APPENDIX A

GEOLOGY AND SUBSURFACE HYDROLOGY

This appendix discusses the geology and subsurface hydrology of the Savannah River Plant (SRP) and its surroundings. Included in the following sections are descriptions of the regional geologic setting, seismology and geologic hazards, hydrostratigraphy, groundwater hydrology, groundwater quality, groundwater use, hydrogeologic interrelationships, groundwater recharge and discharge, and water budget for the Separations area and the Burial Ground.

A.1 GEOLOGY AND SEISMOLOGY

This section contains information on the important geologic features in the region surrounding the SRP and within its boundaries. The geologic features discussed include the regional geologic setting, seismology, and geologic hazards.

A.1.1 REGIONAL GEOLOGIC SETTING

A.1.1.1 Tectonic Provinces

The North American continent is divided tectonically into foldbelts of recent or ancient deformation, and platform areas where flat-lying or gently tilted rocks lie upon basements of earlier foldbelts (King, 1969). The Southeastern United States contains two platform areas (the Cumberland Plateau province and the Coastal Plain province) and three foldbelts (the Blue Ridge province, the Valley and Ridge province, and the Piedmont province) (Figure A-1).

The Savannah River Plant is located in the Aiken Plateau physiographic division of the Atlantic Coastal Plain province (Figure A-1) (Cooke, 1936; Du Pont, 1980a). The center of the Plant is approximately 40 kilometers southeast of the fall line that separates the Atlantic Coastal Plain province from the Piedmont province (Davis, 1902). Crystalline rocks of the Piedmont (Precambrian and Paleozoic age) underlie a major portion of the gently seaward-dipping Coastal Plain sediments of Cretaceous and younger age (Figure A-1). Sediment-filled basins of Triassic and Jurassic age (their exact age is uncertain) occur within the crystalline basement throughout the Coastal Plain of Georgia and the Carolinas (Du Pont, 1980a). One of these, the Dunbarton Triassic Basin, underlies parts of the Plant (Figure A-1) (Du Pont, 1980a; Stephenson, Talwani, and Rawlins, 1985).

A.1.1.2 Stratigraphy*

Metamorphic and Crystalline Basement Rock

Near the center of the Plant, metamorphic and crystalline rock are buried beneath about 280 meters of unconsolidated-to-semiconsolidated Coastal Plain sediments (Marine, 1966). The surface of the rock dips to the southeast at a gradient of about 6.8×10^{-3} (6.8 meters/kilometer) (Siple, 1967), and the rock is exposed at the fall line about 40 kilometers northwest of the SRP. | TE

Immediately overlying the basement rock is a layer of saprolite, which is the residual product of weathering of the crystalline and metamorphic rock. The combined saprolite and basal clay at the bottom of the Coastal Plain Sediments forms an effective seal that restricts the flow of water between the Coastal Plain sediments and the basement complex.

Triassic-Jurassic Sedimentary Rock

The Dunbarton Basin, formed by normal faulting of the crystalline and metamorphic basement rock during the Triassic-Jurassic Period, is filled by sandstones, shales, and conglomerates, and buried beneath about 370 meters of Coastal Plain sediments (Figure A-1). The northwest boundary of the basin has been well defined by seismic traverses and by a well that penetrated 490 meters of Triassic-Jurassic rock and then passed into the crystalline and metamorphic rock below. The southeast margin is not as well defined, because there are no well data similar to those defining the northwest margin (Marine, 1976). The depth to the bottom of the Dunbarton Basin is not known from well penetration. A well near the center of the basin that was drilled to a depth of 1300 meters did not penetrate the underlying crystalline rock.

The rocks of the Dunbarton Basin consist of poorly sorted shale, siltstone, | TE
sandstone, and conglomerate. The coarser material is found near the northwest margin, where fanglomerates are abundant. Nearer the center, sandstone, silt- | TE
stone, and shale predominate; however, the sorting is always extremely poor (Marine and Siple, 1974).

Cretaceous Sediments

The terminology for the stratigraphic units used in this EIS is modified from that used by Siple (1967). The Middendorf and Black Creek Formations (GCS, 1986) have been determined to be more accurate nomenclature for what had been referred to as the "Tuscaloosa Formation" in many studies of groundwater at

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*The accepted names for stratigraphic units have evolved over the years as additional information on the age of the units and their correlation with similar units in other areas has surfaced. This is reflected in the different names used by authors to identify subsurface units. The stratigraphic nomenclature used in this document is the same as the usage of authors whose works have been referenced. Therefore, different portions of the text might use different names for the same geologic units. Likewise, the same name may be used for geologic units or portions of units that are otherwise different. Figure A-2 shows the correlation of units used by the various authors. The terminology used in this document is largely that of Siple (1967).

the Savannah River Plant. Figure A-2 shows a tentative correlation of these units to stratigraphic terminology described in recent publications.

The Cretaceous-Age sands and sediments (Figure A-2) consist primarily of fluvial and estuarine deposits of cross-bedded sand and gravel with lenses of silt and clay. They rest directly on saprolite, a residual clay from weathering of the crystalline and metamorphic rock. The Cretaceous Sediments are overlain conformably by the Ellenton Formation but, near the Fall Line where the Ellenton is absent, they are overlain unconformably by sediments of Tertiary and Quaternary age (Siple, 1967). The Cretaceous Sediments crop out in a belt that extends from western Tennessee to North Carolina. In South Carolina, this belt is 15 to 50 kilometers wide. The thickness of the Cretaceous Sediments ranges from 0 at the Fall Line to about 230 meters beneath the L-Reactor on the Savannah River Plant.

In this area, the Cretaceous Sediments consist of light gray-to-white, tan, and buff-colored, cross-bedded quartzitic-to-arkosic coarse sand and gravel, with lenses of white, pink, red, brown, and purple silt and clay (Siple, 1967). Ferruginous sandstone concretions, siderite nodules, and lenses of kaolin 0.5 to 12 meters thick are present in the Cretaceous Sediments. The chief minerals in the sediments are quartz, feldspar, and mica, which were derived from weathering of the igneous and metamorphic rocks of the Piedmont province to the northwest.

Ellenton Formation

The Ellenton Formation (terminology after Siple, 1967), which overlies the Cretaceous Sediments (Figure A-2), consists of dark lignitic clay with coarse sand units. It is thought to be Paleocene in age and is unconformably overlain by the Congaree Formation (of the Eocene Epoch). The Ellenton Formation sediments are entirely within the subsurface; they range to about 30 meters in thickness.

The lignitic clay is dark gray to black, sandy, and micaceous. It is interbedded with medium quartz sand and contains pyrite and gypsum. The upper part of the formation is characterized by gray salty-to-sandy clay with which gypsum is associated. This clay is about 3 to 5 meters thick in the central part of the Plant; it thickens to 10 meters in A- and M-Areas. The lower part consists generally of medium-to-coarse clayey quartz sand, but it contains very coarse and gravelly quartz sand in some areas (Siple, 1967).

Congaree Formation

The Congaree Formation (terminology after Siple, 1967) was included in the McBean Formation by Cooke (1936), and this usage was followed by the U.S. Army Corps of Engineers (COE, 1952) during the original foundation studies for the construction of the SRP (Marine and Root, 1978). The lower part of the original McBean was raised to formational status and called the Congaree Formation and the Warley Hill Marl by Cooke and MacNeil (1952). In discussing geology and groundwater at the Plant, Siple (1967) used the term "McBean" to include both deposits that are equivalent to the Claiborne Formation/Group of the Gulf Coastal Plain and only the upper part of these deposits. In much of the area studied by Siple, the two units could not be distinguished, either where exposed or in well logs (Marine and Root, 1978). TE

Subsequent investigations at the Plant have shown that it is desirable to distinguish the McBean Formation - as used in the restricted sense, rather than as used by Siple (1967) - from the Congaree Formation. These two units are separated by a clay layer informally called the "green clay" (Figure A-2).

TC TC The Congaree and McBean deposits strike about N 60°E and dip at a gradient of about 1.5×10^{-3} to 1.7×10^{-3} (1.5 meters/kilometer to 1.7 meters/kilometer) toward the south or southeast (Siple, 1967). Their thickness ranges from zero near the fall line to about 76 meters in southeastern Allendale County. In the central part of the Plant, the Congaree and McBean deposits are about 61 meters thick, of which about 37 meters is the Congaree Formation.

TC In the vicinity of the Separations Areas, the Congaree Formation consists of gray, green, and tan sand with some layers of gray, green, or tan clay (Marine and Root, 1978). In the northwest part of the Plant, it consists primarily of tan clayey sand. It is slightly glauconitic in some places and slightly calcareous in others. A pisolitic clay zone at the base of the Congaree and McBean deposits defines the base of the Congaree Formation (Siple, 1967).

The green clay layer at the top of the Congaree Formation appears to be discontinuous in the northwest SRP area (i.e., updip). To the south, the green clay appears to thicken to about 7 meters in L-Area and 18 meters in the southeastern portions of the Plant to become what is called in Georgia the Blue Bluff Marl of the Lisbon Formation. The Marl is found at the Vogtle Nuclear Power Station in Georgia, in wells in the southern part of the SRP, and in offsite areas to the south. The green clay is gray to green, dense, and occasionally indurated (Marine and Root, 1978). The induration of the clay is caused commonly by dense compaction and siliceous cement. Calcareous cement is usually absent from this zone but, farther south, calcareous cement might be more common.

TC Although subdivision of the Congaree and McBean group might be warranted in the SRP area and in other parts of South Carolina and Georgia, such subdivision appears less warranted toward the Fall Line, because the shoreward facies of each unit grade into a comparatively thin zone, and criteria for distinguishing them become doubtful (Siple, 1967). This is confirmed by drilling in M-Area, where the green clay is thin and discontinuous and the sediments of both McBean and Congaree are very similar in appearance.

McBean Formation

TE TE As discussed above, the term "McBean" was used originally to designate all deposits of the same age as the "Claiborne" sediments of the Gulf Coastal Plain in this area; it is now used to designate only the upper part of these sediments. The McBean Formation can be divided into two subunits: an upper unit consisting of tan, clayey sands and occasionally red sand (Marine and Root, 1978), and a lower unit consisting of light, tan-to-white calcareous, clayey sand (Figure A-2). This lower unit is locally called the "calcareous zone"; in some places, it contains void spaces that resulted in rod drops and lost circulation during drilling operations (COE, 1952). To the northwest, these void spaces appear to decrease, so no calcareous zone exists in M-Area. However, to the southeast, the calcium carbonate content of the zone increases, as do void spaces. Southeast of the Plant, the zone becomes a limestone with only small amounts of sand.

