SRR-CWDA-2021-00035
Revision 0

Erosion Analysis for the Saltstone Disposal Facility

March 2021

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Prepared for U.S. Department of Energy Under Contract No. DE-AC09-09SR22505

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ACRONYMS/ABBREVIATIONS

AMS	annual maximum series
DOE	U.S. Department of Energy
FTF	F-Tank Farm
GCL	Geosynthetic Clay Liner
GSA	General Separations Area
HDPE	High Density Polyethylene
HTF	H-Tank Farm
MPV	Maximum Permissible Velocity
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
NRC	Nuclear Regulatory Commission
NRCS	Natural Resources Conservation Service
PDS	partial duration series
PFE	Precipitation Frequency Estimate
PMP	Probable Maximum Precipitation
RUSLE	Revised Universal Soil Loss Equation
SCDHEC	South Carolina Department of Health and Environmental Control
SCS	Soil Conservation Society
SDF	Saltstone Disposal Facility
SDU	Saltstone Disposal Unit
SPF	Saltstone Production Facility
SRNS	Savannah River Nuclear Solutions
SRS	Savannah River Site
USDA	U.S. Department of Agriculture
USGS	United States Geologic Survey
USLE	Universal Soil Loss Equation
WMO	World Meteorological Organization

1.0 INTRODUCTION

Disposal of salt solution at the Savannah River Site (SRS) began in June of 1990 with very low activity liquid waste and has continued until present day. Salt solution is treated via the Saltstone Production Facility (SPF) into a grout slurry, which is then pumped into Saltstone Disposal Units (SDUs) at the Saltstone Disposal Facility (SDF) where it cures (or hardens) into the final waste form called saltstone. The SDUs currently containing saltstone are SDUs 1, 2A, 2B, 3A, 4, 5A, 5B, and 6. [SRR-CWDA-2019-00110] Note that historically SDUs 1 and 4 have also been referred to as Vaults 1 and 4.

In support of continued waste disposal operations at the SDF, additional SDUs will be constructed and filled with saltstone. [SRR-LWP-2009-00001] Once disposal operations end, the facility will be prepared for permanent closure. [SRR-CWDA-2020-00005]

The *Closure Plan for the Z-Area Saltstone Disposal Facility* (SRR-CWDA-2020-00005) indicates that an engineered closure cap will be installed over the SDF. The goal of a closure cap is to isolate the radioactivity and chemicals through multiple barriers to prevent against structural damage and water infiltration. Water can serve as a medium to transport waste into the surrounding area, both from surface and subsurface mechanisms. Infiltration water can also compromise the integrity of the closure cap layers through various degradation phenomena, such as erosion. Designing the closure cap system to withstand large rainfall episodes that will accelerate erosion on the top and sides of the cap will ensure the resilience of cover system for thousands of years into the future.

This closure cap will consist of (from the top-down) a top soil layer, an upper backfill layer, an erosion barrier layer, a geotextile fabric, a middle backfill layer, a geotextile fabric, an upper lateral drainage layer, a geotextile fabric, a high density polyethylene (HDPE) geomembrane, a geosynthetic clay liner (GCL), a foundation layer (backfill with bentonite admix), a lower backfill layer, a geotextile filter fabric, and a lower lateral drainage layer.

1.1 Purpose

The objective of this report is to estimate soil loss rates due to erosion on the SDF closure cap. Using a sediment loss calculation method that considers climate conditions, rainfall, soil makeup, and individual layer function, the SDF closure cap can be shown to isolate contaminants and minimize outsider disturbance of the system. It will also ensure natural forces will not disturb the closed system, such that there will be no need for ongoing maintenance once construction is completed.

This report details erosion events that could occur after the closure of SDF based on current conceptual models. Analyses described herein evaluate the risk of erosion based on these potential events, and on the conceptual design of the SDF closure cap.

1.2 Background

Storage of any waste in a landfill poses the potential for contamination of soil groundwater, and surface water. Hazardous wastes pose a special concern as many of these substances are resistant to biological or chemical degradation for a prolonged period of time. Therefore, hazardous waste landfills should be built to such a standard that would prevent leachate from migrating. Leachate is defined as a liquid that has interacted with layers of waste material, and may be composed of liquids from precipitation, groundwater, initial moisture storage, and chemical reactions occurring within the waste materials. Designing to control leachate includes liner systems, draining layers, and a final cap or cover (EPA/600/N-20/2019).

Degradation driven by erosion is a product of complex interactions between the natural and built environment that vary spatially and temporally, making an assessment of these migration patterns difficult to quantify. Surface erosion occurs when detachable particles on slopes are exposed to overland (surficial) flow due to rainfall. Other detachment mechanisms include freeze/thaw cycles, wind erosion, and animal burrowing. Hillslope angle and climate are key influencers on the erosion risk in a certain region. Soil texture and the physical and chemical makeup also determine how well the soil will hold together or whether it is further vulnerable to erosion. Highly compacted soil can lead to higher rates of overland flow due to less infiltration occurring as the soils ability to absorb the free water has been compromised, resulting in higher erosion rates (Yanshuang et al. 2020).

Designs of closure caps and cover systems should consider the mechanisms in each individual layer that can impact long-term performance. Such factors are listed in Table 1.2-1.

Table 1.2-1: Mechanisms that can adversely affect cover system performance (Daniel and Gross 1996)

Layer	Factor
Surface Layer	Insufficient or excessive slope Erosion by water and/or air Slope instability Insufficient nutrients or inadequate soil texture to support vegetation Inadequate soil thickness and thus water storage capacity to maintain adequate vegetation Undesirable vegetative species
Protection Layer	Erosion by water Slope instability Accidental human intrusion Intrusion by burrowing animals Root penetration Inadequate soil texture to support vegetation
Drainage Layer	Excessive clogging Insufficient flow rate capacity Insufficient number or flow rate capacity of outlets Freeze effects Slope instability
Barrier	Cracking due to wet-dry effects, freeze-thaw effects, differential settlements, seismic motions Deep root penetration Insufficient resistance to gas flow Slope instability Creep of all materials
Foundation Layer	Insufficient strength

Empirically driven erosion models such as the Revised Universal Soil Loss Equation (RUSLE) provide a framework for determining soil loss due to erosion based on multiple causative factors. RUSLE incorporates rainfall (R), topography (LS), soil erodibility (K), cover management (C), and support practice (P) to predict soil erosion rates.

1.3 General SRS Site Description

SRS covers an 802 square kilometer area across Aiken, Allendale, and Barnwell counties in western South Carolina. The western border of SRS is defined by the Savannah River.

Nuclear development activities at SRS have resulted in liquid waste being stored in two tank farms, H-Tank Farm (HTF) and F-Tank Farm (FTF), within 51 underground storage tanks. As the waste is removed from the waste tanks, it is processed, and low activity waste streams are sent to the SPF for saltstone production. The SDF is located in Z Area, which is in the central region of the SRS referred to as the General Separations Area (GSA). The GSA is located atop a ridge that forms the drainage divide between two watersheds, the Upper Three Runs watershed and the Fourmile Branch watershed.

The region has a humid subtropical climate, characterized by hot summers and mild winters. The average temperatures vary statewide from mid-50's to mid-60's in the winter, to mid-60's to mid-70's in the summer (Fahrenheit). Precipitation is a common occurrence in South Carolina—no month averages less than two inches anywhere in the state. The maximum precipitation occurs in March and July, with the minimum during May and November. There is no defined wet or dry season. At SRS the average annual rainfall is typically 45 to 50 inches.

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2.0 CLOSURE CAPS

A closure cap's resistance to erosion is strongly associated with the properties of the surface layer and selection of the vegetative cover, as well as the geometry of the closure cap design and the properties of the selected materials. Section 2.1 provides a brief discussion of surface layer vegetation. Section 2.2 provides a detailed discussion of the SDF conceptual closure cap design.

2.1 Surface Layer and Vegetation

The primary function of the surface layer is to withstand water-driven erosion and provide means to promote vegetation. The surface layer is the first line of defense to prevent liquid percolation in lower layers. This is done by managing surface runoff and minimizing seepage capacity within the system. The minimum thickness of the surface layer is determined based on the rooting mechanisms of the surface vegetation. Shallow-rooting plants such as grass need 0.15-m of soil (5.91 inches) for healthy roots to survive. As described in Section 2.2, the top layer of the SDF closure cap will consist of 6 inches of topsoil with properties similar to naturally occurring surface soils at SRS.

Vegetation plays an important role in the success of an engineered closure cap. Plants help dissipate energy from rain before it contacts the topsoil layer, lowering the potential for erosion. Plants with a shallow root system help to promote evapotranspiration and therefore the water storage capacity of soils while decreasing drainage. The vegetation also provides an aesthetic component to the closure cap, with the goal of the appearance of a natural hill.

The selection of vegetation is important to consider; the plant should be native as not to disrupt ecosystem regimes. The plant type should be able to survive extreme weather, survive with minimal nutrients and maintenance, and not attract potential burrowers. Information from Hanson and Juska (1969) in Figure 2.1-1 and Table 2.1-1 below show the generally recommended vegetation for closure caps. It is expected that the SDF cover will be Bahiagrass at the time of closure. The topsoil will be sourced on-site and will be sandy loam to loamy sand (Benson and Benavides 2018 [SRRA107772-000009]).

Figure 2.1-1: Major Regions of Grass Adaptations in the U.S. (Hanson and Juska 1969)

Table 2.1-1: Grass species recommended for use as permanent vegetative covers in the four regions of grass adaptation (Hanson and Juska 1969)

Region	Species	Seeding Time[1]	Seeding Rate[2] (kg/ha)	Comments
Cool-humid (Region 1)	Kentucky bluegrass	Spring & Fall	20	Do not use named varieties
	Tall fescue	Spring & Fall	40	Use K-31 or Alta varieties; can winter kill north of Interstate 80
	Perennial ryegrass	Spring & Fall	40	Do not use named varieties
	Smooth brome	Spring & Fall	20	Use southern type except in extreme northern part of region
	Redtop	Spring & Fall	15	Not very tolerant of mowing; good for wet conditions
	Weeping lovegrass	Spring & Early Summer	5	Use in southern quarter of region only since less winter hardy than other species
Warm-humid (Region 2)	Bermudagrass	Spring & Early Summer	10	Do not use named varieties
	Bahiagrass	Early Summer	20	Do not use named varieties unless cold tolerance is important
	Zoysia	Summer	See Reference	Propagated vegetatively
	St. Augustine grass	Early Summer	See Reference	Propagated vegetatively; common is coarser textured than named varieties
Warm-arid & semi-arid (Region 3)	Bermudagrass	Spring	10	Do not use named varieties
	Buffalograss	Spring	25	Use only in the eastern quarter of the region
	St. Augustine grass	Early Summer	See Comment	Use only in extreme southern part of region at low elevation
Cool-arid & semi-arid (Region 4)	Bermudagrass	Early Summer	10	Do not use named varieties; use only in extreme southern part of region
	Buffalograss	Spring & Early Summer	25	Use only in eastern quarter of region
	Sideoats grama	Spring	35	Use Blue grama is less than 380 mm of precipitation
	Fairway wheatgrass	Spring	25	Best adapted to norther half of region, use Crested wheatgrass in the southern part at elevations of 1,500 to 2,700 m

Notes:

[1] For species that can be seeded spring and fall, fall seedlings are almost always more successful.

