environmental Report (WSRC 1997b).

The water of Upper Three Runs is soft, usually clear, and low in nutrients. The temperature ranges from approximately 41°F to 78°F (5°C to 26°C), with lows occurring from December through February. The highest temperature and lowest flow are normally observed in July. Temperature, pH, and dissolved oxygen levels in the stream meet South Carolina Water Classification Standards for Class B streams. Conductivity, suspended solids, and alkalinity concentrations increase in the downstream direction, but the concentrations are low at all stations. Nutrient levels are also low, although phosphorus and nitrate levels are highest during the spring and summer, possibly due to offsite agricultural activities.

The effluents include process wastes, cooling water, surface runoff, and ash basin effluent. The F/H-Area Effluent Treatment Facility (ETF) discharges into Upper Three Runs near SRS Road C. Tims Branch (Figure 1.3.4-2), a tributary to Upper Three Runs, has received trace amounts of radioactivity and heavy metals contamination and is currently receiving elevated levels of nitrates from M Area. Total discharges to Upper Three Runs range from approximately 10 gpm to over 1,000 gpm. By comparison, the minimum recorded flow at the Highway 278 gage about 10 mi (16.1 km) upstream on Upper Three Runs is 66 cfs, which is approximately 30,000 gpm.

The cation exchange capacity (CEC) ranged from 0.1 to 12.4 milliequivalent per 100 grams (meq/100 g) in all Upper Three Runs and tributary sediments, indicating low CEC values throughout the Upper Three Runs watershed. Elevated levels of nickel were found in Tims Branch sediments, probably originating from the nickel-plating operations in M Area. Sediments from the Upper Three Runs watershed exhibited background levels of Cs-137 ($\leq$ 2 pCi/g) and naturally occurring radionuclides (K-40, radium, Tl-208, and natural uranium).

The swamp forest of the Upper Three Runs floodplain consists primarily of bald cypress (*Taxodium distichum*) and tupelo gum (*Nyssa aquatica*), while the bottomland hardwoods associated with the stream are mostly sweet gum (*Liquidambar styraciflua*), red oak (*Quercus rubra*), and beech (*Fagus grandifolia*). The stream is well shaded in most reaches.

Leaf litter input is high, and the leaves are rapidly broken down by macroinvertebrate shredders. The relatively complete canopy results in low periphyton and macrophyte biomass, especially in summer when the creek is most shaded. The periphytons that do occur are largely green algae and diatoms.

Sampling conducted in 1984 and 1985 found ichthyoplankton densities to be low, with spotted suckers the dominant taxon. Crappie and darters also composed a large portion of the overall ichthyoplankton population. The dominant fish species found were redbreast sunfish, spotted suckers, channel catfish, and flat bullhead. Species numbers tend to peak in the spring and drop in the summer.

1.3.4.1.4.2 Fourmile Branch

Fourmile Branch originates on SRS and flows southwest across the site toward the Savannah River. In the Savannah River Swamp, when C Reactor operated, part of Fourmile Branch flowed to Beaver Dam Creek, which flows directly into the Savannah River through a breach in the natural levees. With C Reactor shut down, Fourmile Branch flows parallel to the river behind the natural levees and enters the river through a breach downriver from Beaver Dam Creek.

Fourmile Branch receives nonradioactive effluents from C, F, and H Areas, which increase the hardness, nutrient content, and trace metal concentrations in the water. From March 1955 to June 1985, Fourmile Branch also received 180,000 gpm of cooling water from the production reactor in C Area. During this period, water quality in the thermal reaches of the creek generally reflected the waters of the Savannah River, which served as source water for C Reactor.

Fourmile Branch has been greatly influenced by the temperature and volume of cooling water it once received from the C-Area production reactor. The native swamp forest has been eliminated, and the stream is mostly unshaded. Above its thermal reach, the water quality of Fourmile Branch resembles that of other nonthermal streams on the site. Samples taken from 1983 to 1985 showed this portion of Fourmile Branch to have higher conductivity, nitrate (as N), calcium, and sodium levels than Upper Three Runs. Levels of copper, cadmium, mercury, nickel, lead, chromium, and zinc were at or near detection limits. Water temperatures in the nonthermal reaches of Fourmile Branch averaged approximately 62.6°F (17°C), with highs usually less than 86°F (30°C).

Water quality samples for Fourmile Branch are collected monthly, and the data are presented in the annual SRS Environmental Report (WSRC 1997b). The mean temperature, the pH range, and the mean dissolved oxygen concentration were similar to those for Upper Three Runs at SRS Road C during the same period. The mean concentrations of most other parameters measured were higher or approximately equal to those for Upper Three Runs. Turbidity, volatile solids, chemical oxygen demand, nitrites, nitrates, and manganese were lower in Fourmile Branch than in the lower reaches of Upper Three Runs (measured at SRS Road C).

When C Reactor was in operation, only the thermophilic blue-green algae (i.e., *Phormidium* and *Oscillatoria* spp.) survived regularly in waters exceeding 122°F (50°C). Leaf decomposition was low due to the absence of macroinvertebrate shredders. The macroinvertebrate populations exhibited low biomass and low densities except for some oligochaetes, nematodes, and chironomids that were more tolerant to heat. Upstream from this zone, diatoms were the predominant and most diverse primary producers. Blue-green algae of the genera Microcoleus, Schizothrix, and Oscillatoria were found in decaying organic surfaces such as submerged logs and leaf litter. Besides the thermophilic blue-green algae, the mosquito fish was the only other survivor during periods of thermal stress.

Following reactor shutdown in 1985, the macroinvertebrate density and biomass increased. Many fish species have readily reinvaded during this period, and fish catch rates have increased markedly. It is expected that the current biology of Fourmile Branch will more closely resemble that of other site streams.

1.3.4.2 Floods

This section describes the flood history and potential types of flooding at SRS. The section also discusses design considerations, frequency and effects of locally intense precipitation at the MFFF site, and flood protection requirements at the MFFF site. The probable maximum flood (PMF) at the site is characterized by a water level of 224.5 ft (68.4 m) above msl, as discussed in Section 1.3.4.2.3. The design basis flood for the MFFF site is based on an annual recurrence frequency of 1×10^{-5} and is associated with a water level of 207.9 ft (63.4 m) above msl, as discussed in Section 1.3.4.2.4.

1.3.4.2.1 Flood History

All the floods represented by the data in this section were the result of excess precipitation runoff and the associated creek or stream flooding. No floods have been caused by surge, seiche, dam failure, or ice jams.

1.3.4.2.1.1 Flood History of the Savannah River

Annual maximum daily flows for the Savannah River are presented in Table 1.3.4-3. Historical records span from 1796 to1999. The earliest historical data were determined primarily from high-water marks; flow gauging by the USGS began in 1882. The record historical flood at Augusta, Georgia, occurred in 1796, with an estimated discharge of 360,000 cfs; the peak flow recorded by the USGS (350,000 cfs) occurred on October 3, 1929. Since Strom Thurmond Dam was constructed, no major flood has occurred at Augusta, Georgia. The U.S. Army Corps of Engineers simulated the October 3, 1929, storm event using current control requirements. The unregulated peak flow of 350,000 cfs resulted in a regulated peak flood flow of 252,000 cfs at Augusta, Georgia.

A statistical analysis of Savannah River annual maximum flows downstream at Augusta, Georgia, was conducted using the Log Pearson Type III distribution. For the 30-year period from 1921 to 1950, before construction of Strom Thurmond Dam, the mean annual maximum flow was 92,600 cfs, the 10-year maximum flow was 211,000 cfs, and the estimated 50-year maximum flow was 362,000 cfs. After construction of the Strom Thurmond Dam, the Savannah River flows were controlled to meet various demands: hydroelectric power, water supply allocations, flood control, water qualities, habitat, recreation, and aquatic plant control. For the 44-year period from 1956 to 1999, after construction of Strom Thurmond Dam, the mean annual maximum flow, based on mean daily flow rates, was 36,300 cfs, the 10-year maximum flow was 55,400 cfs, and the estimated 50-year maximum flow was 74,600 cfs.

1.3.4.2.1.2 Flood History of Upper Three Runs

The instantaneous annual maximum flows for Upper Three Runs gauging stations at Highway 278 near SRS Road C and at SRS Road A are listed in Table 1.3.4-4. The station at Highway 278 has the longest historical record.

For Upper Three Runs at Highway 278, the maximum flood recorded was 820 cfs on October 23, 1990, and the corresponding flood stage elevation was 183.5 ft (55.9 m) above msl. Similarly, the maximum flow at SRS Road C was 2,040 cfs (129.4 ft [39.4 m] above msl) on October 12, 1990, and at SRS Road A was more than 2,580 cfs (97.9 ft [29.8 m] above msl) on October 12, 1990. No dams are located in the Upper Three Runs watershed.

1.3.4.2.1.3 Flood History of Tims Branch

The annual maximum daily flows for station 02197309 on Tims Branch at SRS Road C are listed in Table 1.3.4-5. Data for water years 1974, 1975, and 1977 to 1984 were not available.

The maximum flood discharge recorded for Tims Branch was 129 cfs on October 12, 1990, with a corresponding gage height of approximately 145.7 ft (44.4 m) above msl. The highest flood stage level recorded was approximately 146.7 ft (44.7 m) above msl on May 29, 1976.

1.3.4.2.1.4 Flood History of Fourmile Branch

The annual instantaneous maximum flows for Fourmile Branch gage stations at SRS Road C, SRS Road A-7, and SRS Road A-12.2 are listed in Table 1.3.4-6. The maximum floods occurred on August 2, 1991. The flood elevation at SRS Road C was 194.2 ft (59.2 m) above msl, at SRS Road A-7 was 161.9 ft (49.3 m) above msl, and at SRS Road A-12.2 was 116.7 ft (35.6 m) above msl.

1.3.4.2.2 Flood Design Considerations

The MFFF site is located on topographic high points and is well inland from the coast. The only significant impoundments, Par Pond and L Lake, are relatively small and sufficiently lower than the MFFF site. There is no safety threat to the MFFF site from high water.

The calculated PMF water level for the Savannah River at the VEGP site (Figure 1.3.4-4) is 118 ft (36 m) above msl without wave run-up. With wave run-up, the water may reach as high as 165 ft (50.3 m) above msl. Because the minimum plant grade near the MFFF site is approximately 270 ft (82.3 m) above msl, it is well above the flood stage. If the valley storage effect between Strom Thurmond Dam and VEGP is taken into account, this results in a lower flood peak and lower flood stage.

Flood levels due to precipitation, as a function of return period (annual probability of exceedance), for the Upper Three Runs, Tims Branch, Fourmile Branch, and Pen Branch basins have been calculated. Results indicate that the probabilities of flooding at F Area and the MFFF site are significantly less than 1.0E-05 per year. The basin hydrologic routing method was used to calculate the flood level as a function of the annual probability of exceedance, as described in Section 1.3.4.2.4.

1.3.4.2.3 Effects of Local Intense Precipitation

This section describes flood design considerations for F Area and the MFFF site. Unusually intense local rainfalls occurred on SRS on July 25, 1990; August 22, 1990; October 10-12, 1990; and October 22-23, 1990. Although over 6 in (15.2 cm) of rain fell in a 10-mi^2 (25.9 km^2) area during the August 22 storm, this amount is just 20% of the six-hour probable maximum precipitation (PMP) of 31.0 in (78.7 cm).

1.3.4.2.3.1 F Area and MFFF Site

The six-hour, 10-mi^2 (25.9 km^2) PMP is 31 in (78.7 cm), with a maximum intensity of 15.1 in (38.4 cm) in one hour. This rainfall was adjusted to a point PMP of 19 in (48.3 cm) in one hour and used to generate the PMF for the small watershed of the unnamed tributary on Upper Three Runs. The unnamed tributary on Upper Three Runs is near F Area and is located about 0.40 mi (0.6 km) northwest of F Canyon. Incremental rainfall for one-hour periods adjacent to the PMP was also determined as shown in Table 1.3.4-7. A synthetic hydrograph was used to determine peak flow. The peak stage corresponding to the PMF is 224.5 ft (68.4 m) above msl or approximately 45 ft (13.7 m) below the F-Area and MFFF site grade. Because F Area and the MFFF site lie near a watershed divide, incident rainfall naturally drains away from the facilities.

Unusual short-duration heavy rainfall occurred in F Area in August 1990 and October 1990. Total rainfall measured in F Area was as follows:

- On August 22, 1990, 6.1 in (15.5 cm) of rainwater was collected
- Between October 11 and 12, 1990, about 10 in (25.4 cm) was collected.

1.3.4.2.4 Flood Hazard Recurrence Frequencies

Flood levels have been calculated due to precipitation as a function of annual probability of exceedance for Upper Three Runs, Tims Branch, Fourmile Branch, Pen Branch, and Steel Creek upstream from L-Lake basins. A basin hydrologic routing method was employed to calculate the flood level as a function of the annual probability of exceedance. The procedures used for the method are presented next.

Step 1. Hyetographs (rainfall depth or intensity as a function of time) for various return periods were synthesized based on rainfall intensity-duration-frequency data.

Step 2. The Hydrologic Modeling System computer code was used to calculate basin peak flow based on the hyetograph for a given return period and basin properties.

Step 3. The peak flow calculated by HEC-HMS (Step 2) was then used in the Computer Model for Water Surface Profile Computations (WSPRO) to calculate the flood water elevations. WSPRO was developed by the USGS for the Federal Highway Administration. WSPRO uses a step-backwater analysis method to calculate water surface elevations for one-dimensional, gradually varied, steady flow through bridges and overtopping embankments.

Step 4. Steps 2 and 3 were repeated for each return period.

Steps 1 through 4 were applied to both the Upper Three Runs and Fourmile Branch basins.

1.3.4.2.4.1 Design Basis Flood

Flood flows and elevations for the Upper Three Runs, Tim Branch, Fourmile Branch, and Pen Branch basins were calculated by the steps described above. Table 1.3.4-8 presents the synthesized 24-hour storm hyetographs for various annual probabilities of exceedance. Table 1.3.4-9 shows the calculated flood elevations at A, C, E, F, H, K, S, Y, and Z Areas, and Table 1.3.4-10 shows the MFFF site design basis flood as a function of performance category, respectively. The design basis flood for DOE moderate hazard (PC-3) and high hazard (PC-4) facilities is given in Table 1.3.4-10. MFFF principal SSCs are evaluated for an annual recurrence frequency of 1×10^{-5} for a design basis flood with an elevation of 207.9 ft (63.4 m) above msl. The elevation of the MFFF site is 272 ft (82.9 m) above msl. The MFFF site is a dry site for consideration of the design basis flood.

1.3.4.2.5 Potential Dam Failures (Seismically Induced)

1.3.4.2.5.1 Reservoir Description

The only significant dams or impoundment structures that could affect the safety of SRS are large dams on the Savannah River and its tributaries upstream of Augusta, Georgia (Figure 1.3.4-7). Section 1.3.4.1 contains information on these structures. The Stephens Creek Dam is owned by SCE&G. All other dams on the Savannah River are owned by the U.S. Army Corps of Engineers. The dams on the Tugaloo and Tallulah rivers are owned by Georgia Power Company. The dams on the Keowee and Little Rivers are owned by Duke Power Company.

1.3.4.2.5.2 Dam Failure Permutations

A domino failure of the dams on the Savannah River and its tributaries upstream of VEGP was analyzed in the VEGP Final SAR (Georgia Power Company 1987). The worst possible case resulted from Jocassee Dam failing during a combined standard project flood and earthquake, with the resulting chain reaction.

Using conservative assumptions, this worst dam failure would yield a peak flow of 2,400,000 cfs at Strom Thurmond Dam. This rate, undiminished in magnitude, was transferred to below Augusta, Georgia. However, because of the great width of the floodplain, routing of the dam failure surge to the VEGP site (river-mi 151 [river-km 243]) resulted in a peak discharge of 980,000 cfs, with a corresponding stage of 141 ft (43 m) above msl.

1.3.4.2.5.3 Unsteady Flow Analysis of Potential Dam Failures

No dams are located near SRS areas. Therefore, this section does not apply.

1.3.4.2.5.4 Water Level at Facility Site

The peak water surface elevation of the Savannah River that corresponds to wave run-up of a wind-induced wave, superimposed upon the passage of a flood wave resulting from a sequence of dam failures, is discussed in Section 1.3.4.2.2.

1.3.4.2.6 Probable Maximum Surge and Seiche Flooding

No large water bodies exist near the site; therefore, this section does not apply. Run-up of flood waters from the worst combination of wind and waves on the Savannah River is not a hazard at the site because the peak flood elevation is well below minimum plant grade, and the maximum wave under the worst circumstances is less than 3 ft (0.9 m).

1.3.4.2.7 Ice Flooding

Because of regional climatic conditions, the formation of significant amounts of ice on streams and rivers rarely occurs. The Hartwell, Richard B. Russell, and Strom Thurmond dams moderate water temperature extremes, making ice formation on the Savannah River at SRS unlikely.

No historical ice flooding has been noted, although ice has, on several occasions, been observed in the Savannah River. Because the sites are so much higher than the nearest streams and rivers, it is not considered credible that they could be affected by ice flooding, even if the climatic conditions were conducive to ice formation.

1.3.4.2.8 Flooding Protection Requirements

Because the site is located on a local topographic high, there is no threat to SRS from flooding, as described in previous sections. Special flooding protection requirements are not necessary to ensure the safety of F Area and the MFFF site because they are located at elevations well above the maximum flood.

1.3.4.3 Regional Hydrogeology (Within 75-Mile Radius)

1.3.4.3.1 Regional Hydrogeological Setting

Two hydrogeologic provinces are recognized in the subsurface beneath the SRS region (Figure 1.3.4-9). The uppermost province, which consists of the wedge of unconsolidated Coastal Plain sediments of Late Cretaceous and Tertiary ages, is referred to as the Southeastern Coastal Plain hydrogeologic province. It is further subdivided into aquifer or confining systems, units, and zones. The underlying province, referred to as the Piedmont hydrogeologic province, includes Paleozoic metamorphic and igneous basement rocks and Upper Triassic lithified mudstone, sandstone, and conglomerate in the Dunbarton basin (see Section 1.3.5.1). For reference, a geological time scale is shown in Figure 1.3.4-10.

The following hydrogeological characteristics are of particular interest.

- The layered structure of the coastal plain sediments effectively controls migration of contaminants in the subsurface, limiting vertical migration to deeper aquifers.
- Between the ground surface and the primary drinking water aquifer(s) are several low permeability zones, which restrict vertical migration from a given point source.
- The abundance of clay size material and clay minerals in the aquifer and aquitard zones affects groundwater composition and vertical migration. The concentration of some potential contaminants, especially metals and radionuclides, may be attenuated by exchange and fixation of dissolved constituents on clay surfaces.
- The recharge area(s) for the deeper drinking water aquifers used are updip of SRS, near the Fall Line. Some recharge areas are located at the northernmost fringe of the site.
- Recharge for the water table aquifers, namely the Upper Three Runs and Gordon aquifers, is primarily from local precipitation.
- Discharge of groundwater from the Upper Three Runs and Gordon aquifers is typically to the local streams on SRS.
- Groundwater at SRS is typically of low ionic, low dissolved solids and moderate pH (typically ranging from 4.4 to 6.0). Other constituents such as dissolved oxygen and alkalinity are more closely associated with recharge and aquifer material. Dissolved

oxygen is typically higher in the updip and near-surface recharge areas, and alkalinity, pH and dissolved solids are typically higher in those portions of the aquifer regions containing significant carbonate materials.

- The presence of an upward vertical gradient or "head reversal" between the Upper Three Runs and Gordon aquifers and the Crouch Branch aquifer is significant in that it prevents downward vertical migration of contaminants into deeper aquifers over much of central SRS (Figure 1.3.4-11).

1.3.4.3.2 Hydrostratigraphic Classification and Nomenclature of Coastal Plain Sediments

The method for establishing a nomenclature for the hydrogeologic units in the following discussion generally follows the guidelines set forth by the South Carolina Hydrostratigraphic Subcommittee.

A hydrogeologic unit is defined by its hydraulic properties (i.e., hydraulic conductivity, hydraulic head relationships, porosity, leakance coefficients, vertical flow velocity, and transmissivity) relative to those properties measured in the overlying and underlying units. The properties are measured at a type well or type well cluster location (Figure 1.3.4-12). Aquifers and confining units are mapped on the basis of the hydrogeologic continuity, potentiometric conditions, and leakance-coefficient estimates for the units. These properties are largely dependent on the thickness, areal distribution, and continuity of the lithology of the particular unit. However, a hydrogeologic unit may traverse lithologic unit boundaries if there is not a significant change in hydrogeologic properties corresponding to the change in lithology.

1.3.4.3.2.1 Delineation and Classification of Units

The hydrostratigraphic classification is based on aquifer and confining units ranked at four levels (I through IV).

Level I - Hydrogeologic Province

A hydrogeologic province is a major regional rock and/or sediment package that behaves as a single unified hydrologic unit. The names, areal extent, and underlying geological context of the regional hydrogeologic provinces used in this report are the same as those defined by Miller and Renken (1988) as regional hydrologic systems. For example, the "Southeastern Coastal Plain *hydrologic* system" of Miller and Renken reads "Southeastern Coastal Plain *hydrogeologic* province" in this report (Figure 1.3.4-13).

Level II - Aquifer and Confining Systems

These define the primary or regional units of the hydrogeologic province. The aquifer system may be composed of a single aquifer or two or more coalescing aquifers that transmit groundwater on a regional basis. Aquifer systems may be locally divided by confining units that impede groundwater movement but do not greatly affect the regional hydraulic continuity of the system. A confining system may be composed of a single confining unit or two or more confining units that serve as an impediment to regional groundwater flow. The regional aquifer/confining systems at SRS are presented in Figures 1.3.4-9 and 1.3.4-14.

SRS is located near the updip limit of the aquifer and confining systems comprising the Coastal Plain sediments in the region. Here, the lateral continuity and thickness of the clay and clayey sand beds that constitute the confining systems decrease, and the beds become increasingly discontinuous. Where the clay beds no longer separate the overlying and underlying aquifers, the updip limit of a confining system is defined. Updip from this line, the overlying and underlying aquifer systems coalesce into a single unified aquifer system. Where aquifer systems have combined, some of the individual aquifer and confining units may persist in the updip-combined system.

Level III - Aquifer and Confining Units

These are the fundamental units of the classification. An aquifer is a mappable (~400 mi^2 [> 1036 km^2]) body of rock or sediments that is sufficiently permeable to conduct groundwater and yield significant quantities of water to wells and springs. A confining unit, on the other hand, is a mappable (~ 400 mi^2 [> 1036 km^2]) body of rock or sediments of significantly lower hydraulic conductivity than an adjacent aquifer that serves as an impediment to groundwater flow into or out of an aquifer. A confining unit's hydraulic conductivity may range from nearly zero to some value distinctly lower than that of the nearby aquifer. The assignment of a unit level and name to a hydrostratigraphic unit does not imply a quantitative ranking of hydraulic continuity but is intended to distinguish relative differences in hydraulic properties between adjacent units. Where the confining unit that separates one aquifer from another thins and becomes laterally discontinuous and/or is breached by faults and fractures, the overlying and underlying aquifers coalesce and a single unified aquifer may be defined. The aquifer/confining units in the SRS region are presented in Figure 1.3.4-13.

Level IV - Aquifer and Confining Zones

Aquifers and confining units may be informally subdivided into zones that are characterized by properties significantly different from the rest of the unit, such as hydraulic conductivity, water chemistry, lithology, and/or color. For example, an aquifer may contain a "confining zone" such as the "tan clay" confining zone of the Upper Three Runs aquifer. Conversely, a confining unit may contain an "aquifer zone" such as the "middle sand" aquifer zone of the Crouch Branch confining unit. The "Fernandina permeable zone" is a zone in the Lower Floridan aquifer in coastal areas of Georgia, where the permeability greatly exceeds that of the rest of the aquifer.

In the study area, zonal differentiation is undertaken on a local site-specific scale where useful and necessary distinctions are made in the hydraulic characteristics of specific aquifer or confining units. Thus, the intermittent but persistent clay beds in the Dry Branch Formation, informally referred to as the "tan clay" in previous SRS reports, is designated the "tan clay" confining zone of the Upper Three Runs aquifer. The "tan clay" confining zone is defined specifically for the Dry Branch clay in the General Separations Area of SRS. Correlative clay beds in other parts of the study area may usefully be designated a confining zone but would be given a separate and distinct name.

1.3.4.3.3 Southeastern Coastal Plain Hydrogeologic Province

The Southeastern Coastal Plain hydrogeologic province underlies 120,000 mi^2 (310,799 km^2) of the Coastal Plain of South Carolina, Georgia, Alabama, Mississippi, and Florida and a small contiguous area of southeastern North Carolina. This hydrogeologic province grades laterally to the northeast into the Northern Atlantic Coastal Plain aquifer system and to the west into the Mississippi embayment and Coastal Lowlands aquifer systems. In South Carolina, the northern and northwestern limits of the province are its contact with crystalline rocks at the Fall Line, which marks the updip limit of Coastal Plain sediments.

The Southeastern Coastal Plain hydrogeologic province comprises a multilayered hydraulic complex in which retarding beds composed of clay and marl are interspersed with beds of sand and limestone that transmit water more readily. Groundwater flow paths and flow velocity for each of these units are governed by the unit's hydraulic properties, the geometry of the particular unit, and the distribution of recharge and discharge areas. The Southeastern Coastal Plain hydrogeologic province can be divided into seven regional hydrologic units. These are four regional aquifer units separated by three regional confining units. Six of the seven hydrologic units are recognized in the SRS area and are referred to as hydrogeologic systems. These systems have been grouped into three aquifer systems divided by two confining systems, all of which are underlain by the Appleton confining system. The Appleton separates the Southeastern Coastal Plain hydrogeologic province from the underlying Piedmont hydrogeologic province. The regional lithostratigraphy and hydrostratigraphic subdivision of the Southeastern Coastal Plain hydrogeologic province is shown in Figure 1.3.4-9.

In descending order, the aquifer systems beneath SRS are the Floridan aquifer system, the Dublin aquifer system, and the Midville aquifer system (Figure 1.3.4-9). In descending order, the confining systems are the Meyers Branch confining system, the Allendale confining system, and the Appleton confining system.

Beneath SRS, the Midville and Dublin aquifer systems each consists of a single aquifer, the McQueen Branch aquifer and Crouch Branch aquifer, respectively. Downdip, beyond SRS, these aquifer systems are subdivided into several aquifers and confining units.

The Floridan aquifer system consists of two aquifers in the study area: the Upper Three Runs aquifer and the underlying Gordon aquifer, which are separated by the Gordon confining unit. Northward, the Gordon and Upper Three Runs aquifers coalesce to form the Steed Pond aquifer.

The Allendale and Meyers Branch confining systems each consists of a single confining unit in the study area: the McQueen Branch and Crouch Branch confining units, respectively. The basal Appleton confining system is thought to consist of a single confining unit in the study area. The confining unit ("Appleton"), however, has not been formally defined owing to insufficient data. Downdip, each confining system may be subdivided into several confining units and aquifer units.

Where the confining beds of the Allendale confining system no longer regionally separate the Dublin and Midville aquifer systems hydrologically, the Dublin-Midville aquifer system is defined (Figures 1.3.4-9 and 1.3.4-14). Similarly, where the Meyers Branch confining system no longer regionally separates the Floridan aquifer system from the underlying Dublin-Midville aquifer system, the entire sedimentary sequence from the top of the Appleton confining system to the water table is hydraulically connected and the Floridan-Midville aquifer system is defined.

In general, the number of aquifer systems present beneath SRS decreases updip (Figure 1.3.4-13) due to pinching out of confining units in the updip direction. Thus, in the southern site area, three aquifer systems are designated. As the confining systems become ineffective flow barriers updip, the number of aquifer systems decreases to one (Floridan-Midville) in the northern site region. As indicated in Figure 1.3.4-13, the nomenclature and stratigraphic position of the two aquifer system areas is dependent on which confining system (Allendale or Meyers Branch) pinches out.

The following discussion treats each of the hydrogeologic units in greater detail. It presents the units in descending order, from the water table to the Piedmont hydrogeologic province. Within each unit, the discussion traces the unit updip. In general, confining layers pinch out and aquifers coalesce in an updip direction.

1.3.4.3.3.1 Floridan Aquifer System

The Floridan aquifer system is defined as a vertically continuous sequence of carbonate rocks of generally high permeability that are mostly of middle and late Tertiary age. The rocks are hydraulically connected in varying degrees, and their permeability is generally an order to several orders of magnitude greater than that of the rocks that bound the system above and below. Thus, the definition of the Floridan aquifer system is partly lithologic and partly hydraulic. The system is sometimes referred to as the principal artesian aquifer in South Carolina, Georgia, and Alabama. The rocks that characterize the main body of the Floridan aquifer system are mostly platform carbonates.

The Floridan aquifer system includes the platform carbonates, as well as the updip equivalent clastics that are in hydrogeologic communication with the carbonates. The updip clastic facies equivalents of the Floridan carbonate rocks are not considered to be part of the Floridan aquifer system. However, they are hydraulically connected with it and are part of its regional flow system. Thus, the updip clastic facies equivalent of the Floridan aquifer system and the carbonate phase of the Floridan aquifer system are treated as a single hydrologic unit (the Floridan aquifer system). The updip clastic facies equivalents represent the recharge areas for the downdip Floridan. The downdip carbonate phase of the Floridan aquifer system is used extensively in the southeastern part of the South Carolina Coastal Plain as an aquifer.

The transition zone between the carbonate rocks of the Floridan and the updip clastic facies equivalents of the system is the approximate northern extent of the thick carbonate platform that extended from the Florida peninsula through the coastal area of Georgia to southwestern South Carolina during early Tertiary time. The transition zone extended toward the north to a line approximated by the updip limit of the Santee Limestone platform carbonate beds. At SRS, which lies mostly north of the line established for the updip limit of the carbonate phase of the Floridan aquifer system, there are thin beds and lenses of limestone that may be either connected to the main limestone body or isolated from it, owing in part to depositional isolation or to postdepositional erosion or diagenetic alteration. They are considered part of the updip clastic phase of the Floridan.

1.3.4.3.3.2 Carbonate Phase of the Floridan Aquifer System

The carbonate phase of the Floridan aquifer system that develops in the southernmost fringe of SRS, just south of well C-10 (Figure 1.3.4-12), is divided into the Upper and the Lower Floridan aquifer units, separated by the "middle confining unit." The hydraulic characteristics of the carbonate phase of the Floridan aquifer system vary considerably in the South Carolina-Georgia region. This variation results from several different processes, the most important being the dissolution of calcium carbonate by groundwater. The variability in the amount of dissolution is strongly influenced by the chemical composition of the water and the local differences in geology and lithology that affect the rate of groundwater movement.

Hydraulic parameters data for the Floridan aquifer system are given in Table 1.3.4-11.

1.3.4.3.3.3 Clastic Phase of the Floridan Aquifer System

The updip clastic phase of the Floridan aquifer system dominates in the SRS region and consists of a thick sequence of Paleocene to late Eocene sand with minor amounts of gravel and clay and a few limestone beds. At the southern fringe of SRS, the clastic sediments of the aquifer system grade directly into the platform limestone that forms the carbonate phase of the Floridan. The lithologic transition between the clastic phase and the carbonate phase of the aquifer system does not represent a hydrologic boundary, and the two lithofacies are in direct hydrogeologic communication. The Floridan aquifer system overlies the Meyers Branch confining system throughout the lower two-thirds of the study area. Toward the north, the confining beds of the Meyers Branch confining system thin and become intermittent, and the entire Floridan aquifer system coalesces with the Dublin-Midville aquifer system to form the Floridan-Midville aquifer system (Figures 1.3.4-9 and 1.3.4-14).

In the central portion of SRS, clay to sandy clay beds in the Warley Hill Formation (Figure 1.3.4-9) support a substantial head difference between overlying and underlying units. These fine-grained sediments constitute the Gordon confining unit, which divides the system into two aquifers: the Gordon aquifer and the overlying Upper Three Runs aquifer. The former of the two is between the lower surface of the Gordon confining unit and the upper surface of the Crouch Branch confining unit. Updip, the Warley Hill sediments do not support a substantial head difference; thus, there is only one aquifer (the Steed Pond aquifer).

The sedimentary sequence that corresponds to the updip clastic phase of the Floridan aquifer system is penetrated in the P-27 reference well (Figure 1.3.4-12) near the center of SRS. The system at P-27 is 216 ft (65.8 m) thick; the base is at 48 ft (14.6 m) above msl, and the top occurs at the water table, which is at 264 ft (80.5 m) above msl, or 10 ft (3.1 m) below land surface. Groundwater in F Area varies in elevation from 190 to 220ft (58 to 67 m) above msl and is found at a depth of over 50 ft (15 m) below existing ground level (Figure 1.3.4-20). The system includes 22 ft (6.7 m) of clay in five beds, and the remainder consists of sand and clayey sand beds. The stratigraphic units that constitute the clastic phase of the Floridan aquifer system include the Fourmile Formation and the locally sandy parts of the Snapp Formation of the Black

Mingo Group, all of the Orangeburg and Barnwell Groups, and the overlying Miocene/Oligocene "Upland unit" (Figure 1.3.4-9).

Recharge of the Floridan aquifer system occurs generally in the northwestern part of the study area, where rainfall percolates into the outcrop of the Gordon and Upper Three Runs aquifers. The Savannah River has the greatest areawide influence on water levels, followed by the South Fork Edisto River and, to a much lesser degree, the Salkehatchie River. In the updip portion of the study area, Upper Three Runs controls the direction of groundwater movement. Here, the Gordon confining unit has been breached by the stream, creating a groundwater sink that induces flow out of the Gordon toward the stream. Using an average transmissivity value of 300 ft^2/day (28 m^2/day) and an average hydraulic gradient of 25 ft/mi (4.7 m/km) near Upper Three Runs, an estimated 112,000 gal/day (423,920 L/day) is being discharged through each 1-mi (1.6-km) strip of the aquifer along the creek, for a total of 1.4 million gal/day (5.3 million L/day).

The transmissivity of the clastic and carbonate phases of the Floridan aquifer system is lowest near their updip limits because of the reduced aquifer thickness there. Transmissivity increases rapidly from the northwest to the southeast along the Savannah River through the clastic facies and across the limestone facies change of the Floridan aquifer system.

Upper Three Runs Aquifer

The Upper Three Runs aquifer occurs between the water table and the Gordon confining unit and includes all strata above the Warley Hill Formation (in updip areas) and the Blue Bluff Member of the Santee Limestone (in downdip areas) (Figure 1.3.4-9). It includes the sandy and sometimes calcareous sediments of the Tinker/Santee Formation and all the heterogeneous sediments in the overlying Barnwell Group. The Upper Three Runs aquifer is the updip clastic facies equivalent of the Upper Floridan aquifer in the carbonate phase of the Floridan aquifer system (Figure 1.3.4-13).

The Upper Three Runs aquifer is defined by the hydrogeologic properties of the sediments penetrated in well P-27 (Figure 1.3.4-12) located near Upper Three Runs in the center of SRS. Here, the aquifer is 132 ft (40.2 m) thick and consists mainly of quartz sand and clayey sand of the Tinker/Santee Formation; sand with interbedded tan to gray clay of the Dry Branch Formation; and sand, pebbly sand, and minor clay beds of the Tobacco Road Formation. Calcareous sand, clay, and limestone, although not observed in the P-27 well, are present in the Tinker/Santee Formation throughout the General Separations Area near well P-27.

Downdip, at the C-10 reference well, the Upper Three Runs aquifer is 380 ft (116 m) thick and consists of clayey sand and sand of the upper Cooper Group; sandy, shelly limestone, and calcareous sand of the lower Cooper Group/Barnwell Group; and sandy, shelly, limestone and micritic limestone of the Santee Limestone (Figure 1.3.4-12).

Water-level data are sparse for the Upper Three Runs aquifer except within SRS. The hydraulic-head distribution of the aquifer is controlled by the location and depth of incisement of creeks that dissect the area. The incisement of these streams and their tributaries has divided the interstream areas of the water table aquifer into "groundwater islands." Each "groundwater island" behaves as an independent hydrogeologic subset of the water table aquifer with unique recharge and discharge areas. The stream acts as the groundwater discharge boundary for the interstream area. The head distribution pattern in these groundwater islands tends to follow topography and is characterized by higher heads in the interstream area with gradually declining heads toward the bounding streams (Figure 1.3.4-15). Groundwater divides are present near the center of the interstream areas. Water table elevations reach a maximum of 250 ft (76 m) above msl in the northwest corner of the study area and decline to approximately 100 ft (30 m) above msl near the Savannah River.

Porosity and permeability of the Upper Three Runs aquifer are variable across the study area. In the northern and central regions, the aquifer yields only small quantities of water, owing to the presence of interstitial silt and clay and poorly sorted sediments that combine to significantly reduce permeability. Local lenses of relatively clean, permeable sand, however, may yield sufficient quantities for domestic use. Such high-permeability zones have been observed in the General Separations Area (defined as F, E, S, H, and Z areas) near the center of the study area and may locally influence the movement of groundwater.

Porosity and permeability were determined for Upper Three Runs aquifer sand samples containing less than 25% mud. Porosity averages 35.3%; the distribution is approximately normal, but skewed slightly toward higher values. Geometric mean permeability is 31.5 Darcies (23 m/day [76.7 ft/day]) with about 60% of the values between 16 and 64 Darcies (12 and 48 m/day [39 and 156 ft/day]).

Pumping-test and slug-test results in the General Separations Area indicate that hydraulic conductivity is variable, ranging from less than 1.0 ft/day (0.3 m/day) to 32.8 ft/day (10 m/day). Hydraulic conductivity values derived from long-duration, multiple-well aquifer tests are in the range of 10 ft/day (3 m/day), which may be a more reliable estimation of average hydraulic conductivity. At the south end of the study area, near well C-10, sediments in the aquifer become increasingly calcareous, the amount of silt and clay tends to decline, and permeability and yields generally increase. Here, hydraulic conductivity values are in the 59 ft/day (18 m/day) range.

The majority of hydrogeologic data available on the Upper Three Runs aquifer is from wells in the General Separations Area at SRS. Thus, the discussion that follows is largely focused on that area. The Upper Three Runs aquifer is divided into two aquifer zones divided by the "tan clay" confining zone. In the General Separations Area, the "upper" aquifer zone consists of all saturated strata in the upper parts of the Dry Branch Formation and the Tobacco Road Formation that lie between the water table and the "tan clay" confining zone. The aquifer zone has a general downward hydraulic potential into the underlying aquifer unit. The confining beds of the "tan clay" located near the base of the Dry Branch Formation impede the vertical movement of water and often support a local hydraulic head difference. The "lower aquifer" zone of the Upper Three Runs aquifer occurs between the "tan clay" confining zone and the Gordon confining unit and consists of sand, clayey sand, and calcareous sand of the Tinker/Santee Formation and sand and clayey sand of the lower part of the Dry Branch Formation.

Slug tests, minipermeameter tests, pumping tests, and sieve analyses have been used to calculate hydraulic conductivity values for the "upper" aquifer zone near the General Separations Area. Hydraulic conductivity values derived from 103 slug tests range from a high of 45.4 ft/day (14 m/day) to a low of 0.07 ft/day (0.02 m/day) and average (arithmetic mean) 5.1 ft/day (1.5 m/day).