The McBean Formation is considered the shoreward facies of the Santee limestone to the southeast (Siple, 1967). In the SRP area, the calcareous zone may represent a tongue of the Santee limestone. Toward the fall line to the northwest of the SRP, it becomes more difficult to distinguish the several Eocene formations, and Siple (1967) maps the Eocene deposits as undifferentiated. In the northwest SRP area (M-Area), the calcareous zone is replaced by a clayey sand unit.

Barnwell Formation

The Barnwell Formation (terminology after Siple, 1967) directly overlies the McBean Formation and is exposed over a considerable area of Aiken and Barnwell Counties. The formation thickens to the southeast from zero in the northeastern part of Aiken County to about 27 meters at the southeast boundary of Barnwell County. In the Separations Areas, the unit is about 30 meters thick. TC

The Barnwell Formation consists mainly of deep red, fine-to-coarse clayey sand and compact, sandy clay. Other parts of the formation contain beds of mottled gray or greenish-gray sandy clay and layers of ferruginous sandstone that range in thickness from 0.03 to 1 meter. Beds of limestone occur in the Barnwell Formation in Georgia, but none have been recognized in South Carolina. Factors indicate that a considerable part of the Barnwell Formation was deposited as a calcareous sandstone in a near-shore or estuarine environment. Some evidence of the original calcareous nature of the formation is indicated by the comparatively high proportion of calcium carbonate found in groundwater circulating in this unit (Siple, 1967).

In the Separations Areas, the Barnwell Formation is divisible into three parts:

1. The lowest unit, the "tan clay," commonly consists of two thin clay layers separated by a sandy zone. The entire unit is about 3 to 4.5 meters thick and is semicontinuous over the area.

2. Above the tan clay is a silty sand unit 0 to 12 meters thick.

3. Above the silty sand is a unit of clayey sand that runs up to 30 meters thick. This sand, which may include beds of silty clay or lenses of silty sand, is slightly less permeable than the underlying silty sand.

Upland Unit

The Upland Unit (Hawthorn equivalent; Siple, 1967) is exposed over a very large area of the Atlantic Coastal Plain and is perhaps the most extensive surficial deposit of Tertiary age in this region. It is bounded on top and bottom by erosional unconformities and is present at the surface in the higher areas of Aiken County. It ranges in thickness from 0 in northwestern Aiken County to about 25 meters near the Barnwell-Allendale County Line.

The Upland Unit consists of a fine, sandy, phosphatic marl or soft limestone, and brittle shale resembling Fuller's earth. Updip, however, in the vicinity of Aiken and Barnwell Counties, it is characterized by tan, reddish-purple, and gray sandy, dense clay that contains coarse gravel, limonitic nodules, and disseminated pods of kaolinitic material.

Tertiary Alluvium

Alluvial deposits of Late Tertiary age occur irregularly and discontinuously on the interstream divides. They are composed of coarse gravel and poorly sorted sand and have been tentatively classified by Siple (1967) as Pliocene in age. Their thickness ranges from 1.5 to 6 meters.

Terrace Deposits

Cooke (1936) recognized seven marine terraces of Pleistocene age on the Atlantic Coastal Plain in South Carolina. He indicated that the four highest terraces are present in the Savannah River Valley. The deposits that may be associated with these terraces are about 10 meters thick or less (Cooke, 1936).

Holocene Alluvium

Alluvium of Holocene age occurs in the tributary and main channels of the Savannah River. These deposits, which are generally cross-bedded and heterogeneous in composition, range in thickness from 1.5 to 9 meters (Siple, 1967).

A.1.1.3 Geomorphology

The SRP is located on the Aiken Plateau as defined by Cooke (1936). The Aiken Plateau slopes from an elevation of approximately 200 meters at the Fall Line to an elevation of about 75 meters to the southeast. The surface of the Aiken Plateau is highly dissected and is characterized by broad, interfluvial areas and narrow, steep-sided valleys. Because of the Plant's proximity to the Piedmont Province and the Savannah River, it has somewhat more relief than the near-coastal areas, with onsite elevations ranging from 27 to 104 meters above sea level. Relief on the Aiken Plateau is as much as 90 meters (Siple, 1967). The plateau is generally well drained, although small, poorly drained depressions occur. These depressions are similar in character to Carolina bays.

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On the Aiken Plateau there are several southwest-flowing tributaries to the Savannah River. These streams commonly have asymmetrical valley cross sections, with the northwest slope being gentler than the southeast slope. This is because the stream courses are generally parallel to the strike of the Coastal Plain formations. Erosion of the Coastal Plain sediments by the water course results in gentle dip slopes on the northwest, or updip, sides of the valleys. The landforms produced by these geomorphic processes resemble cuestas.

Since the early 1950s, the flow rates of Four Mile Creek and Pen Branch, including Indian Grave Branch, have been increased from about 1 cubic meter per second to the present 12 cubic meters per second by the discharge of cooling water and process effluent directly into the creeks. The stream profiles of the two creeks are beginning to change owing to erosion of the stream channels and deposition near the mouths of the creeks. Depositional environments in both creeks presently extend from their deltas to approximately 2.4 kilometers below SRP Road A, where near-neutral (neither erosion nor deposition) conditions exist (Ruby, Rinehart, and Reel, 1981).

A.1.2 SEISMOLOGY AND GEOLOGIC HAZARDS

A.1.2.1 Geologic Structures and Seismicity

The down-faulted Dunbarton Triassic Basin underlies the SRP and contains several interbasinal faults. However, the sediments overlying these faults show no evidence of basin movement since their deposition during the Cretaceous Period (Siple, 1967; Du Pont, 1980a). Other Triassic-Jurassic basins have been identified in the Coastal Plain tectonic province of South Carolina and Georgia; these features may be associated with the South Georgia Rift (Du Pont, 1980a; Popenoe and Zietz, 1977; Daniels, Zietz, and Popenoe, 1983). The Piedmont, Blue Ridge, and Valley and Ridge tectonic provinces, which are associated with Appalachian Mountain building, are northwest of the fall line (Figure A-1). Several fault systems occur in and adjacent to the Piedmont and the Valley and Ridge tectonic provinces; the closest of these, the Belair Fault Zone (about 40 kilometers from the SRP), is not capable of generating major earthquakes (Case, 1977).

There is no conclusive evidence of recent displacement along any fault within 300 kilometers of the SRP with the possible exception of (a) the geophysically inferred faults (Lyttle et al., 1979; Behrendt et al., 1981; Talwani, 1982; Hamilton, Berendt, and Ackermann, 1983) in the meizoseismal area of the 1886 Charleston earthquake, which occurred approximately 145 kilometers from the Plant (Du Pont, 1982a), and (b) seismically inferred strike-slip motion on the northwest flank of the Dunbarton Basin (Stephenson, Talwani, and Rawlins, 1985). Table A-1 shows the significant geologic structures and fault systems in the SRP region and gives the age of last movement.

Surface mapping, subsurface boring, and geophysical investigations at the SRP have failed to detect any faulting of the sedimentary strata that would affect SRP facilities. Several surficial faults, generally less than 300 meters in length and with displacements of less than 1 meter, have been mapped; however, none of these are considered capable, as they are overlain by younger sediments that show no evidence of faulting. The time since the last movement on these surficial faults is believed to be 0.5 million years or more (Du Pont, 1980a).

Two major earthquakes have occurred within 300 kilometers of the SRP: the Charleston earthquake of 1886, which had an epicentral modified Mercalli intensity (MMI) of X, and was located about 145 kilometers from the SRP; and the Union County, South Carolina, earthquake of 1913, which had an epicentral shaking of MMI VII to VIII, and was located approximately 160 kilometers from the SRP (Langley and Marter, 1973). An estimated peak horizontal shaking of 7 percent gravity (0.07g) was calculated for the site during the 1886 earthquake (DOE, 1982b). Site intensities and accelerations for other significant earthquakes are listed in Table A-2.

Probabilistic and deterministic analyses have established a design-basis, horizontal earthquake acceleration of 0.20g for key seismic-resistant buildings

Table A-1. Significant Geologic Structures in SRP Region[a]

Structural feature	Closest point to site: km	Closest point to site: Direction	Age of last movement
Valley and Ridge Province Faults	350	NW	Late Paleozoic
Blue Ridge Province Faults (Carterville, Whitestone, and Fries-Hayesville-Altoona Faults)	280	NW	Late Paleozoic
Cape Fear Arch	250	NE	Pleistocene
Brevard Fault Zone	225	NW	Pre-Mesozoic
Westerfield Fold-Fault System	225	NE	Pre-Eocene
Deep River Basin (N.C. and S.C.)	215	NE	Triassic-Jurassic
Gold Hill Fault	210	NW	Late Paleozoic
Columbia Triassic Basin	155	NE	Pre-Cretaceous
Towaliga Fault, Kings Mt. Belt	135	NW	Late Paleozoic
Clubhouse Crossroads Faults	115	SE	Pre-Miocene (?)
Columbia Reverse Faults and Clastic Dikes	105	NE	Late Miocene
Charleston Triassic (?) Basin	80	SE	Triassic-Jurassic
Decatur-Coffee County (Georgia) Graben and Faults	65	SE	Pre-Pliocene
Eastern Piedmont Fault System (Modoc, Flat Rock, Goat Rock, Bartletts Ferry, and Towaliga Faults)	65	NW	Late Paleozoic
Belair Fault Zone	40	NW	Pre-Miocene to Recent[b]
Langley Graben	27	NW	Pre-Miocene (?)
Dunbarton Triassic (?) Basin	Onsite	Onsite	Pre-Late Cretaceous

[a]Source: Du Pont, 1980a.
[b]NRC has determined that, although age of last movement is not precisely known, Belair Fault Zone is not capable in sense of 10 CFR 100 (Case, 1977).

at the SRP. This acceleration has a return period of about 5000 years (Du Pont, 1982b).