[2] Seeding rates assume single species. Reduce rates by the number of components in mixtures. Minimum % pure live seed of 70 is assumed (% pure live seed = % germination x purity). If the % pure live seed is less than 70, increase seed rate accordingly.

2.2 Conceptual Design of the SDF Closure Cap

This section provides an overview of the SDF closure cap design to provide the necessary context for understanding the discussions throughout this report.

The layers and materials of the current closure cap design are based on *Saltstone Disposal Facility Closure Cap Concept and Infiltration Estimates* (WSRC-STI-2008-00244), while the geometry and the layout of the closure cap has been updated to accommodate larger SDUs per *Saltstone Disposal Facility Closure Cap Concept Update for Large-Scale Disposal Units* (SRR-CWDA-2018-00087).

The topsoil layer will be sourced on-site and will consist of sandy loam to loamy sand. The upper and middle backfill layers will consist of clayey sands from on-site. The erosion barrier will consist of angular stone from a local quarry. Pore space will be filled with sand or fine textured soil with the same properties as the backfill layers. The upper lateral drainage layer will use a uniformly graded coarse sand. Water flowing from the middle backfill layer will drain laterally. The geotextile layers will consist of a nonwoven polymeric material that is shielded from ultraviolet radiation and oxidation. The composite barrier consists of an HDPE geomembrane over a GCL (Benson and Benavides 2018 [SRRA107772-000009]).

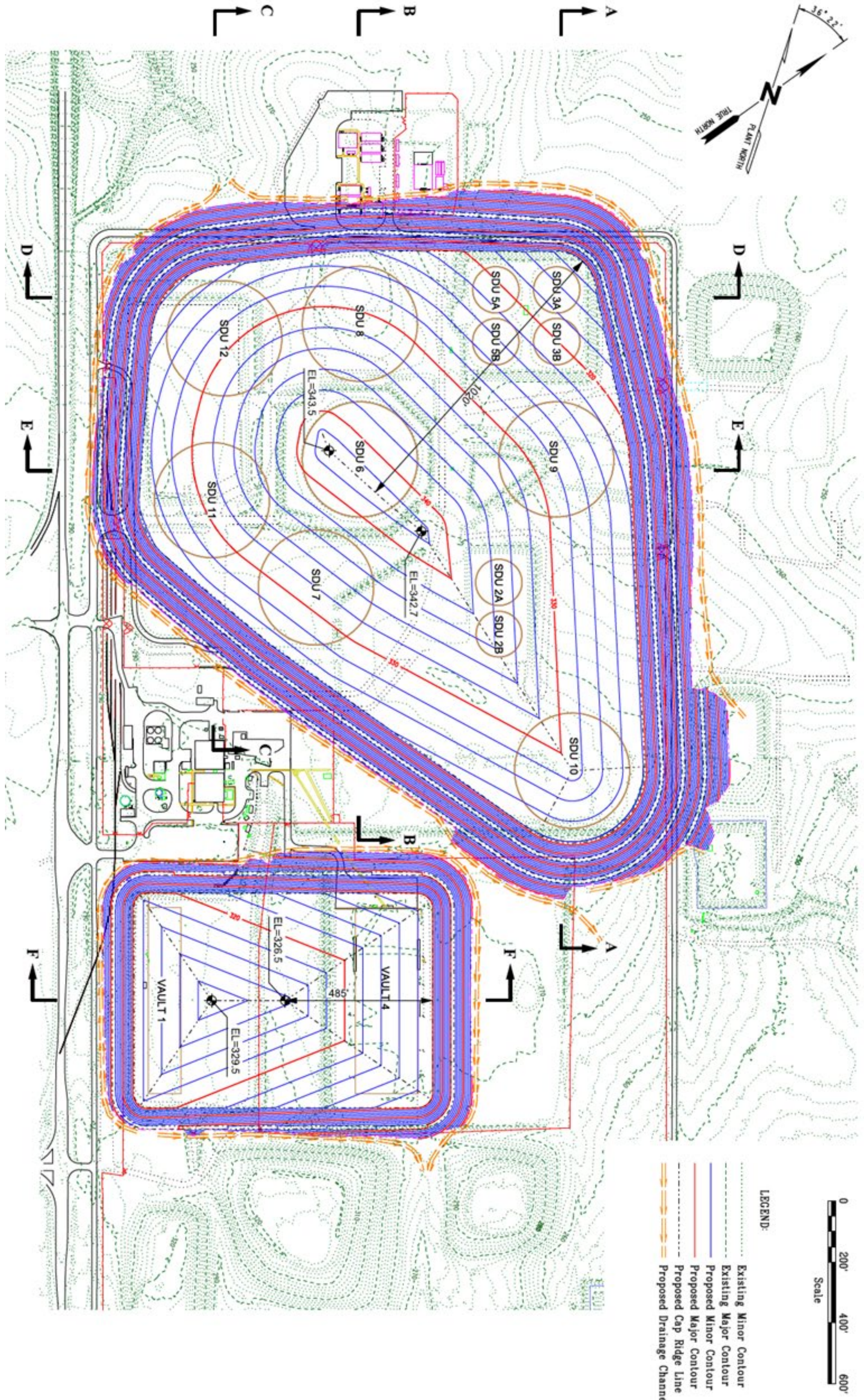
Overall design specifications include 3H:1V embankment slopes and a surface slope of 3%. This surface slope represents an update relative to the conceptual design described in WSRC-STI-2008-00244. The increased slope at the surface (i.e., 3% slope instead of 1.5% slope) was adopted to meet closure requirements specified in the regulation *SWM: Solid Waste Landfills and Structural Fill*. [SCDHEC[1] R.61-107.19] Although the surface of the closure cap has a 3% slope, lower layers of the closure cap have a slightly steeper slope of 4% to promote better drainage. The closure cap design is preliminary; however, it does provide sufficient information for planning purposes, evaluating the closure cap configuration relative to its constructability and functionality, and for estimating infiltration rates over time through modeling.

The SDF closure cap is primarily intended to provide physical stabilization of the site, minimize infiltration, and provide an intruder deterrent. Although they are collectively referred to as a single feature because of design similarity, two distinct closure caps are anticipated to be constructed over the SDUs at the end of the operational period: one large closure cap for the cylindrical SDUs and one smaller closure cap for the rectangular SDUs (see Figure 2.2-1). Cross sections from this conceptual closure cap design are also provided (see Figure 2.2-2 and Figure 2.2-3). [SRR-CWDA-2018-00087]

Table 2.2-1 identifies each of the SDF closure cap layers and their anticipated thicknesses. These layers are graphically depicted in Figure 2.2-4.

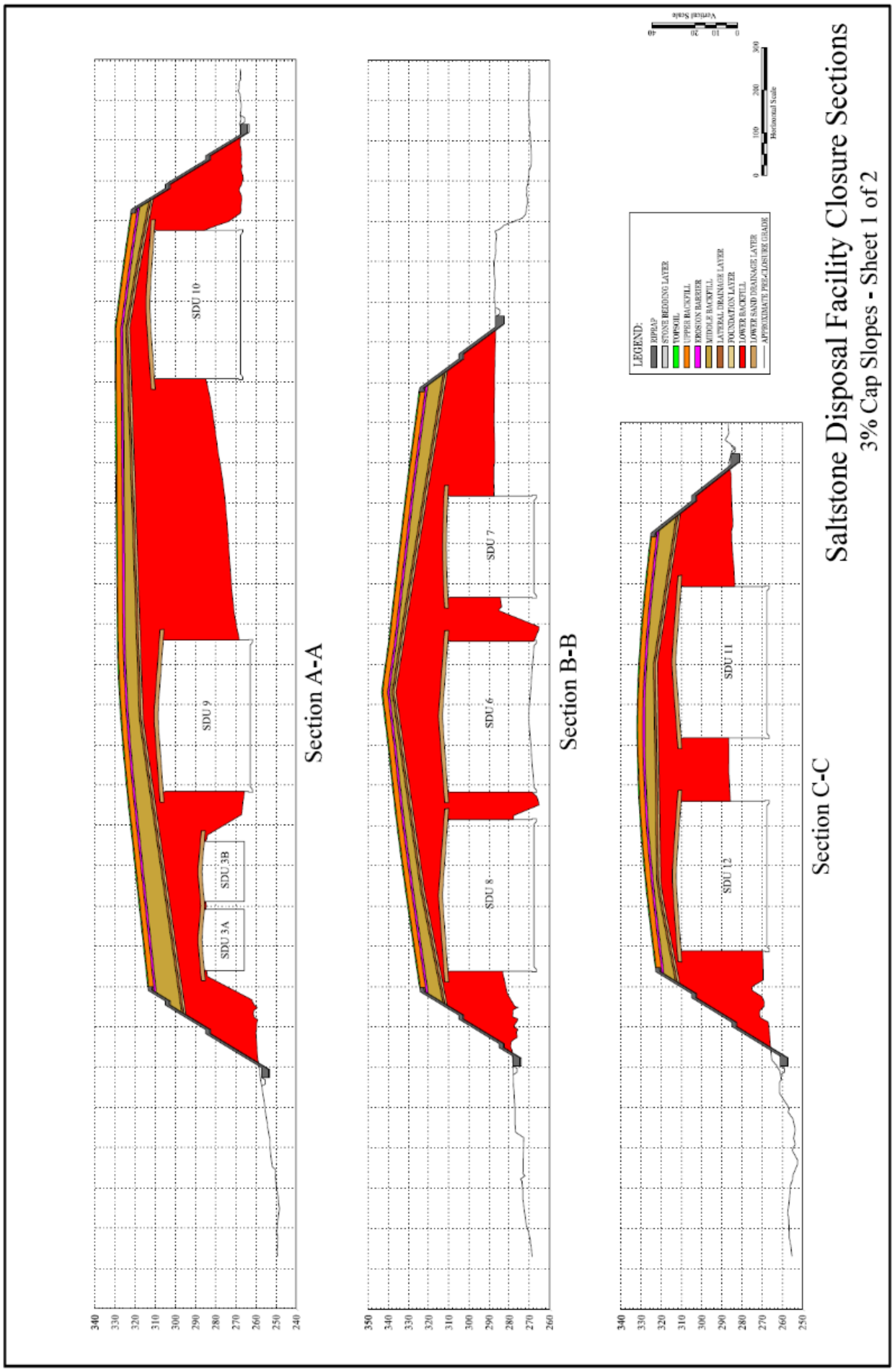
[1] SCDHEC = South Carolina Department of Health and Environmental Control