As stated previously, the "tan clay" confining zone at the General Separations Area separates the "upper" aquifer zone from the "lower" aquifer zone in the Upper Three Runs aquifer. This zone is a leaky confining zone. Total thickness of the "tan clay" confining zone, based on measurements at 46 wells distributed throughout the General Separations Area, ranges from 0 to 32.8 ft (0 to 10 m) and averages 11 ft (3.4 m). The sandy clay to clay beds range from 0 to 18 ft (0 to 5.5 m) in thickness and average 7 ft (2.1 m). The clayey sand beds range from 0 to 12 ft (0 to 3.7 m) and average 3 ft (1 m).

Laboratory analyses, including horizontal and vertical hydraulic conductivity, were run on 28 selected clayey sand samples and 55 sandy, often silty clay, and clay samples from the various confining units and "low-permeability" beds in the aquifers. The results are presented in Table 1.3.4-11. The generally accepted value of effective porosity used to determine vertical-flow velocities is 5% for the clay to sandy clay beds and 12% for the clayey sand beds.

Recharge to the Upper Three Runs aquifer occurs at the water table by infiltration downward from the land surface. In the "upper" aquifer zone, part of this groundwater moves laterally toward the bounding streams while part moves vertically downward. The generally low vertical hydraulic conductivities of the "upper" aquifer zone and the intermittent occurrence of the "tan clay" confining zone retard the downward flow of water, producing vertical hydraulic-head gradients in the "upper" aquifer zone and across the "tan clay" confining zone.

Downward hydraulic-head differences in the "upper" aquifer zone vary from 4.5 to 5.4 ft (1.4 to 1.64 m), and differences across the "tan clay" are as much as 15.8 ft (6.5 m) in H Area. At other locations in the General Separations Area, the head difference across the "tan clay" confining zone is only 0.1 to 3.2 ft (0.3 to 1 m), essentially what might be expected due simply to low vertical flow in a clayey sand aquifer. Therefore, the ability of the "tan clay" confining zone to impede water flow varies greatly over the General Separations Area.

Groundwater leaking downward across the "tan clay" confining zone recharges the "lower" aquifer zone of the Upper Three Runs aquifer. Most of this water moves laterally toward the bounding streams; the remainder flows vertically downward across the Gordon confining unit into the Gordon aquifer. All groundwater moving toward Upper Three Runs leaks through the Gordon confining unit or enters small streams. Vertical hydraulic-head differences in the "lower" aquifer zone range from 1.5 to 3.2 ft (0.5 to 1 m) in H Area and indicate some vertical resistance to flow.

Gordon Confining Unit

Clayey sand and clay of the Warley Hill Formation and clayey, micritic limestone of the Blue Bluff Member of the Santee Limestone constitute the Gordon confining unit. The Gordon confining unit separates the Gordon aquifer from the overlying Upper Three Runs aquifer. The unit has been informally termed the "green clay" in previous SRS reports.

In the study area, the thickness of the Gordon confining unit ranges from about 5 to 85 ft (1.5 to 26 m). The unit thickens to the southeast. From Upper Three Runs to the vicinity of L Lake and

Par Pond, the confining unit generally consists of one or more thin clay beds, sandy mud beds, and sandy clay beds intercalated with subordinate layers and lenses of quartz sand, gravelly sand, gravelly muddy sand, and calcareous mud. Southward from L Lake and Par Pond, however, the unit undergoes a stratigraphic facies change to clayey micritic limestone and limey clay typical of the Blue Bluff Member. The fine-grained carbonates and carbonate-rich muds constitute the farthest updip extent of the "middle confining unit" of the Floridan aquifer system (the hydrostratigraphic equivalent of the Gordon confining unit), which dominates in coastal areas of South Carolina and Georgia.

North of the updip limit of the Gordon confining unit, the fine-grained clastics of the Warley Hill Formation are thin, intermittent, and no longer effective in regionally separating groundwater flow. Here, the Steed Pond aquifer is defined. Although thin and intermittent, the clay, sandy clay, and clayey sand beds of the Warley Hill Formation can be significant at the site-specific level and often divide the Steed Pond aquifer into aquifer zones.

The values for hydraulic conductivity obtained from the Gordon confining unit are comparable to the average vertical hydraulic conductivity values of clayey sand (8.9×10^{-3} ft/day [2.71×10^{-3} m/day]) and sandy clay to clay (1.7×10^{-4} ft/day [5.09×10^{-5} m/day]) calculated for 83 samples analyzed in the Tertiary/Cretaceous section. Selected parameters determined for the unit are listed in Table 1.3.4-11.

Gordon Aquifer

The Gordon aquifer consists of all the saturated strata that occur between the Gordon confining unit and the Crouch Branch confining unit in both the Floridan-Midville aquifer system and the Meyers Branch confining system. The aquifer is semiconfined, with a downward potential from the overlying Upper Three Runs aquifer observed in interfluvial areas, and an upward potential observed along the tributaries of the Savannah River where the Upper Three Runs aquifer is incised. The thickness of the Gordon aquifer ranges from 38 ft (12 m) at well P-4A to 185 ft (56 m) at well C-6 (Figure 1.3.4-12) and generally thickens to the east and southeast. Thickness variations in the confining lithologies near the Pen Branch Fault suggest depositional effects owing to movements on the fault in early Eocene time. The Gordon aquifer is partially eroded near the Savannah River and Upper Three Runs. The regional potentiometric map of the Gordon aquifer (Figure 1.3.4-16) indicates that major deviations in the flow direction are present where the aquifer is deeply incised by streams that drain water from the aquifers.

The Gordon aquifer is characterized by the hydraulic properties of the sediments penetrated in reference well P-27 located near the center of SRS. The unit is 75.5 ft (23 m) thick in well P-27 and occurs from 125 to 48 ft (38 to 15 m) above msl. The aquifer consists of the sandy parts of the Snapp Formation and the overlying Fourmile and Congaree Formations (Figure 1.3.4-9). Clay beds and stringers are present in the aquifer, but they are too thin and discontinuous to be more than local confining beds. The aquifer in wells P-21 and P-22 (Figure 1.3.4-16) includes a clay bed that separates the Congaree and Fourmile Formations. The clay bed appears sufficiently thick and continuous to justify splitting the Gordon aquifer into zones in the southeastern quadrant of SRS.

Downdip, the quartz sand of the Gordon aquifer grades into quartz-rich, fossiliferous lime grainstone, packstone, and wackestone, which contain considerably more glauconite than the updip equivalents. Porosity of the limestone as measured in thin-section ranges from 5% to 30% and is mostly moldic and vuggy.

South of SRS, near well ALL-324 (Figure 1.3.4-12), the Gordon aquifer consists of interbedded glauconitic sand and shale, grading to sandy limestone. Farther south, beyond well C-10, the aquifer grades into platform limestone of the Lower Floridan aquifer of the carbonate phase of the Floridan aquifer system.

The Gordon aquifer is recharged directly by precipitation in the outcrop area and in interstream drainage divides in and near the outcrop area. South of the outcrop area, the Gordon aquifer is recharged by leakage from overlying and underlying aquifers. Because streams such as the Savannah River and Upper Three Runs cut through the aquifers of the Floridan aquifer system, they represent no-flow boundaries. As such, water availability or flow patterns on one side of the boundary (stream) will not change appreciably due to water on the other side. In the central part of SRS, where the Gordon confining unit is breached by faulting, recharge to the Gordon aquifer is locally increased.

Most of the Gordon aquifer is under confined conditions, except along the fringes of Upper Three Runs (i.e., near the updip limit of the Gordon confining unit) and the Savannah River. The potentiometric-surface map of the aquifer (Figure 1.3.4-16) shows that the natural discharge areas of the Gordon aquifer at SRS are the swamps and marshes along Upper Three Runs and the Savannah River. These streams dissect the Floridan aquifer system, resulting in unconfined conditions in the stream valleys and probably in semiconfined (leaky) conditions near the valley walls. Reduced head near Upper Three Runs induces upward flow from the Crouch Branch aquifer and develops the "head reversal" that is an important aspect of the SRS hydrogeological system (Figure 1.3.4-11). The northeast-southwest oriented hydraulic gradient across SRS is consistent and averages 4.8 ft/mi (0.9 m/km). The northeastward deflection of the contours along Upper Three Runs indicates incisement of the sediments that constitute the aquifer by the creek.

Hydraulic characteristics of the Gordon aquifer are less variable than those noted in the Upper Three Runs aquifer. Selected parameters are given in Table 1.3.4-12. Hydraulic conductivity decreases downdip near well C-10 owing to poor sorting, finer grain size, and an increase in clay content.

1.3.4.3.3.4 Floridan-Dublin Aquifer System

Over most of the study area, the Meyers Branch confining system extends north of the Allendale confining system, hydraulically isolating the Floridan from the underlying Dublin and Dublin-Midville systems (Figures 1.3.4-9 and 1.3.4-14). However, in a small region in the eastern part of the study area near well C-5, clay beds of the Meyers Branch confining system thin dramatically, leakance values increase, and the Floridan and Dublin aquifer systems are in overall hydraulic communication. In this region, the Floridan and Dublin aquifer systems coalesce to form the Floridan-Dublin aquifer system (Figure 1.3.4-14). Thick, continuous clay beds in the underlying Allendale confining system continue to hydrogeologically isolate the Midville and Floridan-Dublin aquifer systems.

The Floridan-Dublin aquifer system is divided into three aquifers in the study area. In descending order, these include the Upper Three Runs, Gordon, and Crouch Branch aquifers separated by the Gordon and Crouch Branch confining units (Figures 1.3.4-9 and 1.3.4-13). The Upper Three Runs and Gordon aquifers coalesce updip forming the Steed Pond aquifer. The Crouch Branch aquifer is continuous across the entire study area.

The Floridan-Dublin aquifer system is defined by the hydrogeologic properties of sediments penetrated in well C-5 located north of the town of Barnwell. Here, the system is 560 ft (171 m) thick and includes all sediments from the water table to the top of the McQueen Branch confining unit. The Upper Three Runs aquifer is 144 ft (44 m) thick and consists entirely of sand. The Gordon aquifer is 108 ft (33 m) thick and consists of two sand beds that total 105 ft (32 m). The Crouch Branch aquifer is 244 ft (74 m) thick and consists of two sand beds that total 230 ft (70 m).

1.3.4.3.3.5 Floridan-Midville Aquifer System

Northwest of Upper Three Runs, the permeable beds that correspond to the Floridan and Dublin-Midville aquifer systems are often in hydrologic communication owing to the thin and laterally discontinuous character of the intervening clay and silty clay beds, to faulting that breaches the confining beds, and to erosion by the local stream systems that dissect the interval. Here, the Floridan and Dublin-Midville aquifer systems coalesce to form the Floridan-Midville aquifer system (Figures 1.3.4-9, 1.3.4-13, and 1.3.4-14).

The Floridan-Midville aquifer system is divided into three aquifers: in descending order, the Steed Pond aquifer, the Crouch Branch aquifer, and the McQueen Branch aquifer, separated by the Crouch Branch and McQueen Branch confining units. Both the Crouch Branch and the McQueen Branch aquifers extend northwestward from the southern part of SRS. The Steed Pond aquifer is the updip hydrostratigraphic equivalent of the Gordon and Upper Three Runs aquifers (Figure 1.3.4-13). At the northern fringe of the study area, the Steed Pond and underlying Crouch Branch aquifers coalesce and a single, yet unnamed, aquifer unit is present.

The Floridan-Midville aquifer system is defined by the hydrogeologic properties of the sediments penetrated in the GCB-1 type well located in the A/M Area in the northwest corner of SRS (Figure 1.3.4-12). Near GCB-1, the system is 557 ft (170 m) thick and includes all sediments from the water table to the top of the Appleton confining system. The Steed Pond aquifer is 97 ft (30 m) thick at the GCB-1 well and consists of 86 ft (26 m) of sand in four beds. The Crouch Branch aquifer is 167 ft (51 m) thick and consists of 139 ft (42 m) of sand in four beds. It is overlain by the Crouch Branch confining unit, which is 81 ft (25 m) thick and consists of 31 ft (9 m) of clay in four beds. The McQueen Branch aquifer is 169 ft (52 m) thick and consists of 147 ft (45 m) of sand in three beds. The McQueen Branch confining unit is 43 ft (13 m) thick and consists of 28 ft (9 m) of clay in two beds.

Steed Pond Aquifer

North of Upper Three Runs where the Floridan-Midville aquifer system is defined, the permeable beds that correspond to the Gordon and Upper Three Runs aquifers of the Floridan aquifer system are only locally separated, owing to the thin and intermittent character of the intervening clay beds of the Gordon confining unit (Warley Hill Formation) and to erosion by the local stream systems that dissect the interval. Here, the aquifers coalesce to form the Steed Pond aquifer of the Floridan-Midville aquifer system.

The Steed Pond aquifer is defined by hydrogeologic characteristics of sediments penetrated in well MSB-42 located in A/M Area in the northwest corner of SRS. The aquifer is 97 ft (29.6 m) thick. Permeable beds consist mainly of subangular, coarse- and medium-grained, slightly gravelly, submature quartz sand and clayey sand. Locally, the Steed Pond aquifer can be divided into zones. In A/M Area three zones are delineated, the "Lost Lake" zone, and the overlying "M Area" aquifer zones, separated by clay and clayey sand beds of the "green clay" confining zone.

In A/M Area, water enters the subsurface through precipitation, and recharge into the "M-Area" aquifer zone occurs at the water table by infiltration downward from the land surface. A groundwater divide exists in the A/M Area in which lateral groundwater flow is to the southeast towards Tims Branch and southwest towards Upper Three Runs and the Savannah River floodplain. Groundwater also migrates downward and leaks through the "green clay" confining zone into the "Lost Lake" aquifer. The "green clay" confining zone that underlies the "M-Area" aquifer zone is correlative with the Gordon confining unit south of Upper Three Runs.

1.3.4.3.3.6 Meyers Branch Confining System

The Meyers Branch confining system separates the Floridan aquifer system from the underlying Dublin and Dublin-Midville aquifer systems (Figures 1.3.4-9 and 1.3.4-13). North of the updip limit of the confining system, the Floridan and Dublin-Midville aquifer systems are in hydraulic communication and the aquifer systems coalesce to form the Floridan-Midville aquifer system (Figure 1.3.4-14).

Sediments of the Meyers Branch confining system correspond to clay and interbedded sand of the uppermost Steel Creek Formation, and to clay and laminated shale of the Sawdust Landing/Lang Syne and Snapp Formations (Figure 1.3.4-9). In the northwestern part of the study area, the sediments that form the Meyers Branch confining system are better sorted and less silty, with thinner clay interbeds. This is the updip limit of the Meyers Branch confining system (Figure 1.3.4-13).

Crouch Branch Confining Unit

In the SRS area, the Meyers Branch confining system consists of a single hydrostratigraphic unit, the Crouch Branch confining unit, which includes several thick and relatively continuous (over several kilometers) clay beds. The Crouch Branch confining unit extends north of the updip limit of the Meyers Branch confining system where the clay thins and is locally absent and faulting observed in the region locally breaches the unit. Here, the Crouch Branch confining unit separates the Steed Pond aquifer from the underlying Crouch Branch aquifer. Downdip, generally south of the study area, the Meyers Branch confining system could be further subdivided into aquifers and confining units if this should prove useful for hydrogeologic characterization.

As indicated earlier (Figure 1.3.4-11), a hydraulic-head difference persists across the Crouch Branch confining unit near SRS. Owing to deep incisement by the Savannah River and Upper Three Runs into the sediments of the overlying Gordon aquifer, an upward hydraulic gradient (vertical-head reversal) persists across the Crouch Branch confining unit over a large area adjacent to the Savannah River floodplain and the Upper Three Runs drainage system. This "head reversal" is an important aspect of the groundwater flow system near SRS and provides a natural means of protection from contamination of the lower aquifers.

The total thickness of the Crouch Branch confining unit where it constitutes the Meyers Branch confining system ranges from 57 to 184 ft (17.4 to 56.1 m). Updip, the thickness of the Crouch Branch confining unit ranges from 3.3 to 104 ft (< 1 to 31.7 m). The confining unit dips approximately 16 ft/mi (5 m/km) to the southeast. The confining unit is comprised of the "upper" and "lower" confining zones, which are separated by a "middle sand" zone.

In general, the Crouch Branch confining unit contains two to seven clay to sandy clay beds separated by clayey sand and sand beds that are relatively continuous over distances of several kilometers. The clay beds in the confining unit are anomalously thin and fewer in number along a line that parallels the southwest-northeast trend of the Pen Branch and Steel Creek Faults and the northeast-southwest trending Crackerneck Fault. The reduced clay content near the faults suggests shoaling due to uplift along the faults during deposition of the Paleocene Black Mingo Group sediments.

In A/M Area, the Crouch Branch confining unit can often be divided into three zones: an "upper clay" confining zone is separated from the underlying "lower clay" confining zone by the "middle sand" aquifer zone. The "middle sand" aquifer zone consists of very poorly sorted sand and clayey silt of the Lang Syne/Sawdust Landing Formations. The "middle sand" aquifer zone has a flow direction that is predominantly south/southwest toward Upper Three Runs.

In places, especially in the northern part of A/M Area, the "upper clay" confining zone is very thin or absent. Here, only the "lower clay" confining zone is capable of acting as a confining unit and the "middle sand" zone is considered part of the Steed Pond aquifer. Similarly, when the clay beds of the "lower clay" confining zone are very thin or absent, the "middle sand" aquifer zone is considered part of the Crouch Branch aquifer. This is the case in the far northeastern part of the study area.

The "lower clay" confining zone has been referred to as the lower Ellenton clay, the Ellenton clay, the Peedee clay, and the Ellenton/Peedee clay in previous SRS reports. It consists of the massive clay bed that caps the Steel Creek Formation. The zone is variable in total thickness and, based on 31 wells that penetrate the unit, ranges from 5 to 62 ft (1.5 to 19 m) and averages 24 ft (7.3 m) thick.

1.3.4.3.3.7 Dublin Aquifer System

The Dublin aquifer system is present in the southeastern half of SRS and consists of one aquifer, the Crouch Branch aquifer. It is underlain by the Allendale confining system and overlain by the Meyers Branch confining system (Figures 1.3.4-9 and 1.3.4-13). The updip limit of the Dublin aquifer system in the study area corresponds to the updip limit of the Allendale confining system. North of this line, the Dublin-Midville aquifer system is defined.

The thickness of the Dublin aquifer system generally increases toward the south and ranges from approximately 175 to 290 ft (53 to 88 m). The top of the unit dips 3.79 m/km (20 ft/mi) to the southeast. The unit thins to the east toward the Salkehatchie River and to the west toward Georgia. Near the updip limit of the system, thicknesses are variable and probably reflect the effects of movement along the Pen Branch Fault during deposition of the middle Black Creek clay.

The Dublin aquifer system was defined and named for sediments penetrated by well 21-U4 drilled near the town of Dublin in Laurens County, Georgia. The upper part of the Dublin aquifer system consists of fine to coarse sand and limestone of the lower Huber-Ellenton unit. Comparable stratigraphic units serve as confining beds in the SRS area and are considered part of the overlying Meyers Branch confining system. To the east near the Savannah River, clay in the upper part of the lower Huber-Ellenton unit forms a confining unit that separates an upper aquifer of Paleocene age from a lower aquifer of Late Cretaceous age. The upper aquifer is the Gordon aquifer, and their confining unit constitutes the Meyers Branch confining system of the SRS region. The lower part of the Dublin aquifer system consists of alternating layers of clayey sand and clay of the Peedee-Providence unit.

Sediments typical of the Dublin aquifer system are penetrated in the reference well P-22 (Figure 1.3.4-12). The system consists of the well-sorted sand and clayey sand of the Black Creek Formation and the moderately sorted sand and interbedded sand and clay of the Steel Creek Formation. The aquifer is overlain by the clay beds that cap the Steel Creek Formation. These clay beds constitute the base of the Meyers Branch confining system.

The Dublin aquifer system is 213 ft (65 m) thick in well P-22; the top is at an elevation of -223 ft (-68 m) above msl and the bottom at -436 ft (-133 m) above msl. The Dublin aquifer system includes five clay beds in this well.

In the southern part of the study area and farther south and east, the Dublin aquifer system shows much lower values for hydraulic conductivity and transmissivity, probably due to the increase of fine-grained sediments toward the coast.

1.3.4.3.3.8 Dublin-Midville Aquifer System

The Dublin-Midville aquifer system underlies the central part of SRS. The system includes all the sediments in the Cretaceous Lumbee Group from the Middendorf Formation up to the sand beds in the lower part of the Steel Creek Formation (Figure 1.3.4-9). The system is overlain by the Meyers Branch confining system and underlain by the indurated clayey silty sand and silty clay of the Appleton confining system. The updip limit of the system is established at the updip pinchout of the overlying Meyers Branch confining system (Figure 1.3.4-13). The downdip limit of the Dublin-Midville aquifer system is where the Allendale becomes an effective confining system (Figure 1.3.4-13). The Dublin-Midville and the updip Floridan-Midville aquifer systems are referred to as the Tuscaloosa aquifer.

The thickness of the Dublin-Midville aquifer system ranges from approximately 250 to 550 ft (76 to 168 m). The dip of the upper surface of the system is about 20 ft/mi (3.8 m/km) to the southeast. Near the downdip limit of the system, thicknesses are variable and probably reflect the effects of movement along the Pen Branch Fault. Shoaling along the fault trace resulted in a relative increase in the thickness of the aquifers at the expense of the intervening confining unit.

The Dublin-Midville aquifer system includes two aquifers: the McQueen Branch aquifer and the Crouch Branch aquifer, separated by the McQueen Branch confining unit. The two aquifers can be traced northward, where they continue to be an integral part of the Floridan-Midville aquifer system and southward where they constitute the aquifers of the Midville and Dublin aquifer systems, respectively.

The Dublin-Midville aquifer system is defined at the type well P-27. Here, the system is 505 ft (153 m) thick and occurs from -82 ft (-25 m) above msl to -587 ft (-179 m) above msl. It consists of medium- to very coarse-grained, silty sand of the Middendorf Formation and clayey, fine to medium sand and silty clay beds of the Black Creek Formation. The system includes a thick clay bed, occurring from -329 ft (-100 m) above msl to -384 ft (-117 m) above msl, which constitutes the McQueen Branch confining unit.

A regional potentiometric surface map prepared for the Tuscaloosa aquifer indicates that the Savannah River has breached the Cretaceous sediments and is a regional discharge area for the Floridan-Midville aquifer system, the Dublin-Midville aquifer system, and the updip part of both the Dublin and Midville aquifer systems. The Savannah River, therefore, represents a no-flow boundary preventing the groundwater in these aquifer systems from flowing southward into Georgia.

Crouch Branch Aquifer

The Crouch Branch aquifer constitutes the Dublin aquifer system in the southern part of the study area. Farther south, the Dublin aquifer system can be subdivided into several aquifers and confining units. In the central part of the study area, the Crouch Branch aquifer is the uppermost of the two aquifers that constitute the Dublin-Midville aquifer system. Farther north in the northwestern part of SRS and north of the site, the Crouch Branch aquifer is the middle aquifer of the three aquifers that constitute the Floridan-Midville aquifer system.

The Crouch Branch aquifer is overlain by the Crouch Branch confining unit and is underlain by the McQueen Branch confining unit. It persists throughout the northern part of the study area, but near the updip limit of the Coastal Plain sedimentary clastic wedge, the Crouch Branch confining unit ceases to be effective and the Crouch Branch aquifer coalesces with the Steed Pond aquifer.

The Crouch Branch aquifer ranges in thickness from about 100 to 350 ft (30 to 107 m). Thickness of the unit is variable near the updip limit of the Dublin aquifer system where sedimentation was affected by movement along the Pen Branch Fault. The reduced clay content in this vicinity suggests shoaling due to uplift along the fault during Late Cretaceous and Paleocene time, resulting in the deposition of increased quantities of shallow-water, coarse-grained clastics along the crest of the fault trace. The sandy beds act hydrogeologically as part of the Crouch Branch aquifer, resulting in fewer and thinner, less persistent clay beds in the overlying and underlying confining units.

The Crouch Branch aquifer thins dramatically in the eastern part of the study area at the same general location where the underlying McQueen Branch confining unit and the overlying Crouch Branch confining unit thicken at the expense of Crouch Branch sand. Clay beds in the Crouch Branch aquifer generally thicken in the same area and constitute as much as 33% of the unit at well C-6 (Figure 1.3.4-12).

Sediments of the Crouch Branch aquifer are chiefly sand, muddy sand, and slightly gravelly sand intercalated with thin, discontinuous layers of sandy clay and sandy mud. Hydraulic conductivity of the Crouch Branch aquifer ranges from 28 to 228 ft/day (8.5 to 69 m/day). Comparatively high hydraulic conductivity occurs in a northeast-southwest trending region connecting D Area, Central Shops, and R Area and defines a "high permeability" zone in the aquifer. Here, hydraulic conductivities range from 117 to 227 ft/day (36 to 69 m/day). The "high permeability" zone parallels the trace of the Pen Branch Fault and reflects changing depositional environments in response to movement along the fault as described above. South of the trace of the Pen Branch Fault, hydraulic conductivity for the aquifer reflects the return to a deeper water shelf/deltaic depositional regime. A potentiometric map for the Crouch Branch aquifer is presented in Figure 1.3.4-17.

1.3.4.3.3.9 Allendale Confining System

The Allendale confining system is present in the southeastern half of the study area and separates the Midville aquifer system from the overlying Dublin aquifer system (Figure 1.3.4-9). In the study area, the Allendale confining system consists of a single unit, the McQueen Branch confining unit. The confining system is correlative with the unnamed confining unit that separates the Middendorf and Black Creek aquifers and with the Black Creek-Cusseta confining unit. The system dips approximately 27 ft/mi (6.7 m/km) to the southeast and thickens uniformly from about 50 ft (15.2 m) at the updip limit to about 200 ft (61 m) near the eastern boundary of the study area. The rate of thickening is greater in the east than in the west. The updip limit of this confining system is established where pronounced thinning occurs parallel to the Pen Branch Fault.

Sediments of the Allendale confining system are fine grained and consist of clayey, silty sand, clay, and silty clay and micritic clay beds that constitute the middle third of the Black Creek Formation. North of the updip limit of the confining system, where the McQueen Branch confining unit is part of the Dublin-Midville aquifer system, the section consists of coarser-grained, clayey, silty sand and clay beds.

McQueen Branch Confining Unit

The McQueen Branch confining unit is defined by the hydrogeologic properties of the sediments penetrated in well P-27 (Figure 1.3.4-12). At its type-well location, the McQueen Branch confining unit is 55 ft (17 m) thick and is present from -329 to -384 ft (-100 to -117 m) above msl. Total clay thickness is 45 ft (14 m) in three beds, which is 82% of the total thickness of the unit, with a leakance coefficient of 1.03×10^{-5} ft/day (3.14×10^{-6} m/day). The confining unit in well P-27 consists of the interbedded, silty, often sandy clay and sand beds that constitute the middle third of the Black Creek Formation.

The clay beds tend to be anomalously thin along a line that parallels the southwest-northeast trend of the Pen Branch Fault and the north-south trend of the Atta Fault. The reduced clay content in these areas suggests shoaling due to uplift along the faults during Upper Black Creek-Steel Creek time.

1.3.4.3.3.10 Midville Aquifer System

The Midville aquifer system is present in the southern half of the study area; it overlies the Appleton confining system and is succeeded by the Allendale confining system. In the study area, the Midville aquifer system consists of one aquifer, the McQueen Branch aquifer. South of well C-10 (Figure 1.3.4-12), the system may warrant further subdivision into several aquifers and confining units. Thickness of the unit ranges from 232 ft (71 m) at well P-21 to 339 ft (103 m) at well C-10. Variation in the thickness of the unit, as well as the updip limit of the system, results from variation in the thickness and persistence of clay beds in the overlying Allendale confining system. Near the Pen Branch Fault, contemporaneous movement on the fault may have resulted in shoaling in the depositional environment, which is manifested in a thickening of the sands associated with the Midville aquifer system. The upper surface of the aquifer system dips approximately 25 ft/mi (4.73 m/km) to the southeast across the study area.

The Midville aquifer system was defined and named for the hydrogeologic properties of the sediments penetrated in well 28-X1, near the town of Midville in Burke County, Georgia. Here, the upper part of the aquifer system consists of fine to medium sand of the lower part of the Black Creek-Cusseta unit. The Midville is comparable to the lower portion of the Chattahoochee River aquifer and correlative with the Middendorf aquifer.

McQueen Branch Aquifer

The McQueen Branch aquifer occurs beneath the entire study area. It thickens from the northwest to the southeast and ranges from 118 ft (36 m) at well AIK-858 to 339 ft (103 m) at well C-10 to the south. Locally, thicknesses are greater along the trace of the Pen Branch Fault because of the absence and/or thinning of clay beds that compose the overlying McQueen Branch confining unit. The upper surface of the McQueen Branch dips approximately 25 ft/mi (4.7 m/km) to the southeast.

The McQueen Branch aquifer is defined for the hydrogeologic properties of sediments penetrated by well P-27 near the center of the study area. Here, it is 203 ft (62 m) thick and occurs from -384 to -587 ft (-117 to -180 m) above msl. It contains 183 ft (56 m) of sand in four beds, (which is 90% of the total thickness of the unit). The aquifer consists of silty sand of the Middendorf Formation and clayey sand and silty clay of the lower one-third of the Black Creek Formation. Typically, a clay bed or several clay beds that cap the Middendorf Formation are present in the aquifer. These clay beds locally divide the aquifer into two aquifer zones.

Eight pumping tests of the McQueen Branch aquifer were made in F and H Areas, in the central part of the study area. Hydraulic conductivity values ranged from 53 to 210 ft/day (16 to 64 m/day) and averaged 18 ft/day (36 m/day). Three pumping tests of the aquifer were performed: two in F Area and one in L Area. Hydraulic conductivity ranged from 41 to 290 ft/day (13 to 88 m/day) in F Area and was 93 ft/day (28 m/day) in L Area.

1.3.4.3.3.11 Appleton Confining System

The Appleton confining system is the lowermost confining system of the Southeastern Coastal Plain hydrogeologic province and separates the province from the underlying Piedmont hydrogeologic province. It is equivalent to the Black Warrior River aquifer and to the basal unnamed confining unit. The confining system is essentially saprolite of the Paleozoic and Mesozoic basement rocks and indurated, silty and sandy clay beds, silty clayey sand and sand beds of the Cretaceous Cape Fear Formation. Thickness of saprolite ranges from 6 to 47 ft (2 to 14 m), reflecting the degree of weathering on the basement unconformity prior to deposition of the Cape Fear terrigenous clastics. Thickness of saprolite determined from the Deep Rock Borings study (DRB, described in Section 1.3.5.1.7) ranges from 30 to 97 ft (9 to 30 m) and averages 40 ft (12 m) in wells DRB-1 to DRB-7. In the northern part of the study area, the Cape Fear Formation pinches out and the Appleton confining system consists solely of saprolite.

Some variability in thickness is noted along the trace of the Pen Branch Fault. It dips at about 31 ft/mi (5.9 m/km) to the southeast and thickens from 15 ft (4.6 m) in well C-2 near the north end of the study area to 72.2 ft (22 m) in well C-10 in the south. Sediments of the confining system do not crop out in the study area. Thinning of the Appleton confining system in well PBF-2 (Figure 1.3.4-12) is probably a result of truncation of the section by the Pen Branch Fault.

The confining system consists of a single confining unit throughout the study area. Toward the coast, however, the Appleton confining system thickens considerably and includes several aquifers. The aquifers included in the confining system in the downdip region are poorly defined because few wells penetrate them. They are potentially water-producing, but the depth and generally poor quality of water in the aquifers probably precludes their utilization in the foreseeable future. The Appleton confining system includes no aquifer units or zones in the northern and central parts of the study area.

Fine- to coarse-grained sand beds, often very silty and clayey, occur in the upper part of the Cape Fear Formation in the southern part of the study area. The sand appears to be in communication with sand of the overlying McQueen Branch aquifer system and is included with that unit.

1.3.4.3.4 Hydrogeology of the Piedmont Province

The basement complex, designated the Piedmont hydrogeologic province in this report, consists of Paleozoic crystalline rocks, and consolidated to semiconsolidated Upper Triassic sedimentary rocks of the Dunbarton basin. All have low permeability. The hydrogeology of the province was studied intensively at SRS to assess the safety and feasibility of storing radioactive waste in these rocks. The upper surface of the province dips approximately 36 ft/mi (11 m/km) to the southeast. Origins of the crystalline and sedimentary basement rocks are different, but their hydraulic properties are similar. The rocks are massive, dense, and practically impermeable except where fracture openings are encountered. Water quality in these units is also similar. Both contain water with high alkalinity and high levels of calcium, sodium, sulfate, and chloride. The low aquifer permeability and poor water quality in the Paleozoic and Triassic rocks render them undesirable for water supply in the study area.

1.3.4.4 Area Hydrogeological Characteristics – General Separations Areas

Field activities at the various site facilities are reported in the annual SRS Environmental Report (WSRC 1997b). In the past, the focus of F-area facilities has been on chemical separations; changes in the site mission have impacted operations in the General Separations Area, including the construction and startup of the Tritium Facilities and various waste management facilities (Defense Waste Processing Facility, E-Area Vaults, and the Consolidated Incineration Facility).

1.3.4.4.1.1 Water Usage

Water usage at the F-Area/E-Area facilities varies from year to year and is a function of increased or decreased site activities. Current data for pumping in F/E Area is reported in the SRS Annual Environmental Report (WSRC 1997b). Operation of production water wells has not caused subsidence of the F-Canyon foundation nor influenced potential contaminant flow paths in the post-Cretaceous aquifers.

1.3.4.4.1.2 Hydrogeologic Setting

The General Separations Area sits above a water table ridge, defined on the south by Fourmile Branch and on the north and west by Upper Three Runs (Figure 1.3.4-18). The ridge is dissected on the northern flank by Crouch Branch (between E Area and H Area) and McQueen Branch (east of Z Area). Thus, the facilities lie above minor groundwater divides; flow at the water table is generally away from the facilities and toward the nearest surface water. The majority of water that reaches the water table beneath the General Separations Area is discharged into either Upper Three Runs (or its tributaries) or Fourmile Branch.

In general, there is very limited downward migration of groundwater across the Meyers Branch confining system beneath the General Separations Area. Therefore, the hydrostratigraphic units linked to General Separations Area operations are the Upper Three Runs aquifer (the water table aquifer), the Gordon confining unit, and the Gordon aquifer. A discussion of the hydraulic properties and hydraulic gradients for these units is included above under Section 1.3.4.3.3. Hydraulic conductivity values for the Upper Three Runs, Gordon, and Steed Pond aquifers are presented in Table 1.3.4-12.

1.3.4.5 Groundwater Chemistry

1.3.4.5.1 Regional Groundwater Chemistry

SRS groundwater quality samples are collected quarterly, and the data, as well as interpreted results, are presented in the Annual SRS Environmental Report (WSRC 1997b). For illustrative purposes, Table 1.3.4-13 presents a set of water analyses from sources within SRS and vicinity. The location of industrial and municipal groundwater users near SRS is shown in Figure 1.3.4-19. The pumpages are tabulated in Table 1.3.4-14.

An investigation of the geochemistry of the water residing in the principal aquifer units at SRS was undertaken as part of the Baseline Hydrologic Investigation (Bledsoe, Aadland, and Sargent 1990). This study investigated the effects of the mineralogy of the aquifer materials, source of the water, and the effect of biological activity on the evolution and chemistry of the groundwater. Groundwater chemistry and geologic data utilized for this study were obtained from monitoring wells and core samples collected during drilling activities. The majority of the ensuing discussions were adapted directly from this report.

The primary source of groundwater at SRS is precipitation. As the water migrates away from the source or recharge area, it experiences a decrease of pH and an increase in total dissolved solids. In addition, the overall chemistry changes as it encounters different aquifer material. The primary recharge areas for the deeper aquifers in the SRS vicinity are located near the Fall Line or Coastal Plain onlap. From there, the groundwater migrates in a general southwesterly direction. The extent to which the local discharge and recharge areas impact the groundwater chemistry is dependent upon the depth of a particular aquifer system below ground surface and the overall aquifer material. Recharge for the water table aquifers is derived from local, recent precipitation at the site as evidenced by elevated amounts of short-lived isotopes, such as tritium, and the ionic composition of the groundwater.

Tritium levels in local precipitation are in excess of the normal background levels for the Northern Hemisphere. Washout from the atmosphere during periods of precipitation has elevated the concentration of rainfall tritium to where pre- and post-1954 rainfall-derived water can clearly be distinguished in groundwater. The year 1954 is significant in that it represents the beginning of SRS facility operations. The impact of rainfall-derived tritium on the groundwater is observed in groundwater resident at depths of less than 200 ft (61 m).

The ionic composition of the groundwater also clearly reflects a meteoric origin of the water. Chemical data from rainwater collected near SRS exhibit approximately the same ratio of sodium to chlorine as that in seawater, which is a principal source of atmospheric salts, but higher levels of sulfate and calcium. These latter constituents are commonly contributed to the atmosphere over landmasses by natural biological processes and industrial emissions.

1.3.4.5.1.1 Aquifer Materials

Groundwater principally resides in the pore spaces of the sandy aquifers. In these aquifers, quartz is the dominant mineral. Despite its abundance, its effect on overall water chemistry is negligible due to the low reactivity of this quartz (except in cases of extremely basic pH). The minerals that potentially impact the chemistry of the groundwater are less abundant. Minerals identified by x-ray diffraction and x-ray fluorescence data include feldspars and a host of phyllosilicates (i.e., clays and micas). Other non-silicate minerals such as pyrite, gypsum, barite, calcite, and hematite were also identified, but these are relatively sparse and have little impact on the overall groundwater chemistry. Clay minerals present include kaolinite, smectites and in minor amounts, illite.

1.3.4.5.1.2 Groundwater Chemistry (Hydrochemical Facies)

The evolution of groundwater in the Coastal Plain sediments can be defined from the source or recharge areas down the hydraulic gradient within the aquifer. Although groundwaters at SRS are very dilute, they show significant changes in the levels of dissolved oxygen, redox potential, dissolved trace constituents, and in the major cations and anions present. The variations in these major constituents are useful in delineating the chemical reactions, which occur during the chemical development of the groundwater.

On the northern edge of the site where there is a single aquifer system (Figure 1.3.4-14), the waters are of very low total dissolved solids (less than 20 mg/L). They contain high concentrations of dissolved oxygen, have pH lower than 6.0, and are classified as mixed water types (i.e., there are no predominant cations or anions in the water). The confining units that separate the aquifers are only of local extent and the hydraulic gradient is downward from the Tertiary formations into the underlying Cretaceous formations over much of this portion of the site. The Cretaceous aquifer receives recharge from Tertiary units where the confining units are thin or absent.

South of this region, where two or more aquifer systems are present (Figure 1.3.4-14), the waters become geochemically distinctive because of bio-geochemical and geochemical interaction with the water and the sediments and buried organic materials. Water samples in both of the aquifers are shown to have a predominance of calcium-bicarbonate. The presence of calcium-bicarbonate is most frequently attributed to the dissolution of $CaCO_3$. Several reaction mechanisms are known to exist for the dissolution reactions. The dissolution by weak carbonic acid

$$CaCO_3 + H_2CO_3 \dashrightarrow Ca^{2+} + 2HCO_3^- \qquad (1.3.4\text{-}2)$$

produces two bicarbonate ions per calcium ion whereas the hydrolysis reaction produces a single bicarbonate plus a hydroxyl ion.

$$CaCO_3 + H_2O \dashrightarrow Ca^{2+} + HCO_3^- + OH^- \qquad (1.3.4\text{-}3)$$

In either case, equal amounts of alkalinity are produced by the reaction so that the bicarbonate concentration calculated from alkalinity data in this study are not useful indicators to distinguish the reaction mechanisms. It is probable that both reactions contribute in the Tertiary aquifers. There have not been sufficient ^{13}C isotopic data obtained on these aquifer units or direct measurement of dissolved inorganic carbon to generalize at the present time.