On June 8, 1985, an earthquake with a local magnitude of 2.6 (maximum intensity MM III) and a focal depth of 0.96 kilometer occurred at the SRP. The epicenter was just to the west of C- and K-Areas (Figure A-3). The acceleration produced by the earthquake was less than 0.002g. No aftershocks were recorded by the SRP Seismic Network (Stephenson, Talwani, and Rawlins, 1985).

A.1.2.2 Seismic Events and Liquefaction Potential

Liquefaction is the transformation of water-saturated granular material from a solid or semisolid state to a liquid state; this results from an increase in the pore water pressure, which is caused by intense shaking. Earthquakes may cause liquefaction of near-surface, water-saturated silts and sands, making the materials lose their shear strength and flow (Keller, 1979).

The seismicity of the SRP is discussed in Section A.1.2.1. As noted in that section, liquefaction induced by earthquakes with a maximum horizontal acceleration of less than 0.20g is not a potential problem for SRP facilities (Du Pont, 1980a; Langley and Marter, 1973).

A.2 GROUNDWATER RESOURCES

This section discusses the groundwater resources at the SRP. For the purposes of this environmental impact statement (EIS), the definition of groundwater resources includes hydrostratigraphy, groundwater hydrology, and groundwater quality.

A.2.1 HYDROSTRATIGRAPHY

Three distinct hydrogeologic systems underlie the SRP: (1) the Coastal Plain sediments, where water occurs in porous sands and clays; (2) the crystalline metamorphic rock beneath the Coastal Plain sediments, where water occurs in small fractures in schist, gneiss, and quartzite; and (3) the Dunbarton Basin (Triassic/Jurassic Age) within the crystalline metamorphic complex, where water occurs in intergranular spaces in mudstones and sandstones. The latter two systems are unimportant as groundwater resources near the Plant.

The Coastal Plain sediments, which contain several important aquifers, consist of a wedge of stratified sediments that thickens to the southeast. Near the center of the Plant, the sediments are about 300 to 400 meters thick and consist of sandy clays and clayey sands. The sandier beds generally form aquifers and the clayier beds form aquitards. The Coastal Plain sedimentary section at the Plant consists of the Hawthorn, Barnwell, McBean, Congaree, Ellenton, and Tuscaloosa Formations, as defined by Siple, 1967. These units correlate to those used by Geological Consulting Services (GCS, 1986). Figure A-2 shows the correlation of these stratigraphic terms. Table A-3 describes the lithology and water-bearing characteristics of the hydrostratigraphic units underlying the Plant.

The Cretaceous Sediments (Middendorf and Black Creek Formations; GCS, 1986) form a particularly prolific groundwater unit because of their thickness and high permeability. In areas of the South Carolina Coastal Plain within 40 kilometers of the Fall Line, the Cretaceous Sediments are a major supplier of groundwater (Siple, 1967); wells commonly yield more than 5500 cubic meters per day of good-quality water. The Cretaceous Sediments rest on saprolite, a residual clay weathered from the crystalline metamorphic bedrock, and consist of a sequence of sand and clay units. The combined saprolite and basal clay form an effective seal that separates water in the Coastal Plain sediments from water in the crystalline metamorphic rock. The sand units combined are about 140 meters thick and supply water to the Plant.

Paleocene sediments, including the Ellenton Formation, overlie the Cretaceous Sediments and consist of clay with coarse sand units. The known Ellenton sediments are entirely within the subsurface. The clays in the Ellenton are apparently continuous enough to act as a confining bed that separates the water in the Congaree from that in the Black Creek Formation.

The Congaree Formation includes a lower unit of sand with clay layers and an upper clay layer known as the "green clay." The Congaree sand beds constitute an aquifer second only to the Cretaceous Sediments in importance, with yields as high as 3600 cubic meters per day (Siple, 1967). The green clay appears to be continuous and supports a large head difference between the Congaree and the overlying McBean Formation. This head difference is as much as 21 meters near the Central Shops and 24 meters in the Separations Areas, even though the clay layer is only 2 to 3 meters thick in these areas (D'Appolonia, 1980; Du Pont, 1983). North and west of Upper Three Runs Creek, the green clay is discontinuous and, therefore, is effective only locally as a confining unit (aquitard). In the southeastern part of the Plant, the green clay is believed to be about 18 meters thick (Du Pont, 1983).

The McBean Formation, as defined by the SRP (Marine and Root, 1978), consists of a lower unit of calcareous clayey sand and an upper unit of clayey sands (lower part of Dry Branch Formation; GCS, 1986). Groundwater occurs in both units, but neither is a prolific aquifer. The formation is incised by Upper Three Runs Creek and Four Mile Creek.

The Barnwell Formation, which overlies the McBean Formation, consists of (1) a clay unit known as the "tan clay" (part of Dry Branch Formation; GCS, 1986), (2) a silty sand unit (upper part of Dry Branch Formation; GCS, 1986), and (3) a clayey sand unit that can include beds of silty clay or lenses of silty sand (Tobacco Road Equivalent; GCS, 1986). Borings in the Separations Areas and about 2 kilometers east of the Central Shops indicate that the tan clay is about 2 meters thick and that it commonly consists of two thin clay layers separated by a sandy zone (D'Appolonia, 1980; Du Pont, 1983). In some areas of the Plant, the tan clay is not easily identified in foundation borings, drillers' logs, or geophysical logs; however, this clay has not always been readily apparent in soil cores, even in areas where it is known to support a significant head differential.

The Barnwell and Upland Unit (Hawthorn; Siple, 1967) Formations are incised by Upper Three Runs Creek, Four Mile Creek, and their unnamed tributaries. The water table is usually within the Barnwell Formation but in low-lying areas can be in the underlying McBean or Congaree Formations. Because of the large amounts of clay and silt mixed with the sands, the Barnwell generally does not yield water to wells except from occasional sand lenses.

The South Carolina Hazardous Waste Management Regulations (SCHWMR) and the Resource Conservation and Recovery Act (RCRA) [270.14(c)(2)] require the determination of the hydrogeologic zones that are most susceptible to impacts from waste management units. These zones are the unsaturated zone, the uppermost aquifer, the principal confining unit, and the principal confined aquifer (shallowest confined aquifer beneath the SRP). Figure A-2 shows the relationship of these zones to one another and their tentative correlation with other stratigraphic nomenclature. Each hydrogeologic zone is summarized below. TC

Formational terminology used in this discussion is largely that of Geological Consulting Services (GCS, 1986).

The unsaturated zone is a 25- to 45-meter-thick sandy unit containing clay lenses. This zone is comprised of the Upland unit and, in some areas of the Plant, the Tobacco Road and Dry Branch Formations.

The uppermost aquifer is a 35-meter-thick sandy unit composed of two zones. The upper water-table zone, composed primarily of the clayrich, fine-grained sands of the McBean Formation (in some areas of the Plant, areas of higher water table) includes portions of the Dry Branch and Tobacco Road Formations. The lower zone, composed of the coarse-grained Congaree Formation and the upper sand and clay of the Ellenton Formation.

Based on an evaluation of hydraulic properties as well as head differences between subsurface zones, the lower three units of the Ellenton Formation are believed to form the principal confining zone beneath the Plant. These units form a section approximately 15 meters thick composed of two clay beds (middle and lower Ellenton) and the lower Ellenton sand lenses. The sands in these lenses are commonly coarse grained, but generally are supported by a clay matrix that impedes fluid movement. The middle clay is generally a dense, low-permeability clay that can be locally discontinuous or more permeable. The lower clay, however, is an average of 3 meters thick (maximum of 15 meters), is dense, has a low permeability, and is believed to be continuous over the SRP area. Table A-4 summarizes the hydraulic conductivity of the Ellenton Formation.

The confined aquifer is a sandy zone averaging about 30 meters in thickness. This zone is capped by the overlying Ellenton Formation confining unit. In this appendix, the shallowest confined aquifer is referred to as the Black Creek aquifer. The aquifer beneath the Black Creek is referred to as the Middendorf aquifer (see Figure A-2).

A.2.2 GROUNDWATER HYDROLOGY

A.2.2.1 Hydrologic Properties

The flow of groundwater in the natural environment depends strongly on the three-dimensional configuration of hydrogeologic units through which flow takes place. The geometry, spatial relations, and interconnections of the pore spaces determine the effective porosity (percentage of void space effectively transmitting groundwater) and the hydraulic conductivity of the hydrogeologic unit. These factors largely control groundwater flow through geologic media.

The Coastal Plain sediments beneath the Plant are heterogeneous, and they are anisotropic with respect to the hydrologic properties controlling groundwater flow. Tables A-5 and A-6 list typical hydrologic properties of the Coastal Plain sediments in the Separations Areas and A/M-Areas, respectively. These tables indicate that the horizontal component of hydraulic conductivity in the Barnwell Formation is considerably greater than the vertical component. In this case, the horizontal conductivity is at least 100 times the vertical conductivity; consequently, groundwater tends to move laterally within this hydrogeologic unit. Although not shown in Tables A-5 or A-6, this general relationship is expected to apply to all coastal plain sedimentary units (Freeze and Cherry, 1979).

The following paragraphs describe important hydrodynamic properties of specific geologic units beneath the Plant.

Crystalline Metamorphic Rock

Water injection and removal tests on packed-off sections of rock indicate two types of fractures in the crystalline rock (Marine, 1966). The first type consists of minute fractures that pervade the entire rock mass but transmit water extremely slowly. Rock that contains only this type of fracture is called "virtually impermeable rock." The other type of fracture is confined to definite zones that are vertically restricted but laterally correlatable and have larger openings that transmit water faster. Rock that includes this type of fracture is called "hydraulically transmissive rock."

TC

Representative values of hydraulic conductivity are 1.2×10^{-5} meter per day for virtually impermeable rock, and 0.033 meter per day for hydraulically transmissive rock (Marine, 1975). An analysis of a two-well tracer test with tritium indicates a fracture porosity of 0.08 percent in a hydraulically transmissive fracture zone (Webster et al., 1970). Laboratory analyses of cores indicate an average intergranular porosity of 0.13 percent (Du Pont, 1983).

Triassic/Jurassic Sedimentary Rock

The Triassic sediments consist of poorly sorted, consolidated gravel, sand, silt, and clay. The coarser material is presumed to be near the northwest margin of the Dunbarton Basin, where fanglomerates are abundant. Nearer the center of the basin, sand, silt, and clay predominate. The sorting is extremely poor, which causes an extremely low primary porosity in the Triassic rocks (Marine and Siple, 1974). Groundwater does occur in the primary porosity of the Triassic rock, but the hydraulic conductivity is extremely low and water movement is almost nonexistent.