Figure 2.2-1: SDF Closure Cap Conceptual Design Configuration



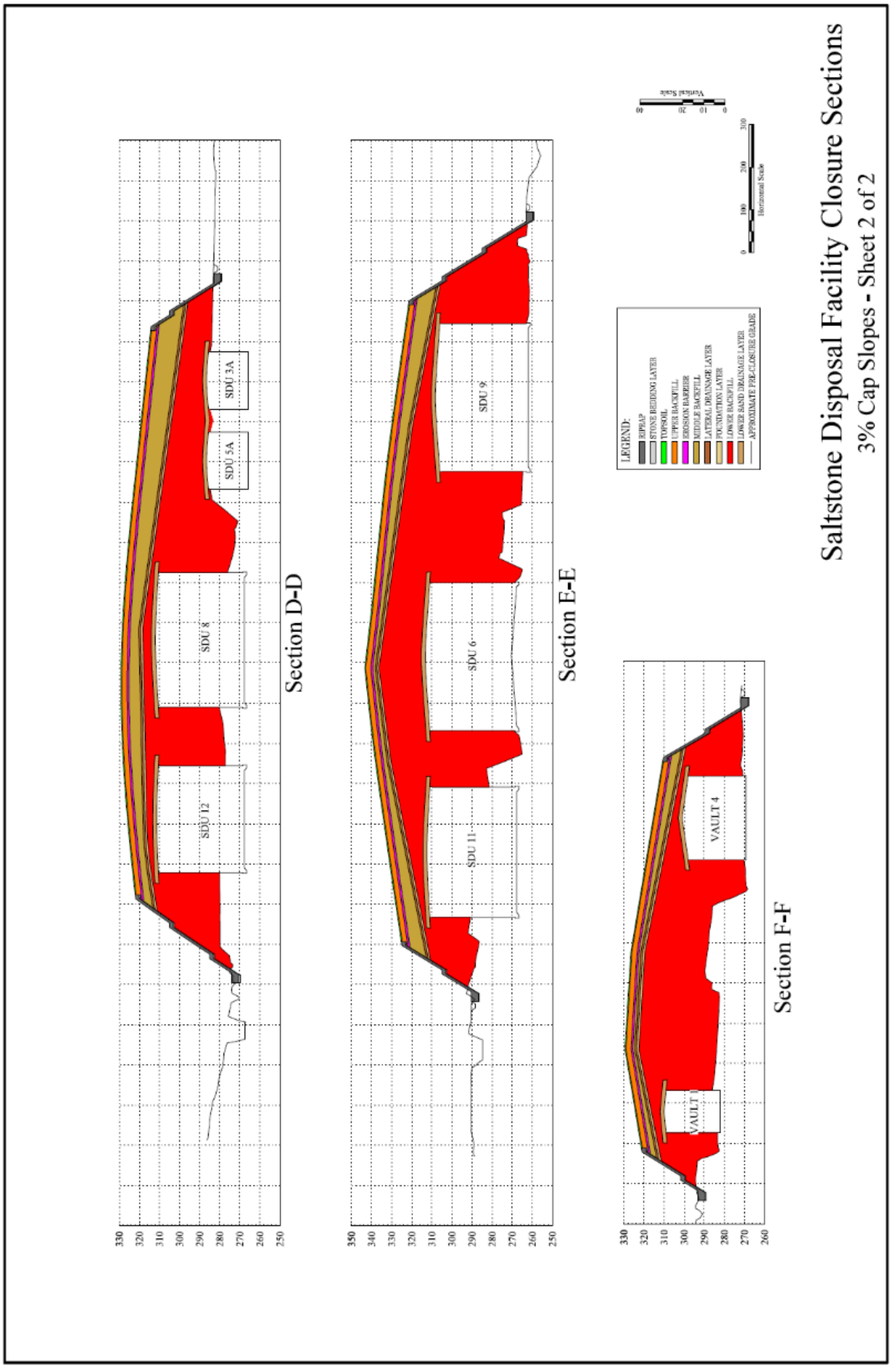
[SRR-CWDA-2018-00087]

Figure 2.2-2: SDF Closure Cap Conceptual Design Cross Sections A, B, and C



[SRR-CWDA-2018-00087]

Figure 2.2-3: SDF Closure Cap Conceptual Design Cross Sections D, E, and F



[SRR-CWDA-2018-00087]

Table 2.2-1: SDF Closure Cap Layers and Layer Thicknesses

Layer [a]	Layer Thickness (in)
Vegetative Cover	N/A
Topsoil	6
Upper Backfill	30
Erosion Barrier	12
Geotextile Fabric [b]	Not specified.
Middle Backfill	12 (minimum, will increase from cap apex to toe due to difference between surface slope and the slope of the upper lateral sand drainage layer)
Geotextile Filter Fabric [b]	0.1 (minimum)
Upper Lateral Sand Drainage Layer	12
Geotextile Fabric [b]	Not specified.
High Density Polyethylene (HDPE) Geomembrane	0.06 (60 mil)
Geosynthetic Clay Liner (GCL)	0.2
Foundation Layer (backfill with bentonite admix) [b]	12
Lower Backfill [b]	12 (minimum, will increase from cap toe to apex due to slope of the upper lateral sand drainage layer)
Geotextile Filter Fabric [b,c]	Not specified.
Lower Lateral Sand Drainage Layer, extends approximately 25 feet from disposal unit [b,c]	24
Geotextile Fabric [b,c]	Not specified.
HDPE Geomembrane [b,c]	0.1
GCL [b,c]	0.2

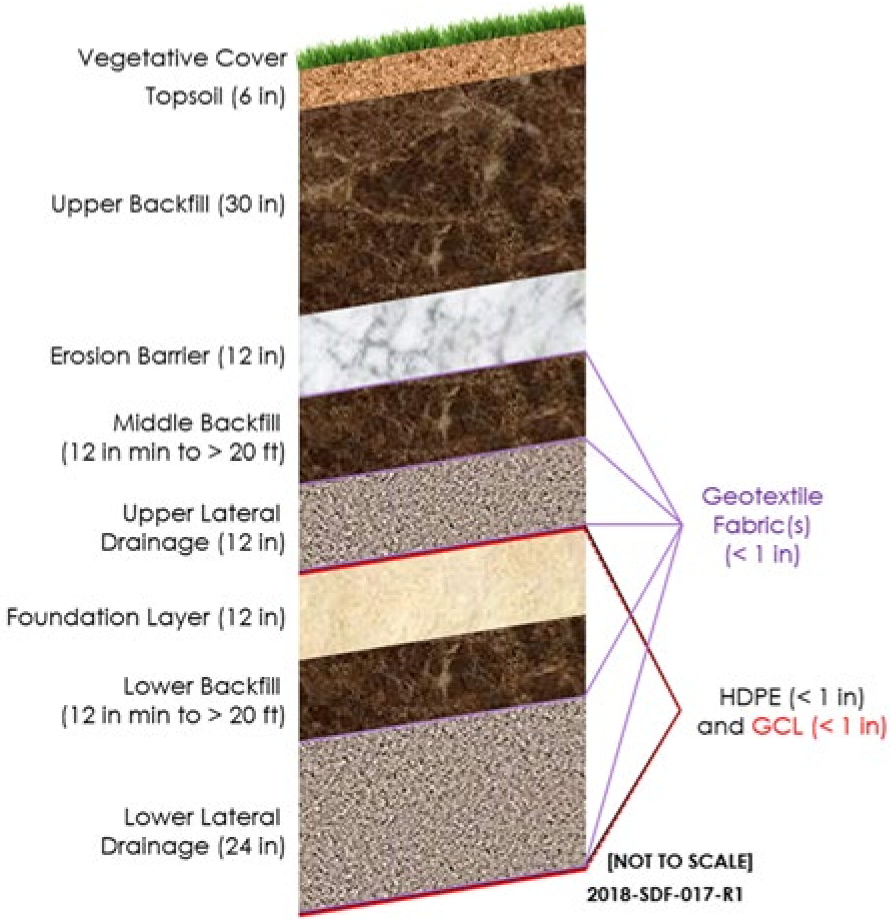
[WSRC-STI-2008-00244, Table 4]

(a) The layers are arranged in the table to reflect their order from top to bottom in the SDF closure cap.

(b) Layer is not included in closure cap modeling.

(c) Layer is above each disposal unit and does not cover the entire SDF area.

Figure 2.2-4: SDF Conceptual Closure Cap Layers



[SRR-CWDA-2019-00001]

The specific functions for each of the design layers are provided in Table 2.2-2.

Table 2.2-2: Functions of the SDF Closure Cap Design Layers

Layer [a]	Layer Function
Vegetative Cover	The vegetative cover will be established to promote runoff, minimize erosion, and promote evapotranspiration. The initial vegetative cover will be a persistent grass such as Bahiagrass. Other vegetation may be considered for the final closure cap design and may be planted at any point during the institutional control period.
Topsoil	The topsoil will be designed to support a vegetative cover, promote runoff, prevent the initiation of gullying, and provide water storage for the promotion of evapotranspiration.
Upper Backfill	The upper backfill will be designed to increase the elevation of the closure cap to that necessary for placement of the topsoil and to provide water storage for the promotion of evapotranspiration.
Erosion Barrier	The erosion barrier will be designed to prevent riprap movement during a PMP event and therefore form a barrier to further erosion and gully formation (i.e., provide closure cap physical stability). It will be used to maintain a minimum 10 feet of clean material above the disposal units to act as an intruder deterrent. It will also act to preclude burrowing animals from access to underlying closure cap layers. It also provides minimal water storage for the promotion of evapotranspiration.
Geotextile Fabric [b]	This geotextile fabric will be designed to prevent the penetration of erosion barrier stone into the underlying middle backfill and to prevent piping of the middle backfill through the erosion barrier voids.
Middle Backfill	The middle backfill will provide water storage for the promotion of evapotranspiration in the event that the topsoil and upper backfill are eroded away; the overlying erosion barrier provides only minimal water storage.
Geotextile Filter Fabric [b]	This geotextile filter fabric will be designed to provide filtration between the overlying middle backfill and the underlying upper lateral sand drainage layer. This filtration will allow water to freely flow from the middle backfill to the upper lateral sand drainage layer, while preventing the migration of soil from the middle backfill to the upper lateral sand drainage layer.
Upper Lateral Sand Drainage Layer	The upper lateral sand drainage layer will be a 1-foot thick coarse sand layer designed to: • Divert infiltrating water away from the underlying disposal units and transport the water to the perimeter drainage system, in conjunction with the underlying composite hydraulic barrier (i.e., HDPE and GCL), and • Provide the necessary confining pressures to allow the underlying GCL to hydrate properly.
Geotextile Fabric [b]	This geotextile fabric will protect the underlying HDPE from puncture or tear during placement of the overlying upper lateral sand drainage layer.
High Density Polyethylene (HDPE) Geomembrane	The HDPE geomembrane will form a composite hydraulic barrier in conjunction with the GCL. The composite hydraulic barrier will be designed to promote lateral drainage through the overlying upper lateral sand drainage layer and minimize infiltration to the disposal units.
Geosynthetic Clay Liner (GCL)	The GCL will form a composite hydraulic barrier described above in conjunction with the HDPE. As part of the composite hydraulic barrier, the GCL is designed to hydraulically plug any holes that may develop in the HDPE.