The samples from monitoring wells screened in the Tertiary section at the P-19 well (Figure 1.3.4-12) site cluster are anomalous in their water chemistry because they are low in total dissolved solids and show no evidence of having had opportunity to react with carbonates (low alkalinity and moderate pH). This is true of the P-19 wells screened in the Upper Three Runs aquifer and Gordon aquifer. In addition, limestones, marls, and clay units are conspicuously absent from the Tertiary section at this locality and, therefore, high vertical permeabilities are expected.

The Cretaceous or deeper aquifers (Midville, Dublin, and or Dublin-Midville) south of Upper Three Runs have a somewhat more complex chemistry. Examination of Piper diagrams for these units shows a marked evolution from sulfate-rich waters at low total dissolved solids toward bicarbonate-rich waters at higher total dissolved solids. The evolution toward calcium-rich waters is not as pronounced as in the Tertiary units. Alkalis (Na+K) are major contributors to the cation compositions, and the waters would be classified as mixed water types or $Na+K-HCO_3$ waters. The reaction pathways toward these compositions are complex and not well understood at present.

The calcium in these waters may be derived from several sources, including dissolution of gypsum from confining beds such as the Rhems (Ellenton) Formation, which is the downdip equivalent of the Lang Syne/Sawdust Landing Formation, the dissolution of calcite or calcium plagioclase, or displacement of calcium by potassium in cation exchange reactions. The alkalis in the Cretaceous aquifer waters are primarily derived from the breakdown of silicate minerals including feldspars, mica, and various clay minerals including illite.

There is no consistent trend in the proportion of potassium to sodium in the waters as total dissolved solids increases. Because potassium is usually the most tightly bound ion in cation exchange reactions, its relative abundance in the samples from the McQueen Branch and Crouch Branch aquifers suggests that cation exchange has not played a dominant role in the evolution of these waters. The exceptions are the samples from well C-10 (Figure 1.3.4-12), where sodium is clearly the dominant cation. In this downgradient locality south of SRS, cation exchange processes have led to water conditions comparable to those formed by exchange processes observed in other regions of the South Carolina Coastal Plain.

Increases in the HCO_3^- concentration are apparently largely through the microbial oxidation of lignite within the aquifers. The ^{13}C signatures of the water are typically light (in the range of -0% to -25%). Usually, these light values indicate an organic source of carbon rather than the dissolution of limestone or other inorganic ion source.

Dissolved oxygen is less than 0.1 mg/L for most of the samples from the Dublin-Midville aquifer system. From Upper Three Runs southward, the aquifers in this system are anaerobic and contain abundant dissolved iron. The iron content in these aquifers is undesirably high, usually between 1 and 5 mg/L. The anaerobic conditions allow the dissolved iron to remain in the ferrous form but have not become reducing to the extent that sulfate has been reduced to the sulfide form.

A high-iron groundwater zone in the Middendorf aquifer (comparable to McQueen Branch), approximately 124 mi (40 km) wide, extends across South Carolina from SRS to North Carolina approximately paralleling the Fall Line. This high-iron zone is inferred to result from the reduction of iron oxyhydroxide grain coatings by bacteria during the oxidation of organic matter within the confined zones of the aquifer. The activity of the iron-reducing bacteria may inhibit the activity of sulfate-reducing bacteria. Sulfate reduction begins further downgradient after the more easily oxidized organics have been consumed.

1.3.4.5.1.3 Water Chemistry - F Area and MFFF Site

A monitoring well network consisting of over 100 wells has been installed to monitor groundwater quality in F Area. Well construction information, including maps showing well location, is provided in the SRS quarterly well inventory. The most recent sampling information is presented in periodic SRS groundwater monitoring reports and the SRS Annual Environmental Report (WSRC 1997b).

The potential local groundwater recharge zone in F Area is the upland area with downward vertical gradients just to the southeast of F Area. Recharge areas for the Cretaceous aquifers are located outside of the SRS boundary. Construction of the F-Area facilities has had no effect on groundwater recharge areas and, groundwater has had no effect on construction activities. Construction of the MFFF site will have no adverse effect on groundwater recharge areas, and groundwater will have no effect on construction activities.

1.3.4.6 Groundwater Hydrology at the MFFF Site

Section 1.4.2 of *Natural Phenomena Hazards and Design Criteria and Other Characterization Information for the Mixed Oxide (MOX) Fuel Fabrication Facility at Savannah River Site (U)*, (WSRC 2000b) and the *MOX Fuel Fabrication Facility Site Geotechnical Report* (DCS 2000) discuss the groundwater hydrology at SRS and the MFFF site. This section presents a summary of groundwater hydrology for the MFFF site.

The groundwater conditions at the MFFF site have the same characteristics as F Area. Groundwater in the shallow, intermediate, and deep aquifers at the MFFF site flows in different directions, depending on the depths of the streams that cut the aquifers. The Upper Three Runs aquifer is the shallow aquifer beneath the MFFF site that flows to the north and discharges into Upper Three Runs. The Gordon aquifer underlies the Upper Three Runs aquifer at the MFFF site and flows horizontally toward the Savannah River. Groundwater in the intermediate and deep aquifers flows horizontally towards the Savannah River southeast toward the coast.

Groundwater at the MFFF site also moves vertically. In the Upper Three Runs and Gordon aquifers, flow moves downward until its movement is obstructed by impermeable material. Operating under a different set of physical conditions, groundwater in the intermediate and deep aquifers flows mostly horizontally. At the MFFF site, flow from deeper aquifers moves upward due to higher water pressure below the confining unit between the upper and lower aquifer systems. This upward movement helps to protect the lower aquifers from contaminants found in the shallow Upper Three Runs aquifer. Groundwater in F Area varies in elevation from 190 to 220 ft (58 to 67 m) above msl and is found at a depth of over 50 ft (15 m) below existing ground level (Figure 1.3.4-20).

Groundwater quality in F Area and the MFFF site is not significantly different from that for SRS as a whole. It is abundant, usually soft, slightly acidic, and low in dissolved solids. High dissolved iron concentrations occur in some aquifers. Where needed, groundwater is treated to raise the pH and remove iron.

The *2000 RCRA Part B Permit Renewal Application* (WSRC 2000a) provides a comprehensive discussion of groundwater contamination plumes in F Area and covers the MFFF site. Also, the

Application for a Hazardous Waste Part B, Post-Closure Care Permit, Mixed Waste Management Facility, Hydrogeological Characterization (U) (WSRC 1992) defines the soil and groundwater contamination from past wastewater discharge into the seepage basin. The Old F-Area Seepage Basin is located just west of the MFFF site as shown on Figure 11.1-1 in Chapter 11. The *Groundwater Mixing Zone Application for the Old F-Area Seepage Basin (U)* (WSRC 1997a) describes the justification and basis for the groundwater mixing zone application in support of the Record of Decision (ROD) for closure of the seepage basin.

The selected remedial action for closure of the Old F-Area Seepage Basin consisted of stabilizing the contaminated soil within the basin by an in-situ cement slurry mixing method, filling the basin with clean soil, and capping the basin. The contaminated soil zone within the Old F-Area Seepage Basin was remediated in 2000.

These reports indicate that there is no known soil or groundwater contamination beneath critical structures located on the MFFF site. This was confirmed with the recent comprehensive geotechnical investigations conducted in 2000 at the MFFF site. During the site exploration program, radiological testing was performed for drill cuttings and all samples. Radioactive contamination was not detected in samples obtained from the Upper Three Runs aquifer or Gordon aquifer, which are the upper aquifers at the MFFF site.

These reports also indicate that the groundwater contamination plumes in F Area are well defined as to extent and direction of movement. The identified contamination plumes in F Area have well-defined monitoring and testing programs that are in compliance with State and EPA requirements. The *2000 RCRA Part B Permit Renewal Application* (WSRC 2000a) indicates that the northwest plume from the Old Radioactive Waste Burial Ground, located southeast of F Area, will not pass beneath the MFFF site. The Old F-Area Seepage Basin reports indicate that the groundwater contamination plume is located at a depth of over 70 ft (21.3 m) and extends beneath a portion of the northwest corner of the MFFF site boundary. The plume migration is to the north towards Upper Three Runs and away from the MFFF site. Therefore, further migration of the contaminated plume onto the MFFF site is not anticipated. Continued dilution of this contamination plume in the northwest portion of the MFFF site is expected to occur from northward-flowing groundwater beneath the MFFF site.

During the 2000 geotechnical investigations, radiological testing was performed for drill cuttings and samples to ensure worker protection and acceptability of samples for transport over public highways. The scans consisted of local reading with a G-M meter from each location for which materials were removed for geotechnical testing. The nominal sensitivity for worker protection and transportation measurements is 0.1 mrem/hr. Following field measurements, select samples were analyzed in the laboratory for gross alpha and gross beta with minimum detectable activities of about 200 nCi/gm of gross alpha and about 100 pCi/gm of gross beta. Radioactive contamination was not detected in samples obtained at the MFFF site.

Subsequent to the 2000 geotechnical investigations, DOE reported exceedances of drinking water maximum contaminant levels in the Old F-Area Seepage Basin monitoring wells. As a consequence of the exceedances in wells FNB-13, FNB-14, and FNB-15, DCS performed a groundwater survey on the MFFF site before beginning additional geotechnical work. Results of that sampling indicate that there was no groundwater located above the "tan clay" confining zone of the Dry Branch Formation. The Upper Three Runs aquifer below the "tan clay" confining zone of the Dry Branch Formation, which is at least 70 ft (21.3 m) below the MFFF site, is apparently contaminated from upgradient sources in F Area and not solely from the Old F-Area Seepage Basin. Concentrations of gross alpha and beta activity, tritium, uranium, and trichloroethyene exceeded maximum contaminant limits for drinking water. The source of groundwater contamination is from various heavy industrial and nuclear operations over the past 50 years in the F Area. The contaminant plume appears to originate inside F Area and extends beneath the MFFF site with movement in a fan-like direction of groundwater flow under the MFFF site. Contamination is most pronounced under the western edge of the site. Contamination was confined to the groundwater below the "tan clay" confining zone of the Dry Branch Formation. The deepest MFFF construction activities are anticipated to occur at least 30 ft (9.1 m) above the zone of contamination (WSRC 2002a).

The planned site construction, preparation, and development for the MFFF facilities will be confined within the near-surface soils that comprise the Upper Three Runs aquifer. Only surface grading and shallow excavation are anticipated to level the northwest area of the MFFF site for construction of parking lots, roads, and shallow spread foundations to support the Technical Support Building and Administration Building. Excavations will not extend at depth to the groundwater level. The planned construction activities will not have any adverse effects on the existing aquifer systems beneath the MFFF site.

Tables

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Table 1.3.4-1. Flow Summary for the Savannah River and Savannah River Site Streams (values in ft^3/sec)

	Mean	STD Dev.	7Q10	7-Day Low Flow
Savannah River				
at Augusta, GA	9493	2611	4332	3746
at SRS Boat Dock	----	----	4293	3773
at Hwy 301 [a]	10397	2830	4411	3991
at Clyo	12019	3687	5211	4513
Upper Three Runs				
at Hwy 278	105	8	56	55
at SRS Road C	211	30	100	86
at SRS Road A	245	41	100	84
Beaver Dam Creek				
at 400D	81.5	8.7	0.01	18
Fourmile Branch				
at SRS Site 7	17.8	5.4	0.58	3.2
Pen Branch				
at SRS Road B	7.5	8.2	0.27	0.22
at SRS Road A-13	210	45	5.5	8.8
Steel Creek				
at Hattiesville Bridge	160	12.3	12.9	12.0
Lower Three Runs				
below Par Pond	38.4	10.4	1.2	0.9
near Snelling, SC	85.8	27.9	16	15

[a] Eleven years are missing between 1971 and 1982.

NOTE: The flow data used for computing statistics for the Savannah River and SRS streams were based on U.S. Geological Survey stream gage measurements after construction of Thurmond Dam. Values listed for seven-day low-flow, 10-year recurrence (7Q10) are based on adjusted "natural" flows (i.e., without the effects of cooling water discharges from SRS reactors).

Data from WSRC 2000b

Table 1.3.4-2. Water Quality of the Savannah River Above SRS for 1983 to 1987

Analyte	Units	No. of Analyses	Min	Max	Mean
Alkalinity	mg/L	36	13	23	18.28
Aluminum	mg/L	36	0.08	0.95	0.38
Ammonia	mg/L	36	0.04	0.27	0.11
Cadmium	mg/L	36	0	0	0
Calcium	mg/L	36	3.1	4.24	3.62
Chloride	mg/L	36	4	13	7.73
Chromium	mg/L	36	0	0.01	0.01
Conductivity	µS/cm	36	54	107	80.42
Copper	mg/L	36	0	0	0
DO	mg/L	72	6.4	24	9.42
Fixed residue	mg/L	36	1	17	7.69
Iron	mg/L	36	0.27	1.39	0.62
Lead	mg/L	36	0	0	0
Magnesium	mg/L	36	0.98	1.55	1.31
Manganese	mg/L	36	0.06	0.1	0.08
Mercury	mg/L	36	0	0	0
Nickel	mg/L	36	0	0.03	0.02
Nitrate + Nitrite	mg/L	36	0.02	0.63	0.27
Phosphate	mg/L	36	0.03	0.09	0.06
Sodium	mg/L	36	4.67	11.6	8.93
Sulfate	mg/L	36	4	9	6.82
Suspended Solids	mg/L	36	3	18	9.69
Temperature	C	36	8.9	24.8	17.48
Total Dissolved Solids	mg/L	36	48	85	63.89
Total Solids	mg/L	36	54	96	73.58
Turbidity	NTU	36	2.22	3.3	9.66
Volatile Solids	mg/L	36	1	7	2.34
Water Volume	L	36	1.08E+11	2.31E+12	8.4E+11
Zinc	mg/L	36	0	0.02	0.01
pH	pH	36	5.7	7.8	6.44

Data from WSRC 2000b

Table 1.3.4-3. Annual Maximum Instantaneous Discharges of the Savannah River at Augusta, Georgia, for Water Years 1921 Through 1999 (USGS Flow Data, 1922-1999)

Year	Discharge (cfs)	Year	Discharge (cfs)
1921	129,000	1961	34,800
1922	92,000	1962	32,500
1923	59,700	1963	31,300
1924	56,400	1964	87,100
1925	150,000	1965	34,600
1926	55,300	1966	39,300
1927	39,000	1967	35,900
1928	226,000	1968	35,900
1929	191,000	1969	45,600
1930	350,000	1970	25,200
1931	26,100	1971	63,900
1932	93,800	1972	33,700
1933	48,200	1973	40,200
1934	73,200	1974	32,900
1935	63,700	1975	45,600
1936	258,000	1976	33,300
1937	90,200	1977	34,200
1938	65,300	1978	43,100
1939	82,400	1979	37,300
1940	252,000	1980	47,200
1941	52,200	1981	17,300
1942	115,000	1982	30,700
1943	132,000	1983	66,100
1944	141,000	1984	34,000
1945	62,100	1985	25,700
1946	109,000	1986	21,000
1947	90,200	1987	29,200
1948	76,100	1988	13,600
1949	172,000	1989	20,200
1950	32,500	1990	35,300
1951	41,400	1991	59,200
1952	39,300	1992	22,100
1953	35,200	1993	45,100
1954	25,500	1994	40,700
1955	23,900	1995	33,600
1956	18,600	1996	34,400
1957	18,000	1997	26,300
1958	66,300	1998	43,000
1959	28,500	1999	19,000
1960	34,900		

Note: Station 02197000; drainage area 7,508 square miles (including Butler Creek drainage area). The maximum instantaneous discharge since gaging by the USGS began in 1882 is 350,000 cfs on October 3, 1929. The maximum historical flow is 360,000 cfs in 1796.

Data from WSRC 2000b

Table 1.3.4-4. Annual Maximum Instantaneous Discharges of Upper Three Runs for Water Years 1967 Through 1999

Water Year	Discharge at Highway 278[a] (cfs)	Discharge at SRS Road C[b] (cfs)	Discharge at SRS Road A[c] (cfs)
1967	320	-[d]	
1968	237	-	-
1969	301	-	-
1970	303	-	-
1971	420	-	-
1972	382	-	-
1973	472	-	-
1974	260	-	-
1975	341	586	-
1976	429	732	1230
1977	304	540	717
1978	344	646	Not gauged
1979	341	680	996
1980	420	880	951
1981	308	582	620
1982	364	696	793
1983	472	880	1010
1984	466	840	861
1985	400	962	893
1986	360	802	780
1987	370	819	869
1988	278	460	428
1989	304	613	592
1990	202	869	572
1991	820	2040	2580
1992	742	1010	926
1993	421	1280	1100
1994	302	826	667
1995	412	1240	1010
1996	240	691	638
1997	242	840	709
1998	596	-	1200
1999	252	-	717

[a] Station 02197300; drainage area 87 square miles.
[b] Station 02197310; drainage area 176 square miles.
[c] Station 02197315; drainage area 203 square miles.
[d] Indicates discharge point that was not monitored.

Data from WSRC 2000b

Table 1.3.4-5. Annual Maximum Instantaneous Discharges of Tims Branch for Water Years 1974 Through 1995, Station 02197309

Water Year	Discharge at SRS Road C (ft^3/s)[a]	Gage Height (feet msl)
1974	N/A	N/A
1975	N/A	N/A
1976	61	6.17
1977	N/A	N/A
1978	N/A	N/A
1979	N/A	N/A
1980	N/A	N/A
1981	N/A	N/A
1982	N/A	N/A
1983	NM	NM
1984	N/A	N/A
1985	41	144.76
1986	42	144.88
1987	63	145.16
1988	38	144.28
1989	38	144.26
1990	91	145.27
1991	129	145.69
1992	61	144.77
1993	107	145.47
1994	77	145.07
1995	107	145.47

[a] Drainage area 17.5 square miles.
N/A = data not available.
NM = discharge point not monitored.
Data from WSRC 2000b

Table 1.3.4-6. Annual Maximum Daily Discharges of Fourmile Branch for Water Years 1980 Through 1999

Water Year	Discharge at SRS Road C[a] (cfs)	Discharge at SRS Road A-7[b] (cfs)	Discharge at SRS Road A-12.2[c] (cfs)
1980	288	204	903
1981	123	-[d]	585
1982	262	177	745
1983	136	163	678
1984	267	189	692
1985	149	121	621
1986	211	181	415
1987	161	163	436
1988	89	74	102
1989	-	157	392
1990	-	1230	1060
1991	-	-	-
1992	135	465	493
1993	126	500	477
1994	90	176	-
1995	179	610	595
1996	89	156	200
1997	-	254	299
1998	-	773	837
1999	-	194	264

[a] Station 02197340; drainage area 7.53 square miles.
[b] Station 02197342; drainage area 12.5 square miles.
[c] Station 02197344; drainage area 22.0 square miles.
[d] Indicates discharge unknown.

Data from WSRC 2000b

Table 1.3.4-7. Probable Maximum Precipitation for F Area

Time (hr)	Incremental Rainfall (in)	Total Rainfall (in)
0	–	0
1	2.2	2.2
2	2.8	5
3	3.1	8.1
4	15.1	23.2
5	4.9	28.1
6	2.7	30.8

Data from WSRC 2000b

Table 1.3.4-8. Hour Storm Rainfall Distributions as a Function of Annual Probability of Exceedance

Annual Probability of Exceedance	2E-02	1E-02	2E-03	1E-03	2E-04	1E-04	2E-05	1E-05
				Rainfall	(inches)			
Hour 1	0.035	0.039	0.052	0.058	0.074	0.082	0.103	0.114
Hour 2	0.062	0.070	0.093	0.104	0.132	0.147	0.185	0.204
Hour 3	0.083	0.094	0.124	0.138	0.176	0.196	0.247	0.272
Hour 4	0.242	0.273	0.361	0.403	0.515	0.571	0.721	0.795
Hour 5	0.393	0.445	0.587	0.656	0.838	0.929	1.174	1.294
Hour 6	0.524	0.593	0.783	0.874	1.117	1.239	1.566	1.725
Hour 7	0.725	0.819	1.082	1.208	1.544	1.712	2.163	2.384
Hour 8	1.863	2.106	2.781	3.105	3.969	4.401	5.562	6.129
Hour 9	1.139	1.287	1.700	1.898	2.426	2.690	3.399	3.746
Hour 10	0.628	0.710	0.937	1.047	1.338	1.483	1.875	2.066
Hour 11	0.414	0.468	0.618	0.690	0.882	0.978	1.236	1.362
Hour 12	0.338	0.382	0.505	0.564	0.720	0.799	1.009	1.112
Hour 13	0.117	0.133	0.175	0.196	0.250	0.277	0.350	0.386
Hour 14	0.076	0.086	0.113	0.127	0.162	0.179	0.227	0.250
Hour 15	0.048	0.055	0.072	0.081	0.103	0.114	0.144	0.159
Hour 16	0.035	0.039	0.052	0.058	0.074	0.082	0.103	0.114
Hour 17	0.035	0.039	0.052	0.058	0.074	0.082	0.103	0.114
Hour 18	0.028	0.031	0.041	0.046	0.059	0.065	0.082	0.091
Hour 19	0.028	0.031	0.041	0.046	0.059	0.065	0.082	0.091
Hour 20	0.021	0.023	0.031	0.035	0.044	0.049	0.062	0.068
Hour 21	0.021	0.023	0.031	0.035	0.044	0.049	0.062	0.068
Hour 22	0.021	0.023	0.031	0.035	0.044	0.049	0.062	0.068
Hour 23	0.014	0.016	0.021	0.023	0.029	0.033	0.041	0.045
Hour 24	0.014	0.016	0.021	0.023	0.029	0.033	0.041	0.045
Accumulation	6.900	7.800	10.300	11.500	14.700	16.300	20.600	22.700

Data from WSRC 2000b

Table 1.3.4-9. Design Basis Flood for SRS Areas

PERFORMANCE CATEGORY	1	2	3	4
ANNUAL EXCEEDANCE PROBABILITY	**2E-03**	**5E-04**	**1E-04**	**1E-05**
TIMS BRANCH BASIN (A-AREA)				
Flood (cfs)	2399	3568	5154	8233
Flood Elevation (feet above msl)	247.1	247.4	247.6	248.2
FOURMILE BRANCH BASIN (C-AREA)				
Flood (cfs)	2072	3040	4413	7102
Flood Elevation (feet above msl)	189.3	190.3	191.5	193.6
FOURMILE BRANCH BASIN (E-AREA)				
Flood (cfs)	1440	2155	3189	5246
Flood Elevation (feet above msl)	202.0	203.0	204.4	207.9
UPPER THREE RUNS BASIN (F-AREA)				
Flood (cfs)	11966	17396	25022	39576
Flood Elevation (feet above msl)	144.4	146.6	148.6	150.9
FOURMILE BRANCH BASIN (F-AREA)				
Flood (cfs)	1683	2507	3700	6058
Flood Elevation (feet above msl)	193.2	194.2	195.5	197.7
FOURMILE BRANCH BASIN (H-AREA)				
Flood (cfs)	1404	2103	3113	5126
Flood Elevation (feet above msl)	236.1	236.8	237.1	239.2
PEN BRANCH BASIN (K-AREA)				
Flood (cfs)	4430	6224	8638	13185
Flood Elevation (feet above msl)	176.3	177.7	179.7	182.5
INDIAN GRAVE BRANCH BASIN (K-AREA)				
Flood (cfs)	781	1087	1524	2326
Flood Elevation (feet above msl)	180.5	181.1	181.8	182.9
UPPER THREE RUNS BASIN (S-AREA)				
Flood (cfs)	11966	17396	25022	39576
Flood Elevation (feet above msl)	151.8	153.4	155.3	158.2
UPPER THREE RUNS BASIN (Z- AND Y-AREAS)				
Flood (cfs)	11966	17396	25022	39576
Flood Elevation (feet above msl)	158.5	160.4	161.7	163.8

Data from WSRC 2000b

Table 1.3.4-10. Design Basis Flood for MFFF Site

PERFORMANCE CATEGORY	1	2	3	4
ANNUAL EXCEEDANCE PROBABILITY	2E-03	5E-04	1E-04	1E-05
UPPER THREE RUNS BASIN				
Flood (cfs)	11966	17532	25022	39576
Flood Elevation (feet above msl)	146.4	148.4	150.5	153.1
FOURMILE BRANCH BASIN				
Flood (cfs)	1440	2155	3189	5246
Flood Elevation (feet above msl)	202.0	203.0	204.4	207.9

Data from WSRC 2000b

Table 1.3.4-11. Hydraulic Parameters of the Carbonate Phase of the Floridan Aquifer

Parameter	Value [Mean] (Average)	Maximum	Minimum	Comments
Transmissivity	[1,486 m^2/day]	9,290 m^2/day	30 m^2/day	Floridan undifferentiated, South Carolina
		46,450	929	Upper Floridan, various areas, Georgia
		3,066	2,601	Upper Floridan, Savannah, Georgia
	(929 to 4,645)			Upper Floridan, Coastal South Carolina
		20,066	186	Lower Floridan
		465	46	Lower Floridan
		929	65	Updip clastic phase
Hydraulic Conductivity	(53 to 122 m/day)			Upper Floridan, Beaufort County
		31 m/day	23 m/day	Lower Floridan, Coastal South Carolina

Data from WSRC 2000b

Table 1.3.4-12. Parameters Determined for the Upper Three Runs Aquifer

Parameter	Value [Mean] (Average)	Range Maximum	Range Minimum	Comments
Hydraulic conductivity (vertical)	[2.71×10^{-3} m/d]	1.55×10^{-1} m/d	8.2×10^{-3} m/d	Clayey sand samples
Hydraulic conductivity (horizontal)	[3.38×10^{-3} m/d]	7.3×10^{-1}	9.66×10^{-4}	Clayey sand samples
Porosity	[40%]	55%	10%	Clayey sand samples
Effective porosity	12%			Clayey sand samples
Hydraulic conductivity (vertical)	5.09×10^{-3} m/d	6.4×10^{-3} m/d	1.04×10^{-3} m/d	Sandy clay samples
Hydraulic conductivity (horizontal)	1.24×10^{-4} m/d	9.85×10^{-2}	7.77×10^{-4}	Sandy clay samples
Porosity	41%	71%	23%	Sandy clay samples
Effective porosity	5%			Sandy clay samples
Leakance coefficient		2.58×10^{-4} m/d	4.11×10^{-4} m/d	

Data from WSRC 2000b

Table 1.3.4-13. Water Quality of the Savannah River Below SRS (River-Mile 120) for 1992-1994

Analyte	Units	No. of Analyses	Min	Max	Mean
Alkalinity	mg/L	48	13	26	19.24
Aluminum	mg/L	36	0.08	0.64	0.4
Ammonia	mg/L	48	00.02	0.44	0.13
BOD 5 Day	mg/L	12	0.7	1.8	1.29
Cadmium	mg/L	36	0	0	0
Calcium	mg/L	38	3.26	5.02	4.18
Chloride	mg/L	36	4	12	6.27
Chromium	mg/L	36	0	0.01	0.01
Conductivity	µS/cm[a]	48	51	114	83.93
Copper	mg/L	36	0	0	0
DO	mg/L	84	5.8	21	8.77
Fecal Colloms	MPNECMED[b]	12	430	9300	3749.17
Fixed Residue	mg/L	36	1	42	8.81
Iron	mg/L	36	0.40	1.32	0.79
Lead	mg/L	36	0	0	0
Magnesium	mg/L	36	0.92	1.52	1.3
Manganese	mg/L	36	0.03	0.1	0.07
Mercury	mg/L	36	0	0.92	0.23
Nickel	mg/L	36	0	0.03	0.02
Nitrate + Nitrite	mg/L	48	0.11	0.47	0.29
pH	pH	1	6.7	6.7	6.7
Phosphate	mg/L	36	0.03	0.01	0.06
Sodium	mg/L	36	5.28	13	9.29
Sulfate	mg/L	36	4	11	7.64
Suspended Solids	mg/L	36	3	48	11.31
TOC	mg/L	12	1.5	14	5.08
Temperature	C	60	1	30	17.83
Total Dissolved Solids	mg/L	36	49	105	65.94
Total Phosphate	mg/L	12	0.07	0.13	0.1
Total Solids	mg/L	36	54	120	77.26
Turbidity	JTU[c]	48	2.66	32.4	10.77
Volatile Solids	mg/L	36	1	9	2.72
Water Volume	L	36	4E+11	2.68E+12	9.58E+11
Zinc	mg/L	36	0	0.01	0.01
pH	pH	36	5.9	7.2	6.34
pH (lab)	pH	12	6.7	7	6.86

[a] microsiemens per centimeter
[b] Maximum probable number per 100 mL
[c] Jackson turbidity units

Data from WSRC 2000b

Table 1.3.4-14. Pumpage for Municipal Supplies

Location	User	Distance From SRS Center (miles)	Number Served	Average Daily Use (gpd x 10^6)	Water-Bearing Formation[a]	Type Source
Aiken County, SC						
1	City of Aiken	22	28,000	2.0	"Tuscaloosa"[b]	Springs
2	Town of Jackson	10	3,152	0.175	"Tuscaloosa"	2 Wells
3	Town of New Ellenton	11	4,000	0.300	"Tuscaloosa"	2 Wells
4	Town of Langley	19	1,330	0.130	"Tuscaloosa"	2 Wells
5	College Acres	15	1,264	0.065	"Tuscaloosa"	3 Wells
6	Bath Water Dist.	19	1,239	0.325	"Tuscaloosa"	2 Wells
7	Beech Island	18	4,500	0.300	"Tuscaloosa"	3 Wells
8	Talatha	10	1,260	0.040	"Tuscaloosa"	2 Wells
9	Breezy Hill	22	4,500	0.233	"Tuscaloosa"	4 Wells
10	Burnettown	20	1,200	0.150	"Tuscaloosa"	2 Wells
11	Montmorenci	17	4,232	0.423	"Tuscaloosa"	2 Wells
12	Warrenville	19	788	0.300	"Tuscaloosa"	4 Wells
13	Johnstown	18	1,560	0.144		
	Nowlandville	18	1,232	0.100	"Tuscaloosa"	1 Well
	Gloverville	18	1,440	0.144		
14	Belvedere	24	6,300	0.362	"Tuscaloosa"	5 Wells
Barnwell County, SC						
15	Barnwell	15	6,500	4.0	Congaree	11 Wells
16	Williston	15	3,800	0.700	Santee "Tuscaloosa"	4 Wells
17	Blackville	22	2,975	0.300	"Tuscaloosa"	3 Wells
18	Hilda	22	315	0.009	"Tuscaloosa"	1 Well
19	Elko	17	315	0.010	Santee	1 Well
Burke County, GA						
20	Girard	16	210	0.020	"Tuscaloosa"	3 Wells

[a] Many of these wells are gravel-packed from the bottom of the well to the free water table; thus, the water-bearing formation may not be clearly defined.
[b] "Tuscaloosa" refers to undifferentiated Cretaceous formations of the Lumbee Group.

Data from WSRC 2000b

Figures

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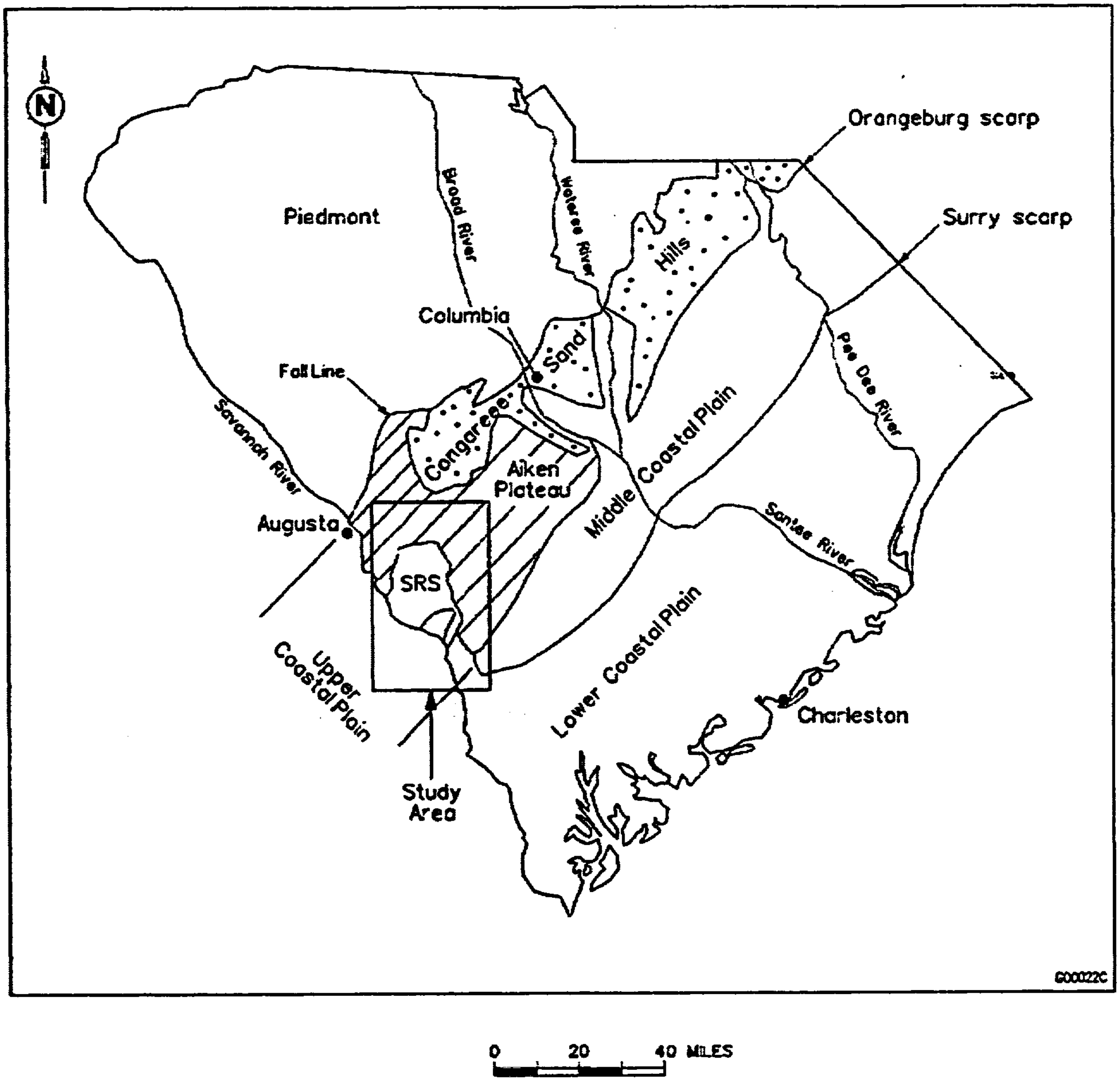

Data from WSRC 2000b

Figure 1.3.4-1. Regional Physiographic Provinces of South Carolina

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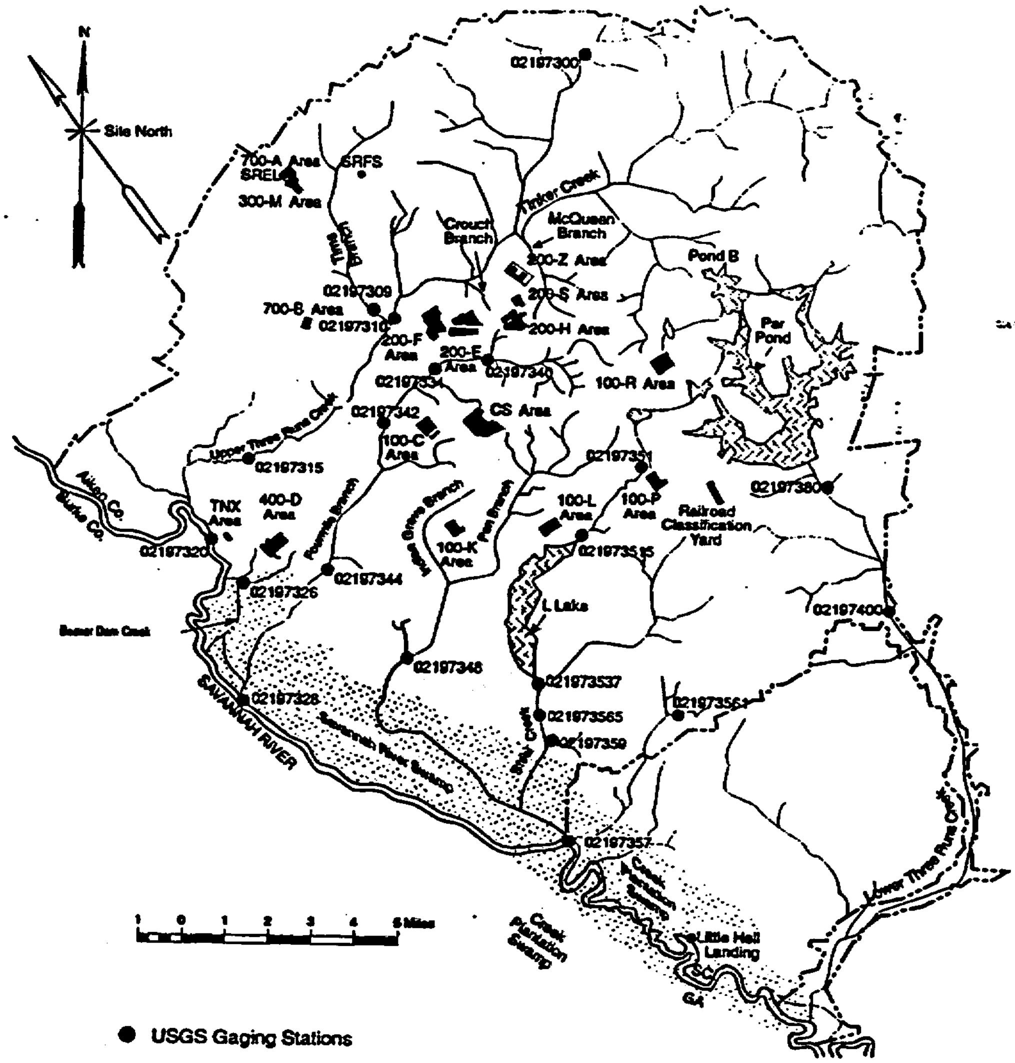

Data from WSRC 2000b

Figure 1.3.4-2. Surface Drainage Map of SRS Showing the Savannah River Swamp and Gauging Stations