TC

The hydraulic conductivity of the Triassic sedimentary rock, as determined from field tests, ranges from 4×10^{-6} to 4×10^{-9} meter per day (Marine and Siple, 1974). Average total porosity is 8.0 percent for sandstones and 3.3 percent for mudstones. Average effective porosity is 7.0 percent for sandstones and 0.53 percent for mudstones (Du Pont, 1983).

Cretaceous Sediments

TC

According to a field study of the Cretaceous Sediments aquifer (Tuscaloosa or Black Creek/Middendorf equivalent), the average transmissivity is 1500 square meters per day, and the median is 1400 square meters per day (Marine and Routt, 1975). Storage coefficients determined for the formation averaged 4.5×10^{-4}, and Siple (1967) assumed effective porosities of 20 to 30 percent (Du Pont, 1983).

Ellenton Formation

In general, Siple (1967) did not distinguish between the Ellenton and the Cretaceous Sediments aquifer in reporting the results of pumping tests.

Because there is no piezometric map exclusively of the Ellenton Formation, little is known about the lateral flow of water within the formation. Table A-4 summarizes recent hydraulic conductivity data collected on the Ellenton Formation.

Congaree Formation

The results of two tests conducted near the center of the Plant indicate a hydraulic conductivity of nearly 40 meters per day in the Congaree Formation, although one of the values (0.73 meter per day) for M-Area is 50 times less than this. The median conductivity value obtained in 10 slug tests (decay of an instantaneous head change) in sandy zones of the Congaree Formation in the Separations Areas is 1.8 meters per day (Root, 1977a,b). The median conductivity, as determined in two water-level recovery tests, is 1.5 meters per day (Du Pont, 1983).

Data from laboratory tests conducted by the U.S. Army Corps of Engineers (COE, 1952) indicate a median value of 43 percent for the total porosity of the upper part of the Congaree Formation. The effective porosity is estimated to be 20 percent. A pumping test in the northwest portion of the plant yielded a value of 14 percent (Du Pont, 1983). TC

McBean Formation

The median hydraulic conductivity of the upper sand of the McBean Formation (equivalent to Lower Dry Branch Formation; GCS, 1986) has been reported to be 0.13 meter per day, about twice that of the calcareous zone (Du Pont, 1983). An effective porosity of 20 percent is reasonable.

Fluid losses during drilling operations make the calcareous zone appear very permeable. However, the results of pumping tests in the zone indicate a low hydraulic conductivity (Du Pont, 1983). Apparently, zones of higher permeability do not connect over large distances, and the regional permeability of the calcareous zone is lower than drilling observations suggest.

Barnwell Formation

Pumping tests to determine the hydraulic conductivities of the Barnwell Formation (Du Pont, 1983) indicate the median conductivity to be 0.04 meter per day for the clayey sand unit (Tobacco Road equivalent; GCS, 1986). Although no tests were made on the silty sand unit, a pumping test in a sand lens within this unit indicated a hydraulic conductivity of 0.3 meter per day.

Upland Unit

Because the Upland Unit (Hawthorne equivalent; Siple, 1967) in the SRP area is usually unsaturated, no pumping tests have been performed. There is no piezometric map of the formation in the SRP area. Flow paths are predominantly vertical; there are only short horizontal flow paths.

A.2.2.2 Head Relationships

The elevation of the free-standing groundwater above a sea-level datum is referred to as the hydraulic head. Figure A-4 shows the hydraulic heads for the principal hydrostratigraphic units near the center of the Plant, typified by H-Area. These data are for one location in the Separations Areas where water-level differences are probably at their maximum. Near the discharge areas of creek valleys, water elevations of the several Tertiary aquifers converge. Although not shown in this figure, the head in the lower part of the Cretaceous aquifer (Middendorf equivalent) is generally higher than that in the shallower aquifer (Black Creek) by at least 6 meters (DOE, 1984).

Figure A-4 indicates that the water elevation in the Ellenton Formation is above that in the Cretaceous Sediments aquifer. The cause of this appears to be continuous pumping from the Cretaceous Sediments aquifer in H-Area, which has created a cone of depression in these deeper units but probably has not affected water levels significantly in the Ellenton aquifer. Figure A-5 shows the cones of depression in the potentiometric surface of the Cretaceous Sediments aquifer in F- and H-Areas (Killian et al., 1987a). TC

The hydraulic heads shown in Figure A-4 also indicate that there is not a direct hydraulic connection between the Ellenton and the overlying Congaree Formation. Although the clays that separate the Ellenton and the Congaree are not thick, they are apparently extensive and continuous enough to impede the hydraulic connection. A pisolitic clay at the base of the Congaree appears to be extensive and might constitute the principal confining bed that separates the Congaree and the deeper hydrologic system (Siple, 1967). The upper part of the Ellenton is a sandy clay, which also functions as a confining bed between the Ellenton and the Congaree.

Finally, Figure A-4 shows that the head in the Congaree Formation in the Separations Areas is the lowest of any hydrostratigraphic unit in the Coastal Plain system. This is attributable to two conditions: (1) the low permeability of the green clay, through which recharge must take place, and (2) the high hydraulic conductivity of the Congaree sands below the green clay, which enhances lateral movement and discharge to the deeper creek valleys. The upward recharge of water to the Congaree from the Ellenton-Cretaceous Sediments aquifer system is also impeded by clay layers at the base of the Congaree and in the Ellenton.

Figures A-6 and A-7 describe the head difference between the water in the Black Creek and Congaree Formations. The two maps show a change due to improved data control (more measuring points) and, to a lesser extent, show the effects of pumpage on and off the SRP. Had the data control available in 1987 been available in 1982, it is quite likely the maps would have been very similiar.

TC

The more recent data (Bledsoe, 1987) are more accurate. The earlier map was based on limited data and was included in the Draft EIS, because it was the best data available at the time of the publication of the Draft EIS.

The head in the Congaree is higher than that of the Cretaceous Sediments in an area surrounding A- and M-Areas and in the vicinity of P- and R-Areas and Par Pond. Figure A-8 shows the vertical-head relationships along a cross-section passing through M-Area, where the Cretaceous Sediments aquifer water elevation is below that of the Congaree. A continuous decline in head with depth indicates that this location is a recharge area for the Cretaceous Sediments aquifer, as is much of the area of the Aiken Plateau northwest of the Plant.

TC Hydraulic head reversal discussed above is not fixed in time or space, as water levels fluctuate in response to a number of factors such as aquifer use, i.e., pumping onsite for water supply and process water and pumping offsite for agricultural, industrial, and municipal purposes; the amount of natural recharge received by the different aquifers; and climatic factors. The discussion in this section demonstrates the complexity and the transient nature of the hydrogeologic regime beneath the SRP (see Figures A-12, A-17, and A-20).

Because of flow directions and head relationships, the potential for offsite impacts on water quality in the Black Creek aquifer is extremely small. The most important factor for offsite impacts is the prevailing flow direction for water in the Black Creek toward the Savannah River, not toward municipalities that border the Plant. The most important factor for onsite impacts is the upward gradient between the Congaree and the Upper Tuscaloosa over parts of the SRP.

TE Impacts on the Black Creek aquifer have been confirmed in one monitoring well cluster on the SRP. This cluster is in the western recharge area (A- and M-Areas), where the clay barrier thins beneath an area where spillage from rail cars and transfer facilities took place during the early days of SRP operation. The migration of these constituents is being defined; their source has been under remediation for nearly two years. Data analyzed to date do not define any flow paths for these constituents toward offsite water users. The area of final discharge of the groundwater originating from these sources is the Savannah River. These constituents would require at least several hundred years to reach the river. The pumpage of recovery wells (and supply wells for process water) in A- and M-Areas increases this travel time.

Where the upward gradient exists between the Black Creek and the Congaree, water is prevented from flowing into the Black Creek aquifer. An exception occurs in areas where large volumes of water are pumped from the Black Creek; in these areas, pumpage could reverse the upward gradient. The area most susceptible to these impacts is H-Area, where the head differential is relatively small and pumpage is great. A modeling study (Duffield, Buss, and Spalding, 1987) indicates that a maximum head differential (downward potential) of about 5 feet has developed in the eastern portion of H-Area (see Figure A-5). Moderate pumpage from the Black Creek also occurs in U-Area, the Central Shops Area, TNX-Area, the Classification Yard, and the U.S. Forest Service offices. The potential for reversing the upward gradient that occurs naturally in these areas is significantly less than that in H-Area. Any contaminants that would be drawn into the Black Creek by this pumpage would flow to the pumping well and, therefore, would not impact offsite areas.

Water elevations in the McBean Formation (includes lower portion of Dry Branch Formation; GCS, 1986) exhibit a difference of about 0.6 meter in hydraulic head between the top of the McBean and its base (Du Pont, 1983). This indicates a better hydraulic connection between the sandy unit of the McBean and the calcareous zone than that between the McBean and either the Congaree Formation below or the Barnwell Formation above. As previously noted, the green clay impedes the downward movement of water from the McBean to the Congaree in the central part of the Plant, as illustrated by a hydraulic-head differential of about 17 meters. Moreover, the tan clay in the Barnwell (Siple, 1967) impedes the vertical movement of water from the Barnwell into the McBean. Although the tan clay is not as continuous as the green clay, the head differential between the Barnwell and the McBean is about 4 meters where the tan clay is present. TC TE

Figure A-4 shows the relationship of water elevations in the Barnwell Formation to those in the formations below. The hydraulic head decreases with depth within the Barnwell Formation. Although the tan clay impedes the downward movement of water, the McBean Formation is recharged by water that passes through this hydrostratigraphic unit.

The water table is commonly within the Barnwell Formation (equivalent to Tobacco Road and upper Dry Branch Formations; GCS, 1986), although in the creek valleys it successively occupies positions in the lower formations. Surface drainage and topography strongly influence the flow path at every point on the potentiometric surface. Even small tributaries of the larger creeks cause depressions in the water table, diverting groundwater flow toward them. Because the Upland Unit in the SRP region is usually unsaturated, a potentiometric map has not been constructed. Flow paths are predominantly vertical, although there are some short, horizontal flow paths along perched water tables.