Table 2.2-2: Functions of the SDF Closure Cap Design Layers (Continued)

Foundation Layer (backfill with bentonite admix) [b]	Provide structural support and required contours for slope of 4% for overlying layers. Provide relatively low-permeability layer directly above lower backfill.
Lower Backfill [b]	The lower backfill will be designed to: • Provide structural support for the rest of the overlying closure cap • Produce the required contours and produce a slope of 4% for the overlying layers • Produce the maximum 3:1 side slopes of the closure cap • Promote drainage of infiltrating water away from and around the disposal units
Geotextile Filter Fabric [b,c]	This geotextile filter fabric will be designed to provide filtration between the overlying lower backfill and the underlying lower lateral sand drainage layer. This filtration will allow water to freely flow from the lower backfill to the lower lateral sand drainage layer, while preventing the migration of soil from the lower backfill to the lower lateral sand drainage layer.
Lower Lateral Sand Drainage Layer, extends approximately 25 feet from disposal unit [b,c]	The lower lateral sand drainage layer will extend approximately 25 feet from each disposal unit and is designed primarily to prevent buildup of hydraulic head on top of the disposal units. The portion of this drainage layer extending beyond each disposal unit roof edge will be constructed atop backfill soils around the SDUs.
Geotextile Fabric [b,c]	This geotextile fabric will be designed to protect the underlying HDPE from puncture or tear during placement of the overlying lower lateral sand drainage layer.
HDPE Geomembrane [b,c]	The HDPE will be designed to form a composite hydraulic barrier in conjunction with the GCL. The composite hydraulic barrier will be designed to promote lateral drainage through the overlying lower lateral sand drainage layer and minimize infiltration to the disposal units.
GCL [b,c]	The GCL will form a composite hydraulic barrier in conjunction with the HDPE as described above. As part of the composite hydraulic barrier, the GCL is designed to hydraulically plug any holes that may develop through the HDPE.

[WSRC-STI-2008-00244, Table 5]

(a) The layers are arranged in the table to reflect their order from top to bottom in the SDF closure cap.

(b) Layer is not included in closure cap modeling.

(c) Layer is above each disposal unit and does not cover the entire SDF area.

Finally, Table 2.2-3 provides the approximate closure cap thicknesses over each SDU. The average lower backfill thicknesses come from Table 7.1-1 of SRR-CWDA-2018-00068, wherein the values were estimated by examining the cross sections shown in Figure 2.2-2 and Figure 2.2-3. The approximate closure cap thickness is then estimated as the sum of:

- the lower lateral drainage layer thickness (2 ft),
- the average backfill thickness (varies by SDU),
- the foundation layer thickness (1 ft),
- the upper lateral drainage layer thickness (1 ft),
- the middle backfill layer (assumed to be 1 ft, based on the minimum thickness),

- the erosion barrier thickness (1 ft),
- the upper backfill thickness (2.5 ft), and
- the topsoil thickness (0.5 ft).

This estimate gives no credit to HDPE, GCL, or geotextile fabrics. The minimum closure cap thickness was estimated to be approximately 14 feet (over SDU 1) and the maximum closure cap thickness was nearly 30 feet (over SDUs 2A and 2B).

Table 2.2-3: Approximate Average Closure Cap Thickness Over Each SDU

SDU	Average Lower Backfill Thickness (ft) Based on Conceptual Closure Cap Design	Approximate Closure Cap Thickness Over SDU (ft)
SDU 1	4.9	13.9
SDU 2A	20.1	29.1
SDU 2B	20.1	29.1
SDU 3A	12.6	21.6
SDU 3B	17.0	26.0
SDU 4	4.9	13.9
SDU 5A	18.9	27.9
SDU 5B	18.9	27.9
SDU 6	18.7	27.7
SDU 7	12.0	21.0
SDU 8	5.5	14.5
SDU 9	6.7	15.7
SDU 10	5.6	14.6
SDU 11	7.1	16.1
SDU 12	5.3	14.3

3.0 INPUTS AND ASSUMPTIONS

This section introduces the variables and impactors that affect erosion rate estimates. The biggest risk to the integrity of the closure cap outside of animal burrowers or external intruders is precipitation and the associated probable maximum precipitation (PMP) event.

Section 3.1 discusses precipitation rates. Section 3.2 discusses the development of the site-specific PMP estimates, which define the duration and intensity of the most intense rainfall events expected for a specified return period. Section 3.3 describes the soil properties. Finally, Section 3.4 provides a brief summary of current and anticipated future land use.

3.1 SRS Precipitation Data and Estimates

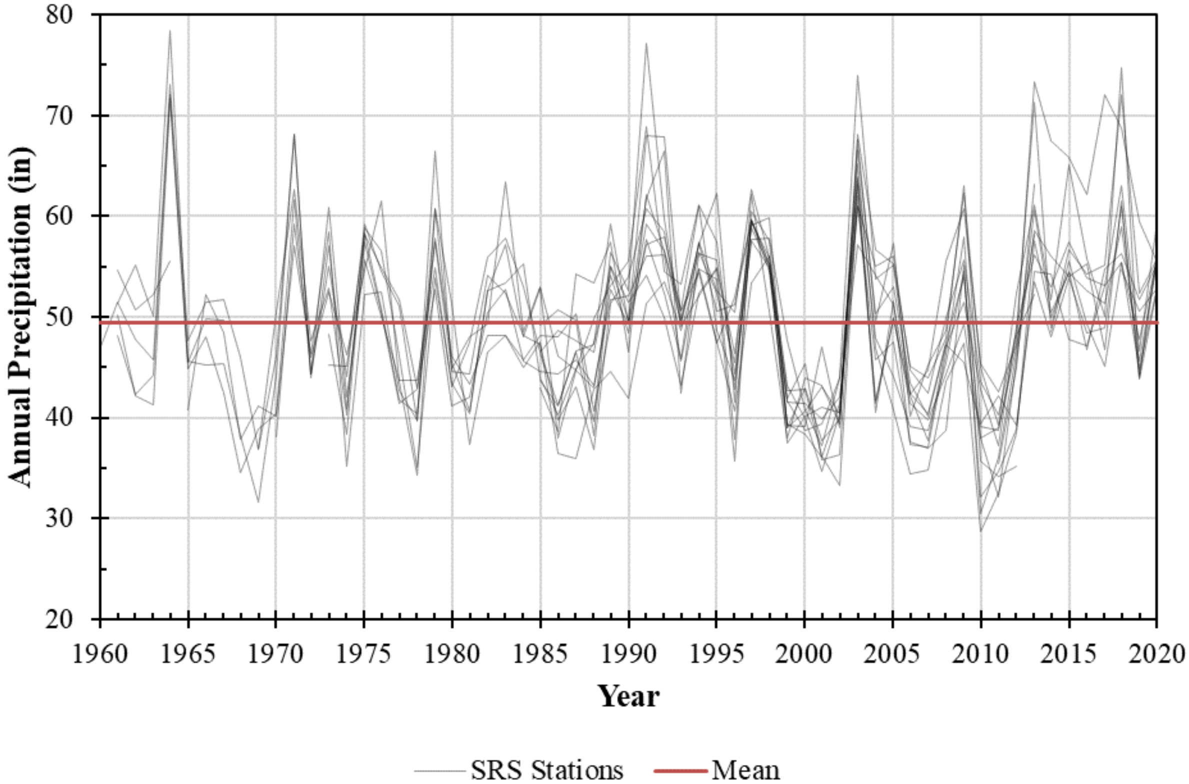
For developing inputs for their long-term percolation estimates, Benson and Benavides (2018) (SRRA107772-000009) used precipitation data from one weather station at SRS from 1964 through 2016. Based on this data, it was estimated that annual precipitation at SRS ranged from 29 inches (729 mm) to 72 inches (1,830 mm), with a mean of 47 inches (1,196 mm) .

For the evaluation of erosion in this report, data from additional weather stations at SRS will also be considered and recent data (through 2020) will also be incorporated to provide a more complete analysis of variability.

Throughout the history of operations at SRS, 13 weather stations have been employed to gather precipitation data. These stations are located across the site. These weather stations collected data over differing periods, for example the first weather station started collecting data in 1952 and in 1960 three additional stations were installed. Periodically, some stations have been taken offline for maintenance or due to budgetary limitations. Currently, 11 stations are in active operation.

Figure 3.1-1 shows the annual precipitation at SRS from 1960 through 2020 for all 13 stations. This figure also shows the mean across all stations and all years: a value of 49.4 inches (1255 mm). This larger data set has a range of 29 inches (729 mm) to 78.4 inches (1,991 mm).

Figure 3.1-1: Annual Precipitation at SRS from 1960 through 2020



Collectively, the data from these weather stations provides 583 data points for annual precipitation at SRS. Table 3.1-1 provides a statistical summary of the comprehensive data set from 1960 through 2020. Values are provided in both inches and millimeters. Because of the larger dataset, this table provides a wider distribution range relative to the more limited dataset used by Benson and Benavides (2018) (SRRA107772-000009). It is also noted that the mean is slightly higher (1,255 mm versus 1,196 mm).

Table 3.1-1: Summary of Annual Precipitation at SRS

Statistic	in	mm
Maximum	78.4	1,991
95th Percentile	63.4	1,610
75th Percentile	55.2	1,401
Median	48.7	1,237
25th Percentile	42.9	1,090
5th Percentile	36.8	935
Minimum	28.7	729
Mean	**49.4**	**1,255**
Standard Deviation	8.5	217

3.2 SRS PMP

Designing the closure cap system to withstand large and future heavy rainfall periods will ensure the resilience of the closure cap for thousands of years into the future. Designing for a probable maximum precipitation (PMP) event will ensure that the closure cap is capable of withstanding these rare rain events.

A PMP event is defined as "the greatest depth of precipitation for a given duration meteorologically possible for a design watershed or a given size storm area at a particular location at a particular time of year" (WMO-No. 1045[b], 2009). In other words, a PMP storm is based on a design event, or that a storm of a given return period will produce an estimated flood having the same return period. For example, a 100-year rainfall event would result in a 100-year flood. Design storms are developed by a statistical analysis of climatological records. One weakness in these records is that they do not limit a design storm to a certain region and its temporal and spatial distribution. In short, it does not define the basin conditions (soil type, vegetation coverage, amount of paved structures) that can greatly influence the amount of runoff. Therefore, a 100-year storm event might not produce a 100-year flood if the ground is presently saturated or drought conditions are present, meaning that the resulting flood might be less or greater than the defined return period.