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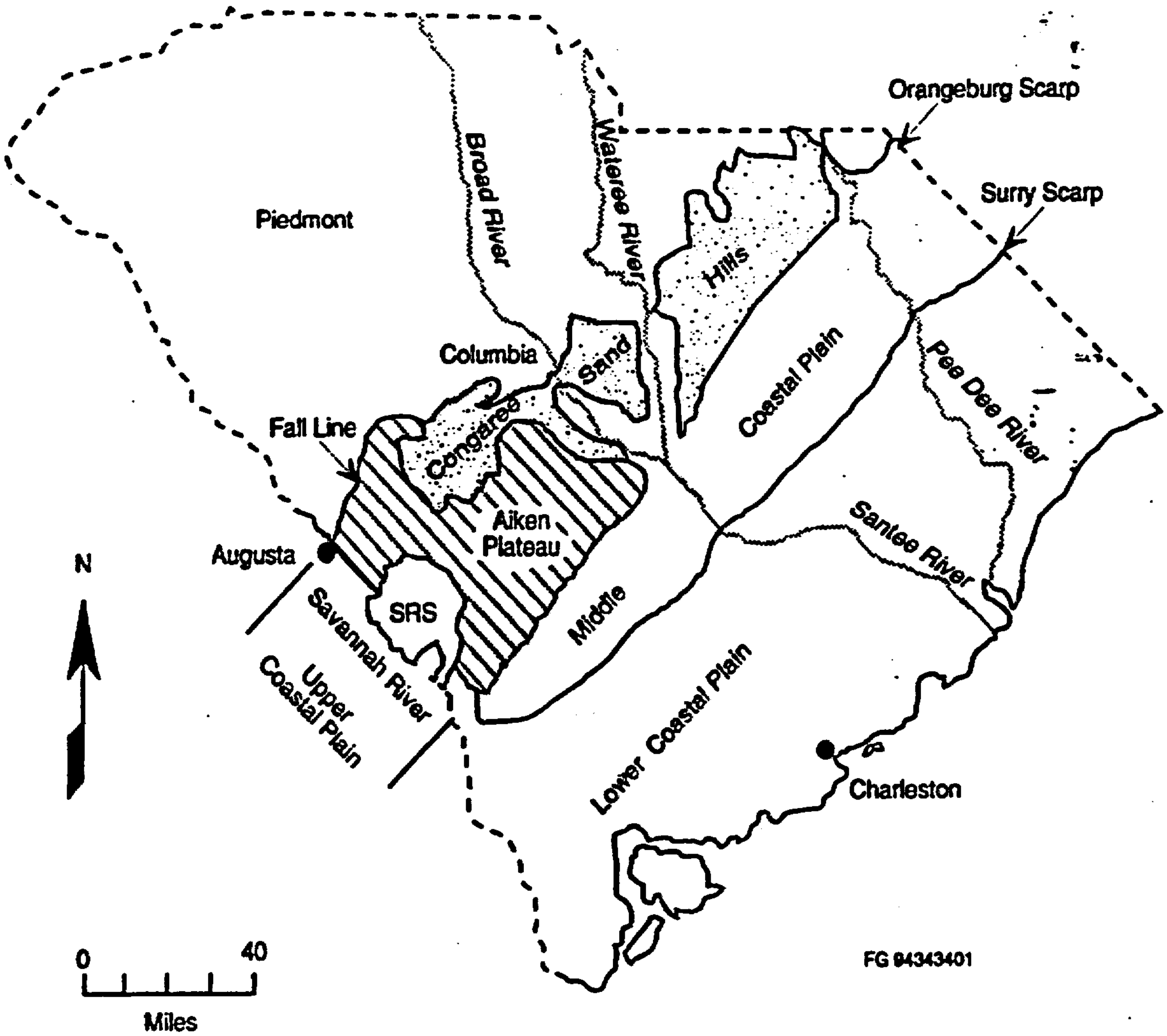

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Figure 1.3.4-3. Physiography of the SRS Area

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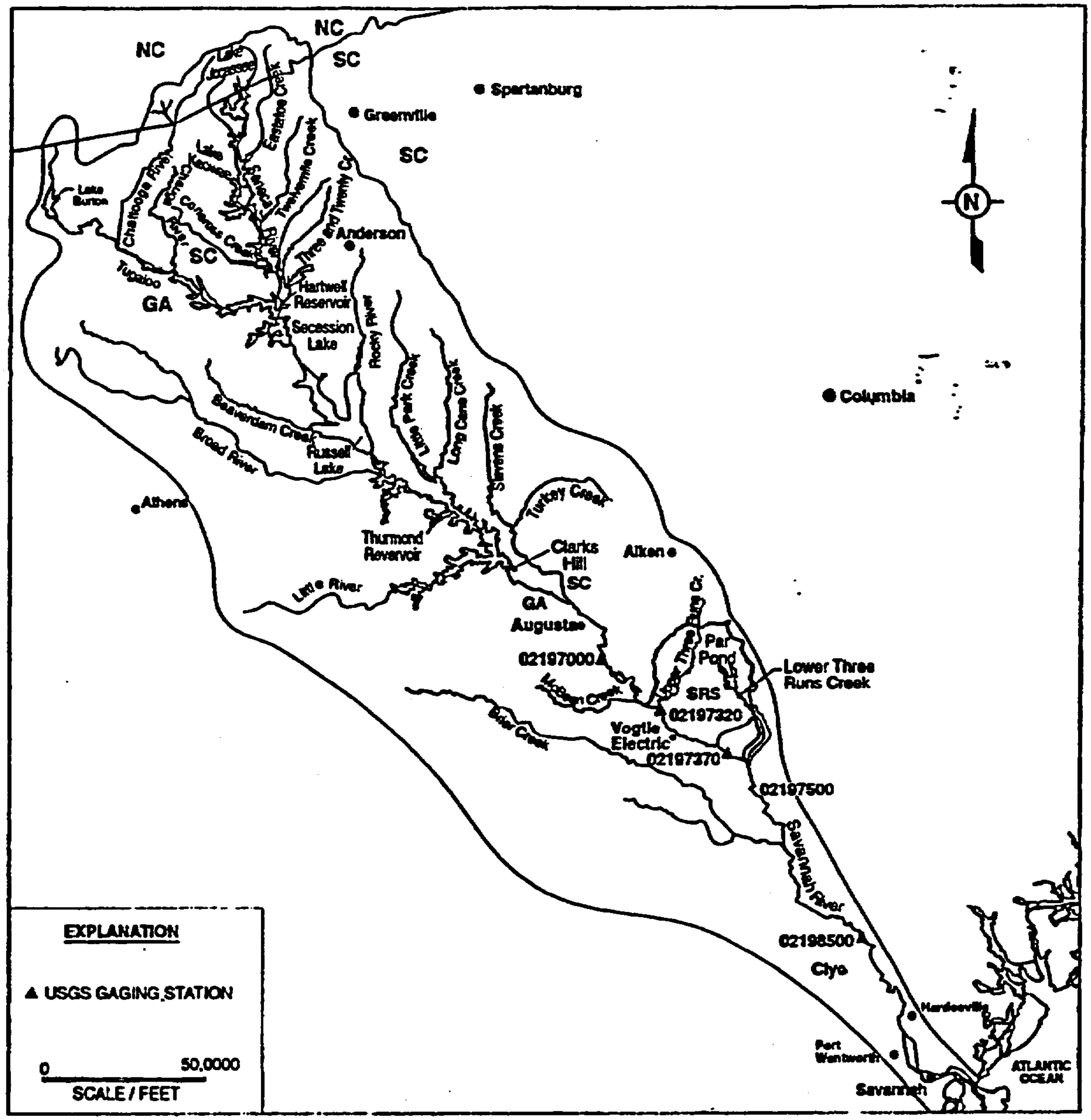

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Figure 1.3.4-4. Savannah River Basin

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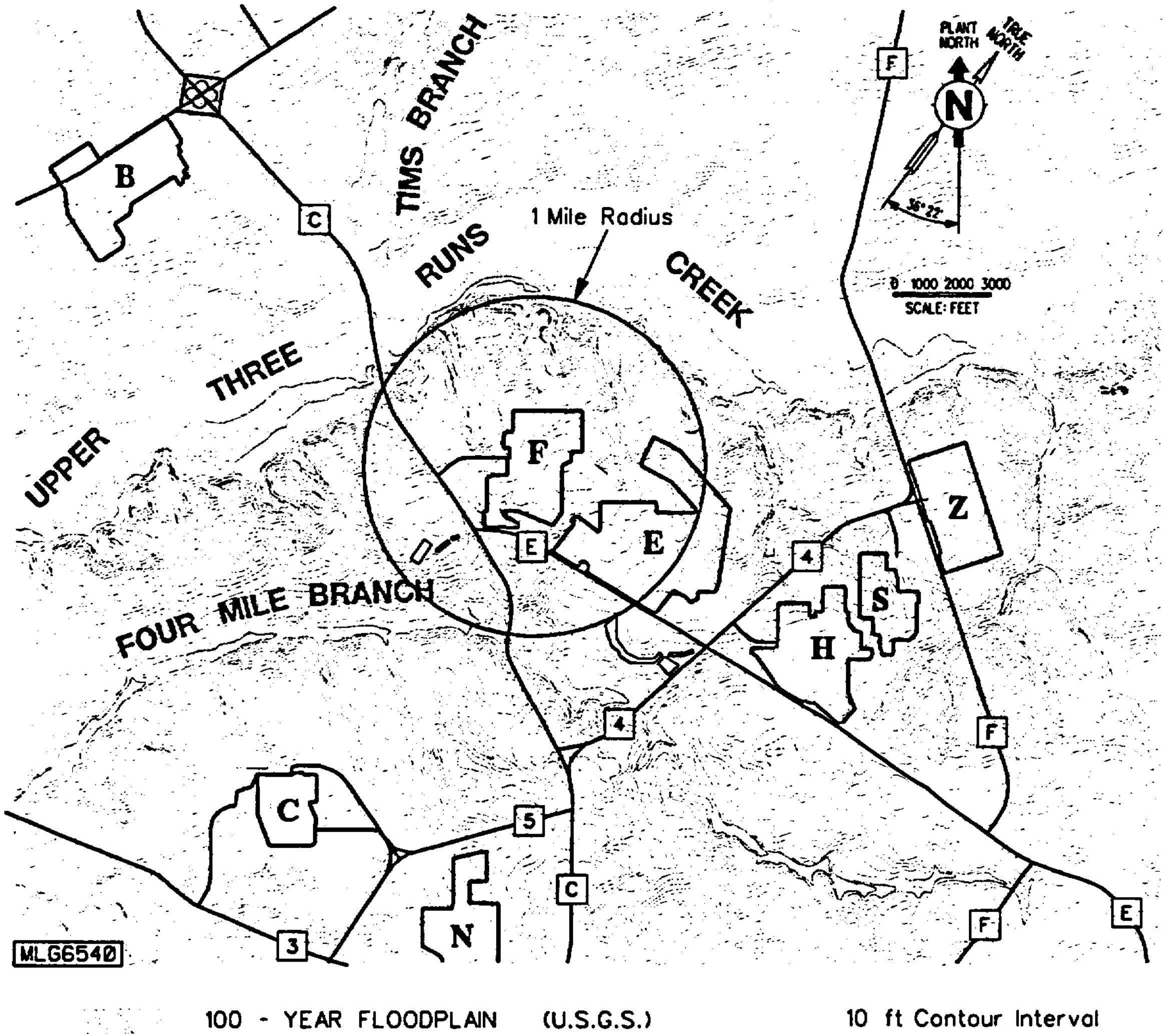

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Figure 1.3.4-5. Topographic Map of F Area and Surrounding Area

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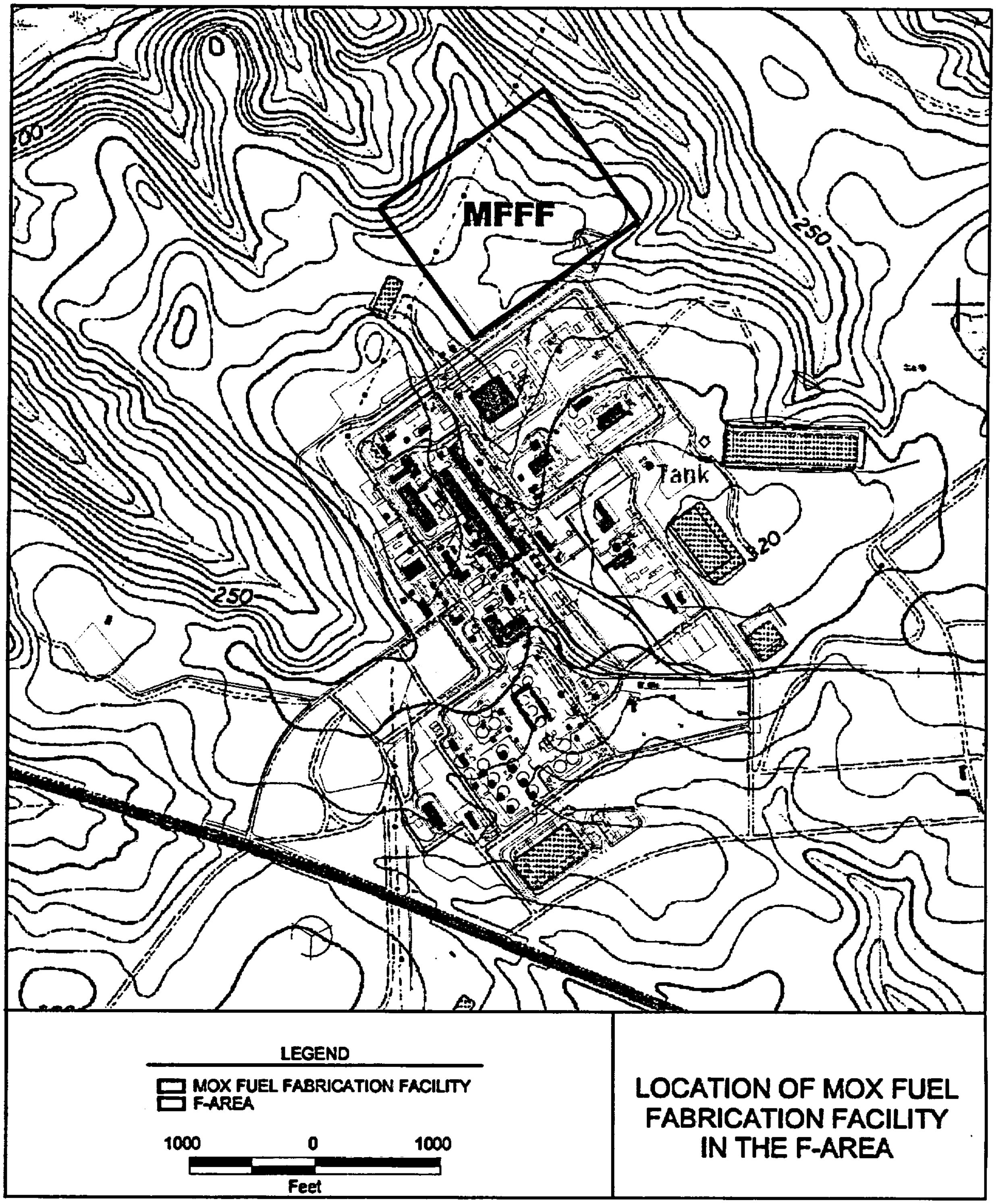

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Figure 1.3.4-6. Location of the MFFF in F Area

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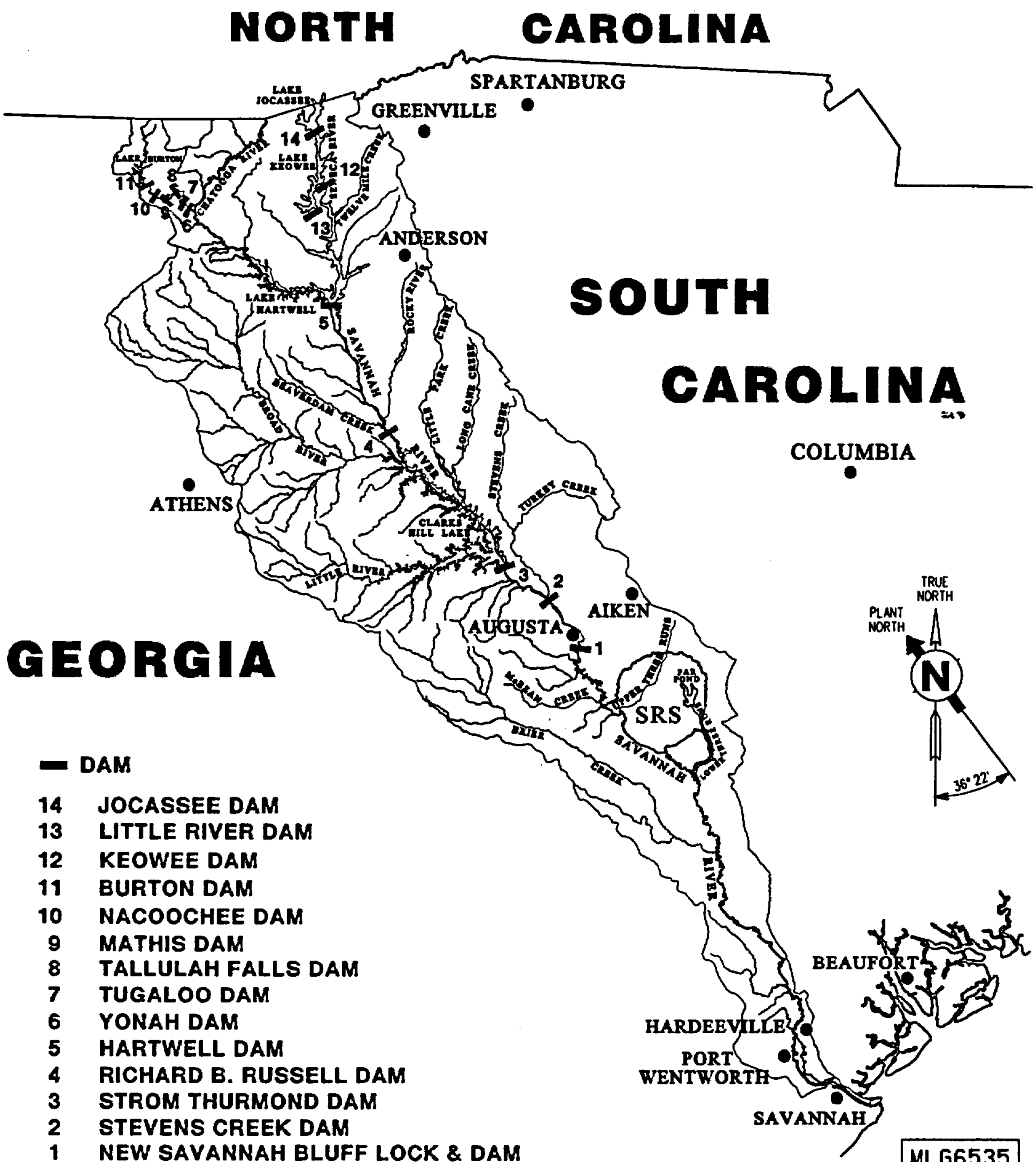

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Figure 1.3.4-7. Savannah River Basin Dams Upstream of SRS

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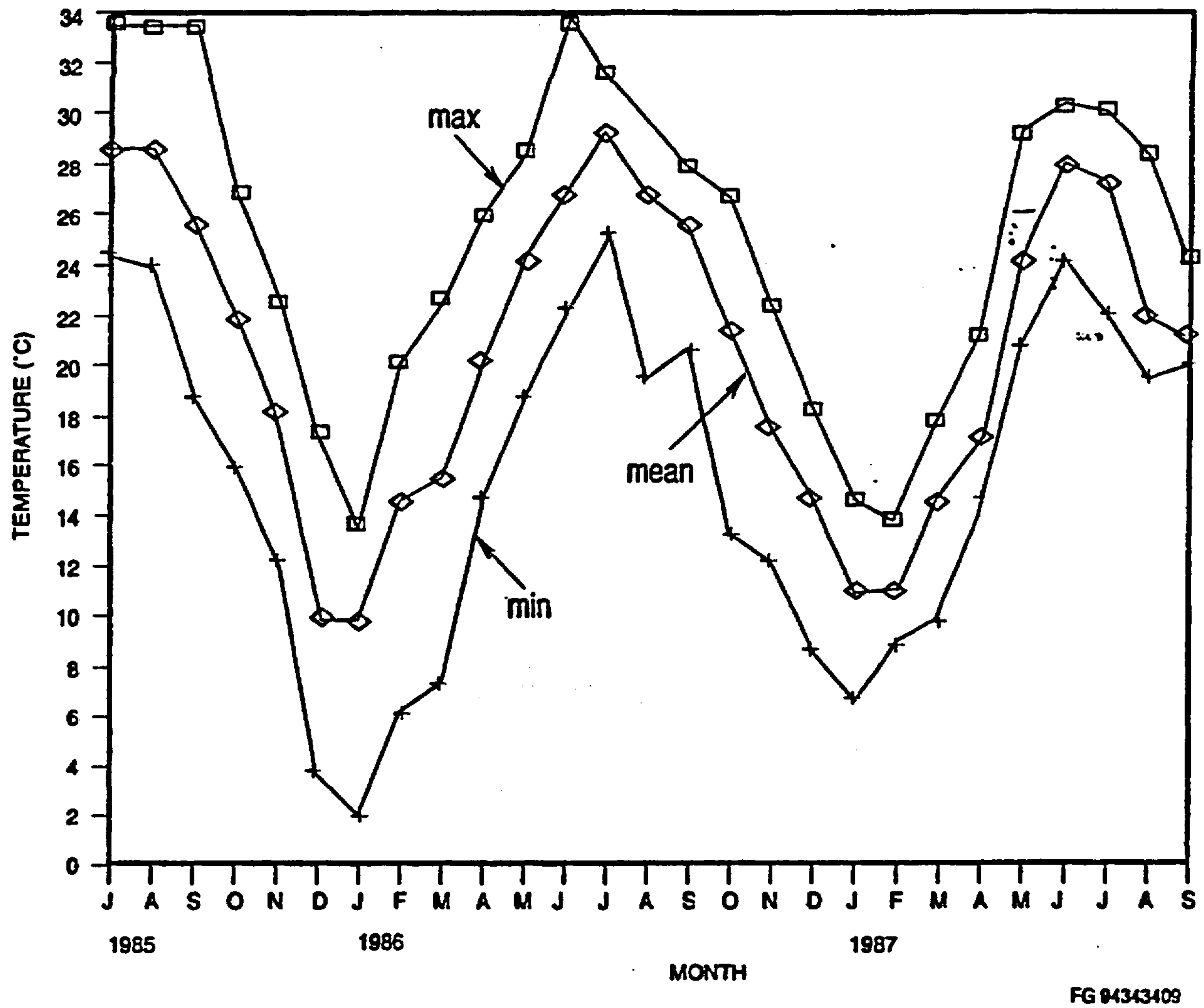

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Figure 1.3.4-8. Monthly Range and Mean Water Temperature of Fourmile Branch for June 1985 Through September 1987

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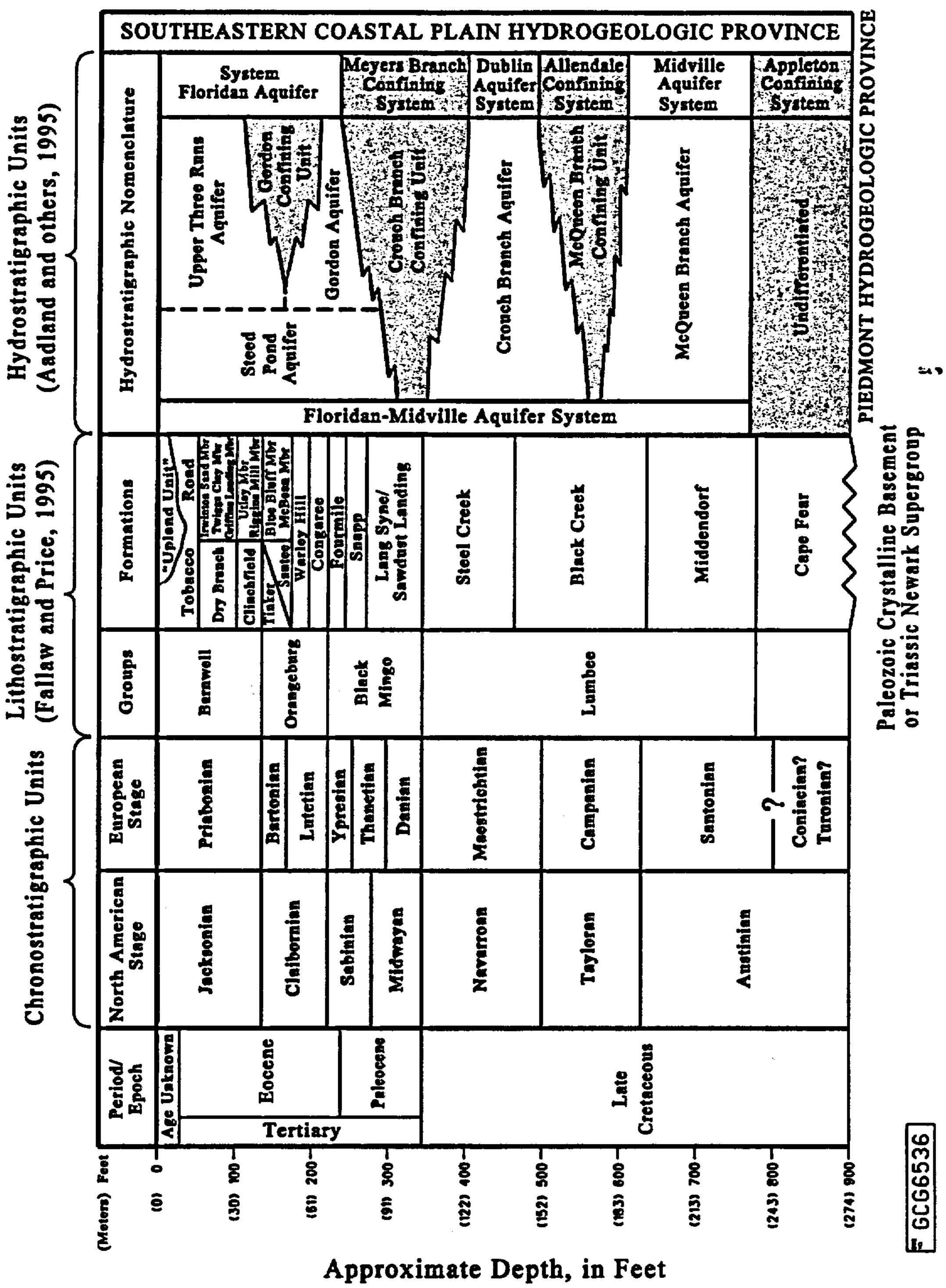

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Figure 1.3.4-9. Comparison of Chronostratigraphic, Lithostratigraphic, and Hydrostratigraphic Units in the SRS Region

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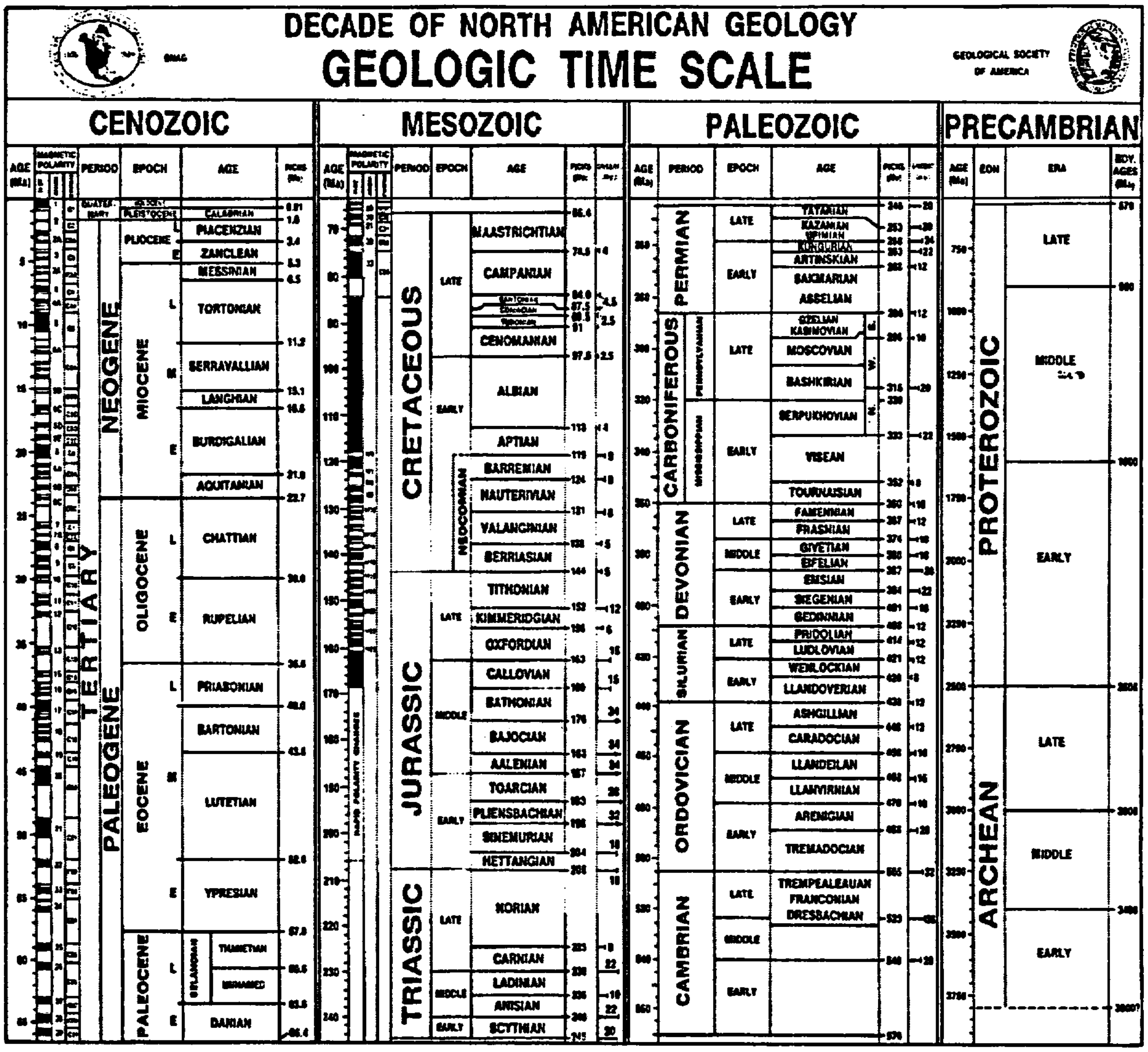

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Figure 1.3.4-10. Geologic Time Scale

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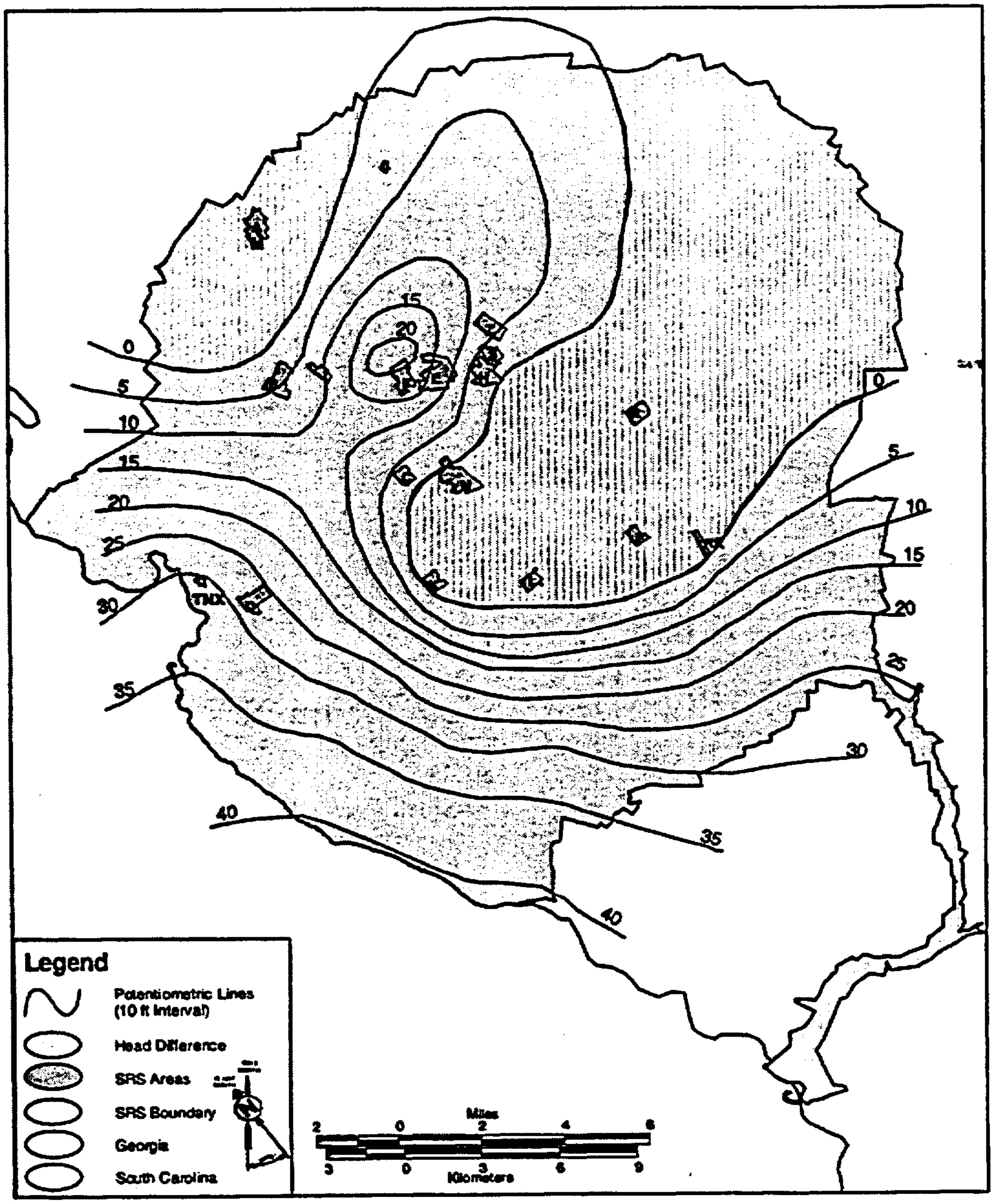

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Figure 1.3.4-11. Hydraulic Head Difference Across the Crouch Branch Confining Unit, July 1990

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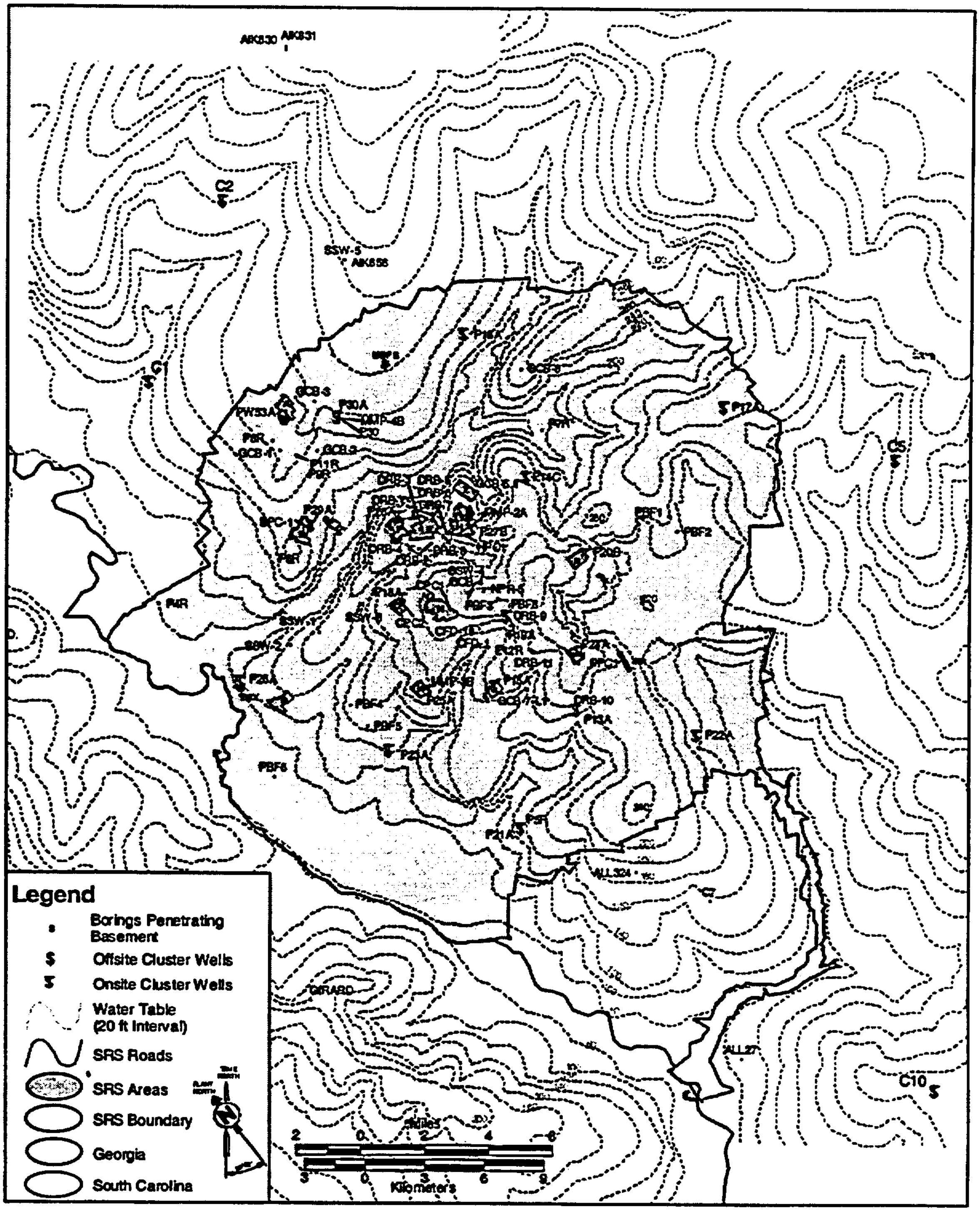

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Figure 1.3.4-12. Location of Type and Reference Wells for Hydrostratigraphic Units at SRS