A.2.2.3 Groundwater Flow

Water moves through the ground from areas of high head to areas of lower head. In general, on the Atlantic Coastal Plain, the gradient is seaward from the higher areas of the Aiken Plateau toward the continental shelf. Of major significance is the modification of this general southeastward movement caused by the incision of the Savannah and Congaree Rivers and their tributaries (see Figure A-9). Groundwater in the regions of these rivers and tributaries is diverted toward the hydraulic low caused by natural discharge to the surface water. The depth of dissection of streams at the SRP has a significant influence on the direction of flow in most hydrostratigraphic units. The direction of flow in the shallow groundwater is most affected by small streams; in the deeper groundwater, it is affected by major tributaries. The direction of flow in the Paleocene and deeper formations is affected mainly by the Savannah River. Locally, the direction of flow in any unit can be modified by groundwater withdrawals from wells.

The velocity (V) of groundwater flow can be calculated by the following formula:

$$V = \frac{IK}{e} \qquad \text{(A-1)}$$

where:

- I = hydraulic gradient
- K = hydraulic conductivity
- e = effective porosity

The velocity also can be measured directly by tracers. Table A-7 lists typical vertical and horizontal groundwater velocities for important hydrogeologic units on the SRP.

Figures A-9 and A-10 show hydraulic heads of the Cretaceous Sediments, which constitute the primary aquifer in the region. Where the elevation of the outcrop area is high, as on the Aiken Plateau north of the Plant, water naturally recharged to the aquifer exceeds that naturally discharged to local streams; this excess water moves southeastward through the aquifer. Where the elevation of the outcrop area is low, as along the Savannah River Valley in the northwest section of the Plant, water naturally discharges from the aquifer to the river. Under the Plant, the direction of groundwater movement in the Cretaceous sands is southwesterly toward the Savannah River Valley.

On the Plant, the recharge of the Congaree is by groundwater flow from offsite areas and by the infiltration of precipitation; the shallower formations on the Plant are recharged by the infiltration of precipitation (about 40 centimeters per year) (Root, 1983). However, discharge into Upper Three Runs Creek and the Savannah River has a dominant effect on Congaree groundwater flow (Figure A-11). Over parts of the Plant area, hydraulic heads in the Congaree are lower than those in the Cretaceous Sediments aquifer, precluding downward flow into the Cretaceous Sediments in these areas (Figure A-7). However, as noted in Section A.2.2.2, in two areas this condition is reversed, indicating that the Cretaceous Sediments aquifer might receive recharge from the overlying Congaree aquifer. Also, in small local areas where the Cretaceous Sediments aquifer head normally exceeds the head in the Congaree aquifer, drawdown from water production wells in the Cretaceous Sediments aquifer might lower its head below that of the Congaree, creating a potential for localized downward flow (Figure A-5).

On a regional basis, the dissecting creeks divide the groundwater in the Congaree and higher formations into discrete subunits. Even though the hydraulic characteristics of the formations might be similar throughout the area, each subunit has its own natural recharge and discharge areas. In the central part of the Plant, the only stream that intersects the Congaree is Upper Three Runs Creek.

The McBean Formation (terminology from Siple, 1967) is incised by Upper Three Runs Creek, several of its larger tributaries, Four Mile Creek, Pen Branch, and Steel Creek. Thus, groundwater that enters the McBean Formation over much of the interior of the Plant is restricted to its connection with other subunits of the McBean because of stream incision.

The water table at the Plant is commonly within the Barnwell Formation (terminology from Siple, 1967), although in the creek valleys it successively occupies positions in the lower formations. Surface drainage and topography strongly influence the water-table flow path. Even small tributaries of the larger creeks cause depressions in the water table, diverting groundwater flow toward these creeks. The Upland Unit, which is perhaps the most extensive surficial deposit in this region, usually is unsaturated. Its flow paths are predominantly vertical, although there are short horizontal paths.

The overall flow pattern of the unsaturated zone at the Plant is vertical. Precipitation infiltrates into the Barnwell Formation and percolates downward, with the greatest amount eventually reaching the Congaree Formation. The tan clay diverts some water in the Barnwell laterally to creeks. The green clay diverts more water in the McBean Formation laterally to creeks. The remaining water is believed to move vertically into the Congaree Formation. The Ellenton and Cretaceous Sediments aquifer are separated hydraulically from the Congaree and are not recharged significantly on the site. Both the primary recharge and discharge controls on the water in the Cretaceous Sediments are outside the SRP area. The Cretaceous Sediments act as a conduit through which water passes beneath the SRP area en route from recharge zones in the Aiken Plateau to discharge zones in the Savannah River Valley.

Figure A-12 shows the distribution of groundwater flow between hydrologic units in the vicinity of A- and M-Areas. Although not specifically applicable to the entire SRP subsurface, the relationships shown in this figure are generally the same as those that can be expected in other parts of the Plant.

A.2.3 GROUNDWATER QUALITY

A.2.3.1 Regional Groundwater Quality

The water in the Coastal Plain sediments tends to be of good quality; hence, it is suitable for industrial and municipal use with minimal treatment. It is generally soft, slightly acidic, and low in dissolved and suspended solids (Du Pont, 1983). Table A-8 lists the results of chemical analyses of groundwater from various regional formations in the Coastal Plain sediments; the following paragraphs describe these results. The descriptions will focus on the total dissolved solids (TDS) content of the groundwater, because the amount of dissolved solids is a consideration in the suitability of the water for domestic use and because it can serve as a measure of the presence of some types of contaminants.

Crystalline Metamorphic Rock

Water from the crystalline metamorphic rock has a TDS content of about 6000 milligrams per liter, which is largely calcium (500 milligrams per liter), sodium (1300 milligrams per liter), sulfate (2500 milligrams per liter), and chloride (1100 milligrams per liter).

Triassic/Jurassic Sedimentary Rock

Two water samples from the Dunbarton Basin of Triassic/Jurassic Age had TDS contents (almost entirely sodium chloride) of about 12,000 and 18,000 milligrams per liter (Du Pont, 1983).

Cretaceous Sediments Aquifer

Water from the Cretaceous Sediments aquifer is low in TDS. Because the water is soft and acidic, it has a tendency to corrode most metal surfaces (Siple, 1967). This is especially true if the water contains appreciable amounts of dissolved oxygen and carbon dioxide. The dissolved oxygen content of water from the Cretaceous Sediments around the Separations Areas is very low (Marine, 1976), and the sulfate content is about 13 milligrams per liter. The dissolved oxygen content is inversely related to the sulfate content of the water. In the northwest part of the Plant near the recharge area, water in the Cretaceous Sediments aquifer is near saturation with dissolved oxygen while the sulfate content is very low.

Ellenton Formation

Chemical analyses of water from the Ellenton Formation (Siple, 1967) show a TDS content somewhat higher than that of water from the Cretaceous Sediments aquifer, but still very low at less than 50 milligrams per liter.

Congaree Formation

Table A-8 compares two analyses of water from sands in the Congaree Formation. The analyses are similar to those reported for Eocene limestone (Siple, 1967). The zones in the formation probably contained some calcareous cement, giving rise to relatively high concentrations of ionic species in the water.

McBean Formation*

Samples of water from Eocene sand (Lower Dry Branch equivalent; GCS, 1986) and limestone probably include some water from both the sandy and calcareous zones. The water from these zones is low in TDS, with that from sandy zones being much lower. The differences in the chemical characteristics of water from the two zones are readily apparent. Well HC3D in the upper sandy zone has a TDS content of 14 milligrams per liter and low concentrations of all other constituents. The other wells, which are screened in the calcareous zone, have a TDS content of more than 50 milligrams per liter and high concentrations of calcium and bicarbonate. The pH of water from the calcareous zone is near 7, while that of water from the sandy zone is generally less than 5.

Barnwell Formation*

Table A-8 lists five analyses of water from the Barnwell Formation (Tobacco Road and upper Dry Branch equivalents; GCS, 1986) in the Separations Areas. The TDS content is low, and the concentrations of calcium and bicarbonate ions are not as high as in the McBean and Congaree Formations. The pH of water from the Barnwell Formation is slightly acidic, similar to that of groundwater from other formations in the area.

A.2.3.2 Mixed Chemical and Radionuclide Contamination

Groundwater is monitored at 49 of the 54 SRP hazardous and mixed waste management facilities for the parameters listed in Table A-9. Nine of the 54 facilities have been designated as RCRA interim-status hazardous waste management facilities. These are the F-Area seepage basins (three basins), H-Area seepage basins (three basins), M-Area settling basin and Lost Lake, and the inactive Mixed Waste Management Facility (MWMF) within the operating low-level radioactive waste burial grounds between F- and H-Areas. Groundwater contamination at the F- and H-Area seepage basins and the M-Area settling TE

*Stratigraphic terminology from Siple, 1967. See Figure A-2.

basin is discussed here to provide examples of the modes of contamination, possible pathways of contaminants, and water quality within the SRP subsurface. Appendix B discusses contamination at other facilities covered in this EIS in detail.

The seven unlined basins and Lost Lake have received hazardous wastes and radioactive materials since the mid- to late-1950s. Geophysical and geochemical testing and groundwater monitoring have been performed at these sites to assess the nature, extent, and rate of migration of hazardous wastes and hazardous constituents (DOE, 1985).

Suspected contaminants were identified by a statistical comparison of upgradient and downgradient water quality known as the Student's t-test. Assuming an appropriate experimental design as well as a good sampling and analysis technique, the t-test can provide a basis for rejecting or not rejecting sampling variation as a possible factor to account for the difference between upgradient and downgradient wells when the number of samples taken is small. Rejecting sampling variation at some level of confidence means that the difference between wells is due to factors other than sampling variation. A failure to reject means that the difference between wells could be sampling variation, among other factors. The cutoff points for f-test scores were probabilities of less than or equal to 0.05 and greater than 0.25. Values less than or equal to 0.05 were classified as probable contaminants; those greater than 0.25 were improbable contaminants. Scores between these two values were considered to be possible contaminants.

Tables A-10 and A-11 list the contaminant potential based on the t-test for selected parameters at the F-Area and H-Area seepage basins, respectively. Statistical analyses performed in 1983 identified elevated values of TDS, sodium, nitrate, gross alpha, and gross beta in relation to the values for upgradient monitoring wells at the F- and H-Area seepage basins. The low pH of the groundwater in downgradient monitoring wells also reflected the operation of the seepage basins in these two waste management areas.