Given the importance of the PMP for predicting potential erosion, a detailed analysis was performed to develop and justify an updated set of recommended PMP values. Earlier PMP estimates at SRS have been based on an analysis method described in Eliasson's *A statistical model for extreme precipitation* (1997); this method will hereafter be referred to as the Eliasson Method and is described in Section 3.2.1. This report also uses an alternative approach for estimating PMP values that was developed by the National Oceanic and Atmospheric Administration (NOAA) and is described in Section 3.2.2. Section 3.2.3 presents the results for previous PMP estimates at SRS. Section 3.2.4 updates the PMP estimates using both the Eliasson Method and the NOAA Method. Finally, Section 3.2.5 summarizes the PMP analyses and provides recommendations for future use.

3.2.1 Eliasson Method for Estimating PMP at SRS

The Eliasson Method is a statistical model for extreme precipitation which relies on the mean, standard deviation, and high annual observed precipitation, known as the annual maximum series (AMS), corresponding to each station during each year of record. The Eliasson method for estimating the PMP starts by selecting the highest AMS (highest observed precipitation over a given period) for each calendar year of record. Any precipitation values that are not associated with the AMS were not included in this analysis.

The AMS values can be determined from precipitation records collected from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC). The NOAA NCDC precipitation records are available at various weather stations for 15-minute, hourly, and daily records.

Note that a precipitation measurement or observation that has been constrained by clock hours which occur in regular intervals requires conversion to an unconstrained value, where an unconstrained value is an observation for a defined duration regardless of the periodicity of the

[b] WMO = World Meteorological Organization

measurements. Such conversions are necessary because maximum 60-minute or 24-hour amounts seldom fall within a single hourly or daily observation period. (NOAA Atlas Vol. 14, Hershfield, 1961). For example, a rainfall event that starts at 5:30 pm and continues until 6:30 pm would be recorded in the hourly datasets as two separate rainfall events (for the 5:00 pm hour and the 6:00 pm hours), each with half the magnitude of the actual rainfall that occurred over a one-hour period.

To adjust for this offset in recorded time, SRS application of the Eliasson Method uses a "bias factor" to estimate true precipitation values. Recommended bias factors are provided in Table 3.2-1.

Table 3.2-1: Recommended Bias Factors for Scaling AMS Values

Rainfall Accumulation Interval	Bias Factor
24 hours	1.01
6 hours	1.02
3 hours	1.03
1 hour	1.13
15 minutes	1.13

Source: WSRC-TR-98-00329, Table XVI and SRNL-STI-2013-00664, Table 5.3.

Since the Eliasson Method uses multiple variables and statistically derived constants, it is helpful to define these inputs before presenting the applicable formulas. Table 3.2-2 defines each of the inputs considered when using the Eliasson Method. The formulas described below are dependent upon using consistent units; for the analysis within this report, inches of rainfall are used.

Table 3.2-2: Definitions of Eliasson Method Inputs (Eliasson, 1997)

Variable	Definition
μ	True mean of the AMS values at a single location (in inches)
σ	True standard deviation of the AMS values at a single location (in inches)
CV	coefficient of variation (unitless), or the ratio of the standard deviation and the mean, of the AMS values for a single location
x	PMP value (in inches) for a single location based on the μ and CV
$\bar{\mu}$	The mean of the means of AMS values at multiple locations across a specific region (in inches)
$\overline{CV}$	The means of the coefficients of variation (unitless) of the AMS values for multiple locations across a specific region
$\bar{x}$	PMP value (in inches) for a single location based on the $\bar{\mu}$ and $\overline{CV}$
RP	Return period (in year)
σ	True standard deviation (in inches)
P	Given probability of non-exceedance (unitless, 0 to 1)
Constant 1	0.5772 (estimated by Eliasson 1997)
Constant 2	1.283 (estimated by Eliasson 1997)
Constant 3	0.77942 (determined as the inverse of Constant 1)
Constant 4	0.44988 (determined as Constant 1 divided by Constant 2)
y	Extreme Value function for a given return period
Bias Factor	See Table 3.2-1

From Eliasson (1997), the PMP value (x) for a specific location (i.e., one weather station) is

$$x = \mu + \frac{-ln[-ln(P)] - 0.5772}{1.283}\sigma \qquad \text{Eq. 3-1}$$

Following Eliasson (1997), the Extreme Value function (y) for a given return period is defined as

$$y \equiv -ln[-ln(P)] = -ln\left[-ln\left(1 - \frac{1}{RP}\right)\right] \qquad \text{Eq. 3-2}$$

For example, assuming a return period of five years results in

$$y = -ln\left[-ln\left(1 - \frac{1}{5}\right)\right] = 1.4999 \qquad \text{Eq. 3-3}$$

Note that the Extreme Value function (y) will vary depending upon the desired return period (RP). For convenience, Table 3.2-3 shows the values for y for selected return periods, although Eq. 3-3 is dynamic and can be applied to any return period (RP).

Table 3.2-3: Values for the Extreme Value Function for Selected Return Periods

Return Period (years)	Result of the Extreme Value Function
5	1.4999
10	2.2504
50	3.9019
100	4.6001
500	6.2136
1,000	6.9073
5,000	8.5171
10,000	9.2103

Combining Eq. 3-1, Eq. 3-2, and Eq. 3-3 and then simplifying the expression gives

$$x = \mu + \frac{y - 0.5772}{1.283}\sigma = \mu + (0.7794y - 0.4499)\sigma \qquad \text{Eq. 3-4}$$

Next, the coefficient of variation (CV) is a useful measure in probability theory. It is defined as the ratio of the standard deviation (σ) and the mean (μ)

$$CV = \frac{\sigma}{\mu} \qquad \text{Eq. 3-5}$$

Using this coefficient of variation (CV), the equation for the PMP (Eq. 3-4), may be rewritten as

$$x = \mu[1 + (0.7794y - 0.4499)CV] \qquad \text{Eq. 3-6}$$

Eq. 3-6 is appropriate for estimating the PMP values for a single station, and PMP events at the given station are not expected to exceed the resulting estimates. However, many facilities at SRS do not host their own location-specific weather stations, so there may not be a continuous record of precipitation for each of the facilities. Therefore, a regional PMP estimate is appropriate. Eliasson (1997) notes that while a regional maximum PMP might be equal to the PMP for the station with highest PMP value, a higher PMP value within a given region may exist. Therefore, Eliasson proposed the following approach for developing a regional PMP estimate.

First, find the mean and the standard deviation for the coefficients of variation (μ_{CV} and σ_{CV}, respectively) across all stations within the given region, and find the logarithm of the number of stations ($\log N$). These quantities may then be used to estimate the highest coefficient of variation (CV_{max}) across the region

$$CV_{max} = \mu_{CV} + (\log N)\left(\frac{\sigma_{CV}}{1.283}\right) \qquad \text{Eq. 3-7}$$

Then, Eq. 3-6 can be modified by replacing the station-specific mean (μ) with the mean of the means ($\bar{\mu}$) across all stations and replacing the station-specific coefficient of variation (CV) with the highest coefficient of variation (CV_{max}) across the region, giving a maximum PMP value across the region (x_{max})

$$x_{max} = \bar{\mu}[1 + (0.7794y - 0.4499)CV_{max}] \qquad \text{Eq. 3-8}$$

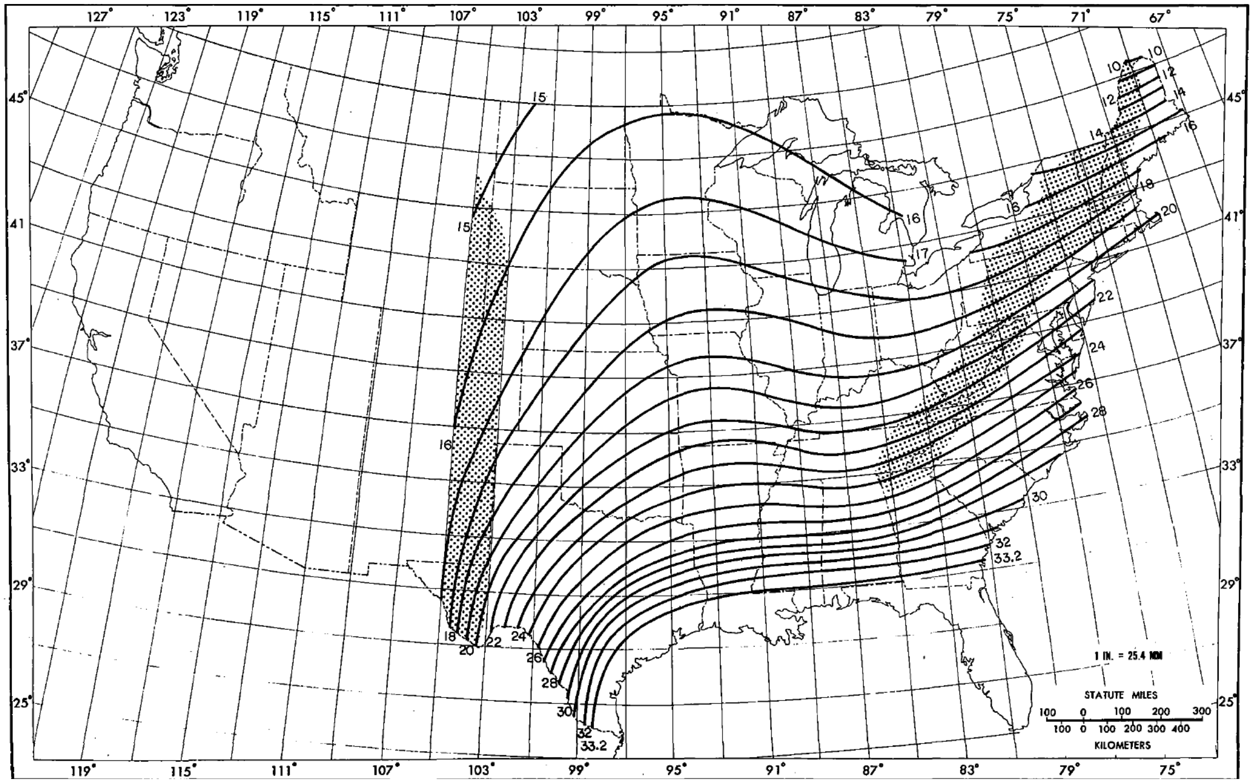
Finally, the x_{max} values should be scaled by the applicable bias factor (from Table 3.2-1) to determine the appropriate PMP value for use in regional evaluations. This approach was used in the previous SRS estimates presented in Section 3.2.3 and the updated estimates presented in Section 3.2.4. The data used for developing the updated PMP estimates are summarized in Appendix A.

3.2.2 NOAA Method for Estimating PMP at SRS

This section describes the NOAA Method for estimating PMP values. This alternative approach uses Precipitation Frequency Estimates (PFEs). The NOAA Precipitation-Frequency Atlas of the United States (NOAA Atlas 14) shows the estimated rainfall accumulation for various durations and return periods (as of February 2021 this is electronically available at the NOAA Website: http://hdsc.nws.noaa.gov/hdsc/pfds/index.html).