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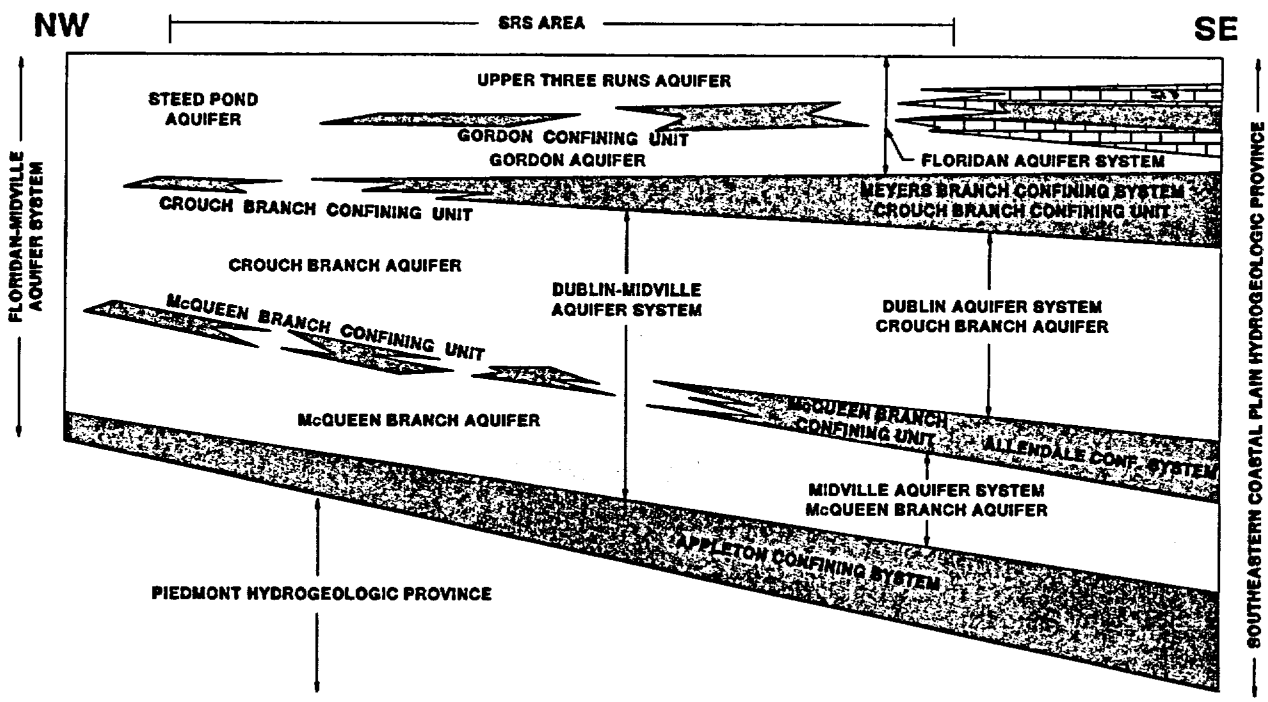

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Figure 1.3.4-13. Hydrogeologic Nomenclature for the SRS Region

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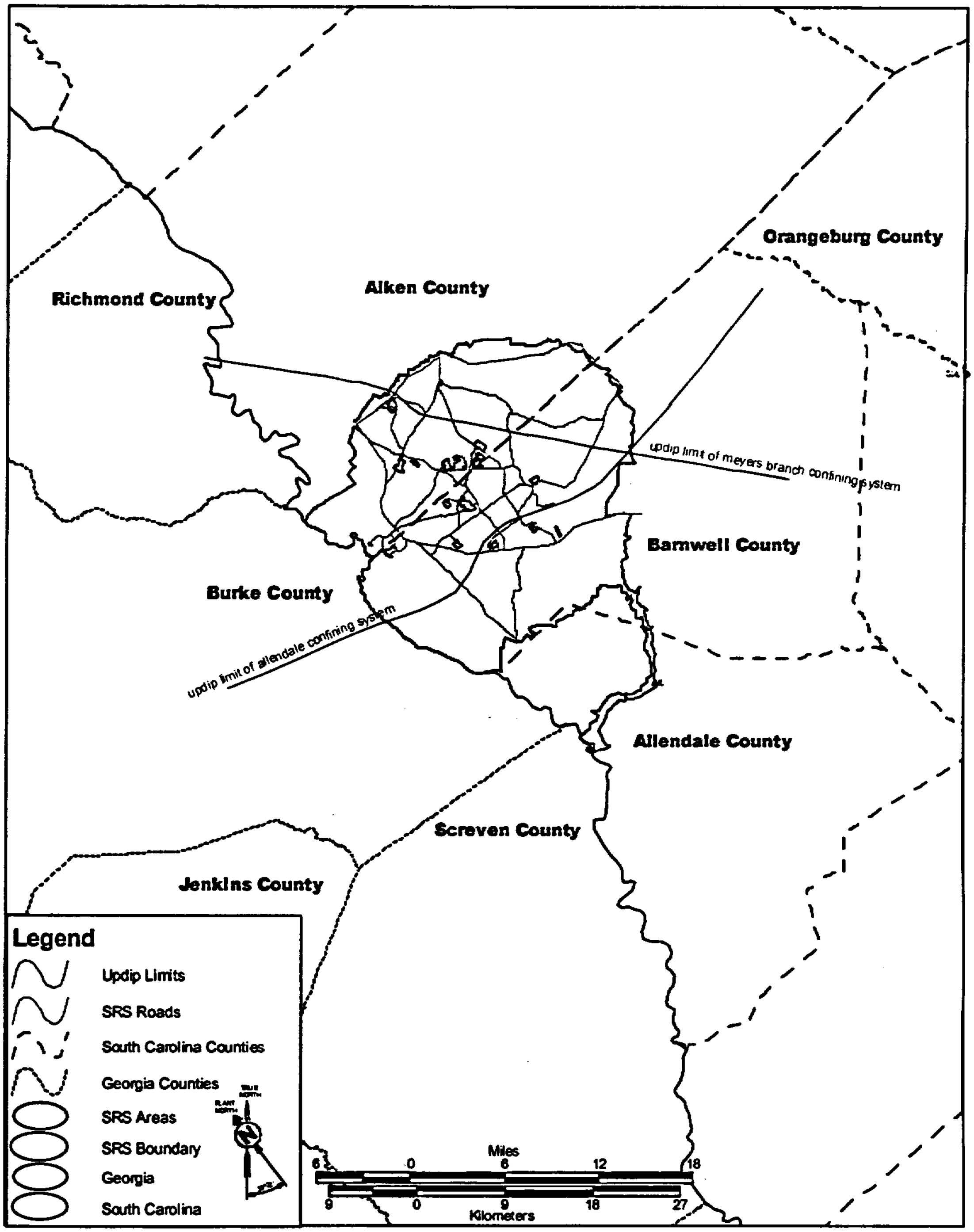

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Figure 1.3.4-14. Location of Aquifer and Confining Systems in the SRS Region

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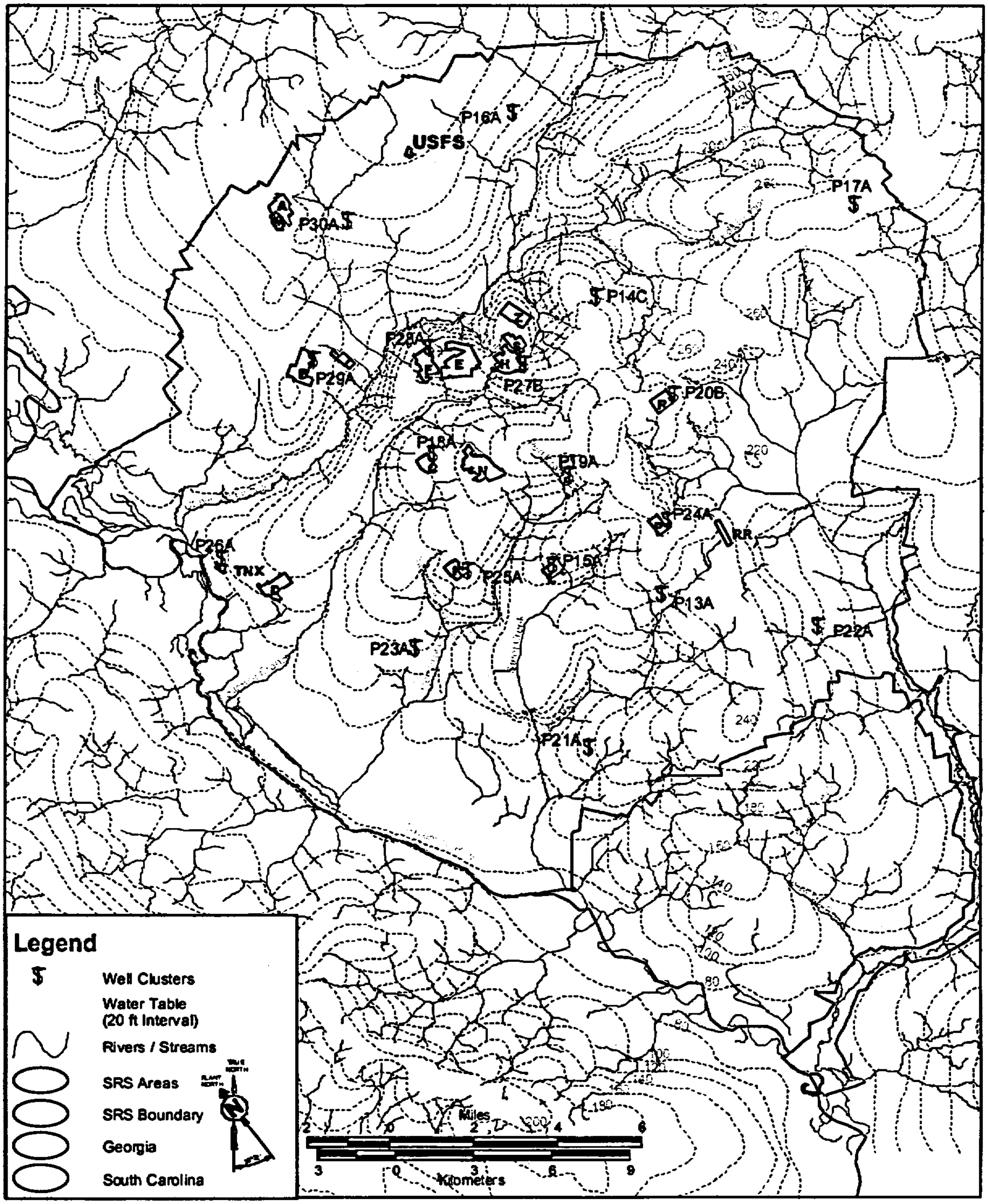

Data from WSRC 2000b

Figure 1.3.4-15. Potentiometric Surface of the Upper Three Runs/Steed Pond Aquifers, 1998 (water table map)

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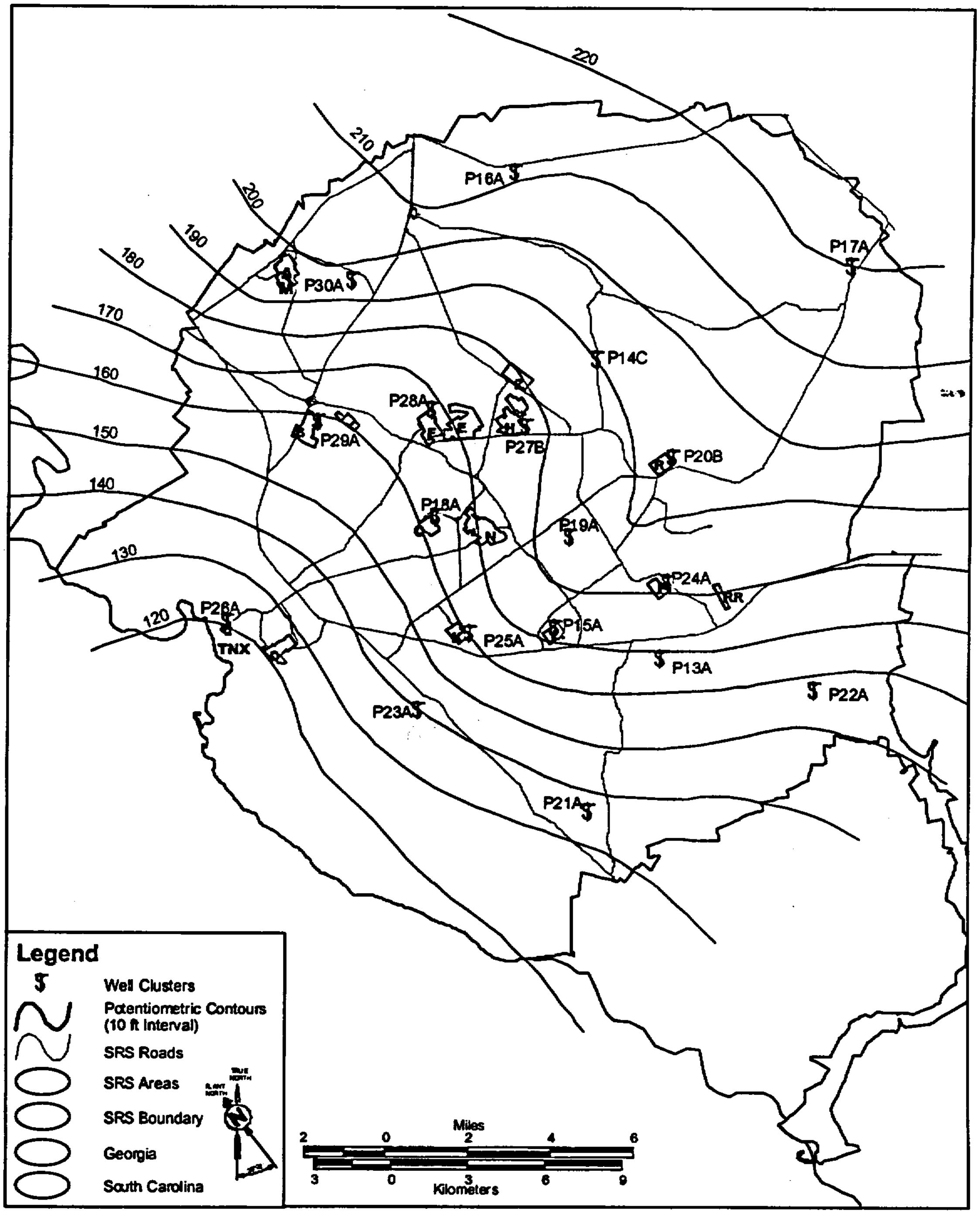

Data from WSRC 2000b

Figure 1.3.4-16. Potentiometric Surface of the Gordon Aquifer

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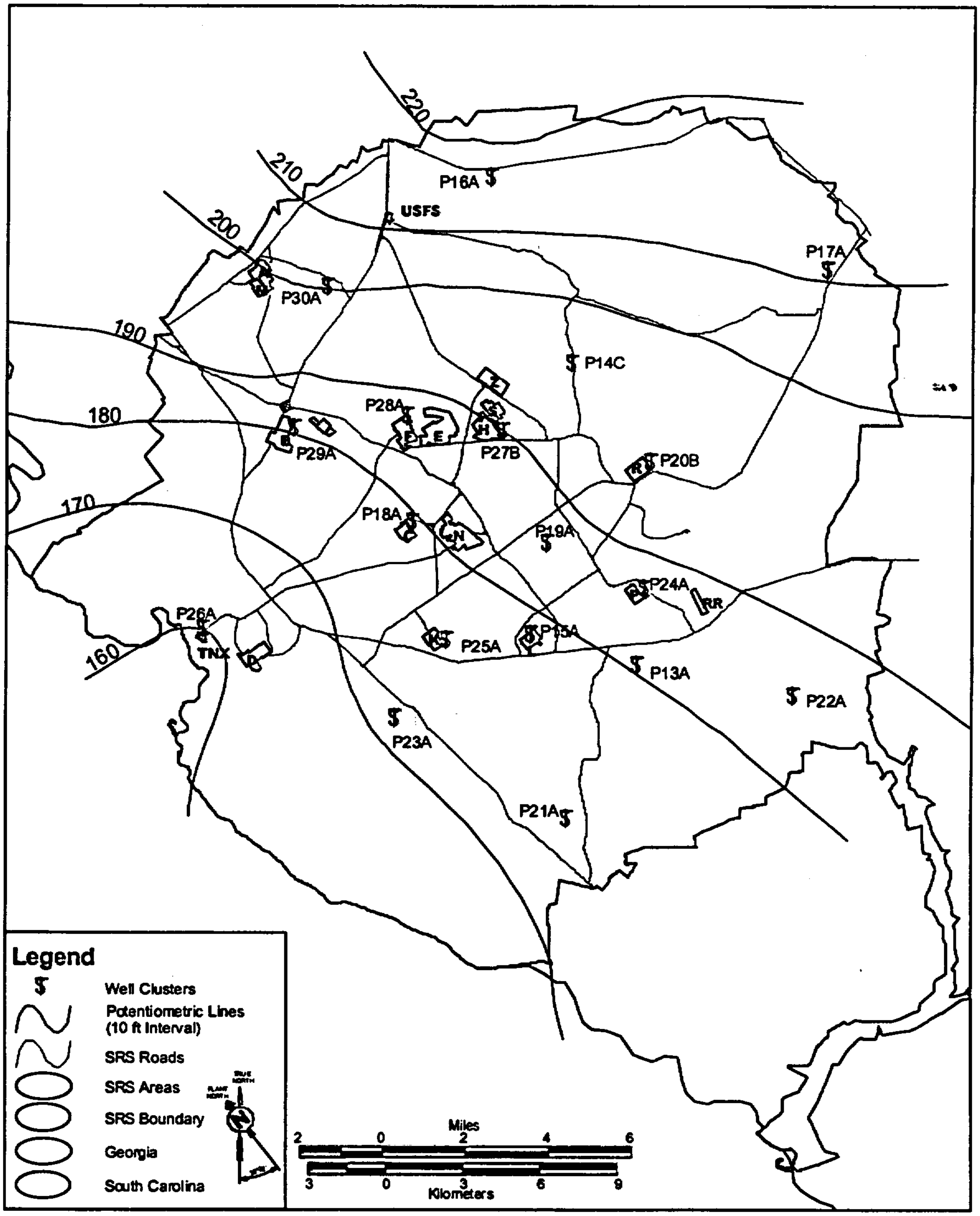

Data from WSRC 2000b

Figure 1.3.4-17. Potentiometric Surface of the Crouch Branch Aquifer

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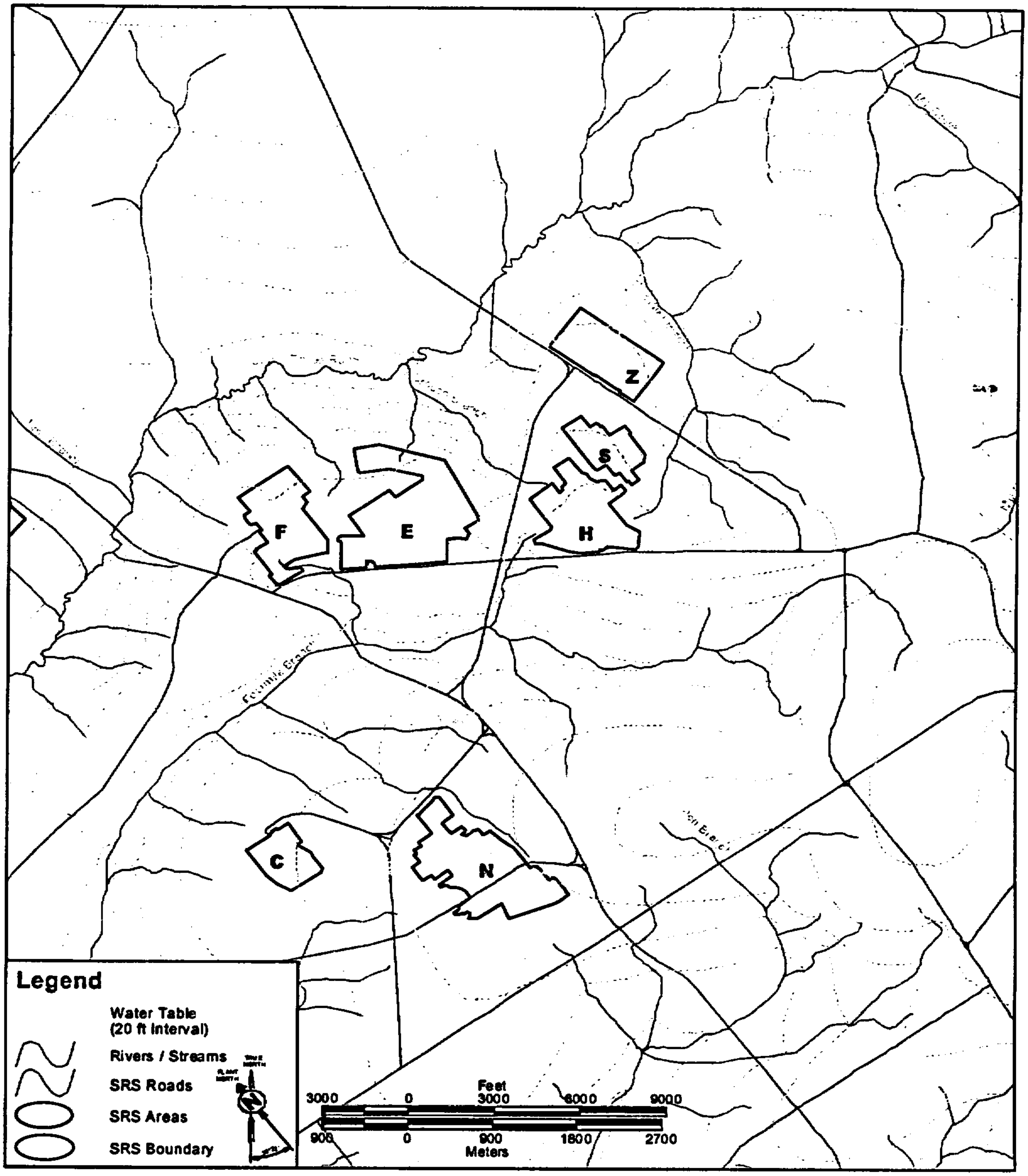

Data from WSRC 2000b

Figure 1.3.4-18. Potentiometric Surface of the Upper Three Runs Aquifer (water table) for the General Separations Area

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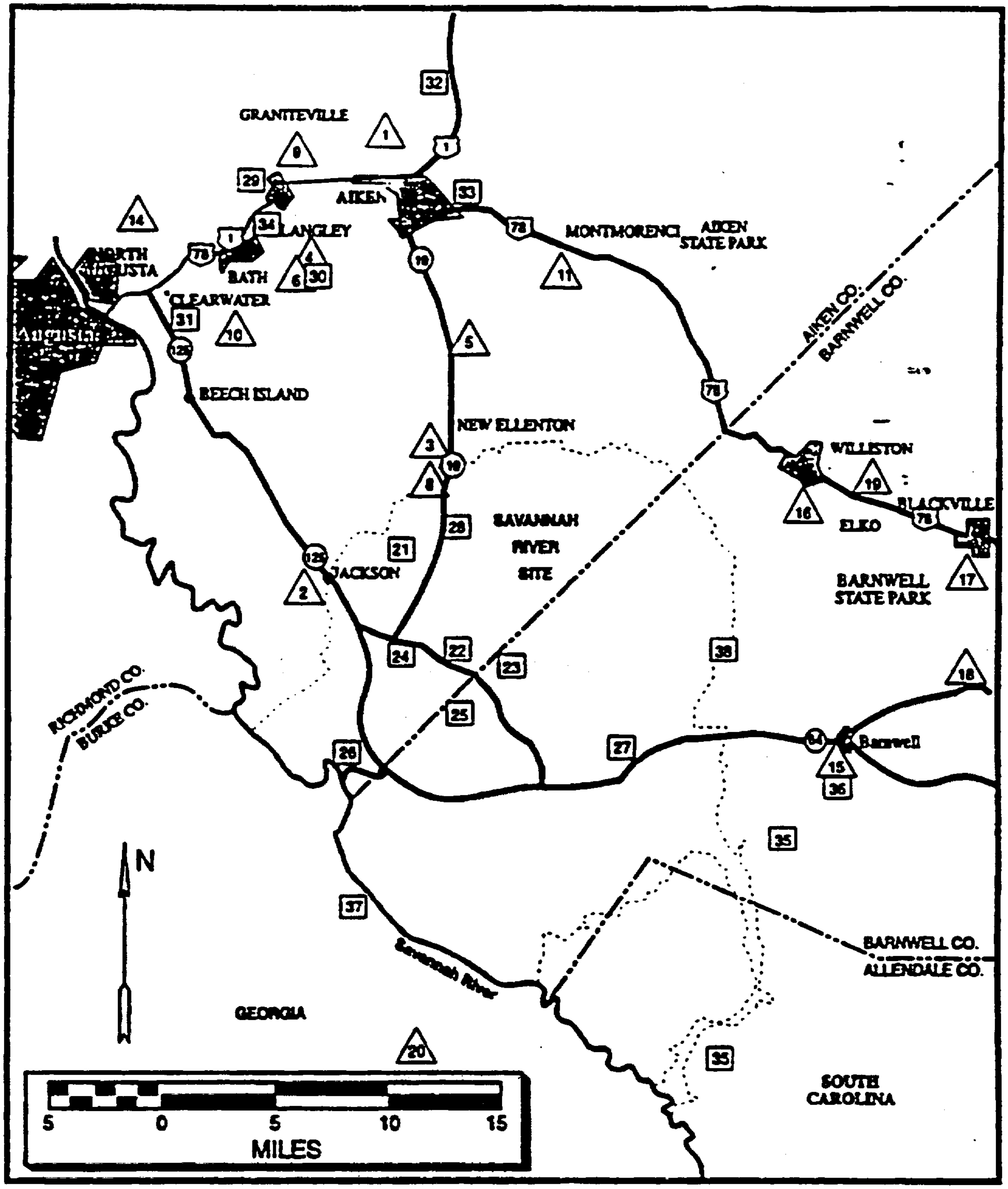

15 MUNICIPAL USER (TYP.)

19 INDUSTRIAL USER (TYP.)

Data from WSRC 2000b

Figure 1.3.4-19. The Location of Industrial and Municipal Groundwater Users Near SRS

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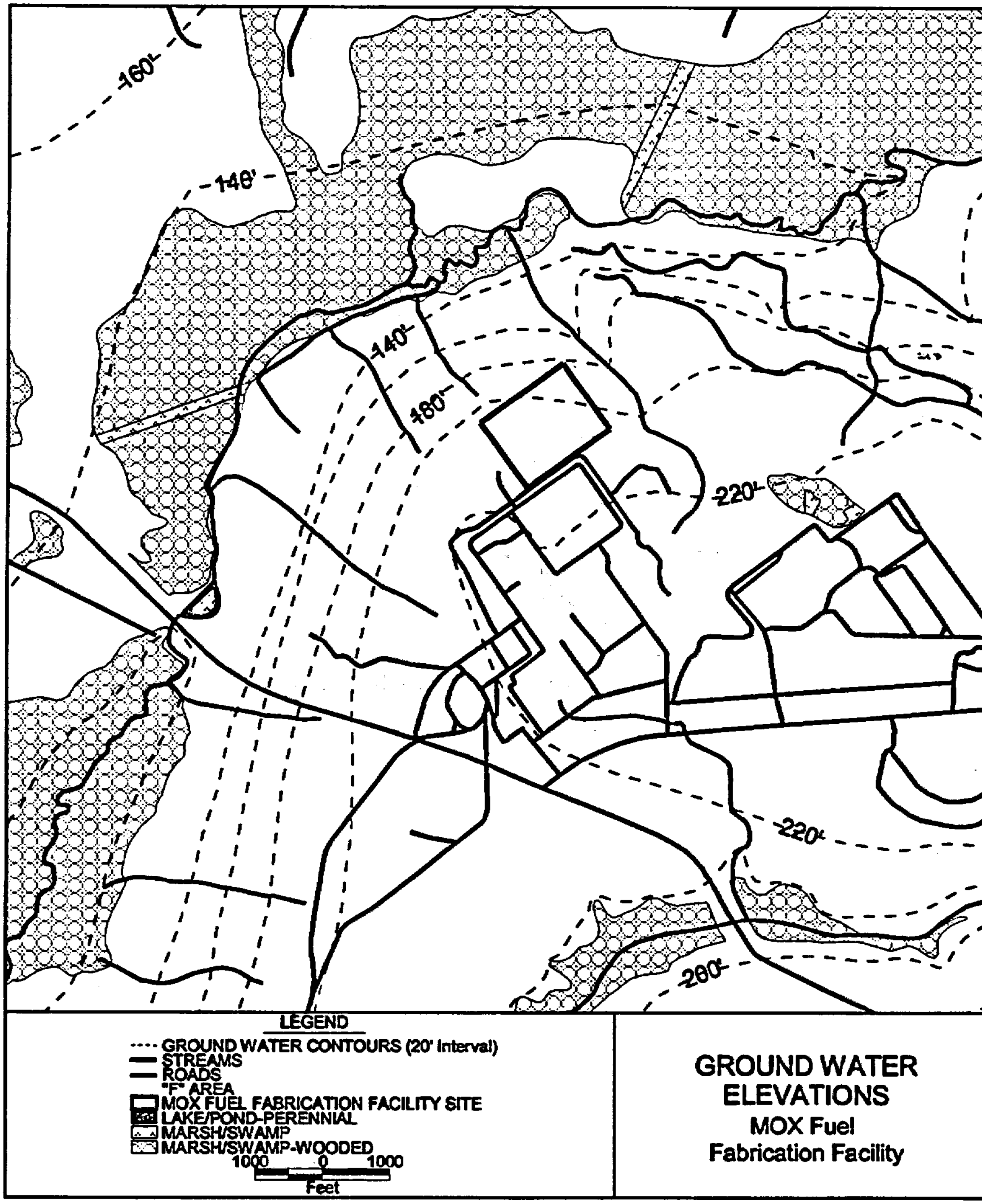

Data from WSRC 2000b

Figure 1.3.4-20. Groundwater Elevations in F Area

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1.3.5 Geology

1.3.5.1 Regional Geology

The following discussion on the regional and MFFF site geology is based on detailed discussions presented in Section 1.4.3 of the *Natural Phenomena Hazards (NPH) Design Criteria and Other Characterization Information for the Mixed Oxide (MOX) Fuel Fabrication Facility at Savannah River Site (U)* (WSRC 2000b) and in the *MOX Fuel Fabrication Facility Site Geotechnical Report* (DCS 2000). The area of interest evaluated includes a radius of about 200 mi (322 km) from SRS and the MFFF site. The information also provides the basis for understanding the regional and SRS geology as applied to the subsurface encountered at the MFFF site.

Many SRS investigations and an extensive literature review have been used to reach the conclusion that there are no geologic threats affecting the MFFF site, except the Charleston Seismic Zone and the minor random Piedmont earthquakes. Although the Pen Branch fault has been regarded as the primary structural feature at SRS that has the characteristics necessary to pose a potential seismic risk, studies have indicated that the fault is not capable.

The southeastern continental margin, within a 200-mi (322-km) radius of SRS, contains portions of all the major divisions of the Appalachian orogen (mountain belt) in addition to the elements that represent the evolution to a passive margin.

Within the Appalachian orogen, several lithotectonic terranes that have been extensively documented include the foreland fold belt (Valley and Ridge) and western Blue Ridge Precambrian-Paleozoic continental margin; the eastern Blue Ridge-Chauga Belt-Inner Piedmont terrane; the volcanic-plutonic Carolina terrane; and the geophysically defined basement terrane beneath the Atlantic Coastal Plain (see Figure 1.3.5-1). These geological divisions record a series of compressional and extensional events that span the Paleozoic. The modern continental margin includes the Triassic-Jurassic rift basins that record the beginning of extension and continental rifting during the early to middle Mesozoic. The offshore Jurassic-Cretaceous clastic-carbonate bank sequence covered by younger Cretaceous and Tertiary marine sediments, and onshore Cenozoic sediments represent a prograding shelf-slope and the final evolution to a passive margin. Other offshore continental margin elements include the Florida-Hatteras shelf and slope and the unusual Blake Plateau basin and escarpment.

From the Cumberland Plateau and the Valley and Ridge provinces to the offshore Blake Plateau basin, the regional geology records the complete cycles of opening and closing of Paleozoic oceans and the opening of a new ocean (Atlantic). Late Proterozoic rifting is recorded in rift-related sediments at the edge of the frontal Blue Ridge province and the Ocoee and Tallulah Falls basins in the western and eastern Blue Ridge, respectively. Passive margin conditions began in the middle Cambrian and persisted through early Ordovician. The Cambro-Ordovician sedimentary section in the Valley and Ridge reflects this condition. The collision-accretionary phase of the Appalachians began in the middle Ordovician and persisted with pulses through the early Permian. Mesozoic rifting of the continents led to the creation of Triassic rift basins on the modern eastern continental margin and ultimately to the creation of the Atlantic Ocean basin. The evolution to a passive margin is recorded in the Cretaceous through Holocene Coastal Plain sediments and offshore carbonate bank and shelf sequences.

The two predominant processes sculpting the landscape during this tectonically quiet period included erosion of the newly formed highlands and subsequent deposition of the sediments on the coastal plain to the east. The passive margin region consists of a wedge of Cretaceous and Cenozoic sediments that thicken from near zero at the Fall Line to about 1,100 ft (335 m) in the center of SRS, and to approximately 4,000 ft (1,220 m) at the South Carolina coast. The fluvial to marine sedimentary wedge consists of alternating sand and clay with tidal and shelf carbonates common in the downdip Tertiary section.

1.3.5.1.1 Valley and Ridge Province

The Valley and Ridge Province (see Figure 1.3.5-1) includes Paleozoic sedimentary rocks consisting of conglomerate, sandstone, shale, and limestone. The shelf sequence was extensively folded and thrust faulted during the Alleghanian collisional event. The physiography is expressed as a series of parallel ridges and valleys that are a result of the erosion of breached anticlines with the oldest layers exposed in the valleys and the younger layers forming the ridges. The topographic expression of the folds is best expressed in the central and southern Appalachians. In the central and northern Appalachians the folded structure is dominant and thrust faults are not as numerous or expressed at the surface. The eastern boundary with the Blue Ridge province is formed by the Blue Ridge-Piedmont thrust. This boundary is distinct in most places along the strike of the Appalachians and marks the change from folded rocks that are not penetratively deformed to rocks that are penetratively deformed.

1.3.5.1.2 Blue Ridge Province

The Blue Ridge geologic province is bounded on the southeast by the Brevard fault zone and on the northwest by the Blue Ridge-Piedmont fault system (see Figure 1.3.5-1). The province is a metamorphosed basement/cover sequence that has been complexly folded, faulted, penetratively deformed, and intruded. These rocks record multiple late Proterozoic to late Paleozoic deformation (extension and compression) associated with the formation of the Iapetos Ocean and the Appalachian orogen. The province consists of a series of westward-vergent thrust sheets, each with different tectonic histories and different lithologies (including gneisses, plutons, metavolcanic, and metasedimentary rift sequences), as well as continental and platform deposits. The Blue Ridge-Piedmont fault system thrust the entire Blue Ridge province northwest over Paleozoic sedimentary rock of the Valley and Ridge province during the Alleghanian orogeny. The Blue Ridge geologic province reaches its greatest width in the southern Appalachians.

The Blue Ridge is divided into a western and an eastern belt separated by the Hayesville-Gossan Lead fault. Thrust sheets in the western Blue Ridge consist of a rift-facies sequence of clastic sedimentary rocks deposited on continental basement, whereas thrust sheets in the eastern Blue Ridge consist of slope and rise sequences deposited in part on continental basement and in part on oceanic crust. Western Blue Ridge stratigraphy consists of basement gneisses, metasedimentary, metaplutonic, and metavolcanic rocks, whereas Eastern Blue Ridge stratigraphy consists of fewer lithologies, more abundant mafic rocks, and minor amounts of continental basement. These divisions of the Blue Ridge are discussed in more detail below.

1.3.5.1.2.1 Western Blue Ridge

The western Blue Ridge consists of an assemblage of Middle Proterozoic continental (Greenville) basement nonconformably overlain by Late Proterozoic to Early Paleozoic rift and drift facies sedimentary rock. The basement consists of various types of gneisses, amphibolite, and gabbroic and volcanic rock and metasedimentary rock. All basement is metamorphosed to granulite or uppermost amphibolite facies. The calculated ages of these rocks generally range from 1,000 to 1,200 Ma (mega annum or millions of years).

The rifting event during the Late Proterozoic through Early Paleozoic that formed the Iapetos Ocean is recorded in the rift-drift sequence of the Ocoee Supergroup and Chillhowie Group. These rocks, basement and sedimentary cover, were all later affected by Taconic and possibly Acadian deformation and metamorphism. The entire composite thrust sheet was transported west as an intact package during the Alleghanian collision event on the Blue Ridge-Piedmont thrust.

1.3.5.1.2.2 Eastern Blue Ridge

The eastern Blue Ridge is located southeast of the western Blue Ridge and is separated from that province by the Hayesville-Gossan Lead fault. The Brevard fault zone forms the southeastern boundary with the Inner Piedmont (see Figure 1.3.5-2). Lithologically, the eastern Blue Ridge is composed of continental slope, rise, and ocean floor metasedimentary rocks in association with oceanic or transitional to oceanic crust. This contrasts with the western Blue Ridge, which contains metasedimentary rocks suggesting continental rift-drift facies of a paleomargin setting. The eastern Blue Ridge is structurally complex with several major thrust faults, multiple fold generations, and two high-grade metamorphic episodes. Metamorphism took place during the Taconic and possibly Acadian orogenies.

1.3.5.1.3 Inner Piedmont Province

The Inner Piedmont province in northwestern South Carolina consists of variably deformed and metamorphosed igneous and sedimentary rocks ranging in age from Middle Proterozoic to Permian (1,100 to 265 Ma). The province consists of the Western Piedmont and the Carolina terrane (see Figure 1.3.5-2). This designation is made because of different tectonic origins for the western and eastern parts of the province. The province can also be subdivided into seven distinctive tectonostratigraphic belts, separated by major faults (e.g., Towaliga fault), contrasts in metamorphic grade, or both. From northwest to southeast, these are the Chauga, Inner Piedmont, Kings Mountain, Charlotte, Carolina Slate, Kiokee, and Belair belts. The metamorphic grade of these belts alternates between low grade (Chauga, Kings Mountain, Carolina Slate, and Belair) and medium to high grade (Inner Piedmont, Charlotte, and Kiokee). The Charlotte and Carolina Slate belts are combined and discussed as the Carolina terrane. The rocks of the Inner Piedmont province have been deformed into isoclinal recumbent and upright folds, which have been refolded and are contained in several thrust sheets or nappes. These metamorphic rocks extend beneath the Coastal Plain sediments in central and eastern South Carolina. The southeastern extent of the Inner Piedmont province underneath the Coastal Plain is unknown.

1.3.5.1.3.1 Western Piedmont

The Western Piedmont encompasses the Inner Piedmont block, the Smith River Allochthon, and the Sauratown Mountains Anticlinorium (see Figure 1.3.5-2). It is separated from the Blue Ridge province on the northwest by the Brevard fault zone. It is separated from the Carolina terrane on the southeast by a complex series of fault zones approximately coincident with the Central Piedmont suture. These faults include Lowndesville, Kings Mountain, Eufola, Shacktown, and Chatham fault zones. The province is a composite stack of thrust sheets containing a variety of gneisses, schists, amphibolite, sparse ultramafic bodies and intrusive granitoids. The protoliths are immature quartzo-feldspathic sandstone, pelitic sediments, and mafic lavas.

1.3.5.1.3.2 Carolina Terrane

The Carolina terrane is part of a late Precambrian-Cambrian composite arc terrane, exotic to North America, and accreted sometime during the Ordovician to Devonian. It consists of felsic to mafic volcanic rock and associated volcaniclastic rock. Middle Cambrian fossil fauna indicate a European or African affinity.

The northeastern boundary of the Carolina terrane is formed by a complex of faults that comprise the Central Piedmont suture (see Figure 1.3.5-2) and separate the terrane from rocks of North American affinity. This structure was reactivated during the later Alleghanian collisional events as a dextral shear fault system. Subsequent investigators have further established understanding of the complicated structure that suggested the Central Piedmont suture is a low-angle normal fault. The Carolina terrane is bounded on the southeast by the Modoc fault zone and the Kiokee belt (see Figure 1.3.5-3).