The reliability of the 1983 results was evaluated when improvements were made in sampling and sample preservation methods in 1984. Pumps were installed to provide adequate flushing of the wells before sampling, and all samples for metals analyses were filtered before preservatives were added. Results following the initiation of the new techniques indicated that inadequate flushing (using a manual bailing technique) and solids in the samples analyzed were contributing to the erroneous positive results previously obtained.

Special sampling and testing for the hazardous constituents identified in 40 CFR 261, Appendix VIII, were performed in 1985 at the F- and H-Area seepage basins. No organic compounds attributable to basin operation were observed in significant concentrations at either location. However, various hazardous constituents were measured in downgradient monitoring wells at the F- and H-Area seepage basins (Table A-12). TC

Contaminants from the F- and H-Area seepage basins migrate to springs along Four Mile Creek (approximately 60 to 500 meters). This migration has been

Table A-12. Hazardous Constituents Measured in Downgradient Monitoring Wells at F- and H-Area Seepage Basins[a]

Constituent	Maximum Concentrations (mg/l)	
	F-Area basins[b]	H-Area basins[c]
Antimony	0.035	0.320
Barium	0.280	0.223
Cadmium	0.70	0.010
Lead	0.167	0.220
Mercury	0.00034	0.72
Nickel	0.100	0.064
Selenium	0.490	d

TC

[a]Constituents were observed during RCRR Appendix VIII data searches performed in January and March of 1985.
[b]Source: Killian et al., 1987a.
[c]Source: Killian et al., 1987b.
[d]Below detection.

verified through observations of a tritium plume from Basin 3 in the F-Area, as shown in Figure A-13. Other contaminants, except those affected by sorption properties of the site soils, are expected to follow the general behavior of the tritium plume.

Routine discharges to the M-Area settling basin (which overflowed to Lost Lake) were discontinued in July 1985. The U.S. Department of Energy (DOE) has submitted a Part B closure plan for this hazardous waste management facility (DOE, 1985, 1987). At the basin and Lost Lake, TDS, chloride, dissolved organic carbon, nitrate, gross alpha, and radium have been observed at concentrations above background values. Table A-13 lists the potential for contamination at the M-Area settling basin. Special studies for hazardous constituents in the groundwater at the settling basin have identified chlorinated hydrocarbons (degreasing compounds); metals were not detected in significant concentrations. However, the pH in downgradient monitoring wells reflects basin operation (DOE, 1985).

Extensive groundwater monitoring studies around A- and M-Areas have been conducted since chlorinated hydrocarbons were discovered in the groundwater in 1981. The distribution of these organic compounds has been determined vertically and horizontally, but assessment studies are continuing (DOE, 1985). Figure A-14 shows a cross-section through the settling basin and Lost Lake depicting isoconcentrations of total chlorinated hydrocarbons. The main body of the plume is moving slowly to the southeast at about 7 to 8 meters per year. Monitoring studies have demonstrated that volatile organics have not migrated beyond the SRP boundary.

A groundwater remediation program was initiated in A- and M-Areas in 1983 to contain the vertical and horizontal migration of the chlorinated hydrocarbon plume in the Tertiary sands and to remove the chlorocarbons from the groundwater. This project involves the use of a 1.5-cubic-meter-per-minute air stripper that is fed by 11 recovery wells (South Carolina Bureau of Air Quality Control Permit 0080-0055-CB and Bureau of Water Pollution Control Permit 10389). On the average, the air stripper has been removing more than 2600 kilograms of chlorinated hydrocarbons per month from the groundwaters.

The characteristics of the movement and extent of contamination at F-, H-, and M-Areas are expected to approximate the behavior of contamination at other waste management units. The specific characteristics of the contamination at other facilities is primarily controlled by: (1) properties of the contaminant(s), (2) depth to groundwater, (3) contaminant retention properties of the subsurface materials, (4) degree of heterogeneity of the subsurface materials, (5) groundwater flow speed and direction, and (6) distance to groundwater outcrop.

Hazardous metal constituents have been observed in groundwater monitoring wells at the low-level radioactive waste burial grounds facility (643-G and 643-7G). Lead and cadmium concentrations averaged about 43 and 39 micrograms per liter (parts per billion), but ranged to 398 and 365 micrograms per liter, respectively. Although approximately 10 tons of mercury have been disposed of at these facilities, little mercury has been observed in monitoring wells.

Concentrations of mercury at the perimeter wells are generally less than 1 microgram per liter (National Primary Drinking Water Standards for lead, cadmium, and mercury are 50, 10, and 2 micrograms per liter, respectively). Because the wells used to measure these constituents were constructed of galvanized casings, the concentrations are considered questionable.

A.2.3.3 Radionuclide Contamination

Radium, tritium, and certain alpha-emitting radionuclides have been detected in the groundwater at concentrations above the standards for all geographic areas but Area 6, and a high level of concern for such contamination has been determined for Areas 2, 4, 5, 7, 8, 9, and 10. Figure 2-1 and Table 2-2 show the locations of these geographic areas.

Because of its high mobility and abundance, tritium is the most prevalent radionuclide that reaches the water table. Other radionuclides in the waste, particularly strontium-90, cesium-137, plutonium-238, and plutonium-239, tend to be adsorbed by the soil column in the groundwater flow paths beneath the seepage basins and the burial grounds. These radionuclides migrate very slowly because they are strongly adsorbed by soil particles.

TE Tritium is present in some waste streams and burial grounds leachates as tritiated water, which behaves like normal water and cannot be separated practically from uncontaminated groundwater. The flow and transport properties of tritiated groundwater are indistinguishable from those of groundwater that has not been affected by tritiated leachate. Based on monitoring performed at the low-level radioactive waste burial grounds, the groundwater beneath the MWMF probably has been contaminated by tritium and, to a lesser extent, by other radionuclides.

Tritium was the only radionuclide detected migrating from the K-Area containment basins to Pen Branch. Weekly water-flow measurements combined with studies of tritium concentrations in Indian Grave Branch, a tributary of Pen Branch, indicated a migration of 7500 curies in 1984.

Tritium discharged to the F- and H-Area seepage basins has migrated from the basins and contaminated the water-table aquifer to concentrations in excess of 40,000,000 picocuries per liter (Du Pont, 1983). The migration of radioactivity from the F- and H-Area seepage basins and the low-level waste burial ground was measured with continuous samplers and flow records in Four Mile Creek in 1984. The total measured migration of tritium was 2320 curies from the F-Area seepage basins and 12,500 curies from the H-Area seepage basins and the low-level waste burial grounds. The amount of strontium-90 that migrated from the F- and H-Area seepage basins was 0.20 and 0.12 curie, respectively. Because of the desorption of cesium-137 in streambeds, the migration of this radionuclide, if it occurs, cannot be measured. Table A-14 shows the 1984 migration of tritium and strontium-90 from the seepage basins.

Table A-14. Migration of Tritium and Strontium-90 from Seepage Basins in 1984 (Ci)

Location	Tritium	Strontium-90
200-F seepage basin to Four Mile Creek (FM-A7 minus FM-4)[a]	2320	0.20
200-H seepage basins to Four Mile Creek (FM-2B minus FM-1)[a]	8020	0.12
Burial Ground and 200-H seepage basin 4 (FM-3A minus FM-3)[a]	4480	0.01
K-Area containment basin to Indian Grave Branch	7500	0.01

[a]Designators for sampling locations on Four Mile Creek.

Many laboratory and field studies of soil-to-water distribution coefficients (K_d) have been conducted on the Plant to relate soil adherence to waste migration (Prout, 1958). These studies reveal that the soil column acts to restrict the free passage of most radionuclides. Radiostrontium, radiocesium, plutonium, and many other radionuclides are largely removed from the flowing groundwater due to adsorption by clay particles. As with most physical and chemical interactions, the amount of adsorption is governed by complex equilibrium equations. Changes in the pH of the groundwater and the mass balance between other constituents are two conditions that can affect the degree of adsorption by clay particles. Changes in these conditions can cause additional contaminants to be adsorbed or some contaminants to be released from the clays, depending on the sense in which the equilibrium is shifted (Freeze and Cherry, 1979).

Two long-lived mobile radionuclides, technetium-99 and iodine-129, form stable anionic species that adhere poorly to soil and tend to migrate at about the speed of the groundwater. Preliminary data indicate that although both technetium and iodine have been found in groundwater by ultrasensitive analytical methods, neither is present in concentrations that can be measured by accepted routine monitoring procedures. The maximum measured concentration of
TE technetium-99 was 20 picocuries per liter, and that of iodine-129 was 1 picocurie per liter (Du Pont, 1983).

Tritium is the principal radioactive contaminant in the groundwater beneath the burial ground. According to calculations, approximately 28,000 curies of tritium are in this plume. Under 643-7G and 643-28G, the water-table aquifer exhibits concentrations that range from about 20,000 to 34,000,000 picocuries per liter. Perimeter monitoring wells generally exhibit lower concentrations, averaging about 300,000 picocuries per liter. However, tritium has reached the Congaree Formation at concentrations of about 20,000 picocuries per liter [National Primary Drinking Water Standard for tritium is 20,000 picocuries per liter] (Hubbard and Emslie, 1984). Table A-15 lists other radionuclides detected in the groundwater beneath the burial ground (Du Pont, 1983).

TC

Table A-15. Radionuclides Detected in Groundwater Beneath Burial Ground[a] (pCi/L)

Radionuclide	Average concentration	Drinking-water standard
Tritium	300,000[b]	20,000
Cobalt-60	13	100
Strontium-90	19	8
Cesium-137	12	200
Plutonium-238	5	15
Plutonium-239	3	
Total Plutonium	8	15[c]

TC TC

[a]The limits for tritium, cobalt-60, strontium-90, and cesium-137 are the maximum concentration limits if only one manmade beta- or gamma-emitting radionuclide is present.

TC [b]Perimeter wells.

[c]Total plutonium.

Approximately 80 percent of the groundwater plume from the low-level radioactive management facility flows toward outcrop springs along Four Mile Creek, in much the same manner as the plume from the F-Area seepage basins (Figure A-11). The remaining plume flows toward Upper Three Runs Creek, but extends only about 200 meters beyond 643-7G. Groundwater in the Congaree Formation in this area flows to Upper Three Runs Creek.