The NOAA PFEs use spatial analysis of historic rainfall data to generate isohyetal maps, which are maps that show lines connecting points where the same amount of rainfall occurs in a given period. An example of an isohyetal map is shown in Figure 3.2-1, which depicts an isohyetal map for the Eastern United States.

Figure 3.2-1: PMP Isohyetal Map (NOAA HMR-51, 1978) for All Seasons for 2 hours over 1,000 Square Miles

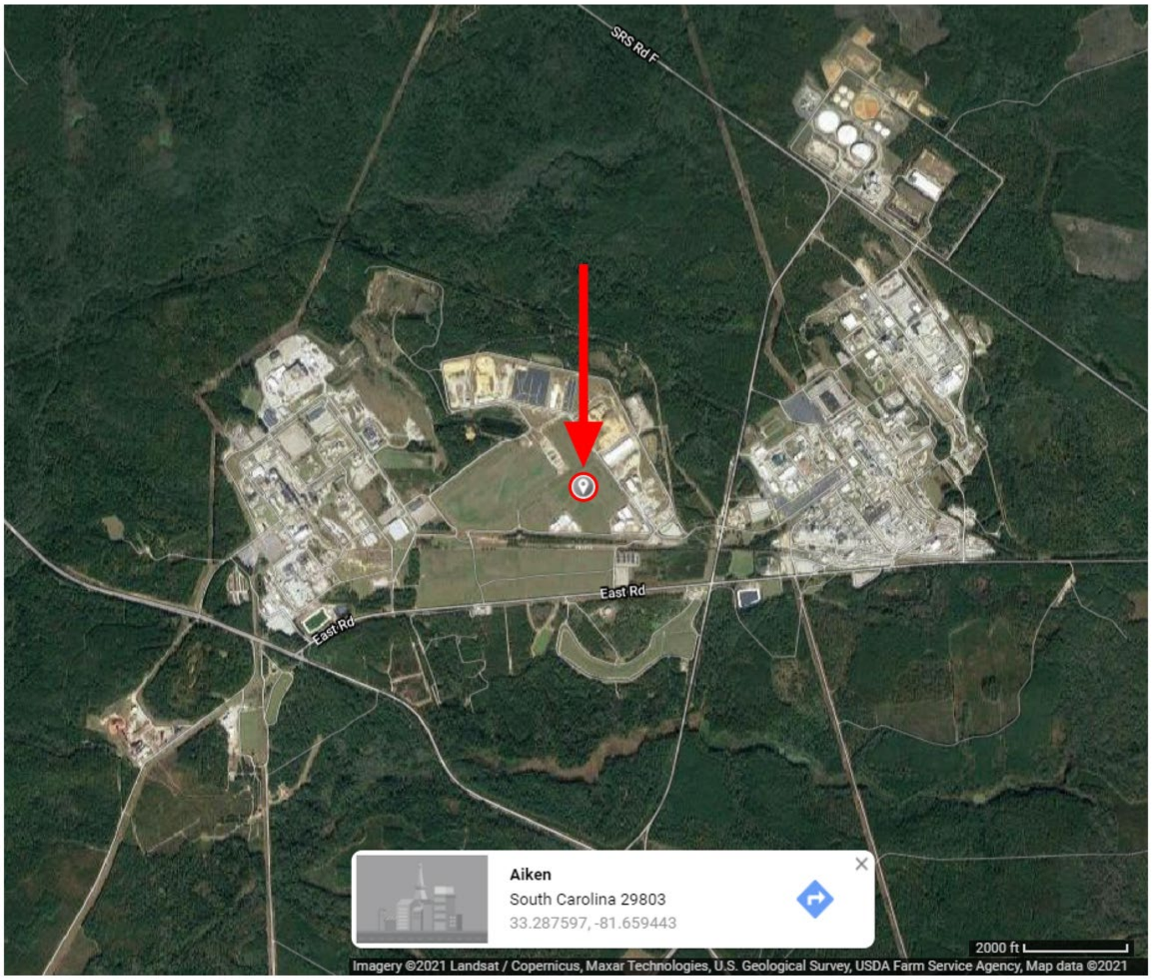


Along with NOAA Atlas 14, the NOAA's PFE website includes a user-interface that allows users to retrieve location-specific PFE data by selecting a state, town, region, or entering coordinates. The website automatically generates plots of precipitation depth or PFE for either partial duration or annual maximum time series. A partial duration series (PDS) is a time series that includes all precipitation amounts for a specified duration at a given station above a pre-defined threshold regardless of year; it can include more than one event in any particular year. (NOAA Atlas 14).

In this study, the coordinates used to generate point precipitation frequency estimates on the NOAA Atlas 14 interactive website to represent climate conditions at the SDF were 33.287597N, 81.659443W, shown in Figure 3.2-2. While this report is specific to the SDF, the intent of selecting this location is to be more centrally located within the GSA (i.e., the facilities depicted in Figure 3.2-2), such that the resulting PMP estimate may be applied to multiple facilities, including FTF and HTF.

The limitation to using the NOAA PFE values is that the system does not currently provide return periods of greater than 1,000 years. For this analysis, depth duration frequency plots based on the rainfall accumulation intervals and based on the average recurrence intervals were generated out to 1,000 years, as shown in Figure 3.2-3 and Figure 3.2-4, respectively. The data was then extrapolated to generate PFE values out to 10,000 years, using logarithmic line-fitting.

Figure 3.2-2: Approximate Location used for NOAA Point Precipitation Frequency Estimates (Image from Google Maps, 2021)



Source: Google Maps Imagery, ©2021 Maxar Technologies, USGS, USDA Farm Service Agency, Map Data ©2021. Image circa Summer 2020. Image modified to show coordinate location of NOAA PFE data.

Figure 3.2-3: Depth Duration Frequency Curves Based on Duration of the Rainfall Accumulation Interval from the NOAA Website

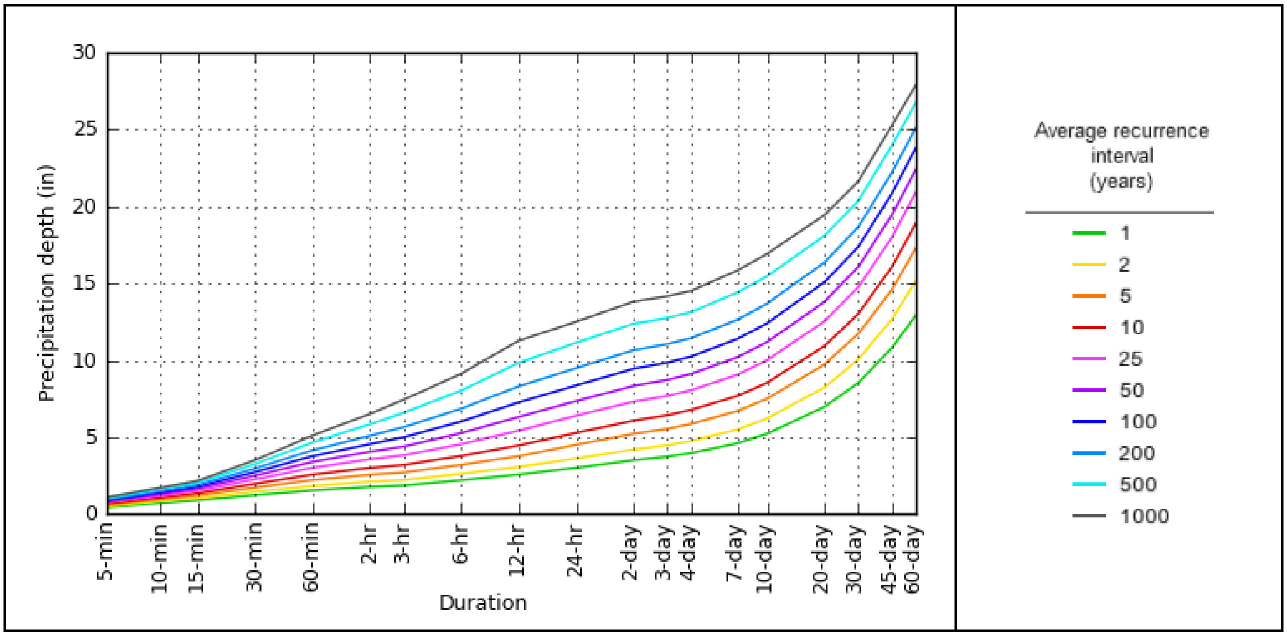
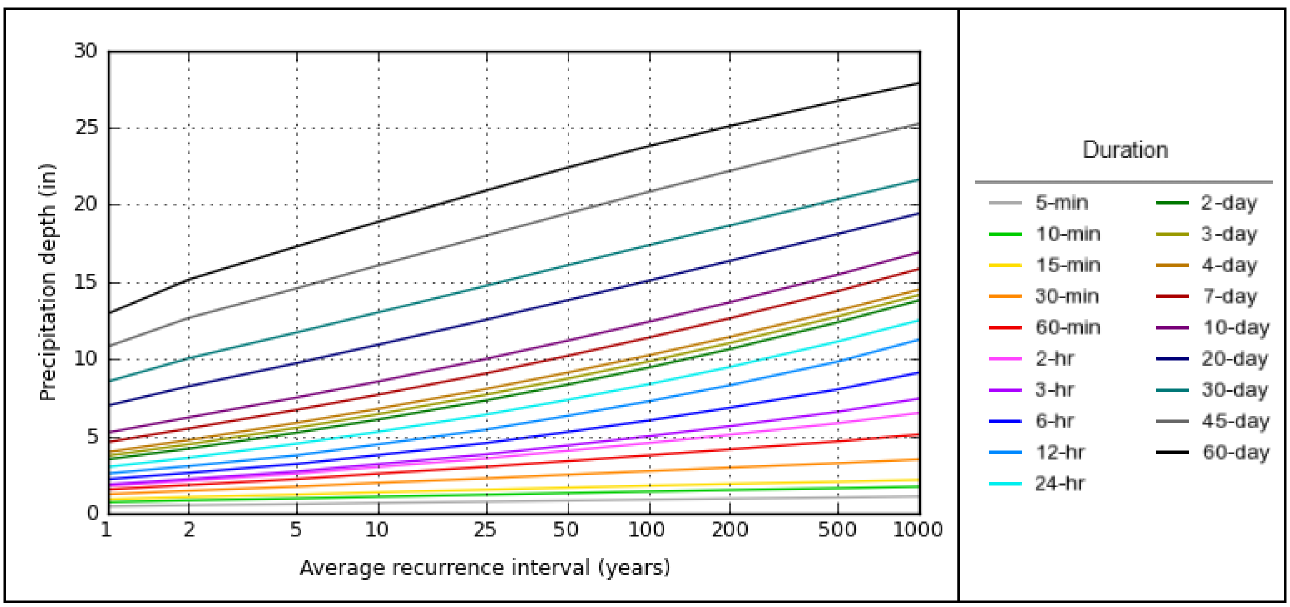


Figure 3.2-4: Depth Duration Frequency Curves Based on Average Recurrence Interval from the NOAA Website



The data for these figures is provided in Table 3.2-4.