The Carolina terrane is the combination of the earlier Charlotte and Carolina slate belts. The belts were initially distinguished by metamorphic grade and were later recognized as the same protolith and thus were combined. Metamorphic grade increases to the northwest from lower greenschist facies to upper amphibolite facies. Pre-Alleghanian structure is dominated by large northeast trending folds with steeply dipping axial surfaces. All country rock of the Carolina terrane has been penetratively deformed, thereby producing axial plane cleavage and foliation.

1.3.5.1.3.3 Kiokee Belt

The Kiokee belt is located between the Carolina terrane and the Belair belt in Georgia and South Carolina (see Figure 1.3.5-3), and is referred to as the Savannah River terrane. The Kiokee belt is bounded on the northwest by the Modoc fault zone and on the southeast by the Augusta fault. It is a medium- to high-grade metamorphic belt with associated plutonism, and is recognized as the Alleghanian metamorphic core. The faults are mylonite zones that overprint the amphibolite facies infrastructure of the core of the belt. The core was deformed and metamorphosed prior to the development of the plastic shear zones bounding it.

The Kiokee belt is an antiformal structure that strikes northeast. The interior is a migmatitic complex of biotite amphibole paragneiss, leucocratic paragneiss, sillimanite schist, amphibolite, ultramafic schist, serpentinite, feldspathic metaquartzite, and granitic intrusions of Late

Paleozoic age. Some of the lithologic units found in the Carolina slate belt may occur at higher metamorphic grade in the Kiokee belt.

1.3.5.1.3.4 Belair Belt

The Belair belt (also Augusta terrane) is locally exposed in the Savannah River valley, near Augusta, Georgia (see Figure 1.3.5-3). It is largely concealed beneath the Atlantic Coastal Plain with several small erosional windows through the Coastal Plain sediments in eastern Georgia. The Belair belt consists of intermediate to felsic volcanic tuffs and related volcaniclastic sediments penetratively deformed and metamorphosed to greenschist facies. The Belair belt contains similar characteristics to the Carolina terrane. Geophysical and well data indicate that the Belair belt extends beneath the Atlantic Coastal Plain.

1.3.5.1.4 Mesozoic Rift Basins

Mesozoic age rift basins are found along the entire eastern continental margin of North America from the Gulf Coast through Nova Scotia (see Figure 1.3.5-4). The basins formed in response to the continental rifting episode that broke up the super continent, Pangea, and led to the formation of the Atlantic ocean basin. Rift basins are exposed in the Piedmont province as well as buried beneath Cretaceous and younger Coastal Plain sediments. Many underlie offshore regions. Structurally, the basins are grabens or half grabens, elongated in a northeast direction and are bounded by normal faults on one or both sides. Several basins were localized along reactivated Paleozoic ductile or brittle fault zones.

There are two belts of basins that trend northeastward along the continental margin from the Carolinas to Pennsylvania. In North and South Carolina, the Deep River, Elberbe and Crowburg basins are included in the eastern belt, and the Dan River and Davie County basins are in the western belt. The Dunbarton, Florence, Riddleville, and South Georgia basins are buried beneath Coastal Plain sediments in the eastern belt (see Figure 1.3.5-5). The basins are generally filled with lacustrine sedimentary and igneous rock.

Strata within the basins consist mainly of non-marine sandstone, conglomerate, siltstone, and shale. Carbonate rocks and coal are found locally in several basins. Igneous rocks of basaltic composition occur as flows, sills, and stocks within the basins and as extensive dike swarms within and outside the basins. These basin fill strata have been described and named the Newark Supergroup. In general, the stratigraphy can be broken out into three sections. The lower section is characteristically fluvial and contains reddish-brown, arkosic coarse-grained sandstone, and conglomerate. The middle section mainly includes sediments of lacustrine origin. These sediments include grey-black fossiliferous siltstone, carbonaceous shale, and thin coal beds. The upper section is a complex of deltaic, fluvial, and lacustrine environments. These sediments include red-brown siltstone, arkosic sandstone, pebbly sandstone, and red and grey mudstone and conglomerate.

The Dunbarton basin beneath SRS has a master border fault dipping to the southeast, and so does the Riddleville basin in Georgia. The Dunbarton basin is not known to contain any basalt sills. The South Georgia Rift, in Georgia and South Carolina, is a much larger, deeper, and more complex basin than either the Riddleville or Dunbarton basins. The basin is as wide as 62.1 mi

(100 km) and as deep as 4.3 mi (7 km). It is not a single basin but is a complex of isolated synrift grabens with limited to major crustal extension. The major border fault dips northward as opposed to southeastward for the master faults bounding Riddleville and Dunbarton basins.

1.3.5.1.5 Atlantic Coastal Plain

The sediments of the Atlantic Coastal Plain in South Carolina are stratified sand, clay, limestone, and gravel that dip gently seaward and range in age from Late Cretaceous to Recent. The sedimentary sequence thickens from essentially zero at the Fall Line to more than 4,000 ft (1,219 m) at the coast. Regional dip is to the southeast, although beds dip and thicken locally in other directions because of locally variable depositional regimes and differential subsidence of basement features such as the Cape Fear Arch and the South Georgia Embayment. A map depicting these regional features and the study area discussed in the following sections is presented in Figure 1.3.5-6.

The Coastal Plain sedimentary sequence near the center of the region (i.e., SRS) consists of about 700 ft (213 m) of Late Cretaceous quartz sand, pebbly sand, and kaolinitic clay, overlain by about 60 ft (18 m) of Paleocene clayey and silty quartz sand, glauconitic sand, and silt. The Paleocene beds are in turn overlain by about 350 ft (107 m) of Eocene quartz sand, glauconitic quartz sand, clay, and limestone grading into calcareous sand, silt, and clay. The calcareous strata are common in the upper part of the Eocene section in downdip parts of the study area. In places, especially at higher elevations, the sequence is capped by deposits of pebbly, clayey sand, conglomerate, and clay of Miocene or Oligocene age. Lateral and vertical facies changes are characteristic of most of the Coastal Plain sequence, and the lithologic descriptions below are therefore generalized. A surface geologic map for SRS is presented in Figure 1.3.5-7. The stratigraphic section, which delineates the coastal plain lithology (see Figure 1.3.5-8), is divided into several formations and groups based principally on age and lithology.

1.3.5.1.5.1 Geology of the Coastal Plain Sediments - General

The following sections describe regional stratigraphy and lithologies, with emphasis on variations near SRS. The data presented are based upon direct observations of surface outcrops; geologic core obtained during drilling of boreholes; microfossil age dating; and borehole geophysical logs. Several key boring locations within the SRS boundaries and in the adjacent regions (presented in Figure 1.3.4-12) are referenced throughout the following discussions.

Rocks of Paleozoic and Triassic ages have been leveled by erosion and are unconformably overlain by unconsolidated to poorly consolidated Coastal Plain. This erosional surface dips approximately 37 ft/mi (7 m/km) toward the southeast. The Atlantic Coastal Plain sediments in South Carolina are stratified sand, clay, limestone, and gravel that dip gently seaward and range in age from Late Cretaceous to Recent. Near the coast, the wedge is approximately 4,000 ft (1,219 m) thick.

1.3.5.1.5.2 Upper Cretaceous Sediments

Upper Cretaceous sediments overlie Paleozoic crystalline rocks or lower Mesozoic sedimentary rocks throughout most of the study area. The Upper Cretaceous sequence includes the basal Cape Fear Formation and the overlying Lumbee Group, which is divided into three formations (see Figure 1.3.4-9). The sediments in this region consist predominantly of poorly consolidated, clay-rich, fine- to medium-grained, micaceous sand, sandy clay, and gravel, and is about 700 ft (213 m) thick near the center of the study area. Thin clay layers are common. In parts of the section, clay beds and lenses up to 70 ft (21 m) thick are present. Depositional environments were fluvial to prodeltaic.

Cape Fear Formation

The Cape Fear Formation rests directly on a thin veneer of saprolitic bedrock and is the basal unit of the Coastal Plain stratigraphic section at SRS. The saprolite ranges from less than 10 ft (3 m) to more than 40 ft (12 m) in thickness and defines the surface of the crystalline basement rocks and sedimentary rocks of the Newark Supergroup (Middle to Upper Triassic age). The thickness of the saprolite reflects the degree of weathering of the basement prior to deposition of the Cape Fear Formation. The Cape Fear Formation is encountered at about 200 ft (61 m) above msl just south of well C-3 in the north and at about 1,200 ft (366 m) above msl at well C-10 (see Figure 1.3.4-12) in the south. The Cape Fear Formation does not crop out in the study area, and its northern limit is north of the C-1 and P-16 wells and south of wells C-2 and C-3. The unit thickens to more than 230 ft (70 m) at well C-10 and has a maximum known thickness of about 700 ft (213 m) in Georgia. The top of the Cape Fear Formation dips approximately 30 ft/mi (5.7 m/km) to the southeast across the study area. The Cape Fear Formation was erosionally truncated prior to deposition of the overlying Middendorf Formation, resulting in a disconformity between the two formations.

Lumbee Group

Three formations of the Late Cretaceous Lumbee Group are present in the study area. These are, from oldest to youngest, the Middendorf, Black Creek, and Steel Creek Formations (see Figures 1.3.4-9).

The Lumbee Group consists of fluvial and deltaic quartz sand, pebbly sand, and clay in the study area. The sedimentary sequence is more clayey and fine-grained downdip from the study area, reflecting shallow to deep marine shelf sedimentary environments. Thickness ranges from about 400 ft (122 m) at well C-3 (see Figure 1.3.4-12) in the north, to about 780 ft (238 m) near well C-10 in the south. At least part of the group crops out in the northern part of the study area but it is difficult to distinguish the individual formations. Consequently, the Lumbee Group was mapped as undifferentiated Upper Cretaceous. The dip of the upper surface of the Lumbee Group is to the southeast at approximately 20 ft/mi (3.8 m/km) across the study area.

The Middendorf Formation unconformably overlies the Cape Fear Formation with a distinct contact. The contact is marked by an abrupt change from the moderately indurated clay and clayey sand of the underlying Cape Fear to the slightly indurated sand and lesser clayey sand of the Middendorf. The basal zone is often pebbly. The contact is unconformable and is marked by a sudden increase in electrical resistivity on geophysical logs. Thickness of the formation ranges from approximately 120 ft (37 m) in well C-2 (see Figure 1.3.4-12) in the north, to 240 ft (73 m) in well C-10 in the south. It has a maximum known thickness of about 520 ft (158 m) in Georgia. The top of the formation dips to the southeast at about 26 ft/mi (4.9 m/km) across the study area. Fossil data for the Middendorf are sparse and the formation is not well dated in the study area.

Paleontological control for the Black Creek is poor updip in South Carolina and Georgia. A Late Cretaceous age has been suggested for the Black Creek Formation, as indicated by various paleontological data from the unit. Sediments assigned to the Black Creek Formation in the vicinity of SRS yield Late Cretaceous paleontological ages and unconformably overlie the Middendorf Formation (see Figure 1.3.4-9).

The Black Creek Formation is penetrated at virtually all well-cluster sites in the study area. The unit ranges in thickness from approximately 150 ft (46 m) at well C-2 in the north to 300 ft (91 m) near the center of the study area in well PBF-3 and to 370 ft (113 m) at well C-10 in the south. The unit dips approximately 22 ft/mi (4 m/km) to the southeast.

The Black Creek is distinguished from the overlying and underlying Cretaceous units by its better sorted sand, fine-grained texture, and relatively high clay content. It is generally darker, more lignitic, and more micaceous, especially in the updip part of the section, than the other Cretaceous units. In much of the study area, the lower one-third of the formation is mostly sand that is separated from the upper two-thirds of the unit by clay beds. These beds are 20 ft (6 m) to 40 ft (12 m) thick in the northern part of the region and more than 150 ft (46 m) at well C-10 in the south. In general, the top of the Black Creek Formation is picked at the top of a clay bed that ranges from 10 ft (3 m) to 25 ft (8 m) in thickness. The clay bed is exceptionally thick but not laterally extensive. For example, it is essentially absent in wells P-21, CPC-1, P-26, and P-29. This suggests lagoonal back barrier bay deposition associated with nearby shorelines. Often the thick clay beds flank the areas where shoaling is suggested owing to uplift along the Pen Branch and Steel Creek faults, which was contemporaneous with deposition. Overall, the Black Creek consists of two thick, fining-upward sequences each capped by thick clay beds. The lower sequence is predominantly silty, micaceous sand in the area of SRS, while the upper sequence is mostly clay and silt.

The Peedee Formation was previously considered by some investigators to be absent in the study area; however, recent paleontological evidence provides dates of Peedee age from sediment samples in the southern part of SRS. Because there is a considerable difference in lithology between the type Peedee and the sediments in the SRS region, Peedee-equivalent sediments in the vicinity of SRS were referred to as the "Steel Creek Member" of the Peedee Formation. The type well for the Steel Creek Formation is P-21, located near Steel Creek. The top of the Steel Creek is picked at the top of a massive clay bed that ranges from 3 ft (1 m) to more than 30 ft (9 m) in thickness. The formation dips approximately 20 ft/mi (3.8 m/km) to the southeast.

The unit ranges in thickness from approximately 60 ft (18 m) at well P-30 (see Figure 1.3.4-12) to 175 ft (53 m) at well C-10 in the south. It has a maximum known thickness of 380 ft (116 m) in Georgia. The Steel Creek section thins dramatically between the ALL-324 and the P-22 wells due to truncation by erosion at the Cretaceous-Tertiary unconformity. The Steel Creek Formation overlies the Black Creek Formation and is distinguished from it by a higher percentage of sand, which is represented on geophysical logs by a generally higher electrical resistivity and lower natural gamma radiation count.

1.3.5.1.5.3 Tertiary Sediments

Tertiary sediments range in age from Early Paleocene to Miocene and were deposited in fluvial to marine shelf environments. The Tertiary sequence of sand, silt, and clay generally grades into highly permeable platform carbonates in the southern part of the study area and these continue southward to the coast. The Tertiary sequence is divided into three groups, the Black Mingo Group, Orangeburg Group, and Barnwell Group, which are further subdivided into formations and members (see Figure 1.3.4-9). These groups are overlain by the ubiquitous "Upland unit."

The Tertiary sedimentary sequence deposited in west-central South Carolina has been punctuated by numerous sea level low stands and/or affected by subsidence in the source areas (which reduced or eliminated sediment availability) resulting in a series of regional unconformities. Four such regionally significant unconformities are defined in the Tertiary stratigraphic section in A/M Area. From base upwards, they include the "Cretaceous-Tertiary" unconformity, the "Lang Syne/Sawdust Landing" unconformity, the "Santee" unconformity and the "Upland unit" unconformity. Based on these unconformities, four sequence stratigraphic units (unconformity bounded sedimentary units) have been delineated (Figure 1.3.4-9).

Sequence stratigraphic unit I includes the sediments deposited between the "Cretaceous-Tertiary" unconformity and the "Lang Syne/Sawdust Landing" unconformity, and includes the Lang Syne/Sawdust Landing Formations undifferentiated of the Black Mingo Group. Sequence stragraphic unit II lies between the Lang Syne/Sawdust Landing unconformity and the Santee unconformity, and includes from oldest to youngest the Fourmile/Congaree Formations undifferentiated, the Warley Hill Formation, the Tinker/Santee Formation of the Orangeburg Group, and the carbonates (Utley Member) of the Clinchfield Formation. The Santee unconformity that caps the sequence is a major erosional event in the SRS region. Sequence stratigraphic unit III lies between the Santee unconformity and the "Upland unit" unconformity, and includes the Dry Branch and Tobacco Road Formations of the Barnwell Group. Sequence stratigraphic unit IV includes all the fluvial sediments overlying the "Upland unit" unconformity.

Black Mingo Group

The Black Mingo Group consists of quartz sand, silty clay, and clay that suggest upper and lower delta plain environments of deposition (Figure 1.3.5-8) generally under marine influences. In the southern part of the study area, massive clay beds, often more than 50 ft (15 m) thick, predominate. Downdip from the study area, thin red to brown sandy clay beds, gray to black clay beds and laminated shale dominate the Black Mingo Group and suggest deposition in clastic shelf environments. At the South Carolina coast, carbonate platform facies-equivalents of the updip Black Mingo clastic sediments first appear. The carbonate units are all referred to as "unnamed limestones." These are equivalent to the thick beds of anhydrite and dolomite of the Paleocene Cedar Keys Formation and the lower Eocene glauconitic limestone and dolomite of the Oldsmar Formation. Both carbonate units are delineated and mapped in coastal Georgia and northeastern Florida.

Basal Black Mingo Group sediments were deposited on the regional "Cretaceous-Tertiary" unconformity that defines the base of sequence stratigraphic unit I. There is no apparent structural control of this unconformity. Above the unconformity, the clay and clayey sand beds of the Black Mingo Group thin and often pinch out along the traces of the Pen Branch and Crackerneck faults. This suggests that coarser-grained materials were deposited preferentially along the fault traces, perhaps due to shoaling of the depositional surface. This, in turn, suggests movement (reactivation) along the faults. This reactivation would have occurred during Black Mingo deposition, that is, in Paleocene and lower Eocene time.

The upper surface of the Black Mingo Group dips to the southeast at 16 ft/mi (3 m/km), and the group thickens from 60 ft (18 m) at well C-2 in the north, to about 170 ft (52 m) near well C-10 in the south. The group is about 700 ft (213 m) thick at the South Carolina coast. Throughout the downdip part of the South Carolina Coastal Plain, the Black Mingo Group consists of the Rhems Formation and the overlying Williamsburg Formation.

Lang Syne/Sawdust Landing Formations

The name of the Ellenton Formation was proposed for a subsurface lithologic unit in the SRS area consisting of beds of dark, lignitic clay and coarse sand, which are equivalent to the Sawdust Landing and Lang Syne Members of the Rhems Formation. It has been suggested that the Sawdust Landing Member and the overlying Lang Syne Member of the Rhems Formation be raised to formational status and replace the term Ellenton in the study area.

In the absence of detailed paleontological control, the Sawdust Landing Formation and the overlying Lang Syne Formation could not be systematically separated for mapping in this region. Thus, they are treated as a single unit; the Lang Syne/Sawdust Landing undifferentiated, on all sections and maps. The sediments of the unit generally consist of two fining-upward sand-to-clay sequences, which range from about 40 ft (12 m) in thickness at the northwestern boundary of SRS to about 100 ft (30 m), near the southeastern boundary. The unit is mostly dark gray to black, moderately to poorly sorted, fine to coarse-grained, micaceous, lignitic, silty and clayey quartz sand interbedded with dark gray clay and clayey silt. Pebbly zones, muscovite, feldspar, and iron sulfide are common. Individual clay beds up to 20 ft (6 m) thick are present in the unit. Clay and silt beds make up approximately one-third of the unit in the study area. The dark, fine-grained sediments represent lower delta plain, bay-dominated environments (Figure 1.3.5-8). Tan, light gray, yellow, brown, purple, and orange sand, pebbly sand, and clay represent upper delta plain, channel-dominated environments.

Snapp Formation (Williamsburg Formation)

Sediments in the study area that are time equivalent to the Williamsburg Formation differ from the type Williamsburg and have been designated the "Snapp Member of the Williamsburg Formation." It has been suggested that the "Snapp Member" of the Williamsburg be raised to formational status. The Snapp Formation is used in this report. The unit is encountered in well P-22 (see Figure 1.3.4-12) in the southeastern part of SRS near Snapp Station. The basal contact with the underlying Lang Syne/Sawdust Landing undifferentiated is probably unconformable. The Snapp Formation appears to pinch out in the northwestern part of SRS and thickens to about 50 ft (15 m) near the southeastern boundary of the site.

The Snapp Formation (Williamsburg Formation) crops out in Calhoun County. The sediments in the upper part of the unit consist of low-density, fissile, dark-gray to black siltstone, and thin layers of black clay interbedded with sand in the lower part. These and similar sediments in Aiken and Orangeburg Counties were probably deposited in lagoonal or estuarine environments (Figure 1.3.5-8). Within and near SRS, the Snapp Formation sediments typically are silty, medium- to coarse-grained quartz sand interbedded with clay. Dark, micaceous, lignitic sand also occurs, and all are suggestive of lower delta plain environments. In Georgia, the unit consists of thinly laminated, silty clay locally containing layers of medium- to dark-gray carbonaceous clay. This lithology is indicative of marginal marine (lagoonal to shallow shelf) depositional environments. Clayey parts of the unit are characterized on geophysical logs as zones of low electrical resistivity and a relatively high-gamma ray response. In the southernmost part of the study area, the Snapp consists of gray-green, fine to medium, well-rounded, calcareous quartz sand and interbedded micritic limestone and limey clay that is highly fossiliferous and glauconitic. This lithology suggests deposition in shallow shelf environments somewhat removed from clastic sediment sources.

The upper surface of the Snapp Formation is defined by the "Lang Syne/Sawdust Landing" unconformity and defines the upper boundary of sequence stratigraphic unit I (Figure 1.3.4-9). The surface has been offset by normal faulting as noted in A/M Area.

Fourmile Formation

Early Eocene ages, derived from paleontological assemblages, indicate that the sand immediately overlying the Snapp Formation in the study area is equivalent to the Fishburne. These sediments were deposited on the "Lang Syne/Sawdust Landing" unconformity and constitute the basal unit of sequence stratigraphic unit II (Figure 1.3.4-9). The Fishburne is a calcareous unit that occurs downdip near the coast. The sand was initially designated the Fourmile Member of the Fishburne Formation. Owing to the distinctive difference in lithology between the type, Fishburne Formation and the time-equivalent sediments observed in the study area, it has been recommended that the Fourmile Member of the Fishburne be raised to formational rank. The term Fourmile Formation is used in this report.

The Fourmile Formation averages 30 ft (9 m) in thickness, is mostly tan, yellow-orange, brown, and white, moderately to well-sorted sand, with clay beds a few feet thick near the middle and at the top of the unit. The sand is very coarse to fine grained, with pebbly zones common, especially near the base. Glauconite, up to about 5%, is present in places, as is weathered feldspar. In the center and southeastern parts of SRS, the unit can be distinguished from the underlying Paleocene strata by its lighter color and lower content of silt and clay. Glauconite and microfossil assemblages indicate that the Fourmile is a shallow marine deposit (Figure 1.3.5-8).

Overlying the Fourmile Formation in the study area is 30 ft (9 m) or less of sand similar to the Fourmile. This sand is better sorted, contains fewer pebbly zones, less muscovite and glauconite, and in many wells is lighter in color. Microfossil assemblages indicate that the sand is correlative with the early middle Eocene Congaree Formation. In some wells a thin clay occurs at the top of the Fourmile, separating the two units; however, the difficulty in distinguishing the Fourmile Formation from the overlying Congaree Formation has led many to include the entire 960 ft (293 m) section in the Congaree Formation.

Orangeburg Group

The Orangeburg Group consists of the lower middle Eocene Congaree Formation (Tallahatta equivalent) and the upper middle Eocene Warley Hill Formation and Santee Limestone (Lisbon equivalent) (see Figure 1.3.4-9). Over most of the study area, these post-Paleocene units are more marine in character than the underlying Cretaceous and Paleocene units; they consist of alternating layers of sand, limestone, marl, and clay.

The group crops out at lower elevations in many places within and near SRS. The sediments thicken from about 85 ft (26 m) at well P-30 near the northwestern SRS boundary to 200 ft (61 m) at well C-10 (see Figure 1.3.4-12) in the south. Dip of the upper surface is 12 ft/mi (2 m/km) to the southeast. Downdip at the coast, the Orangeburg Group is about 325 ft (99 m) thick and is composed of shallow carbonate platform deposits of the Santee Limestone.

In the extreme northern part of the study area, the entire middle Eocene Orangeburg Group is mapped as the Huber Formation. The micaceous, poorly sorted sand, abundant channel fill deposits and cross bedding, and carbonaceous kaolin clay in the Huber is indicative of fluvial, upper delta plain environments (Figure 1.3.5-8).

In the central part of the study area, the group includes, in ascending order, the Congaree, Warley Hill, and Tinker/Santee Formations (see Figure 1.3.4-9). The units consist of alternating layers of sand, limestone, marl, and clay that are indicative of deposition in shoreline to shallow shelf environments (Figure 1.3.5-8). From the base upward, the Orangeburg Group passes from clean shoreline sand characteristic of the Congaree Formation to shelf marl, clay, sand, and limestone typical of the Warley Hill and Santee Limestone. Near the center of the study area, the Santee sediments consist of up to 30 vol% carbonate. The sequence is transgressive, with the middle Eocene Sea reaching its most northerly position during Tinker/Santee deposition.

Toward the south, near wells P-21, ALL-324, and C-10 (see Figure 1.3.4-12), the carbonate content of all three formations increases dramatically. The shoreline sand of the Congaree undergoes a facies change to interbedded glauconitic sand and shale, grading to glauconitic argillaceous, fossiliferous, sandy limestone. Downdip, the fine-grained, glauconitic sand, and clay of the Warley Hill become increasingly calcareous and grades imperceptibly into carbonate-rich facies comparable to both the overlying and underlying units. Carbonate content in the glauconitic marl, calcareous sand, and sandy limestone of the Santee increases towards the south. Carbonate sediments constitute the vast majority of the Santee from well P-21 southward.

Congaree Formation

The early middle Eocene Congaree Formation has been traced from the Congaree valley in east central South Carolina into the study area. It has been paleontologically correlated with the early and middle Eocene Tallahatta Formation in neighboring southeastern Georgia.

The Congaree is about 30 ft (9 m) thick near the center of the study area and consists of yellow, orange, tan, gray, green, and greenish gray, well-sorted, fine to coarse quartz sand, with granule and small pebble zones common. Thin clay laminae occur throughout the section. The quartz grains tend to be better rounded than those in the rest of the stratigraphic column are. The sand is glauconitic in places suggesting deposition in shoreline or shallow shelf environments (Figure

1.3.5-8). To the south, near well ALL-324, the Congaree Formation consists of interbedded glauconitic sand and shale, grading to glauconitic, argillaceous, fossiliferous sandy limestone suggestive of shallow to deeper shelf environments of deposition. Farther south, beyond well C-10, the Congaree grades into platform carbonate facies of the lower Santee Limestone (see Figure 1.3.5-8).

The equivalent of the Congaree northwest of SRS has been mapped as the Huber Formation. At these locations it becomes more micaceous and poorly sorted, indicating deposition in fluvial and upper delta plain environments. On geophysical logs, the Congaree has a distinctive low gamma ray count and high electrical resistivity.

Warley Hill Formation

Unconformably overlying the Congaree Formation are 10 ft (3 m) to 20 ft (6 m) of fine-grained, often glauconitic sand and green clay beds that have been referred to respectively as the Warley Hill and Caw Caw Members of the Santee Limestone. The green sand and clay beds are referred to informally as the "green clay" in previous SRS reports. Both the glauconitic sand and the clay at the top of the Congaree are assigned to the Warley Hill Formation. In the updip parts of the study area, the Warley Hill apparently is missing or very thin, and the overlying Tinker/Santee Formation rests unconformably on the Congaree Formation.

The Warley Hill sediments indicate shallow to deeper clastic shelf environments of deposition in the study area, representing deeper water than the underlying Congaree Formation (Figure 1.3.5-8). This suggests a continuation of a transgressive pulse during upper middle Eocene time. To the south, beyond well P-21, the green silty sand, and clay of the Warley Hill undergo a facies change to the clayey micritic limestone and limey clay typical of the overlying Santee Limestone. The Warley Hill blends imperceptibly into a thick clayey micritic limestone that divides the Floridan Aquifer System south of the study area. The Warley Hill is correlative with the lower part of the Avon Park Limestone in southern Georgia and the lower part of the Lisbon Formation in western Georgia. In the study area, the thickness of the Warley Hill Formation is generally less than 20 ft (6 m). In a part of Bamberg County, South Carolina, the Congaree Formation is not present, and the Warley Hill rests directly on the Williamsburg Formation.

Tinker/Santee Formation

The late middle Eocene deposits overlying the Warley Hill Formation consist of moderately sorted yellow and tan sand, calcareous sand and clay, limestone, and marl. Calcareous sediments dominate downdip, are sporadic in the middle of the study area, and are missing in the northwest (Figure 1.3.5-9). The limestone represents the farthest advance to the northwest of the transgressing carbonate platform first developed in early Paleocene time near the South Carolina and Georgia coasts (Figure 1.3.5-8).

The Santee is divided into three members in the study area: the McBean, Blue Bluff, and Tims Branch Members. The McBean Member consists of tan to white, calcilutite, calcarenite, shelly limestone, and calcareous sand and clay. It dominates the Santee in the central part of the study area and represents the transitional lithologies between clastics in the north and northwest (Tims Branch Member), and fine-grained carbonates in the south (Blue Bluff Member).

The carbonates and carbonate-rich clastics are restricted essentially to three horizons in the central part of the Griffins Landing Member of the Dry Branch Formation, the McBean Member of the Tinker/Santee Formation, and the Utley Limestone member of the Clinchfield Formation (Figures 1.3.4-9, 1.3.5-10, 1.3.5-11). The uppermost horizon includes the carbonates of the Griffins Landing Member of the Dry Branch Formation found below the "tan clay" interval that occurs near the middle of the Dry Branch. The isolated carbonate patches of the Griffins Landing are the oyster banks that formed in the back barrier marsh zone behind the barrier island system (Figures 1.3.5-8 and 1.3.5-11). Underlying the Dry Branch, directly below the regionally significant Santee Unconformity (Figure 1.3.5-10), is the Utley Limestone Member of the Clinchfield Formation. Without the benefit of detailed petrographic and paleontological analysis, the Utley carbonates cannot be systematically distinguished from the carbonates of the underlying Tinker/Santee Formation. Thus, the carbonate-rich sediments between the Santee Unconformity (Figure 1.3.5-10) and the Warley Hill Formation are referred to as the Tinker/Santee (Utley) sequence in this report.

Approximately 40 to 50% of the wells that drilled through the Tinker/Santee (Utley) interval in the GSA penetrated quantities of carbonate ranging from 5 to 78% of the sediment sampled (Figure 1.3.5-9). The calcareous sediment in the GSA consists of calcareous sand, calcareous mud, sandy limestone, muddy limestone, and sandy muddy limestone. Viewing the Tinker/Santee (Utley) sedimentary package parallel to the shoreline (Figure 1.3.5-8), the carbonate-rich sediments would be concentrated in the areas furthest removed from the tidal inlets at the shore face where clastic sediments supplied by riverine input is concentrated. The clastic-rich on the other hand would concentrate opposite the tidal inlet areas where clastic sediment is more readily available. The lateral facies transition of the sediments in the subtidal shelf environment from carbonate-rich to clastic-rich lithologies is therefore gradual and measures in the thousands of feet. Shifting locations of the tidal inlets at the shoreline has resulted in a complex sedimentary package where facies gradually transition from one lithology to another both laterally and vertically.

The GSA is in that part of the mixed clastics/carbonate zone where the clastic sediments generally constitute a greater percentage of the section than the carbonates (Figure 1.3.5-9). Figure 1.3.5-11 illustrates the environments of deposition of the Tinker/Santee (Utley) sediments in the SRS region. In northern SRS, the Tinker/Santee (Utley) sediments are mostly sands and muddy sands (Tims Branch Member) deposited in shoreline to lesser lagoonal and tidal marsh environments (Figure 1.3.5-8). In the central SRS, the sequence was deposited in middle marine shelf environments resulting in a varied mix of lithologies from carbonate-rich sands and muds to sandy and muddy limestones. In southern SRS, the Tinker/Santee (Utley) sediments were deposited further offshore, further removed from riverine clastic input into the shelf environment resulting in deposition of carbonate muds (Blue Bluff Member).

The Blue Bluff Member consists of gray to green, laminated micritic limestone. The unit includes gray, fissile, calcareous clay and clayey micritic limestone and very thinly layered to laminated, clayey, calcareous, silty, fine sand, with shells and hard, calcareous nodules, lenses, and layers. Cores of Blue Bluff sediments are glauconitic, up to 30% in places. The Blue Bluff lithology suggests deposition in offshore shelf environments. Blue Bluff sediments tend to dominate the formation in the southern part of the study area and constitute the major part of the "middle confining unit" that separates the Upper and Lower Floridan aquifers south of the study area.

The Tims Branch Member of the Santee is described as the siliciclastic part of the unit, consisting of fine- and medium-grained, tan, orange, and yellow, poorly to well sorted, and slightly to moderately indurated sand. The clastic lithologies of the Tims Branch Member dominate the Santee in the northern part of the study area. Because the clastic lithologies differ so markedly from the type Santee, the Tims Branch Member of the Santee has been raised to formational rank, namely the Tinker Formation. Because the clastic and carbonate lithologies that constitute the Tinker/Santee sequence in the upper and middle parts of the study area are hydrologically undifferentiated, the units are not systematically separated, and they are designated Tinker/Santee Formation on maps and sections. The thickness of the Tinker/Santee Formation is variable due in part to displacement of the sediments, but more commonly to dissolution of the carbonate resulting in consolidation of the interval and slumping of the overlying sediments of the Tobacco Road and Dry Branch Formations into the resulting lows (Figure 1.3.5-12).

The Tinker/Santee (Utley) interval is about 70 ft (21 m) thick near the center of SRS, and the sediments indicate deposition in shallow marine environments (Figure 1.3.5-11). The top of the unit is picked on geophysical logs where Tinker/Santee (Utley) sediments with lower electrical resistivity are overlain by the more resistive sediments of the Dry Branch Formation (Figure 1.3.5-10). In general, the gamma-ray count is higher than in surrounding stratigraphic units.

Often found within the Tinker/Santee (Utley) sediments, particularly in the upper third of the interval, are weak zones interspersed in stronger carbonate-rich matrix materials, referred to as "soft zones," which are described in 1.3.5.1.5.5.

Barnwell Group

Upper Eocene sediments of the Barnwell Group (see Figure 1.3.4-9) represent the Upper Coastal Plain of western South Carolina and eastern Georgia. Sediments of the Barnwell Group are chronostratigraphically equivalent to the lower Cooper Group (late Eocene). The Cooper Group includes sediments of both late Eocene and early Oligocene age and appears downdip in the Lower Coastal Plain of eastern South Carolina.

Sediments of the Barnwell Group overlie the Tinker/Santee Formation and consist mostly of shallow marine quartz sand containing sporadic clay layers. The upper Eocene stratigraphy of the Georgia Coastal Plain has recently been revised and extended into South Carolina. The Eocene "Barnwell Formation" has been elevated to the "Barnwell Group." In Burke County, Georgia, the group includes (from oldest to youngest) the Clinchfield Formation, Dry Branch Formation, and the Tobacco Road Formation. The group is about 70 ft (21 m) thick near the northwestern boundary of SRS and 170 ft (52 m) near its southeastern boundary. The regionally significant Santee Unconformity that defines of boundary between Sequence Stratigraphic units II and III (Figure 1.3.4-9) separates the Clinchfield Formation from the overlying Dry Branch Formation. The Santee Unconformity is a pronounced erosional surface observable throughout the SRS region (Figures 1.3.4-9 and 1.3.5-10).

In the northern part of the study area, the Barnwell Group consists of red or brown, fine to coarse-grained, well-sorted, massive sandy clay and clayey sand, calcareous sand and clay, as well as scattered thin layers of silicified fossiliferous limestone. All are suggestive of lower delta plain and/or shallow shelf environments (Figure 1.3.5-8). Downdip, the Barnwell undergoes a facies change to the phosphatic clayey limestone that constitutes the lower Cooper Group. The lower Cooper Group limestone beds indicate deeper shelf environments.

Clinchfield Formation

The basal late Eocene Clinchfield Formation consists of light colored quartz sand and glauconitic, biomoldic limestone, calcareous sand, and clay. Sand beds of the formation constitute the Riggins Mill Member of the Clinchfield Formation and are composed of medium to coarse, poorly to well sorted, loose and slightly indurated, tan, clay, and green quartz. The sand is difficult to identify unless it occurs between the overlying carbonate layers of the Griffins Landing Member and the underlying carbonate layers of the Santee Limestone. The Clinchfield is about 25 ft (8 m) thick in the southeastern part of SRS and pinches out or becomes unrecognizable at the center of the site.

The carbonate sequence of the Clinchfield Formation is designated the Utley Limestone Member. It is composed of sandy, glauconitic limestone and calcareous sand, with an indurated, biomoldic facies developed in places. In cores, the sediments are tan and white and slightly to well indurated. Without the benefit of detailed petrographic and paleontological analysis, the Utley carbonates cannot be systematically distinguished from the carbonates of the underlying Tinker/Santee Formation. Thus, the carbonate-rich sediments between the Santee Unconformity (Figures 1.3.4-9 and 1.3.5-10) and the Warley Hill Formation are referred to as the Tinker/Santee (Utley) sequence in this report.

Dry Branch Formation

The late Eocene Dry Branch Formation is divided into the Irwinton Sand Member, the Twiggs Clay Member, and the Griffins Landing Member. The unit is about 60 ft (18 m) thick near the center of the study area. The top of the Dry Branch is picked on geophysical logs where a low gamma-ray count in the relatively clean Dry Branch sand increases sharply in the more argillaceous sediments of the overlying Tobacco Road Sand.

The Dry Branch sediments overlying the Tinker/Santee (Utley) interval in the central portion of SRS were deposited in shoreline/lagoonal/tidal marsh environments (Figure 1.3.5-11). The shoreline retreated from its position in northern SRS during Tinker/Santee (Utley) time to the central part of SRS in Dry Branch time. Progradation of the shoreline environments to the south resulted in the sands and muddy sands of the Dry Branch being deposited over the shelf carbonates and clastics of the Tinker/Santee (Utley) sequence.

The Twiggs Clay Member does not seem to be mappable in the study area. Lithologically similar clay is present at various stratigraphic levels in the Dry Branch Formation. The tan, light-gray, and brown clay is as thick as 12 ft (4 m) in SRS wells but is not continuous over long distances. This has been referred to in the past as the "tan clay" in SRS reports (Figure 1.3.5-10).

The Twiggs Clay Member, which predominates west of the Ocmulgee River in Georgia, is not observed as a separate unit in the study area.

The Griffins Landing Member is composed mostly of tan or green, slightly to well indurated, quartzose calcareous micrite and sparite, calcareous quartz sand and slightly calcareous clay. Oyster beds are common in the sparry carbonate facies (Figure 1.3.5-11). The unit seems to be widespread in the southeastern part of SRS, where it is about 50 ft (15 m) thick, but becomes sporadic in the center and pinches out. Carbonate content is highly variable. In places, the unit lies unconformably on the Utley Limestone Member, which contains much more indurated, moldic limestone. In other areas, it lies on the noncalcareous quartz sand of the Clinchfield. Updip, the underlying Clinchfield is difficult to identify or is missing, and the unit may lie unconformably on the sand and clay facies of the Tinker/Santee Formation. The Griffins Landing Member appears to have formed in lagoonal/marsh environments (Figure 1.3.5-11).

The Irwinton Sand Member is composed of tan, yellow and orange, moderately sorted quartz sand, with interlaminated and interbedded clay abundant in places. Pebbly layers are present, as are clay clast-rich zones (Twiggs Clay lithology). Clay beds, which are not continuous over long distances, are tan, light gray, and brown in color, and can be several feet thick in places. These are the "tan clay" beds of various SRS reports. Irwinton Sand beds have the characteristics of shoreline to shallow marine sediments (Figures 1.3.5-8 and 1.3.5-11). The Irwinton Sand crops out in SRS. Thickness is variable, but is about 40 ft (12 m) near the northwestern site boundary and 70 ft (21 m) near the southeastern boundary.