A.2.4 GROUNDWATER USE

A.2.4.1 Important Aquifers

As noted in Section A.1.1., the subsurface waters in the vicinity of the SRP include six major hydrostratigraphic units. The geohydrologic characteristics of these units, their aeral configurations, and their recharge/discharge relationships control the vertical and horizontal movement of groundwater at the Plant (see Sections A.2 and A.3). Section A.1 explains the stratigraphic nomenclature used at the SRP.

At present, the Plant does not withdraw groundwater from the crystalline, metasediment basement rocks and overlying saprolite. The Cretaceous Sediments aquifer, which is 170 to 250 meters thick at the Plant, is the most important regional aquifer. At the Plant, the Cretaceous Sediments consist of two aquifers separated by a clay aquitard (Figure A-2). The lower aquifer consists of about 90 meters of medium-to-coarse sand (Middendorf); the overlying aquifer (Black Creek) consists of about 45 meters of well-sorted medium-to-coarse sand. The Ellenton Formation clays cap the Cretaceous Sediments forming an aquitard that restricts the flow of groundwater between the Cretaceous Sediments aquifer and the overlying units.

The Congaree is another important regional aquifer. In this area, only the Cretaceous Sediments exceed the Congaree's water-producing potential. The Congaree's intermediate depth (Figure A-5) also makes it attractive for water wells. An extensive clay layer at the base of the Congaree forms a confining bed that separates the permeable sands of the Congaree from the sands in the underlying Ellenton and Cretaceous Sediments units (DOE, 1984). The green clay (Figure A-4), a marker bed at the top of the Congaree, exhibits very low hydraulic conductivity; it is, therefore, a significant aquitard (Section A.2.1), particularly south and east of Upper Three Runs Creek. The SRP does not withdraw large quantities of groundwater from the McBean, Barnwell-Hawthorn, or stream valley alluvium deposits (stratigraphic terminology from Siple, 1967; see Figure A-2). The McBean, however, becomes increasingly more important as an aquifer to the east of the Plant.

The water table is commonly located in the stream valley alluvium deposits and in the Barnwell. The McBean is usually under semiconfined conditions. In contrast, groundwater in the Congaree (to the south and east of Upper Three Runs Creek) and the Cretaceous Sediments is under confined conditions. Cretaceous Sediments water wells near the Savannah River (e.g., in D-Area) often flow because the potentiometric level of the groundwater is greater than the elevation of the land surface. Figure A-4 shows the head relationships near H-Area, close to the center of the Plant. Section A.3 discusses these relationships. Section A.3 also discusses interactions between surface water and groundwater, groundwater flow patterns, recharge/discharge, and water budgets.

A.2.4.2 Regional and Local Groundwater Use

DOE surveyed groundwater use in South Carolina in an area within about 32 kilometers from the center of the SRP. DOE obtained information for this survey from the South Carolina Department of Health and Environmental Control, the South Carolina Water Resources Commission, the U.S. Geological Survey, local universities, and files at the SRP (DOE, 1984; RPI, 1985). The survey did not include users in Georgia, because the strength of groundwater flow toward the Savannah River in the area bordering the river tend to outweigh any hydrologic gradient in the Georgia direction (Du Pont, 1983). See Sections 2.2.2, 2.2.3, 3.1, and 3.2 for information on this phenomenon (Figures A-8, A-15, A-16, and A-17).

This survey found that groundwater is the primary source of water for domestic, industrial, municipal, and agricultural use in the vicinity of the SRP. The Cretaceous Sediments, which occur at shallower depths as they approach the fall line, form the base for most municipal and industrial water supplies in Aiken County. Domestic water supplies depend primarily on the Barnwell, McBean, and Congaree Formations. In Barnwell and Allendale Counties, the Cretaceous Sediments occur at increasingly greater depths; some municipal users, therefore, get their water from the shallower Congaree and McBean Formations or from their limestone equivalents (Section A.1; Du Pont, 1983). In these counties, domestic supplies come from the Barnwell and the McBean Formations.

The survey identified 56 major municipal, industrial, and agricultural groundwater users in the study area. The total estimated pumpage in this area is about 135,000 cubic meters per day. Figures A-15 and A-16 show the locations of the major users and the groundwater flow paths for the Congaree and Cretaceous Sediments aquifer, respectively. Tables A-16 and A-17 provide pertinent data.

Municipal Use

The survey identified 20 municipal users that have a combined withdrawal rate of about 52,605 cubic meters per day (Table A-16). Within the study area, the total municipal pumpage from the Cretaceous Sediments aquifer is about 36,920 cubic meters per day. Total municipal pumpage from the McBean Formation is about 545 cubic meters per day; the Congaree Formation supplies 15,140 cubic meters per day for municipal use.

Industrial and Agricultural Use

The survey identified 36 industrial and agricultural users, including 13 on the SRP. Table A-17 lists these users. Total industrial pumpage from the Cretaceous Sediments is about 71,940 cubic meters per day, including 38,550 cubic meters withdrawn daily by the SRP.

The Sandoz Plant, about 29 kilometers south of the center of the SRP, is the largest offsite industrial user. Since 1978, it has pumped about 4165 cubic meters per day from one Cretaceous Sediments well.

In 1980, irrigation from groundwater sources in Allendale and Barnwell Counties, including areas outside the study area, amounted to average annual pumping rates of 15,000 and 4100 cubic meters per day, respectively (DOE, 1984). Major growth in the use of irrigation systems in these counties has occurred during the last several years. Some of these irrigation systems draw from the Cretaceous Sediments, but some are in the limestone equivalent of the McBean and Congaree Formations. The largest agricultural user identified in the survey, B. Oswald Company, pumps about 8175 cubic meters per day from the Tuscaloosa aquifer. In Barnwell County, the Green Blade Turf Grass Farm withdraws about 1895 cubic meters per day from Tertiary aquifers.

Domestic Use

In addition to large municipal, industrial, and agricultural users, the files of the South Carolina Department of Health and Environmental Control list 25 small communities and mobile home parks, 4 schools, and 11 small commercial interests as groundwater users. Wells serving these users generally have pumps with capacities of 54 to 325 cubic meters per day; they do not draw large quantities of water. Most of these wells produce from shallow aquifers. Total withdrawal from these 40 users is estimated to be less than 2000 cubic meters per day. However, incomplete State records provide little information on screened zone, formation, or actual usage.

Two South Carolina State Parks are within the survey area: Aiken State Park, with seven wells; and Barnwell State Park, with two wells. Several shallow wells produce small quantities of water for SRP guardhouses. The pump capacity of each of these wells is less than 40 liters per minute.

A.2.4.3 SRP Groundwater Use

Table A-18 lists pumping rates for the period 1968 to 1985 for individual areas on the Plant. Figure A-15 shows the locations of most of these areas. The greatest groundwater pumpage on the Plant occurs in A-, F-, and H-Areas. Figure A-18 shows the total pumpage on the Plant. The projected 1985 groundwater use is 26.8 cubic meters per minute. Siple (1967) concluded that (1) the Cretaceous Sediments aquifer can supply about 37.8 cubic meters per minute for SRP operation with no adverse effects on the pumping capabilities of existing 1960 wells; and that (2) potentially, the aquifer could produce more water if the well fields were properly designed. In 1960, SRP pumpage from the Cretaceous Sediments was about 18.9 cubic meters per minute.

A.3 SURFACE WATER/GROUNDWATER RELATIONSHIP

This section provides a summary description of the interrelationships between the various hydrogeologic units that constitute the SRP groundwater system, a description of the recharge and discharge areas on the Plant, and a summary description of a water balance study on the Plant.

A.3.1 HYDROGEOLOGIC INTERRELATIONSHIPS AT SRP

As discussed in Sections A.1.1 and A.2.1, the Coastal Plain sedimentary aquifers at the Plant include the Hawthorn (upland unit), Barnwell, McBean, Congaree, Ellenton, and Cretaceous Sediments (stratigraphic terminology from Siple, 1967; see Figure A-2). Water-table (unconfined) conditions generally occur in the Barnwell aquifer. Groundwater in the underlying units generally occurs under semiconfined and confined conditions. The principal aquitards (units with low hydraulic conductivity) include the tan clay, the green clay, the basal Congaree-Ellenton clay, and clay units in the Cretaceous Sediments (Figures A-1 and A-4).

Precipitation at the Plant averages about 120 centimeters per year. Although there might be both spatial and temporal variations in the fraction of this precipitation that recharges the groundwater, the overall average recharge near the SRP Burial Ground and the Separations Areas is about 30 percent, or 38 centimeters per year. This water moves predominantly in a vertical direction through the unsaturated zone at a rate of about 0.9 to 2.1 meters per day, as determined by tracer tests, to recharge the water table (Haskell and Hawkins, 1964). Upon reaching the water table, the water travels a path that has both vertical and horizontal components. The magnitude of these two components depends on the vertical and horizontal components of the hydraulic conductivity. Clay layers of low hydraulic conductivity tend to impede vertical flow and enhance horizontal flow. If the horizontal hydraulic conductivity is low, water will tend to "pile up" above the clay, and the water table will be high. On the other hand, if the horizontal hydraulic conductivity is high, the water will be conducted more quickly away from the recharge area, and the water table will be low.

The water table is high in H-Area because the tan clay inhibits the downward movement of water and the low horizontal hydraulic conductivity of the Barnwell Formation does not permit rapid removal of the water in a horizontal direction. The hydraulic head builds up in the Barnwell Formation sufficiently to drive the water through the material of low hydraulic conductivity; some goes vertically through the tan clay and some moves laterally to nearby streams.

Water that enters the McBean Formation also follows a path that has both vertical and horizontal components. The water recharging this formation through the tan clay is the nominal surface recharge (38 centimeters per year) minus the amount of water that is removed from the Barnwell by lateral flow (about 25 centimeters per year; see Section A.3.3.1). The discharge points for the McBean Formation are more distant from their respective groundwater divides than those of the Barnwell Formation.

The green clay has a lower hydraulic conductivity than the materials above; as a result, recharge to the Congaree through this clay is less than the recharge to the McBean. In addition, the Congaree has a higher hydraulic conductivity than the materials above; as a result, lateral flow is enhanced, making the potentiometric levels in the Congaree much lower than those above, as shown in Figures A-4 and A-19. The discharge areas for the Congaree are the valleys of the Savannah River and Upper Three Runs Creek.