Table 3.2-4: Depth Duration Frequency Curves from the NOAA Website

	Average Recurrence Interval (yr)									
Duration	**1**	**2**	**5**	**10**	**25**	**50**	**100**	**200**	**500**	**1,000**
5-min	0.453	0.525	0.6	0.673	0.755	0.823	0.888	0.95	1.03	1.09
10-min	0.723	0.84	0.961	1.08	1.2	1.31	1.41	1.51	1.62	1.72
15-min	0.904	1.06	1.22	1.36	1.53	1.66	1.78	1.9	2.04	2.16
30-min	1.24	1.46	1.73	1.97	2.26	2.5	2.73	2.96	3.25	3.5
60-min	1.55	1.83	2.21	2.57	3.01	3.39	3.76	4.15	4.66	5.11
2-hr	1.78	2.11	2.56	3.0	3.56	4.06	4.56	5.1	5.84	6.51
3-hr	1.86	2.21	2.7	3.19	3.82	4.4	5.0	5.65	6.58	7.43
6-hr	2.2	2.62	3.2	3.78	4.55	5.27	6.02	6.84	8.03	9.13
12-hr	2.57	3.06	3.76	4.47	5.42	6.31	7.26	8.31	9.83	11.3
24-hr	3.0	3.61	4.51	5.28	6.4	7.34	8.37	9.49	11.1	12.5
2-day	3.5	4.2	5.22	6.08	7.31	8.34	9.45	10.6	12.4	13.8
3-day	3.73	4.48	5.54	6.42	7.68	8.73	9.84	11	12.8	14.2
4-day	3.97	4.76	5.86	6.77	8.06	9.12	10.2	11.4	13.1	14.5
7-day	4.61	5.5	6.7	7.68	9.07	10.2	11.4	12.6	14.4	15.8
10-day	5.23	6.22	7.5	8.54	10.0	11.2	12.4	13.7	15.5	16.9
20-day	6.97	8.24	9.74	10.9	12.5	13.8	15.1	16.4	18.1	19.4
30-day	8.53	10.1	11.7	13	14.7	16.1	17.4	18.7	20.4	21.6
45-day	10.8	12.7	14.6	16.1	18	19.4	20.8	22.2	24	25.3
60-day	12.9	15.2	17.3	18.9	20.9	22.4	23.8	25.1	26.7	27.9

To extrapolate values beyond 1,000 years, logarithmic line-fitting was performed using the data from Table 3.2-4. The estimated PMP values from extrapolation are shown in Table 3.2-5.

Table 3.2-5: Peak Precipitation Estimates for Selected Return Periods and Rainfall Accumulation Intervals Based on NOAA Depth Duration Frequency Curves

Return Period (years)	Frequency (per year)[a]	Rainfall Accumulation Interval						
		5 minutes	**10 minutes**	**15 minutes**	**1 hour**	**3 hours**	**6 hours**	**24 hours**
1	1.0E+00	0.453	0.723	0.904	1.55	1.86	2.20	3.00
2	5.0E-01	0.525	0.840	1.06	1.83	2.21	2.62	3.61
5	2.0E-01	0.600	0.961	1.22	2.21	2.7	3.2	4.51
10	1.0E-01	0.673	1.08	1.36	2.57	3.19	3.78	5.28
25	4.0E-02	0.755	1.20	1.53	3.01	3.82	4.55	6.4
50	2.0E-02	0.823	1.31	1.66	3.39	4.40	5.27	7.34
100	1.0E-02	0.888	1.41	1.78	3.76	5.00	6.02	8.37
200	5.0E-03	0.950	1.51	1.9	4.15	5.65	6.84	9.49
500	2.0E-03	1.03	1.62	2.04	4.66	6.58	8.03	11.1
1,000	1.0E-03	1.09	1.72	2.16	5.11	7.43	9.13	12.5
2,000	5.0E-04	1.16	1.83	2.31	5.35	7.58	9.25	12.8
5,000	2.0E-04	1.24	1.96	2.47	5.82	8.31	10.2	14.0
10,000	1.0E-04	1.31	2.06	2.60	6.18	8.86	10.8	15.0

Notes: (a) Frequency is estimated as the inverse of the Return Period.

3.2.3 Previous SRS Estimates for PMP

In 1998, *Tornado, Maximum Wind Gust, and Extreme Rainfall Event Recurrence Frequencies at the Savannah River Site* (WSRC-TR-98-00329) provided PMP estimates for SRS using rainfall measurements up to the year 1997. The results from the 1998 analysis are shown in Table 3.2-6.

Table 3.2-6: Peak Precipitation Estimates for Selected Return Periods and Rainfall Accumulation Intervals from WSRC-TR-98-000329

Return Period (years)	Frequency (per year)[a]	Rainfall Accumulation Interval				
		15 minutes	1 hour	3 hours	6 hours	24 hours
10	1.0E-01	1.5	2.7	3.3	3.7	5.0
25	4.0E-02	1.8	3.2	4.0	4.4	6.1
50	2.0E-02	2.0	3.5	4.6	5.0	6.9
100	1.0E-02	2.1	3.9	5.1	5.7	7.8
200	5.0E-03	2.3	4.2	5.8	6.4	8.8
500	2.0E-03	2.6	4.7	6.7	7.4	10.3
1,000	1.0E-03	2.7	5.0	7.4	8.3	11.5
2,000	5.0E-03	2.9	5.4	8.2	9.2	12.8
5,000	2.0E-04	3.2	5.8	9.4	10.7	14.7
10,000	1.0E-04	3.3	6.2	10.3	11.8	16.3
50,000	2.0E-05	3.7	7.0	12.8	15.1	20.6
100,000	1.0E-05	3.9	7.4	14.1	16.7	22.7

Source: WSRC-TR-98-00329, Table XIX.
Notes: (a) Frequency is estimated as the inverse of the Return Period.

Then, in 2013, *Probabilistic Hazard Assessment for Tornadoes, Straight-line Wind, and Extreme Precipitation at the Savannah River Site* (SRNL-STI-2013-00664) the PMP estimates for SRS were updated using rainfall measurements from 1964 to 2012. The results from the 2013 analysis are shown in Table 3.2-7. Note that the 2013 report only provided results for four return periods.

Table 3.2-7: Peak Precipitation Estimates for Selected Return Periods and Rainfall Accumulation Intervals from SRNL-STI-2013-00664

Return Period (years)	Frequency (per year)[a]	Rainfall Accumulation Interval				
		15 minutes	1 hour	3 hours	6 hours	24 hours
2,500	4.0E-03	2.32	5.21	6.75	7.78	9.22
6,250	1.6E-04	2.50	5.66	7.33	8.44	9.97
10,000	1.0E-04	2.60	5.89	7.63	8.78	10.36
25,000	4.0E-05	2.78	6.33	8.21	9.44	11.11

Source: SRNL-STI-2013-00664, Table 5.10.
Notes: (a) Frequency is estimated as the inverse of the Return Period.

Comparing the values for a 10,000-years return period from Table 3.2-6 against the values for a 10,000-years return period from Table 3.2-7 shows the 2013 values are lower. SRNL-STI-2013-00664 attributed the difference in the results more due to a difference in the application of the Extreme Value function (y) than to the expanded record of data used.

3.2.4 Updated PMP Estimates for SRS

Using the Eliasson Method and the NOAA Method, the updated PMP values can be compared against the earlier estimates (Table 3.2-7). As shown, all of the values are generally similar in magnitude.

Table 3.2-8: Comparison of PMP Values

Reference or Method	PMP (in) Return Period of 1,000 years	PMP (in) Return Period of 10,000 years
15-Minute Duration		
WSRC-TR-98-00329	2.7	3.3
SRNL-STI-2013-00664	2.2	2.6
Eliasson Method, Updated	**2.7**	**3.3**
NOAA PDS PFE, Based on Logarithmic Line-Fitting	2.2	2.6
1-Hour Duration		
WSRC-TR-98-00329	5.0	6.2
SRNL-STI-2013-00664	4.8	5.9
Eliasson Method, Updated	**5.1**	**6.4**
NOAA PDS PFE, Based on Logarithmic Line-Fitting	5.1	6.2
24-Hour Duration		
WSRC-TR-98-00329	11.5	**16.3**
SRNL-STI-2013-00664	8.2	10.4
Eliasson Method, Updated	9.7	15.3
NOAA PDS PFE, Based on Logarithmic Line-Fitting	**12.5**	15.0

Note: Values shown in **bold** text indicate the highest value for the given storm duration and return period.

3.2.5 Recommendations for Applying PMP Estimates

Finally, assuming the highest value, regardless of reference or method, provides the most defensible PMP estimate for use in erosion calculations (Table 3.2-9).

Table 3.2-9: Recommended PMP Values

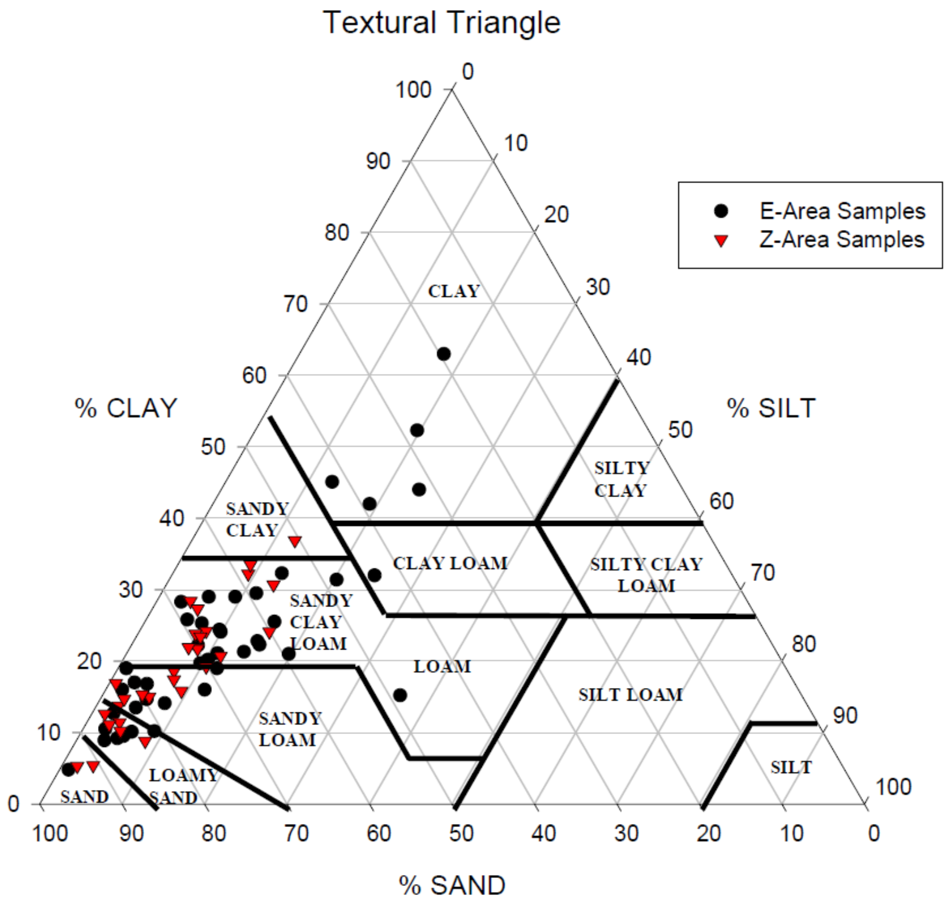
PMP Duration	PMP (in) Return Period of 1,000 years	PMP (in) Return Period of 10,000 years
15-Minute Duration	2.7	3.3
1-Hour Duration	5.1	6.4
24-Hour Duration	12.5	16.3

The 1,000-year return period PMP is appropriate to use for demonstrating compliance to a 1,000-year compliance period, while the 10,000-year return period PMP is appropriate for use in analyses to assess uncertainty.