Tobacco Road Formation

The Late Eocene Tobacco Road Formation consists of moderately to poorly sorted, red, brown, tan, purple, and orange, fine to coarse, clayey quartz sand. Pebble layers are common, as are clay laminae and beds. Ophiomorpha burrows are abundant in parts of the formation. Sediments have the characteristics of lower Delta plain to shallow marine deposits (Figure 1.3.5-8). The top of the Tobacco Road is characterized by the change from a comparatively well-sorted sand to the more poorly sorted sand, pebbly sand, and clay of the "Upland unit." Contact between the units constitutes the "Upland" unconformity. The unconformity is very irregular due to fluvial incision that accompanied deposition of the overlying "Upland unit" and later erosion. As stated previously, the lower part of the Cooper Group (upper Eocene) is the probable downdip equivalent of the Tobacco Road Formation.

"Upland Unit"/Hawthorn/Chandler Bridge Formations

Deposits of poorly sorted silty, clayey sand, pebbly sand, and conglomerate of the "Upland unit" cap many of the hills at higher elevations over much of the study area. Weathered feldspar is abundant in places. The color is variable, and facies changes are abrupt. These sediments are assigned to the Hawthorn Formation. It has been mapped as the "Upland unit," with evidence for a Miocene age. The unit is up to 60 ft (18 m) thick. The environment of deposition appears to be fluvial, and the thickness changes abruptly owing to channeling of the underlying Tobacco Road Formation during "Upland" deposition and subsequent erosion of the "Upland" unit itself. This erosion formed the "Upland" unconformity. The unit is up to 60 ft (18 m) thick.

Lithologic types comparable to the "Upland" unit but assigned to the Hawthorn Formation overlie the Barnwell Group and the Cooper Group in the southern part of the study area. In this area, the Hawthorn Formation consists of very poorly sorted, sandy clay, and clayey sand, with lenses of gravel and thin beds of sand very similar to the "Upland unit." Farther downdip, the Hawthorn overlies the equivalent of the Suwanee Limestone and acts as the confining layer overlying the Floridan Aquifer System. It consists of phosphatic, sandy clay and phosphatic, clayey sand and sandy, dolomitic limestone interbedded with layers of hard, brittle clay resembling stratified fuller's earth.

It has been suggested that the "Upland unit," Tobacco Road Formation, and Dry Branch Formation are similar in granularity and composition, indicating that they might be part of the same transgressive/regressive depositional cycle. The "Upland unit" represents the most continental end member (lithofacies) and the Dry Branch Formation represents the most marine end member. Thus, the "Upland unit" is the result of a major regressive pulse that closed out deposition of the Barnwell Group/Cooper Group depositional cycle. It has also been suggested that the "Upland unit" is correlative with the Chandler Bridge Formation downdip toward the coast. This hypothesis is significant because it implies that there was no major hiatus between the "Upland unit" and the underlying Tobacco Road and Dry Branch Formations. The existence of a hiatus between the units has been reported by numerous studies of the South Carolina Coastal Plain.

1.3.5.1.5.4 Quaternary Surfaces and Deposits

Determining fault capability requires assessing the potential for Quaternary (1.6 - 0.01 Ma) deformation. The Quaternary and neotectonic studies conducted at SRS during 1991-1992 were designed to span the geologic record between deposition of the "Upland unit" and the present, and to determine if deformation has affected Quaternary-age deposits or surfaces. The Quaternary record in the SRS area is preserved primarily in fluvial terraces along the Savannah River and its major tributaries and in deposits of colluvium, alluvium, and eolian sediments on upland interfluve areas (see Figure 1.3.5-7).

SRS lies within the interfluve area between the Savannah and the Salkahatchie Rivers. The drainage systems within the site consist entirely of streams that are tributary to the Savannah River. A series of nested fluvial terraces are preserved along the river and major tributaries. Fluvial terraces are the primary geomorphic surface that can be used to evaluate Quaternary deformation within SRS. However, there is limited data available for the estimation of ages of river terraces in both the Atlantic and Gulf Coastal Plains.

Major stream terraces form by sequential erosional and depositional events in response to tectonism, isostasy, and climate variation. Streams respond to uplift by cutting down into the underlying substrate in order to achieve a smooth longitudinal profile that grades to the regional base level. Aggradation or deposition occurs when down-cutting is reversed by a rise in base level. The stream channel is elevated and isolated from the underlying marine strata by layers of newly deposited fluvial sediments. Down-cutting may resume and the aggraded surface is abandoned. The result is a landform referred to as a fill terrace.

At the SRS there are two prominent terraces above the modern floodplain (see Figure 1.3.5-7). These designations are based on morphology and relative height above local base level. Local base level is the present elevation of the Savannah River channel. In addition, there are other minor terraces: one lower and several higher, older terrace remnants.

The terraces of Upper Three Runs and Steel Creek were mapped on false color, infrared aerial photography, and field checked. Although exposures of fluvial deposits are extremely limited, these terraces are laterally continuous. Upper Three Runs terraces are of interest to SRS because of their position over the Atta and Upper Three Runs faults. The terraces along Steel Creek represent a family of seven sets of well-defined fluvial terraces, one of the best sequences of terraces at SRS. These terraces range from less than 3 to 100 ft (1 to 30 m) above local base level. The lower terraces appear to be fill terraces whereas the higher terraces appear to be strath terraces that cut into Tertiary strata. The Steel Creek drainage parallels the trace of the subsurface Steel Creek fault.

Estimated ages of the terraces are based on several techniques including radiometric carbon-14 dates, soil chronosequences, relative position above base level and correlation to other dated river or marine terraces. The modern floodplain is as old as the latest Pleistocene to Holocene. Others have indicated a much younger age of 4,000 years. Based on soil chronosequences, it is at least 400 ka to perhaps 1 Ma. An early to middle Holocene age (less than 10 ka) has been concluded based on geoarchaeological studies. The terraces on Upper Three Runs range from 11 ka for the lower (1.6 to 14.8 ft [0.5 to 4.5 m]) terrace to 38 to 47 ka for the higher (greater than 30 ft [6 m]) terrace. Overall, the terraces at SRS represent ages from middle Holocene (less than 10 ka) to late Pleistocene (1 Ma).

1.3.5.1.5.5 Carolina Bays

Carolina bays are shallow, elliptical depressions with associated sand rims that are found on the surface of the Coastal Plain sediments. They are found from southern New Jersey to northern Florida with the greatest occurrence in the Carolinas. One hundred ninety-seven confirmed or suspected Carolina bays have been identified at SRS (see Figure 1.3.5-13). The long axes of the bays are oriented S50°E and the sand rims are observed on the east and southeast flanks. Several hypotheses have been provided for the timing and mode of origin for these bays. Theories regarding the origin of bays include meteorite impact, sinks, wind, and water currents. The origin of these features continues to be studied.

The most likely explanation of formation suggests that the bays were formed by action of strong unidirectional wind on water ponded in surface depressions. The resulting waves caused the formation of the sand rims as shoreline features, and the sand rims formed perpendicular to the wind direction. Therefore, the wind that formed the bays observed today was a southwesterly wind.

The Carolina bays are surficial features that have no effect on the subsurface sediments. Based on subsurface core data, it has been demonstrated that a clay layer mapped beneath the bays and beyond had no greater relief beneath the bays than beyond them. Certain identified strata can be mapped and found continuous and undeformed beneath bay and interbay areas. In Horry and Marion Counties, South Carolina, there is no evidence of solution-related subsidence of the

Carolina bays, in spite of the presence of carbonate-rich strata in the subsurface and some localized sink holes of irregular shape with depths on the order of 20 ft (6 m).

The minimum age of the bays is set at middle to late Wisconsinian based on radiocarbon dating. The maximum age can be relatively determined by examination of the formations on which the bays rest. If one assumes a single generation of formation for all bays, then the bays formed after deposition of the Socastee Formation and before the Wando Formation. This places bay formation between 100 and 200 ka. If there is more than one generation, then the bays could be as old as the formations on which they rest.

Carbonate and Soft Zones

Often found within the Tinker/Santee (Utley) sediments, particularly in the upper third of this section, are weak zones interspersed in stronger carbonate-rich matrix materials. These weak zones, which vary in apparent thickness and lateral extent, were recorded where rod drops and/or lost circulation occurred during drilling, low blow counts occurred during standard penetration tests, etc. They have variously been termed as "soft zones," "the critical layer," "underconsolidated zones," "bad ground," and "void." The preferred term used to describe these zones is "soft zones."

The initial COE characterization in 1952 (COE 1952) identified soft zones as being the major concern for foundation design. This initial study made many important observations concerning the formation, geometry, distribution, and physical attributes of soft zones (and potential associated voids) within the Santee Formation. Some of the soft zone observations and hypotheses set forth by the COE report have remained unchanged to this day. However, several important aspects of early soft zone analyses run counter to current thinking on this subject.

Historically, the soft zones were grouted as an expedient way of resolving any potential foundation stability issues. This method continued through the restart of K Reactor where the project chose to grout the Santee formation beneath the cooling water lines to resolve a potential foundation stability issue. The results of that effort were carefully studied and it was found that the grout was not having the desired effect on the subsurface soft zones.

More recently, technology improvements have allowed sampling and testing which have resulted in additional insight to the properties of the soft zone soils. With these properties, advanced analytical techniques have been used to resolve the foundation stability issues without requiring soil remediation. The information provided herein allows for a clearer understanding of the geologic underpinnings that established the carbonates and the attendant soft zones.

In general, where carbonates are found (Figures 1.3.5-9 and 1.3.5-10) soft zones are likely to be found as well. This conclusion is based on a significant study of soil samples from borings, boring logs, geophysical logs, and cone penetration test soundings throughout the General Separation Area (GSA). This review was instrumental in delineating the extent of both carbonates and soft zones. The data were studied in many different ways but resulted in the simple conclusion that although carbonates and soft zones are not found in every drill hole or cone penetrometer test (CPT), they are generally found in every area that was investigated in the GSA.

Isopach maps reveal that carbonate thickness and concentration is directly related to the isopach thickness of the Tinker/Santee (Utley) interval. Where the Santee-Utley interval is thick, carbonate is more concentrated, where the interval is thin, carbonate thickness and concentration is reduced. It is further observed that where carbonate is concentrated in the Santee-Utley section the overlying "Upland unit," Tobacco Road/Dry Branch section (Figure 1.3.5-12) is generally structurally high, and where the carbonate content is reduced or absent the overlying "Upland unit," Tobacco Road/Dry Branch section is generally structurally low. This indicates that the removal (dissolution) of carbonate and the thinning of the Santee-Utley interval occurred in post Tobacco Road time. Since the thickness and distribution of soft zones is closely linked to the thickness and distribution of carbonate, those areas where clastic sediments were initially concentrated and in structurally low areas where a great deal of carbonate has been removed would be areas where soft zones may not be present.

Origin of Carbonates and Soft Zones

The origin of the carbonates in the Tinker/Santee (Utley) interval is fairly clear. The carbonate content ranges from zero to approximately 90%. The presence of glauconite along with a normal marine fauna including foraminifers, molluscs, bryozoans, and echinoderms, indicates that the limestones and limy sandstones were deposited in clear, open-marine water of normal salinity on the inner to middle shelf (Figures 1.3.5-8 and 1.3.5-11). The abundance of carbonate mud (micrite) in the limestones suggests deposition in quiet water below normal marine wave base. The presence of abraded and well-worn skeletal grains indicates that bottom transport by currents or storm-generated waves alternated with quiet-water conditions in which the sediments accumulated.

Viewing the Santee sedimentary package parallel to the shoreline, the carbonate-rich sediments would be concentrated in the areas furthest removed from the tidal inlets at the shore face where clastic sediments supplied by riverine input is concentrated (Figure 1.3.5-8). The clastic-rich sediments on the other hand would concentrate opposite the tidal inlet areas where clastic sediment is more readily available. The lateral facies transition of the sediments in the subtidal shelf environment from carbonate-rich to clastic-rich lithologies is therefore gradual and measures in the thousands of feet. Shifting locations of the tidal inlets at the shoreline has resulted in a complex sedimentary package where facies gradually transition from one lithology to another both laterally and vertically. Therefore, both vertical and lateral lithologic variability in the Tinker/Santee (Utley) sequence is the rule rather than the exception. Locally the contact between carbonate sediments and laterally comparable clastic sediments is often sharply drawn, occurring over distances of only a few feet.

The original thoughts were that the soft zones were the result of the dissolution of the shell debris concentrated in bioherms (oyster banks). This premise has since been proven to be false. Significant study of the deposition of the Tinker/Santee (Utley) sediments precludes the formation of bioherms. Several hypotheses exist concerning the origin of the soft zones: one being that these zones consisted of varying amounts of carbonate material that has undergone dissolution over geologic time leaving sediments that are now subjected to low vertical effective stresses due to arching of more competent soils above the soft zone intervals.

A second hypothesis is based on recent studies that indicate that soft zones occur where silica replacement/cementation of the carbonate occurred. The silicification (by amorphous opaline silica) of the enclosing carbonate sediment would follow and spread along bedding planes, along microfractures of varied orientations and along corridors of locally enhanced permeability (Figure 1.3.5-14). The resulting "soft zone" could be in the form of irregular isolated pods, extended thin ribbons or stacked thin ribbons separated by intervening unsilicified parent sediment. Careful observations of the grouting programs conducted by the COE in the early 1950s, and more recently for the restart of K Reactor, corroborate these recent findings.

Soft zones encountered in one CPT sounding could be absent in the neighboring CPT only a few feet away. Only where silicification has spread far enough away from the bedding planes and/or fractures along which the silica replacement has taken place, where all the intervening sediment is replaced, would the soft zones be large enough and coherent enough to pose a question for the siting of new facilities. In all likelihood, this would be a most uncommon event.

1.3.5.1.6 Regional Physiography

The site region, defined as the area within a 200-mi (322-km) radius of the center of SRS, includes parts of the Atlantic Coastal Plain, Piedmont, and Blue Ridge physiographic provinces. SRS is located on the upper Atlantic Coastal Plain, about 30 mi (50 km) southeast of the Fall Line.

The Atlantic Coastal Plain extends southward from Cape Cod, Massachusetts, to south central Georgia where it merges with the Gulf Coastal Plain. The surface of the Coastal Plain slopes gently seaward. The South Carolina Coastal Plain can be divided into three physiographic belts: Upper, Middle, and Lower Coastal Plain. The Upper Coastal Plain slopes from a maximum elevation of 650 ft (200 m) above msl at the Fall Line to about 250 ft (75 m) above msl on its southeastern boundary (see Figure 1.3.5-15). Primary depositional topography of the Upper Coastal Plain has been obliterated by fluvial erosion. The Upper Coastal Plain is separated from the Middle Coastal Plain by the Orangeburg scarp, which has a relief of approximately 100 ft (30 m) over a distance of a few miles. The Orangeburg scarp is the locus of Eocene, Upper Miocene, and Pliocene shorelines. The Middle Coastal Plain, separated from the Lower Coastal Plain by the Surry scarp, is characterized by lower elevations and subtle depositional topography that has been significantly modified by fluvial erosion. The Lower Coastal Plain is dominated by primary depositional topography that has been modified slightly by fluvial erosion.

The Upper Coastal Plain of South Carolina is divided into the Aiken Plateau and Congaree Sand Hills. The Aiken Plateau, where SRS is located, is bounded by the Savannah and Congaree Rivers and extends from the Fall Line to the Orangeburg scarp. The plateau's highly dissected surface is characterized by broad interfluvial areas with narrow, steep-sided valleys. Local relief is as much as 295 ft (90 m). The plateau is generally well drained, although many poorly drained sinks and depressions exist, especially on the topographically high (above 250 ft [76 m] above msl) "Upland unit." The Congaree Sand Hills trend along the Fall Line northeast and north of the Aiken Plateau. The sand hills are characterized by gentle slopes and rounded summits that are interrupted by valleys of southeast-flowing streams and their tributaries.

The site region contains Carolina bays. (Carolina bays are discussed in detail in the previous section.)

The Piedmont province extends southwest from New York to Alabama and lies adjacent to the Atlantic Coastal Plain. It is the eastern-most physiographic and structural province of the Appalachian Mountains. The Piedmont is a seaward-sloping plateau whose width varies from about 10 mi (16 km) in southeastern New York to almost 125 mi (200 km) in North Carolina; it is the least rugged of the Appalachian provinces. Elevation of the inland boundary ranges from about 200 ft (60 m) above msl in New Jersey to over 1,800 ft (550 m) above msl in Georgia.

The Blue Ridge province extends from Pennsylvania to northern Georgia. It varies from about 30 mi (48 km) to 75 mi (120 km) wide north to south. Elevations are highest in North Carolina and Georgia, with several peaks in North Carolina exceeding 5,900 ft (1,800 m) above msl. Mount Mitchell, North Carolina, is the highest point (6,560 ft [2,000 m]) above msl in the Appalachian Mountains. The Blue Ridge front, with a maximum elevation of 4,000 ft (1,200 m) above msl in North Carolina, is an east-facing escarpment between the Blue Ridge and Piedmont provinces in the southern Appalachians.

1.3.5.1.7 General Geologic Setting at Savannah River Site

The 25-mi (40-km) radius study area is taken from DOE-STD-1022-94 (DOE 1996c) as the area in which to conduct geoscience investigations to locate possible seismogenic sources and surface deformation or to demonstrate that such features do not exist.

SRS is located on the Atlantic Coastal Plain, which is an essentially flat-lying, undeformed wedge of unconsolidated marine and fluvial sediments. The sediments are stratified sand, clay, limestone, and gravel that dip gently seaward and range in age from Late Cretaceous to Holocene. The sedimentary sequence thickens from zero at the Fall Line to more than 4,000 ft (1,200 m) at the coast. The Coastal Plain section is divided into several rock-stratigraphic groups, based principally on age and lithology (see Figure 1.3.5-16). The details of Coastal Plain stratigraphy have been discussed in the preceding section.

Beneath the Coastal Plain sedimentary sequence and below a pre-Cretaceous unconformity are two geologic terranes: (1) the Dunbarton basin, a Triassic-Jurassic Rift basin, filled with lithified terrigenous and lacustrine sediments with possible minor amounts of mafic volcanic and intrusive rock; and (2) a crystalline terrane of metamorphosed sedimentary and igneous rock that may range in age from Precambrian to late Paleozoic (see Figure 1.3.5-17). The Paleozoic rocks and the Triassic sediments were leveled by erosion, forming the base for Coastal Plain sediment deposition. The erosional surface dips southeast approximately 42 ft/mi (8 m/km).

Information about the Dunbarton basement and crystalline terrane comes primarily from deep borings. The U.S. Army Corps of Engineers drilled a single hole into basement rock in 1950 for the startup of the plant. In 1961, the Bedrock Waste Storage Project rock exploration program was conducted to determine the feasibility of long-term storage of radioactive waste in mined rock chambers. Twelve deep rock borings, the DRB well series, were completed into basement to various depths greater than 980 ft (300 m) to accomplish this goal. This information is also augmented by deep borings used to constrain seismic reflection information both in the early

1970s (P-R series) and more recently acquired information (MMP and GCB series). The topography of the crystalline basement is shown on Figure 1.3.5-18.

In addition to the direct information furnished by the deep borings, information about the composition, extent and structure of crystalline terrane and the Dunbarton basin are also provided by potential field geophysical methods. Detailed gravity information concerning SRS and vicinity exists and has been used to provide a detailed gravity map of the site (Figure 1.3.5-19). In addition, high resolution aeromagnetic data are available from the USGS and have been used to produce a high resolution aeromagnetic map of SRS and vicinity (Figure 1.3.5-20). Several recent studies have been the focus on integrating this geophysical information with the boring information listed above to evolve a fairly detailed model of the crystalline terrane and Dunbarton Basin.

1.3.5.1.7.1 Crystalline Terrane

The studies mentioned above have determined that the lithologies and structures in the crystalline terrane are basically similar to that seen in the eastern Piedmont province as exposed in other parts of the southeastern United States. The crystalline rocks form a volcanic – intrusive sequence of calc-alkaline composition, portions of which record both ductile and brittle deformational events. These relationships indicate that these rocks are the metamorphosed and deformed remnants of an ancient volcanic arc that are interpreted to be Carolina terrane equivalents.

The crystalline rocks were mapped as three formations (Figure 1.3.5-17). The Crackerneck Formation consists of weakly to unmetamorphosed and mildly to undeformed volcanic rocks of intermediate to felsic composition with minor amounts of mafic material. The rocks in this formation are represented mainly by tuffs and lapilli tuffs (extrusive volcanic rocks).

The DRB Formation (named after the Deep Rock Borings in which it is found) consists of moderately metamorphosed and highly to moderately deformed volcanic and plutonic rocks of mafic to intermediate compositions. The DRB Formation is cut by deformed amphibolite dikes and by undeformed dikes of basaltic and rhyolitic compositions, indicating that these rocks were intruded both before deformation and after the major episode of deformation had ceased. The DRB Formation may also contain a minor amount of quartz-rich sedimentary rock. However, the identification of this material is uncertain.

The PBF Formation (named after the Pen Branch fault borings in which it is found) occurs as a thin slice between the Dunbarton Basin to the south and the DRB Formation to the north. This formation contains strongly metamorphosed gneisses and amphibolites that have experienced relatively high thermal effects and appear to be deeper equivalents of the DRB Formation. The plutonic rocks of both the DRB Formation and PBF Formation have radiometerically dated crystallization ages of 620 Ma. Based on the association of these rocks with the Carolina terrane, the metavolcanic rocks of the Crackerneck Formation are interpreted to have been deposited unconformably on the DRB formation at about 620 Ma.

Subsequent to the formation of this volcanic stratigraphy, these rocks underwent multiple deformational episodes and chemical changes. The rocks of the DRB formation record highly developed deformational fabrics that indicate that these rocks have undergone significant amounts of ductile shearing at moderately high temperatures. These fabrics, in association with the superposition and juxtaposition of the higher temperature PBF formation, indicate that this deformation resulted from thrust and strike-slip faulting, which placed the PBF formation over the DRB formation. Based on radiometric age dating of biotite in the fault zone, this deformation is Paleozoic in age (approximately 300 Ma). In addition to ductile deformation features, the sub-Cretaceous basement rocks also record the effects of brittle deformation episodes characterized by fractures, brittle faults, and frictional melting. The presence of mineralized veins associated with these fractures and brittle faults indicate that the brittle faulting was often accompanied by the movement of hot waters. Radiometric dating of these effects suggest that at least one phase of brittle deformation occurred around 220 Ma. This age would make this phase of brittle deformation most likely associated with formation of the Dunbarton basin. Other younger brittle deformation features are also present, and are most likely associated with Tertiary deformation in the basement such as the Pen Branch fault. Radiometric dating of fracture filling yielded an age of 23 Ma. However, the radiometric systematics of the mineral dated is not well known so the geologic meaning of this age is uncertain.

1.3.5.1.7.2 Dunbarton Triassic Rift Basin

The Dunbarton basin underlies the southeastern portion of SRS and was first identified based on aeromagnetic and well data. Subsequent seismic reflection surveys, potential field surveys, and additional well data have led to the current understanding of the basin. The structure is currently interpreted as an asymmetric graben approximately 30 mi (50 km) long and 6 to 9 mi (10 to 15 km) wide. The axis of the basin strikes north 63° east, which is parallel to the regional strike of crystalline basement. The basin extends 5 mi (8 km) southwest of the Savannah River and 24 mi (40 km) to the northeast of SRS, where it terminates against a granite body interpreted from magnetic data. The master border fault, named the Pen Branch fault, is on the northwest boundary of the basin and dips to the southeast.

The southeast boundary of the basin is poorly constrained but is interpreted as a fault. Southeast of the Dunbarton basin aeromagnetic and gravity data indicate a terrane heavily influenced by basalt flows and sills. The magnetic data contain numerous high-frequency, closed-contour features indicative of shallow structures, and lower frequency features indicative of deeper-seated features. The host rock is perhaps crystalline metamorphosed rock similar to what is found further to the northwest beneath SRS. It is suggested that this terrane separates the Piedmont orogeny from crust of a different affinity further to the southeast. In effect, the mafic intrusions define the southeastern boundary of the Dunbarton basin and the northern boundary of the South Georgia Rift basin.

Ten wells drilled in the southeastern half of SRS penetrated sedimentary rocks of the Dunbarton basin (see Figure 1.3.5-17). Recovered core is clastic rock. Conglomerate, fanglomerate, sandstone, siltstone, and mudstone are the dominant lithologies. These rocks are similar to the clastic facies in other Newark Supergroup basins. In addition, four of the Pen Branch fault series wells penetrated Triassic rock. Conglomerate and red clayey siltstone are the dominant lithologies in these cores. The lithology and stratigraphy identified in these cores indicate that the proximal side of the basin is to the northwest. There is a larger component of coarse-grained rock types on the proximal side than on the southeast side of the basin. An upward increase of total fines is found in each core. Further, the sediments fine upward in each core. A detailed study of the Dunbarton Basin core that integrated the above observations with some new information grouped the sediments in the basin into four lithofaces:

1. A proximal fan facies occurs near the hanging wall of the Pen Branch fault (see Figure 1.3.5-21) and consists mainly of poorly sorted, matrix-supported conglomerates dominated by debris flows.
2. A distal fan facies includes silty and sandy mudstones interbedded with massive immature sandstones and wackes.
3. A fringe fan facies which is dominated by mudstones but also contains intervals with bioturbation, roots, and caliches, which indicate periods of flooding overprinted during periods of nondeposition by burrowing and soil formation.
4. A braided plain facies includes cross-stratified channel sandstones erbedded with bioturbated mudstones and fine sandstones containing caliches.

The facies relationships described above suggest an asymmetric basin that subsided faster to the northwest than to the southeast. The asymmetry led to greater local relief along the northern boundary, where high-energy fluvial processes dominated, and the resulting sediments were more coarse grained than farther out in the basin. The predominance of alluvial fan facies with abundant mud and debris flows, and caliches in paleosols suggests that the basin and surrounding areas were poorly vegetated, and an arid to semi-arid climate.

Gravity and magnetic modeling suggests that the Triassic section in the Dunbarton basin averages about 1.2 mi (2 km) thick. Boreholes have encountered up to 3,000 ft (899 m) of Triassic fill, but the base of the Dunbarton was not encountered. Seismic reflection data do not unequivocally constrain the base of the basin, as the transition between the Triassic rock and the crystalline terrane is unclear. However, interpreted Triassic reflectors are at least as deep as 3,900 ft (1,188 m) to 12,100 ft (3,688 m).

1.3.5.1.8 Site Geologic Map

A geologic map of the SRS was completed by the USGS and provided to SRS in 1994 and is shown in Figure 1.3.5-7. This map shows the Coastal Plain formations that crop out at the surface. Other, deeper Coastal Plain formations may not be observed at the surface within the boundaries of the site; however, these formations are known to exist in the subsurface based on drill core data and outcrops in nearby regions.

Erosion by the Savannah and Edisto Rivers and tributaries has truncated the uppermost stratigraphic units such as the "Upland unit" and the Tobacco Road Sand. This gives the geologic map its characteristic dendritic pattern and indicates that the strata are sub-horizontal. Deeper and older formations are exposed in stream valley walls Paleocene and Cretaceous formations crop out in nearby regions.

Superposed on the Coastal Plain sediments are a variety of alluvial and colluvial deposits that have resulted from streams cutting the valleys they occupy. The alluvial deposits are located in the stream valleys and on terraces and are indicated on the map (see Figure 1.3.5-7) as Qal 1, Qal 2, and Qt. The reworked sediments are derived from the uppermost Coastal Plain sediments and effectively cover up the deepest formations exposed in the stream valley bottoms.

Contacts separating the geological formations were mapped by examination of natural and manmade surface exposures and from subsurface drill core. Original compilation of field data was done at 1:100,000 scale. The subsequent SRS map is presented at 1:48,000 scale.

1.3.5.2 MFFF Site Geology

In calendar year 2000, 13 exploration borings and 63 CPT holes were used to define site-specific subsurface conditions at the MFFF site. Additional site geotechnical programs previously performed by others adjacent to and on this site were also used to evaluate site subsurface geologic and groundwater conditions. A detailed description of subsurface conditions encountered and previous SRS geotechnical references used for this investigation are described in detail in the *MOX Fuel Fabrication Facility Site Geotechnical Report* (DCS 2000). Exploration boring logs, CPT logs, and initial soil classification test results are also presented in this report. The location of exploration borings and CPT holes used to investigate the MFFF site are shown on Figure 1.3.5-22.

Information available from previous subsurface investigations was instrumental in development of the MFFF geotechnical field exploration program. Results of geotechnical exploration for the Actinide Packaging and Storage Facility (APSF), located adjacent to and south of the MFFF site, revealed the presence of subsurface soft zones. The *F-Area Northeast Expansion Report* (WSRC 1999b) contains results of additional explorations performed in the same vicinity, including the MFFF site area, that indicate that subsurface conditions at the MFFF site are similar to those previously encountered at APSF and nearby areas.

Initial layout of the CPT program for the MFFF site was patterned after the CPT layout that ultimately proved successful in adequately locating potential soft soil zones at the APSF site. As soft zones were encountered on the MOX site during field explorations, additional CPT and exploration holes were added to the plan to identify and delineate the extent of the soft zones found. The resulting CPT and exploration hole spacing, when combined with ones from previous explorations in the same area, was of greater concentration than was initially deemed necessary. The resulting data collection was found to be quite sufficient to identify potential loose soil zones that may be subject to liquification (see Section 1.3.7), as well as the soft zones present. Once the location and extent of the soft zones on the MFFF site were identified, the MFFF principal SSCs, such as the MOX Fuel Fabrication Building and the Emergency Diesel Generator Building were relocated to areas of the site found to be free of soft zones.

The approach for the layout of CPTs and exploration borings at the MFFF site provides confidence that soft and loose soil zones have been effectively identified in the vicinity of MFFF principal SSCs. Exploration spacing in the original geotechnical investigation was greater than desired because the drilling and CPT rigs could not access locations on the existing APSF spoils pile berm slopes. Grading of the slopes was performed in the summer of 2001 so that rig access could be provided to additional exploration hole locations. During the summer of 2002, DCS conducted a supplemental geotechnical investigation to acquire additional subsurface information to provide increased confidence that the size and extent of soft zones beneath the

MFFF principal SSCs are adequately characterized. The results of these supplemental investigations are consistent with the results obtained during the initial site investigations, and supporting design documents will be updated to reflect the new data.

The CPT holes extended from approximately 64 to 140 ft (19.5 to 42.7 m) below present site grade. Each CPT hole provided a continuous profile of the soil conditions encountered at each test location. Seismic, resistivity, and piezometric measurements were obtained in many of the CPT holes. Some soft soil zones related to past solution and deposition activity were identified at depth on the MFFF site. The soft zones encountered were typical to those that have been described in previous F-Area investigations. The CPT holes were used to define limits of the soft zones. MFFF principal SSCs, the MOX Fuel Fabrication Building, and the Emergency Diesel Generator Building were adjusted on the MFFF site so that they are not directly over any identified thick soft zones and to minimize the potential impact of the underlying soft zones. Both static and dynamic analyses have been performed to evaluate the effect of soft zones near MFFF principal SSCs. The location of facilities at the MFFF site is shown on Figure 1.3.5-22.

Subsurface soils at the MFFF site have also been evaluated to determine whether they have any potential for liquefaction during the design basis earthquake event. The potential for liquefaction has been determined using the established groundwater levels for the MFFF site, laboratory, geophysical, and cone penetration test results, and blow count data from exploration borings.

Recognized industry practice methods used to define and determine the potential for liquefaction have been utilized. The design basis earthquake has been used to establish the potential for liquefaction. Section 1.3.7.1 describes these evaluations.

The soil exploration borings extend from approximately 131 to 181 ft (39.1 to 55.2 m) below the present site grade. The exploration borings were used for correlation with the CPT holes and to obtain soil samples for laboratory testing. Three cased holes (exploration borings BH-2, BH-5, and BH-10) from the exploration program were used for downhole seismic testing.

The exploration borings and CPT holes indicate that subsurface conditions encountered at the MFFF site are consistent with all previous investigations performed at SRS in F Area, at and near the site. No unusual subsurface geological or groundwater hydrologic conditions were encountered. Representative geotechnical cross sections at the MFFF site are shown on Figures 1.3.5-23, -24, and -25.

The upper geologic units at the MFFF site are composed of the Barnwell Group. The exploration borings also extended through the Tinker/Santee Formation, Warley Hill Formation, and into the very dense Congaree Formation of the Orangeburg Group. Table 1.3.5-1 presents the correlation of geologic units and engineering units presently being used for geotechnical investigations at SRS. This correlation has been adopted for this geotechnical program, to be consistent with other SRS references being used for the MFFF site. The engineering units shown on Figures 1.3.5-23, -24, and -25 are consistent with the correlation shown on Table 1.3.5-1 and the geologic units discussed in this section and the referenced reports.

The upper groundwater level is within the Upper Three Runs aquifer and as described in Section 1.3.4.2. Based on the results of pore water pressure dissipation testing, the groundwater level at the MFFF site was generally encountered at a depth of 60 ft (21 m) or more below grade at the time of the site exploration program. This groundwater level is expected to fluctuate seasonally. The upper groundwater levels and gradient at the MFFF site is consistent Figure 1.3.4-18.

A comprehensive laboratory testing program has been conducted to establish both static and dynamic design parameters for use in analysis. Laboratory results also indicate that the subsurface geologic units and soil properties at the MFFF site are consistent with those identified in previous investigations in F Area. The same geologic units described for SRS and F Area are found at the MFFF site.

The exploration borings, CPT holes, geophysical test results, and laboratory test results have been used to establish static and dynamic geotechnical design criteria. The geotechnical design criteria have been developed for each representative geologic unit, using the latest standard of practice for geotechnical engineering. The geotechnical design criteria have been correlated with available geotechnical design criteria developed for F Area and other relevant geologic units at SRS to confirm consistency.

1.3.5.3 Tectonic Features

1.3.5.3.1 Definition of Plate Tectonics

Plate tectonics within the 200-mi (322-km) radius of SRS provides the description of the major structural or deformational features of the region, as well as the origins, evolution, and interrelationship of these features. The implementation of natural phenomena hazards mitigation requires that the tectonic elements of the site region should be understood and described in sufficient detail to allow an evaluation of the safety of a proposed or existing facility. The major issue with respect to the tectonic framework and site suitability is concern for tectonic features influencing the seismicity of the region.

Based on previous studies at SRS and elsewhere, there are no known capable or active faults within the 200-mi (322-km) radius of the site that influence the seismicity of the region with the exception of the blind, poorly constrained faults associated with the Charleston seismic zone (see Section 1.3.6).

1.3.5.3.2 Definition of Seismogenic Faults

Various definitions have been established to evaluate the issues of describing the deformational features and relating specific features to seismicity. These definitions are derived from classical geology and regulatory geology. In some cases, the same concept is defined with different terminology. The definitions that follow are taken from the NRC and DOE.

The NRC provided their definition in 10 CFR Part 100, Appendix A, as follows:

Capable fault: a fault, which has one or more of the following characteristics:

1. Movement at or near the ground surface at least once in the past 35,000 years or repeatedly within the past 500,000 years

2. Macro-seismicity instrumentally determined with records of sufficient precision to demonstrate a direct relationship with the fault
3. A structural relationship to a capable fault according to characteristics 1 or 2 such that movement on one could be reasonably expected to be accompanied by movement on the other.

NRC Regulatory Guide 1.165, Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion (March 1997), provides the following definitions:

Capable tectonic source: A capable tectonic source is a tectonic structure that can generate both vibratory ground motion and tectonic surface deformation such as faulting or folding at or near the earth's surface in the present seismotectonic regime.

Seismogenic source: A seismogenic source is a portion of the earth that is assumed to have uniform earthquake potential (same expected maximum earthquake and recurrence frequency) distinct from the seismicity of the surrounding regions. A seismogenic source will generate vibratory ground motion but is assumed not to cause surface displacement. Seismogenic sources cover a wide range of possibilities from a well-defined tectonic structure to simply a large region of diffuse seismicity (seismotectonic province) thought to be characterized by the same earthquake recurrence model. A seismogenic source is also characterized by its involvement in the current tectonic regime (the Quaternary, or approximately the last 2 million years).

The DOE, in DOE-STD-1022-94 (DOE 1996c), provides fault terminology as follows:

Fault: a geologic feature that demonstrates deformation or/and rupture of geologic deposits.

Active fault: a capable tectonic structure that demonstrates surface or near surface deformation of geologic deposits of a recurring nature within approximately the last 500,000 years or once in the last 50,000 years or/and associated with one or more large earthquakes or sustained instrumentally recorded earthquake activity.

Seismic source: seismic events, which contribute significantly (more than 5% to the total seismic hazards) to a probabilistic ground motion assessment.

SRS currently works to DOE-STD-1022-94 (DOE 1996c). At this time, there are no faults classified as active or capable at SRS.

1.3.5.3.3 Crustal Geometry of the Region and SRS Area

1.3.5.3.3.1 Thickness of the Crust

Along continental margins, the nature of the crust changes from continental-type crust to oceanic-type crust. Continental crust is generally thicker, less dense, and chemically distinct from ocean crust. The boundary at the base of either continental or oceanic crust also marks a fundamental change in physical parameters and is referred to as the Mohorovicic discontinuity. Density and P-wave velocity is significantly greater below this layer than above.

With the onset of continental rifting, the North American continent began to break away from Africa. Continental crust was stretched and thinned and was intruded with mafic magmas. At the point that one spreading center became dominant, the continental crust ceased to stretch and ocean crust was generated at the spreading center. This marked the initiation of a passive margin along the Atlantic continental margin.

In general, the thickness of continental crust thins from west to east across the eastern United States continental margin. The zone of transition from continental crust to oceanic crust is thought to underlie the offshore Carolina Trough and the Blake Plateau basin (see Figure 1.3.5-6). A cross section is provided through the continental margin and Baltimore trough (offshore New Jersey) (see Figure 1.3.5-26). This is a typical Atlantic-type margin showing the geometry of oceanic crust to the east and continental crust to the west. The Moho deepens from east to west from about 9 mi (15 km) to about 25 mi (40 km), respectively. The continental crust along the margin has been extended and intruded during Mesozoic rifting and is described as rift stage crust. Further east in the middle of the cross section is a complicated zone of transition from continental crust to oceanic crust. The data that support this interpretive model come largely from seismic reflection and refraction surveys and potential field surveys. Offshore South and North Carolina show a similar geometry of thinning crust (see Figure 1.3.5-27).

Further inland, the base of crust is discerned by following the configuration of the Moho on seismic refraction or reflection lines. From seismic reflection data collected at SRS, the Moho is interpreted at about 18.6 to 19.6 mi (30.0 to 31.5 km) depth. On the deep seismic profiles, a wide ban of reflections (200 to 300 milliseconds wide) at 10.5 to 11.05 seconds are interpreted to be the Moho. A survey from SRS southeast to Walterboro, South Carolina indicates a crust that thins from 23 mi (37 km) beneath the Dunbarton basin to 19.9 mi (32 km) near Walterboro, South Carolina. This interpretation is based on long seismic refraction and wide-angle seismic reflection data and constrained by gravity and aeromagnetic data (see Figures 1.3.5-19 and 1.3.5-20). The effect of continental extension and thinning during the Mesozoic rifting event is thus observed in the configuration of the Moho as well as the geologic evidence from the existence of the Dunbarton basin.