Cretaceous Sediments potentiometric levels in H-Area are above those of the Congaree (Figure A-4), indicating that in this area the Cretaceous Sediments are not recharged naturally from the Congaree. Water in the Cretaceous Sediments passing beneath H-Area is recharged through the Tertiary sediments to the north of the Plant. Some water is discharged from the Cretaceous Sediments upward into the overlying sediments in the Savannah River valley where it borders the Plant. Most of the remaining groundwater moves northwest to the outcrop area of the Cretaceous Sediments, where water discharges directly to the Savannah River and its tributaries (Figure A-10). Water levels in the Cretaceous Sediments in the Savannah River valley are commonly above land surface and wells in these areas flow naturally. Figures A-8, A-9, A-15, and A-16 show that water from either formation does not naturally flow between South Carolina and Georgia. Instead, groundwater moves toward the Savannah River from both states in the vicinity of the SRP site. Figure A-20 shows the vertical head relationships between the Congaree, the upper Cretaceous Sediments aquifer, and the lower Cretaceous Sediments aquifer in the southern part of the Plant. The head relationship between the Congaree and the upper Cretaceous Sediments is the same here as in H-Area, but the difference is greater. This area is greatly influenced by the drawing down of the head in the Congaree, as groundwater flows from the Congaree into the Savannah River valley.

TC

The head relationships in the northwest part of the Plant (M-Area) are quite different, as shown on Figure A-21. In this updip area (Figure A-1), the green clay is very discontinuous and not as thick as it is farther downdip. The tan clay can be missing entirely. Thus, there is little impedance to downward vertical flow within the Tertiary sediments, and the water levels are farther below the land surface than in H-Area. Another very important factor is that the geologic character of the Congaree Formation in M-Area is different from that in H-Area; the geologic material is not as well sorted and its hydraulic conductivity is lower. As a result, the lateral flow of water in the Congaree is insufficient to draw its water level down below that of the Cretaceous Sediments aquifer in M-Area, and a downward head differential exists from the Congaree to the Cretaceous Sediments. Closer to the Savannah River, the discharge from the Congaree draws its water level down below that of the Cretaceous Sediments aquifer.

The locations of areas in which there is a head reversal between the Congaree and the Cretaceous Sediments aquifer, and areas in which there is not, were obtained from a map showing the differences between the Cretaceous Sediments and Congaree potentiometric surface maps (Du Pont, 1983). The resulting head differential map (Figure A-22) shows that the head in the Cretaceous Sediments is higher than that in the Congaree in a broad area within about 10 kilometers from the Savannah River and Upper Three Runs Creek. The head in the Congaree is higher in an area around M-Area and in the vicinity of Par Pond. This map was constructed by subtracting two potentiometric surface maps that contained limited data; thus, it should not be used to predict detailed head relationships, but only to indicate directions of expected vertical gradients in broad areas.

A.3.2 GROUNDWATER RECHARGE AND DISCHARGE AT SRP

Water enters the groundwater system in recharge areas and moves through the system, as dictated by hydraulic gradients and hydraulic conductivities, to discharge areas. Groundwater moves from areas of high potential energy (usually measured by combined elevation and pressure heads) to areas of lower potential energy.

The hydraulic gradient on the Atlantic Coastal Plain is generally southeastward toward the Atlantic Ocean. The southeastward groundwater flow is modified by the incised channels of the Savannah and Congaree Rivers and their tributaries. Groundwater flows toward the areas of low potential energy (low hydraulic head areas) created by natural discharge to stream channels and wetlands.

TC The Savannah River Plant is drained almost entirely by five major streams: Upper Three Runs Creek, Four Mile Creek (including Beaver Dam Creek), Pen Branch, Steel Creek, and Lower Three Runs Creek (Figure A-23). The depth of dissection of these streams has a significant influence on groundwater discharge areas and the directions of groundwater flow. The flow direction in the shallow groundwater, typically in the Barnwell Formation, is most affected by small onsite streams (see, for example, Figures A-24 through A-29). Flow directions in the McBean Formation are affected by Upper Three Runs and Four Mile Creeks (Figure A-30), those in the Congaree Formation by Upper Three Runs Creek and the Savannah River (Figures A-31 and A-9), and those in the Ellenton and Cretaceous Sediments by the Savannah River only. Locally, the direction of normal groundwater flow in any hydrogeologic unit is modified by groundwater withdrawals from wells (Figure A-5). The locations of recharge and discharge areas on the Plant are summarized in Table A-19.

Figure A-15 shows the potentiometric surface of the Cretaceous Sediments aquifer near the Plant. Recharge occurs principally in offsite outcrop areas near the Fall Line. If the elevation of the outcrop area is high, as on the Aiken Plateau northeast of the Plant, precipitation recharged to the Cretaceous Sediments exceeds the groundwater naturally discharged to local streams and withdrawn by water wells. This excess water moves southeastward through the aquifer. Where the elevation of the outcrop is low, as along the Savannah River valley just north of the northwest sector of the Plant, groundwater naturally discharges to the Savannah River. Under the Plant, the groundwater flow in the Cretaceous Sediments is southwesterly toward the river (Du Pont, 1983).

Recharge to the Congaree Formation is principally in offsite areas. At the Plant there is appreciable recharge from the McBean Formation in M- and A-Areas but almost none from overlying units southeast of Upper Three Runs Creek. The natural discharge areas for the Congaree on the Plant are the wetlands along Upper Three Runs Creek and the Savannah River. As shown in Figures A-19, A-31, and A-11, the water levels in the Congaree are drawn down significantly by groundwater discharge to Upper Three Runs Creek and the Savannah River.

Recharge to the McBean Formation is from the Barnwell Formation in the central areas of the Plant and in offsite areas. The natural discharge areas are Upper Three Runs and Four Mile Creeks (Figure A-30).

Thus, in summary, the dissecting creeks divide the groundwater in the Congaree Formation into discrete subunits (see Figure A-23). Depending on the depth of dissection, groundwater is confined to its own subunit. Thus, even though the hydraulic characteristics of the formation might be similar throughout the area, each subunit has its own recharge and discharge areas. If dissection is through most of the formation thickness, then no water will move from one subunit to another. As with the Congaree Formation, creeks in the region dissect the McBean Formation and divide the hydrogeologic unit into separate subunits.

Because the McBean is a shallower formation than the Congaree, smaller creeks with less deeply incised valleys make these divisions. The subunits of the McBean are, therefore, smaller than those of the Congaree. In the Separations Areas, the only stream that cuts into the Congaree is Upper Three Runs Creek, whereas the McBean is incised by Upper Three Runs Creek and several of its larger tributaries, Four Mile Creek, Pen Branch, and Steel Creek. Thus, as shown in Figure A-30, groundwater that enters the McBean in the Separations Area cannot flow to other subunits of the McBean (Du Pont, 1983). TC

The water table at the Plant southeast of Upper Three Runs Creek is commonly within the Barnwell Formation, although in the creek valleys it successively occupies positions in the lower formations (e.g., Figure A-19). Recharge to the Barnwell is from precipitation. Natural discharge from the water table is to the creeks and their tributaries. The surface drainage and topography strongly influence the groundwater flow in the unconfined aquifer. Even small tributaries of the larger creeks cause depressions in the water-table elevation (see Figures A-24 through A-28). The Upland Unit, which overlies the Barnwell on much of the Plant, is unsaturated; its flow paths are predominantly vertical with only short, horizontal flow paths.

Northwest of Upper Three Runs Creek, the water table is much deeper and lies within the McBean Formation (Du Pont, 1985a, b). Discontinuous clays that are believed to correlate to the green clay mark the lower boundary of this unit. The groundwater beneath these clays is in the Congaree Formation under semi-confined conditions. Because the depth of the water table is about 33 meters, streams in this portion of the Plant exhibit little control over groundwater flow.

A.3.3 WATER BUDGET FOR SEPARATIONS AREAS AND SRP BURIAL GROUND

Precipitation falling on the earth's surface enters the groundwater system by infiltration, enters the surface water by runoff, or returns to the atmosphere by evaporation. The water budget is essentially a water-material balance used by hydrologists to determine the distribution of precipitation within the hydrosphere. Hubbard and Emslie (1984) used the water-budget method to determine whether significant groundwater flow paths exist below the Barnwell Formation at the SRP Burial Ground between F- and H-Areas (Figure A-12). TC

A simplified water budget for the Separations Area can be quantified as follows:

$$P - R - G - ET = S \qquad (A-2)$$

where:

P = input precipitation

R = surface and subsurface runoff, water that moves rapidly to drainage ditches and streams

G = water percolated downward to recharge the groundwater at the water table

ET = evapotranspiration, evaporation from the surface and transpiration through vegetation to the atmosphere

S = storage of water, as reflected in the rising and falling of the water table

Groundwater migrates slowly toward places of lower hydraulic potential, discharging as springs, seeps, or the base flow of streams. Over sufficiently long periods, often a water-year, storage can be neglected, so discharge can be assumed to equal recharge.

Mean annual precipitation, runoff, and evapotranspiration were estimated to be 119.4, 5.1, and 76.2 centimeters, respectively. The total groundwater recharge was estimated by subtracting runoff and evaporation from the precipitation, or 38.1 centimeters.

Groundwater in most of the Burial Ground area migrates slowly westward and southward toward Four Mile Creek and its F-Effluent tributary (Figure A-24). Groundwater was seen to enter a tributary of Four Mile Creek at seeps and springs during a rain-free period in May and June 1980. At a "tan clay" outcrop 61 meters above sea level, the groundwater discharge averaged 8.2 liters per second over four measurements made during this period. This measurement, converted to other units and combined with the estimated watershed area of 2.1 square kilometers, gives the groundwater discharge above the tan clay as 0.004 cubic meter per second per square kilometer or 12.7 centimeters per year.

These discharge measurements provide the basis for inferring that a residual recharge of 25.4 centimeters per year (38.1 centimeters minus 12.7 centimeters) reaches aquifers below the tan clay, the McBean, and the Congaree. However, there is believed to be little recharge of the Congaree in this part of the Plant because of the low hydraulic conductivity of the green clay. Root (1983) showed that the assumption of zero recharge of the Congaree could be used in mathematical modeling of groundwater flow at the Burial Ground.