1.3.5.3.4 Tectonic Structures

Tectonic structures of interest in the SRS region include faults, folds, arches, basins (rift and post-rift) and paleoliquefaction features from earthquakes. The various structural features in this section are discussed in terms of the age of the feature, starting with the oldest structures. The age of the structure is to be distinguished from the age of the rock in which the structure formed. The primary interest is on how the age of the feature can be discerned with greater or lesser confidence with respect to the definitions of active and capable features in the previous section.

1.3.5.3.4.1 Paleozoic and Precambrian Structures

Modoc Fault Zone

The Modoc fault zone (see Figure 1.3.5-3), located in South Carolina and Georgia, separates greenschist facies metamorphic rocks of the Carolina terrane (Carolina Slate and Charlotte belts) from the amphibolite facies migmatitic and gneissic rocks of the Kiokee belt. The Modoc fault zone is an east-northeast trending ductile shear zone that can be traced from central Georgia to central South Carolina based on geological and geophysical data. The Modoc fault zone dips steeply to the northwest and contains quartzites, phyllite, paragneiss, and button schists correlative with units in the Asbill Pond Formation of the Carolina terrane. The lower grade Carolina terrane rocks underwent significant granitic sheet intrusion, prograde metamorphism, and penetrative strain during the Alleghanian orogeny. Fabric in the fault zone is characterized by brittle and ductile deformation produced by ductile shear during an early phase of the Alleghanian orogeny (315 Ma). The Modoc zone is overprinted by the Irmo antiform near Columbia, South Carolina. Extension of the Modoc fault zone further to the northeast is uncertain but there are shear zones in North Carolina and Virginia that may be of the same deformational phase. An important normal-sense component exists in the Modoc zone on the northwest flank of the Kiokee belt. The significance of the age of myonitic fabric on this fault at 315 Ma is that the fault is very old and therefore not in the realm of active or capable in terms of regulatory guidance.

Augusta Fault Zone

The Augusta fault zone (see Figure 1.3.5-3) is located near Augusta, Georgia, and juxtaposes amphibolite grade rocks of the Kiokee belt against the greenschist facies rocks of the Belair belt. The fault trends east-northeast and dips approximately 45° southeast. The fault contains two distinct deformation fabrics: a mylonite about 820 ft (250 m) thick is overprinted by a brittle fabric. Kinematic analysis within the mylonite zone reveals a hanging wall down component during the movement history. Furthermore, the hanging wall consists of lower greenschist facies while the footwall contains upper amphibolite facies. Lower grade rocks structurally positioned above higher grade rocks in combination with shear sense indicators suggests a low-angle normal fault movement for the Augusta fault zone. This is a new view of the Augusta fault zone, which previously had been considered a ductile-to-brittle thrust fault or a strike-slip fault. It now appears that ductile faults with a normal sense component were an important aspect of late Alleghanian deformational history. From reported $^{40}Ar/^{39}Ar$ ages from samples along a traverse across the Modoc fault and Augusta fault zones, it is concluded that a 274 Ma cooling age closely dates initiation of extensional movement on the Augusta fault zone. This cooling age indicates the time when the ductile fabric was generated and therefore when the fault moved. This fault does not fall into the capable or active fault definitions of the regulatory guides.

Near Augusta, Georgia, the Augusta fault zone and the southeast edge of the Kiokee belt are offset by the north-northeast trending Belair fault (see Figure 1.3.5-3). It has been suggested that the Belair fault was a tear fault linking two segments of the Augusta fault zone. Within the Atlantic Coastal Plain province sediments, the final stage of movement on the Belair fault occurred during the Cenozoic as high angle reverse faulting that offset the Late Cretaceous uniformity by 100 ft (30 m) and the Early Eocene uniformity by 40 ft (12 m).

It has been suggested that the Modoc fault zone, the Irmo shear zone, and the Augusta fault zone are part of the proposed Eastern Piedmont fault system, an extensive series of faults and splays extending from Alabama to Virginia. Aeromagnetic, gravity, and seismic data indicate that the Augusta fault zone continues in the crystalline basement beneath the Coastal Plain province sediments.

Paleozoic Basement Beneath SRS

Information concerning structural features in the basement beneath SRS is mainly derived from analysis of structural fabrics recorded in core samples from deep borings and at larger scales from geophysical techniques such as gravity and magnetic surveys and seismic reflection profiles. Seismic reflection surveys were conducted onsite in 1972 and 1987 to 1988 to image the basement reflector. In 1972, Seismograph Services Incorporated did a seismic reflection survey as part of the Bedrock Waste Storage Project. Approximately 60 line miles of survey were completed. This was the first survey that indicated the presence of basement faults, some of which disturbed Coastal Plain sediments. Offset reflectors were interpreted as basement faults. No official report was written for the survey.

During the period 1987 to 1988, a more thorough seismic reflection survey of SRS was completed (see Figure 1.3.5-28). The program consisted of two phases, which covered approximately 134 line miles distributed over much of SRS. These data were used to further define basement faults and to image any shallower or deeper structures. Subsequent seismic reflection and field potential geophysical data have led to various basement fault interpretations.

These data were reprocessed and re-interpreted to produce improved images of the Coastal Plain section and faults known to deform Coastal Plain sediments. Recovery of the shallow time section (40-200 milliseconds) in conjunction with recovery of the deep section (7-14 seconds) led to the discovery of additional faults clearly rooted in the midcrust and deforming Coastal Plain sediments.

An integrated analysis of the structural fabric in the basement core in addition to the geophysical data concluded that at least two regional scale ductile faults are present in the basement beneath SRS and vicinity, the Upper Three Runs fault and the Tinker Creek fault. These faults are expressed in the aeromagnetic data as lineaments and are interpreted to be associated with a thrust duplex that emplaces the rocks of the PBF Formation (Tinker Creek Nappe) over the DRB formation (Figure 1.3.5-17). The age of the faulting is constrained by a radiometric age on biotite that dates the movement at about 300 Ma, which would indicate that these faults are part of the Paleozoic Eastern Piedmont fault system.

In order to resolve faulting that deform Coastal Plain sediments, the topography of the basement surface was mapped utilizing the data listed above along with more recently acquired seismic reflection profiles. The map of basement topography indicates that offsets of the basement surface that range from approximately 100 ft (30 m) in magnitude down to the resolution limits of the data are present on the basement surface. However, most of these offsets are of relatively small magnitude and have limited lateral extents. Faults that involve Coastal Plain sediments that are considered regionally significant based on their extent and amounts of offset (i.e., Atta, Crackerneck, Martin, Pen Branch, and Tinker Creek) are shown on Figure 1.3.5-29. The Crackerneck and Pen Branch faults are relatively well constrained with borings. The other faults are projected from geophysical data only and their parameters are less well known. Of these faults the Pen Branch fault has been extensively studied and found to be not capable or not active.

1.3.5.3.4.2 Mesozoic: Extensional Tectonics and Rift Basins

A broad zone of extended (rifted) continental crust formed along the eastern continental margin of the United States, especially the southeastern portion during the early Mesozoic when North America broke away from Africa and South America. This region extends from Florida to Newfoundland and includes the area where SRS exists. The eastern seaboard domain encompasses this extended crust and is a sub-domain of the North American stable continental crust. Its significance is that within stable continental crust, areas of extended crust potentially contain the largest earthquakes. The Eastern Seaboard domain is bounded on the west by the western-most edge of Triassic-Jurassic onshore rift basins or the boundaries of the structural blocks in which they occur (see Figure 1.3.5-5). The eastern boundary is the continental/ oceanic boundary which is coincident with the East Coast magnetic anomaly (see Figure 1.3.5-6). Rifted crust is crust that has been stretched, faulted, and thinned slightly by rifting but is still recognizable as continental crust. The faulting is extensional or normal and down-dropped blocks form rift basins.

Geometric and kinematic arguments suggest that early Mesozoic normal faults may have been reactivated Alleghanian faults. Studies of exposed and buried rift basins in the eastern United States show that the faults controlling basin formation are complex, with border faults of variable dip, antithetic faults of variable displacement, and cross or transfer faults that fragment the basin into sub-basins. Within the SRS region, there is the Dunbarton rift basin, which is part of this tectonic setting. The fault that controls the basin formation, the Pen Branch fault, initially moved as a normal fault during the Triassic. However, it may have been a reactivated Paleozoic fault, and it has moved since the rifting episode.

One locus of major extension during early stages was in the South Georgia rift, which extends from Georgia into South Carolina (see Figure 1.3.5-4). The Dunbarton basin, underlying SRS, is most likely structurally related to that rift basin (see Figure 1.3.5-5). During the later stage of rifting (early Jurassic), the focus of extension was shifted eastward to the major marginal basins that would become the site of the Atlantic Ocean basin. The extension in the onshore, western-most basins, such as the Dunbarton, Florence, and Riddleville, waned. Eventually, rifting of continental crust ceased as sea floor spreading began in the Atlantic spreading center sometime around 175 Ma. The oldest ocean crust in contact with the eastern continental margin is late middle Jurassic. The significance of the age of transition from rifting to seafloor spreading is that the tectonic regime of rifting is no longer acting on the crust in the eastern seaboard domain. The basins are not continuing to form and for the most part, the crust is quiescent. The modern tectonic environment is partly based on ridge push from the Atlantic spreading center, and recent crustal stress measurements indicate a compressive northeast directed stress for the region.

1.3.5.3.4.3 Post-Rift and Cenozoic Structures

The following discussion includes tectonic features that have formed on the continental margin since the end of the Mesozoic rift stage (post-rift stage). Therefore, the discussion will include the late Mesozoic, as well as Cenozoic, tectonic elements. Post-rift tectonism is expressed along the eastern continental margin in a variety of structures originating in the crystalline basement and affecting the deposition of sediments and deformation of Coastal Plain sediments from the

Cretaceous through the Cenozoic. These structures include offshore sedimentary basins, such as the Carolina trough and the Blake Plateau basin; transverse arches and embayments, such as the Cape Fear arch and the Southeast Georgia Embayment; Coastal Plain faulting; and paleoliquefaction features that provide information on the recurrence of the Charleston earthquake.

Outer Margin Basins

Sedimentary basins along the continental margin (offshore) have formed in response to subsidence in the outer continental margin crust. Outer margin subsidence resulted from (1) the extension and thinning of the crust during early Mesozoic rifting followed by thermal contraction as the lithosphere cooled, and (2) from sediment loading on the lithosphere. The outer margin sediment basins formed on this transitional crust (see Figure 1.3.5-27). Toward the continent, continental crust was less altered and thicker. This portion of the margin subsided at a slower rate than the outer margin. Because of the differing rates and total amount of subsidence, a hinge zone developed all along the continental margin. Seaward of the hinge zone the crust is rift-stage continental crust. The crust here has subsided to greater depths. This is also the location of the outer margin basins (see Figures 1.3.5-6 and 1.3.5-27). Landward of the hinge zone, the crust is the thicker, unaltered crust. The depth to crust in this region is significantly shallower with a corresponding thinner veneer of post-rift sediments (see Figures 1.3.5-6 and 1.3.5-27). The Atlantic Coastal Plain is located landward of the hinge zone and has been affected by the outer margin subsidence.

Folding and Arching

Not all tectonism along the continental margin is due to outer margin subsidence. Lithospheric cooling and sediment loading were dominant processes during Middle Jurassic through early Cretaceous. The sediments now present in the outer margin basins are mostly Jurassic and early Cretaceous. Compressional faults, folds and thickness variations in the late Cretaceous and Cenozoic are due to intraplate stress fields rather than margin subsidence. These latest features are seen as highs and lows in the crust that control Coastal Plain sedimentation and are oriented perpendicular to the hinge zone. They are thought to be indicative of continued, episodic, differential crustal movements (tectonic) from Cretaceous through Pleistocene. The sedimentary sections are thinner, incomplete on the highs, or arches, and thicker with complete sections in the lows or embayments. The most prominent arch is the Cape Fear arch near the North Carolina-South Carolina border (see Figure 1.3.5-30). Other arches in the region include the Norfolk arch near the North Carolina-Virginia border, and the Yamacraw arch near the South Carolina-Georgia border (see Figure 1.3.5-31).

The Cape Fear arch has a variable history, receiving sediments during the Late Cretaceous and then acting as a sedimentary divide or arch from Latest Cretaceous through Late Tertiary. Upper Cretaceous Santonian sediments are the oldest strata to completely cover the Cape Fear arch (see Figure 1.3.5-31). Paleocene, Eocene, and Oligocene strata comprise 2,100 ft (640 m) of marine carbonate in the southeast Georgia embayment and thin to the northeast, toward the Cape Fear arch. The sediments become largely terrigenous on the flank of the arch and are completely missing over the crest of the arch; thus suggesting the arch was acting as a sedimentary divide beyond the Oligocene. Uplift on the arch may have continued through the Pleistocene.

Faulting

The most definitive evidence of crustal deformation in the Late Cretaceous through Cenozoic is the reverse sense faulting found in the Coastal Plain section of the eastern United States. In the late 1970s and early 1980s, USGS conducted a field mapping effort to identify and compile data on all young tectonic faults in the Atlantic Coastal Plain. Consequently, many large, previously unrecognized Cretaceous and Cenozoic fault zones were found. Of 131 fault localities cited, 26 were within North and South Carolina (see Figure 1.3.5-32). The identification of Cretaceous and younger faults in the eastern United States is greatly affected by distribution of geologic units of that age. Many of the faults are located in proximity to the Coastal Plain onlap over the crystalline basement. This may be due to the ease of identifying basement lithologies in fault contact with Coastal sediments.

The faults are characterized as mostly northeast trending reverse slip fault zones with up to 62 mi (100 km) lateral extent and up to 250 ft (76 m) vertical displacement in the Cretaceous. The faults dip 40° to 85°. Offsets were observed to be progressively smaller in younger sediments. This may be due to an extended movement history from Cretaceous through Cenozoic. Based on their similar characteristics, Cretaceous and younger faulting in the Coastal Plain is associated into several fault provinces. SRS falls into the Atlantic Coast fault province. A comparison of Cretaceous and younger faulting in SRS found that faulting on SRS shared similar characteristics with the faults in the Atlantic Coastal fault province including orientation and offset history. This comparison concluded that Cretaceous and younger faulting on SRS was not unique in comparison to the Atlantic Coast fault province in general and as a result shared the same seismic hazard.

Offset of Coastal Plain sediments at SRS includes all four Tertiary unconformities. Following deposition of the Snapp Formation, some evidence indicates oblique-slip movement on the existing faults. The offsets involve the entire Cretaceous to Paleocene sedimentary section. In A/M Area, this faulting formed a series of horsts and grabens bounded by subparallel faults that truncate at the fault intersections. The strike orientations of the individual fault segments vary from N 11°E to N 42°E, averaging about N 30°E. Apparent vertical offset varies from 15 to 60 ft (4.5 to 18 m), but throws of 30 to 40 ft (9 to 12 m) are most common.

This faulting was followed by erosion and truncation of the Paleocene section at the Lang Syne/Sawdust Landing unconformity. Subsequent sediments were normal faulted following deposition of the Santee Formation. Typically, the offset is truncated at the Santee unconformity, and the overlying Tobacco Road/Dry Branch formations are not offset. Locally, however, offset of the overlying section indicates renewed movement on new or existing faults after deposition of Tobacco Road/Dry Branch sediments.

In conjunction with these observations of Coastal Plain faults, modern stress measurements provide an indication of the likelihood of Holocene movement. There is a consistent northeast-southwest direction of maximum horizontal compressive stress (N 55-70°E) in the southeast United States. This determination is based on direct in situ stress measurements, focal mechanisms of recent earthquakes, and young geologic indicators. Shallow seismicity in the area, within crystalline terranes, is predominantly reverse character. It is concluded that the northeast directed stress would not induce damaging reverse and strike-slip faulting earthquakes on the Pen Branch fault, a northeast striking Tertiary fault in the area. These same conclusions may be implied for the other northeast trending faults.

In A/M Area at SRS, faulting appears to have been episodic and to have varied in style during the Tertiary. Oblique-slip faulting dominated the Cretaceous/Paleocene events, with a local north-south stress orientation. Subsequently, left-lateral shear on the pre-existing faulting and normal faulting occurred, with a corresponding shift in the direction of maximum compressional stress oriented N 20°E to N 30°E.

Pen Branch Fault

The Pen Branch fault has been regarded as the primary structural feature at SRS that has the characteristics necessary to pose a potential seismic risk. As stated below, studies have indicated that, despite this potential, the fault is not capable.

The Pen Branch fault (see Figures 1.3.5-17 and 1.3.5-29) is an upward propagation of the northern boundary fault of the Triassic Dunbarton basin that was reactivated in Cretaceous/Tertiary time. The fault dips steeply to the southeast. In the crystalline basement, slip was originally down to the southeast, resulting in the formation of the Dunbarton rift basin. However, movement during Cretaceous into Tertiary time was reverse movement, that is, up to the southeast. There could also be a component of strike-slip movement.

The bulk of evidence collected for the Pen Branch Fault Program supports the conclusion that the most recent faulting on the Pen Branch fault is older than 500,000 years. Therefore, the Pen Branch fault is not a capable fault per 10 CFR Part 100, Appendix A. In a study designed to examine only the sediments with an age of 1 Ma or less, deformation was not found to exist.

The Pen Branch fault was identified in the subsurface at SRS in 1989. It was interpreted from seismic reflection surveys and other geologic investigations. A program was initiated at that time to determine the capability of the fault to release potentially damaging seismic energy as defined in NRC regulatory guidelines, 10 CFR Part 100, Appendix A. Separate actions completed under this program title include the following:

- Shallow drilling of Coastal Plain sediments with eight paired drill holes to bracket the location and the amount of displacement on the Pen Branch fault
- Formation of the Earth Science Advisory Committee for independent assessment and verification of the data gathered
- A deep drilling program into the fault zone in basement underlying Coastal Plain sediments
- A high-resolution, shallow seismic reflection survey over the fault trace
- Reprocessing seismic reflection data to enhance the shallow portions of the data and then the deeper portions of the data under separate processing protocols
- Quaternary geology investigation to examine the youngest surfaces and deposits onsite for indications of neotectonism

- Confirmatory Drilling Project: The final investigation carried out under the 1989 Pen Branch Fault Program. The investigation focused on a small zone over the fault where seismic reflection data had been collected previously and indicated that the fault deforms the subsurface reflector at 200 milliseconds two-way travel time. Eighteen drill holes, two to basement and the others to a depth of 300 ft (91.4 m), were arranged to adequately define the configuration of the layers deformed by the fault. Boreholes were spaced over a zone of 800 ft (245 m), north to south. Results suggest that deformation by the fault is limited to the Lang Syne/Sawdust Landing unconformity (~50 Ma) (Stieve et al. 1994). Other interpretations may be offered where offset on the Pen Branch fault involved the Tobacco Road and Dry Branch Formations. However, based on presently available data, the Pen Branch fault is not capable.

It is therefore concluded that the Pen Branch fault is not a capable fault per 10 CFR Part 100, Appendix A.

Belair Fault Zone

The Belair fault is a Cenozoic fault located on the inner margin of the Coastal Plain near Augusta, Georgia (see Figure 1.3.5-3). The fault is really a set of en echelon faults extending at least 15 mi (24 km) and trending northeast. Individual fault segments are 1.25 to 3 mi (2 to 5 km) long. The fault zone places Late Precambrian phyllites of the Belair belt over Middle Tertiary Coastal Plain sediments. All the faults show oblique-reverse slip movement and as much as 100 ft (30 m) of vertical offset has taken place since the deposition of the Barnwell Group sediments. The Belair fault zone has a protracted history of movement in that it initiated as a tear fault on the Augusta fault during the late Alleghanian (Hercynian). The fault was later reactivated as an oblique-reverse slip fault during the Cretaceous. The age of latest movement on the Belair fault zone can only be determined based on available stratigraphic marker horizons. The age of last movement can be bracketed between the age of the sediment that is offset and the age of the stream terrace that caps this strata and is not deformed. The age of the deformed strata can be as young as 40 Ma and the age of the stream fill terrace is between 26,000 and 1,550 years based on carbon-14 dates of peat. This makes the age determination on the fault uncertain because the age of undeformed deposits capping the deformation is poorly defined and because the fault age can only be bracketed based on deposits that precede a large time period unconformity. However, it has been concluded that the Belair fault zone records movement from late Early Cretaceous through at least Eocene, which makes the fault approximately 40 Ma.

Buried or Blind Faulting in the Charleston Seismic Zone

Seismic activity in the southeastern United States has been dominated by the 1886 Charleston, South Carolina, earthquake, aftershocks, and the continuing low-level seismic activity that persists in the area today. The search for structures to explain seismicity near Charleston has been complicated by the absence of surface faulting, fault scarps, or other fault-generated topographic features. Because the seismic zone is buried in the subsurface, the presence of possible causal geologic structures at depth must be inferred through geophysical methods. Many geologic, geophysical, and seismic studies have been completed by a number of researchers since the mid-1970s resulting in the emergence of some widely diverse models and hypotheses. A review of the more recent models reveals that uncertainty still exists on details of the causal relationship between local geologic structures and seismic activity in the region. However, significant progress has been made.

Most hypotheses relating southeast United States seismicity to geologic structure assume activity to occur along preexisting zones of weakness favorably oriented with respect to the ambient stress field. Understanding the regional stress is an essential element in the formation of causative models.

Models developed in the early 1980s involved possible slip along a master decollement located under the coastal plain at a depth of 6.2 to 7.5 mi (10 to 12 km). This was primarily based on interpretations of deep seismic reflection profiling coupled with an inferred orientation of the regional maximum horizontal stress axes in a northwest-southeast direction. The implications of this model were that the observed seismicity near Charleston was not particularly unique to that region and that similar large events could potentially occur anywhere east of the Appalachians. However, there were problems associated with this model. They stem primarily from (1) lack of consensus on the existence of a master decollement, and (2) subsequent data gathered over the years that establishes the preferred regional maximum horizontal stress axis in a northeast direction, making movement along a decollement unlikely.

Spatial association of buried plutons and seismicity has also been noticed in the Charleston region. Stress amplification due to rigidity contrasts between plutons and the country rock near these plutons has also been suggested as a mechanism where the mafic or ultramafic plutons lying deep below the ground surface are inferred from localized gravity highs. However, it is unknown if the large contrasts required exist for this model. An alternative explanation suggests that the plutons are symptomatic of a zone of weakness. Thus, any seismic response to the stress field would occur at the zones of weakness. A problem with this scenario is that mafic bodies defined by gravity highs occur throughout the southeastern United States, but Charleston remains the only location to show evidence of historical earthquake activity.

Recent Models

Eastern United States coastal plain seismic activity occurred in distinct zones superposed on a regional background of very low level seismicity. The most active of these zones and the one assumed likely to be associated with the 1886 Charleston event is the Middleton Place-Summerville Seismic Zone (MPSSZ). The MPSSZ lies some 12 mi (20 km) northwest of Charleston, well within the mesoseismal area of the 1886 Charleston earthquake. It was in this area that the delineation of two possible intersecting faults were identified when relocating instrumentally recorded earthquakes from 1974 to 1980 (see Figure 1.3.5-33). The first was a shallow, northwest-trending fault defined by hypocenters 2.5 to 5 mi (4 to 8 km) deep striking parallel to the Ashley River. This was named the Ashley River fault. The second fault was labeled the Woodstock fault. The Woodstock fault trends north-northeasterly and is defined by planar distribution of hypocenters with depths between 5.6 and 8.1 mi (9 and 13 km). It intersects and appears deeper than the Ashley River fault. Recent studies refine and complement the 1982 effort by utilizing 58 additional well-recorded events located in the MPSSZ from 1980 to 1991. Fault-plane solutions from the new data reinforce the northeast-southwest maximum horizontal stress direction of previous studies. However, the epicentral distribution of this new data displayed no obvious pattern of association with the Ashley River fault or the Woodstock fault. Therefore, the seismicity was divided into sets according to focal mechanism in an attempt to infer a structural cause of the earthquakes. Results of this breakout revealed:

- The first set of data favored a northwest-southeast strike and southwest dip direction, suggesting compatibility with the Ashley River fault zone. Solutions were found to have components of mostly strike-slip and/or reverse faulting mechanisms.
- The second set of data was further divided into two subsets with the first displaying mainly vertical fault planes striking north-south and the second subset striking north northeast-south southwest with shallower dips to the southwest. These two subsets were classified as belonging to the Woodstock fault zone. Solutions of these events revealed mostly strike-slip motion on the vertical fault with a strong thrust component on the shallower dipping events.

Results indicated that the Ashley River and the Woodstock faults are not simple planar features, but resemble zones composed of short segments of varying strike and dip. When location was factored into the analyses, it was found that events associated with all sets of data occurred in the same area. From these observations, it was concluded that the seismicity in the MPSSZ defines the intersection of two fault zones, which are inferred to be the Ashley River fault zone and the Woodstock fault zone.

Paleoseismic Data

Estimating seismic recurrence intervals of moderate to large earthquakes within the southeastern United States is difficult. These difficulties stem from the relatively short (300 years) historical record coupled with an absence of surface faulting, offset features, or prehistoric ruptures.

Geologic field study methods developed to extend the seismic record assess both the temporal and spatial distribution of past moderate and large earthquakes. This assessment is carried out through identification and dating of secondary deformation features resulting from strong ground shaking. In the southeast, this extension of the seismic record has been accomplished through field search for earthquake-induced liquefaction flowage features called "sand blows" associated with prehistoric earthquake-induced paleoliquefaction features.

These features are attributed to prehistoric earthquake induced liquefaction as defined by the transformation of sediments from solid to liquid state caused by increased pore water pressure. The increased pore pressure is caused during or immediately after an earthquake. "Sand blows" are features formed where earthquake shaking causes liquefaction at depth followed by the venting of the liquefied sand and water to the surface.

The following section summarizes paleoliquefaction studies in the southeastern United States. Aspects that are of particular importance to SRS include the following:

- No conclusive evidence of large prehistoric earthquakes originating outside of coastal South Carolina has been found.
- Young fluvial terraces at or slightly above the level of the modern floodplain and Carolina bays are the most likely depositional environments for potentially liquefiable deposits in the SRS region.

Paleoliquefaction Studies in the Eastern United States

Widespread occurrences of earthquake-induced sand blows were originally reported throughout the meizoseismal area of the 1886 Charleston, South Carolina, earthquake. Excavation and detailed analyses of these liquefaction flow features provided the first insight into the pre-history of the Charleston earthquake. Other pre-1886 liquefaction flow features (mostly sand blows) were discovered and investigated near the town of Hollywood, about 15 mi (25 km) west of Charleston. Searches for sand blows were continued throughout the Charleston area and expanded to the remaining coastal South Carolina areas. Eventually, areas of study were broadened to include Delaware, Virginia, North Carolina, and Georgia. The objective was to identify other epicentral regions, if they existed, and to estimate the sizes of pre-1886 earthquakes assuming the areal extent of sand blows caused by an earthquake are a function of earthquake intensity in areas of similar geologic and groundwater settings. Figure 1.3.5-33 shows the study region of current paleoliquefaction areas of interest. To date, no conclusive evidence of large prehistoric earthquakes originating outside of coastal South Carolina have been found.

In coastal South Carolina investigations, identification of paleoliquefaction features generally adheres to specific local geologic criteria. Some specific relations between liquefaction susceptibility and subsequent formation of liquefaction features (sand blows) are summarized below:

- A water table very near the ground surface greatly increases susceptibility to liquefaction (depth <3 ft [<1 m]).
- Virtually all seismically induced liquefaction sites are located in either beach-ridge, backbarrier, or fluvial depositional environments. Of these, beach-ridge deposits were found to be the most favorable for the generation and preservation of seismically induced liquefaction features.
- Due primarily to the effects of chemical weathering, materials older than about 250 ka were less susceptible to liquefaction than were younger deposits. This indicates that the probabilities of sand blows forming in deposits of late Pleistocene and early Holocene age are extremely low.
- The liquefied materials are generally fine-grained, well-sorted (i.e., uniformly graded), clean beach sand. The principal properties of sand that control liquefaction susceptibility during shaking are degree of compaction (measured as relative density by geotechnical engineers), sand-grain size and sorting, and cementation of the sand at grain-to-grain contacts. Fine grained well-sorted sand of ancient and modern beaches are much more susceptible to liquefaction than standard sand used for engineering analyses.
- Features large enough to be interpreted as possibly having an earthquake origin in the low country were found only in sand deposits having total thickness greater than 7 to 10 ft (2 to 3 m).
- The depth of the probable source beds at liquefaction sites is generally less than 20 to 23 ft (6 to 7 m), and the groundwater table is characteristically less than 10 ft (3 m) beneath present ground surface.

Liquefaction features that typify the coastal South Carolina area have been described as sand blow explosion craters and sand-vents/fissures.

Sand Blow Explosion Craters or Filled Sand Blow Craters

Following the onset of seismic loading from a moderate to large earthquake, development of sand blow craters can be described by four sequential phases: (a) an explosive phase, (b) a flowage phase, (c) a collapse phase, and (d) a filling phase. These were first described based on historical accounts and the internal morphology of exhumed features. Figure 1.3.5-34 is a vertical section of a filled sand-blow that is representative of the type observed at most study sites. This feature illustrates characteristics consistent with earthquake-induced liquefaction origin. The soil horizon is cut by an irregular crater and filled with stratified to nonstratified and graded sediments. The fill materials are fine-to medium-grained sand and clasts from the original soil profile, as well as sand from source beds at depths below the exposed C horizon. Sand-blow explosion craters were found primarily on beach deposits, and are notably absent in fluvial settings.

Sand-Vents/Fissures or Sand Volcanoes

Sand volcanoes vent to the surface and leave relict sand mounds. These features generally form in circumstances where the liquefying source zone, at depth, is overlain by a cohesive, finer grained, non-liquefiable layer, or "cap." The thickest part of the mound ranges from a few centimeters to as much as 10 in (25 cm). The mounds are generally thickest directly above source feeder vents that extend downward through clay-bearing stratum. This type of liquefaction feature was rare in beach settings, but commonly found within backbarrier marine sediments and in interbedded fluvial deposits.

Dating paleoliquefaction episodes can be accomplished either qualitatively or quantitatively. Qualitative methods include degree of staining and weathering of sands within the feature, thickness of overlying profiles, and cross cutting relations of one feature compared to another. A more quantitative approach involves radiometric dating of organic material within or cut by the liquefaction feature. An example of a minimum age constraint is dating of roots that have grown into the feature. A maximum constraint can be determined from roots cut by the feature or by dating organic materials recovered from the collapsed area of the crater during the liquefaction episode. The most accurate estimates for the age of a liquefaction episode are obtained from radiometric dating of leaves, pine needles, bark, or small branches that were washed or blown into the liquefaction crater following formation.

Utilizing the above methods, at least four pre-1886 liquefaction episodes were described at approximately 580 +104 (CH-2), 1311+ 114 (CH-3), 3250+ 180 (CH-4), and 5124+ 700 (CH-5) years before the present. CH refers to Charleston source with CH-1 designated as the 1886 earthquake. An even older episode (CH-6) was found to be cut by a CH-5 feature.

Changes in hydrologic conditions (groundwater levels) play an important role in determining an area's susceptibility to liquefaction. On the basis of published sea-level curves, groundwater levels in the southeastern United States have been assumed at or near present levels for only the past 2,000 years. Consequently, the paleoliquefaction record is probably most complete for this period. However, beyond the 2,000 to 5,000 year range, knowledge of groundwater conditions is considerably less reliable, making gaps in the paleoseismic record much more probable.

Paleoliquefaction at the Savannah River Site

Reconnaissance surveys were performed in search of paleoliquefaction sites as far as 40 mi (65 km) inland along the Savannah River. However, no South Carolina paleoliquefaction surveys or studies have yet been performed as far inland as SRS. Several factors suggest that it would be difficult to locate and evaluate the origin of potential liquefaction features within the geomorphic and geologic environment of the SRS. Investigations elsewhere in South Carolina have shown that aerial photographs are useless for locating 1886 and pre-1886 sand blows. The SRS region has no Pleistocene beach ridges for sand-blow crater formation. Young fluvial terraces at or slightly above the level of the modern floodplain and Carolina bays are the most likely depositional environments for potentially liquefiable deposits in the SRS region. However, the search for liquefaction features in these areas is severely limited by the lack of access, high water-table conditions, dense vegetative cover, and few exposures.

Existing exposures in the Savannah River fluvial terraces above the modern floodplain were examined for evidence of liquefaction. Extensive reconnaissance of the Bush Field and Ellenton terraces on the SRS revealed few exposures of adequate depth and extent to evaluate the presence or absence of liquefaction. Terrace alluvium associated with these terraces contains a high percentage of sand, but based on the degree and depth of pedogenic modification and probable depth to the water table, these terraces were judged to have had a relatively low susceptibility to liquefaction during the late Pleistocene and Holocene. In this fluvial environment, the most likely liquefaction features are sand vents or fissures. No evidence of sand vents, fissures, or other liquefaction features were observed in any of the available exposures examined. Recognition of paleoliquefaction features in the pre-Quaternary deposits at SRS would be extremely difficult, if not impossible.

A paleoliquefaction assessment of SRS was prepared by WSRC in 1996. This investigation indicated that several hydrologic, sedimentological, and logistical conditions must be met for seismically induced liquefaction (SIL) to occur and be identified. These included (1) the presence of Quaternary-age deposits; (2) the presence of a shallow groundwater table; (3) proximity to potential seismogenic features; (4) geologic sections of several different types of unconsolidated deposits; and (5) quality and extent of exposure.

Based on these considerations, the floodplains of the Savannah River and its tributaries were identified as the areas on SRS with the highest potential for generating and recording Holocene SIL features. The terraces of the Savannah River and tributaries were also considered potential areas for recording Quaternary SIL features, though these features would likely be older than ones in the floodplains. The upland areas on SRS have a low potential for recording Quaternary SIL because they are pre-Quaternary in age, partially indurated, and generally high above the water table. Paleoliquefaction investigations in the SRS uplands, therefore, only targeted those sites postulated by previous workers as containing evidence of SIL.

Conclusions from this paleoliquefaction assessment fell into two categories: (1) field studies of floodplain deposits along the Savannah River, and (2) evaluation of previously reported paleoliquefaction and neotectonic features located in pre-Quaternary sediments. A brief summary of findings in these two areas follows.

Investigation of banks along 68 mi (110 km) of the Savannah River adjacent to SRS revealed a large number of excellent exposures of floodplain deposits. Most of the exposed deposits were clay and silt, and had a low liquefaction potential. Locally, however, clean sand deposits with a high liquefaction potential were present. Given the extensive amount of exposure and the local presence of liquefiable materials, SIL features would likely be present in these deposits if strong earthquakes had occurred after they were deposited. However, the presence of buried historical objects and radiocarbon dates from these materials illustrated that most or all of the exposed floodplain deposits were historical in age. As no strong ground motions have occurred in historical times in the SRS area, SIL features could not exist in these deposits. Furthermore, the fact that they date to historical times precludes them from providing any information of earlier earthquake history.

The absence of SIL features in the bank exposures does not preclude the possibility that SIL features exist deeper in the section or on the older, higher terraces. In fact, the local presence of liquefiable materials in the Modern floodplain deposits suggests that, if strong prehistoric earthquakes had occurred, SIL features are probably present at depth in the floodplain deposits or on the older/higher terraces. These key areas were not investigated, and exposure is limited.

The upland areas of SRS were considered to have a low potential for recording Quaternary SIL because the deposits are old (pre-Quaternary), generally high above the water table (>30 ft [>10 m]), and are indurated. However, previous investigators described several features in the Tertiary section as clastic dikes, and attributed them to SIL and/or neotectonic activity. The sites were evaluated to determine if they have the diagnostic characteristics that have recently been documented for true SIL.

Four types of post-depositional features were identified: (1) irregularly shaped cutans; (2) structurally controlled cutans; (3) joints; and (4) faults. Cutans are a modification of the texture, structure, or fabric of the host material by pedogenic (soil) processes, either by a concentration of particular soil constituents or in situ modification of the matrix. These features were interpreted through the process of elimination procedure of multiple working hypotheses. None were thought to be the result of SIL. Summary observations of these four elements are given below.

Irregularly Shaped Cutans

The absence of offset on irregularly shaped cutans eliminated the possibility that they were faults, and the undisrupted bedding within and across the feature eliminated the possibility that they were clastic dikes, SIL features, or ice wedges. The higher density of these features near the ground surface and their similarity in appearance to the zone of more intense geochemical alteration at the top of each exposure suggested these features were pedogenic in origin. They were interpreted as an in situ, pedogenic modification of the texture, structure, and fabric of the host material, and therefore were referred to as "irregularly shaped cutans."

Structurally Controlled Cutans

There was no evidence of rapid injection of liquefied material into structurally controlled cutans. The similarity of the material within the features and that of the host material, as well as undisrupted pebbly horizons within and across the features, demonstrated the features were not clastic dikes, ice wedges, or SIL features. The absence of offset across virtually all of the features demonstrated that they did not develop as faults. They were interpreted to have developed through pedogenic processes based on: (1) the similarity and relationships that illustrate the features formed concomitantly with the sub-horizontal zone of more intense geochemical alteration at the top of each exposure, and (2) an overall downward thinning and local pinch-out of the features. Strong preferred orientations at most exposures, parallelism with adjacent joints, and their occurrence along fault planes at one locality, suggested that the orientation of most of the features was controlled by pre-existing structures, and were therefore referred to as "structurally controlled cutans."

Joints

Joints are common on SRS and vicinity. Though their mechanism of formation is not well understood, their age was determined to be constrained by interpretation that cutans often developed along pre-existing joints. The joints, therefore, pre-dated the pedogenic processes that formed the cutans. Highly variable orientations of cutans suggested that the orientation of joints on the SRS was also highly variable. A gradual and consistent change in orientation of cutans over 100 to 200 ft (30 to 60 m) at some outcrops suggested the orientation of joints also locally changed gradually and consistently. A lack of consistent preferred orientations of joints across SRS did not favor a tectonic origin for these features. Furthermore, no clear relationship existed between the joint-controlled cutans and the local topography. The joints, therefore, were probably not related to slope mass wasting. A local, gradual change in orientation over several hundred feet, and the common occurrence of closed depressions on SRS, are consistent with differential settling from subsurface dissolution. This hypothesis was not addressed directly during this study.

Faults

Small-scale faults were clearly present at several locations on and adjacent to SRS. Most faults had normal separations, although one small, sub-vertical feature had a component of reverse motion. All separations observed were less than 3 ft (1 m). The amount of horizontal slip was not determined for any of the faults. Low, medium, and high angle faults were also present. The presence of cutans on several faults suggested that these faults were older than the pedogenic processes that formed the cutans. A 2 ft (0.6 m) thick Pliocene loess deposit overlies one fault zone, indicating these faults are probably older than Pliocene. One fault zone was of particular interest because it was located at the approximate upward projection of the Pen Branch fault. Furthermore, the faults in outcrop trended northeast, sub-parallel to the Pen Branch fault. The relationship between the faults in outcrop and the Pen Branch fault, if any, was not investigated.

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Tables

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Table 1.3.5-1. Correlation of Geologic and Engineering Units for the MFFF Site

Geologic Unit	Engineering Unit Symbol
"Upland Unit" Formation	TR1 and TR1A Layers
Tobacco Road Formation	TR2A and TR2B Layers
Dry Branch Formation	TR3/4 and DB1/3 Layers
Tinker/Santee Formation	DB4/5. ST1 and ST2
Warley Hill Formation	GC Layer
Congaree Formation	CG Layer

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