3.3 Soil Properties

The Z-Area soils have been characterized using the "textural triangle" (Figure 3.3-1) according to the U.S. Department of Agriculture (USDA) system. [WSRC-STI-2006-00198] The results indicate that the texture of the soil is low in silt and high in sand with varying amounts of clay.

Figure 3.3-1: Textural Triangle for E-Area and Z-Area Vadose Zone Soils



[WSRC-STI-2006-00198]

Table 3.3-1 summarizes the physical properties that have been used in Performance Assessment modeling at SRS. These values were developed based on literature reviews and evaluations of available field data (WSRC-STI-2006-00198; WSRC-STI-2008-00244).

Table 3.3-1: Hydraulic Properties of Soils Used for Performance Assessment Modeling

Parameter	Sand	Backfill	Upper Vadose	Lower Vadose
Average Total Porosity (%)	41.7	35	39	39
Average Dry Bulk Density (g/cm^3)	1.55	1.71	1.65	1.62
Average Particle Density (g/cm^3)	2.66	2.63	2.70	2.66
Saturated Horizontal Hydraulic Conductivity (cm/s)	5.0E-02	7.6E-05	6.2E-05	3.3E-04
Saturated Vertical Hydraulic Conductivity (cm/s)	5.0E-02	4.1E-05	8.7E-06	9.1E-05

[SRR-CWDA-2019-00001, Table 4.3-2; developed from WSRC-STI-2006-00198 and WSRC-STI-2008-00244]

For the analyses discussed within this report, soil properties from an additional source are also considered. Specifically, data from the USDA's National Resources Conservation Service (NRCS) that was accessed through the USDA's online Web Soil Survey (https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm). The Web Soil Survey provides soil data and information produced by the National Cooperative Soil Survey. Their database includes soil information for more than 95% of the United States. Data for Aiken County soils comes from Rogers's 1985 *Soil Survey of Aiken County Area*.

Figure 3.3-2 identifies each of the soils in the vicinity of Z Area by unique identifiers. Descriptions for each of these soils, and their associated soil texture classifications, are provided in Table 3.3-2. Soils that only appear on the opposite sides of the local streams, as well as any soils that were estimated to comprise less than 1% of the area of interest, are not included in this table.

Figure 3.3-2: Identification of Soils at Z Area

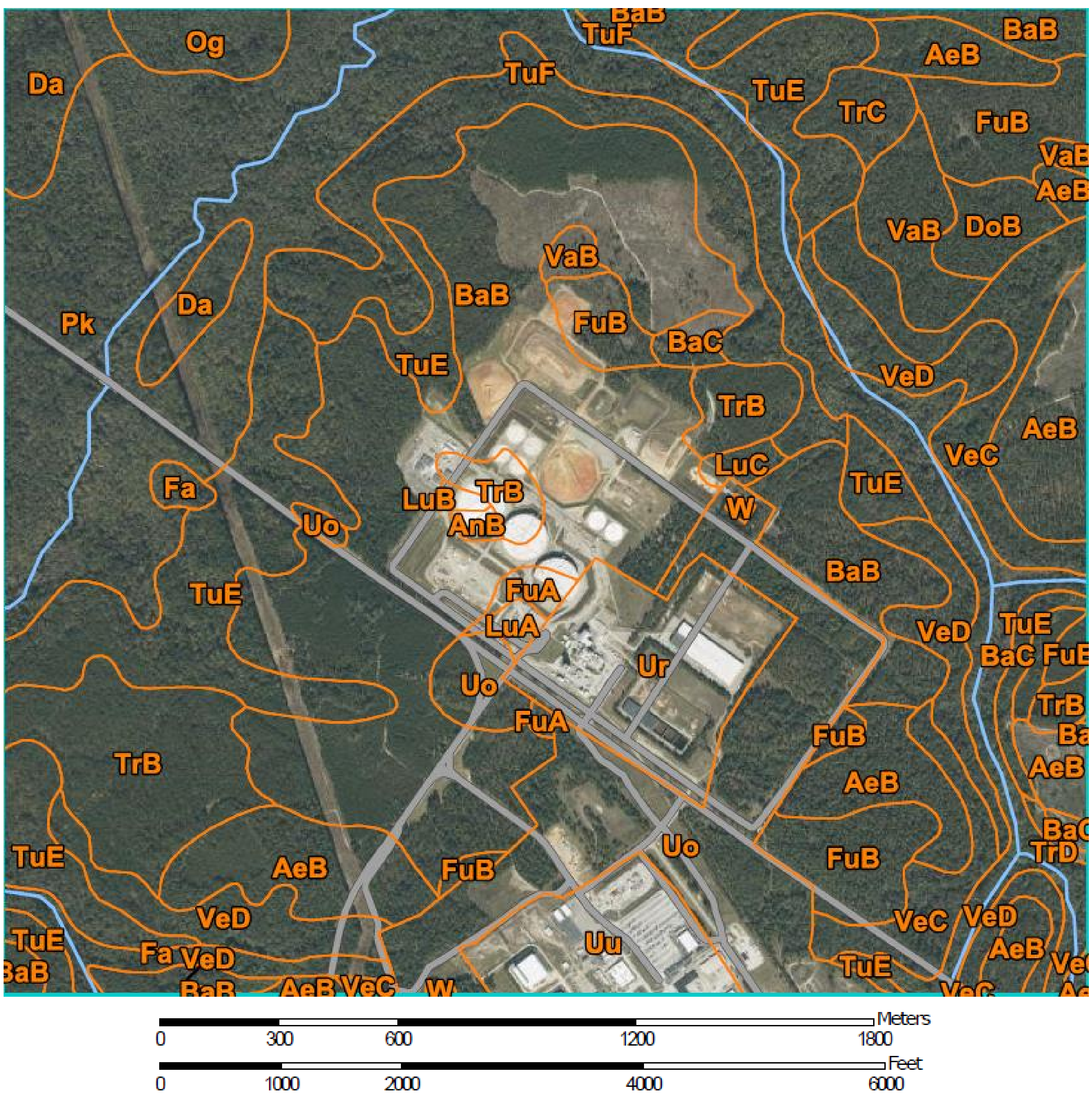


Table 3.3-2: NRCS Soil Texture Data for Selected Soils Identified at Z Area

Map Unit Symbol	Map Unit Name	Approx. Acres on SDF Side [a]	Soil Texture	Clay %	Sand %	Silt %
AeB	Ailey sand, 2 to 6 percent slopes, wet substratum	59.2	Sand	15.9%	73.6%	10.5%
BaB	Blanton sand, 0 to 6 percent slopes	327.4	Sand	11.2%	83.4%	5.4%
Da	Dorovan muck, frequently flooded	34.2	Muck	4.1%	44.3%	51.6%
Fa	Fluvaquents, frequently flooded	18.8	Loamy Sand	3.1%	93.6%	3.3%
FuB	Fuquay sand, 2 to 6 percent slopes	32.2	Sand	19.2%	73.7%	7.1%
Pk	Pickney sand, frequently flooded	186.8	Loamy Sand	5.7%	81.6%	12.7%
TrB	Troup sand, 0 to 6 percent slopes, Carolina and Georgia Sand Hills	79.3	Sand	10.5%	83.9%	5.6%
TuE	Troup and Lucy sands, 15 to 25 percent slopes	123.8	Sand	10.4%	84.7%	4.9%
TuF	Troup and Lucy sands, 25 to 40 percent slopes	64.7	Sand	10.4%	84.7%	4.9%
Uo	Udorthents, friable substratum	135.0	Sandy Loam	15.0%	60.0%	25.0%
Ur	Udorthents-Urban land complex, gently sloping	62.1	Sandy Loam	15.0%	60.0%	25.0%
Uu	Urban land	38.7	N/A	N/A	N/A	N/A
VeC	Vaucluse-Ailey complex, 6 to 10 percent slopes	12.9	Loamy Sand	23.2%	65.2%	11.6%
VeD	Vaucluse-Ailey complex, 10 to 15 percent slopes	43.2	Loamy Sand	23.2%	65.2%	11.6%

Notes: (a) Figure 3.3-2 shows an area of more than 1,680 acres. However, soils that are on opposite sides of the streams from the SDF are not included in the area estimates in this table. The total area of the soils on the SDF side of the area is approximately 1,244 acres (or approximately 74% of the depicted area). Then, because this table also excludes soils which contribute to less than 1% of the total area, the sum of the soils in this table account for approximately 1,220 acres (or approximately 72% of the depicted area).

The soil texture classifications in Table 3.3-2 are based on the percentages of clay, sand, and silt. Most of the area is dominated by soils that are classified as sands. In the highest elevations (e.g., the areas surrounding SDUs 1 and 4) the soils are classified as sandy loams, and in the low-lying areas (e.g., near the streams) the soils are predominantly loamy sands.

Next, Table 3.3-3 provides selected material properties for each of the soils identified in Table 3.3-2. These selected properties are bulk density, saturated hydraulic conductivity, and two sets of "K factor" values, which provide a measure of susceptibility of soil to sheet and rill erosion.

Bulk density is a measure of the dry weight of the soil per unit volume. Soils with higher bulk densities are generally expected to be more resistant to erosion because denser soil particles would require more energy to move. Excluding the Dorovan muck (Da), the bulk density values are all relatively similar, with a range of 1.41 g/cm^3 to 1.72 g/cm^3 and a mean value of 1.56 g/cm^3. These values are consistent with the soil properties presented in Table 3.3-1.

Saturated hydraulic conductivity is a quantitative measure of a saturated soil's ability to transmit water when subjected to a hydraulic gradient. Soils with a relatively high saturated hydraulic conductivity will more readily allow water to infiltrate into the subsurface, while soils with a relatively low saturated hydraulic conductivity are expected to promote greater surface runoff. As with the bulk density, the saturated hydraulic conductivity values are also all relatively similar, with a range of 1.0E-03 cm/s to 9.2E-03 cm/s and a mean value of approximately 5.0E-03 cm/s. These values are generally an order of magnitude lower than that of the sand presented in Table 3.3-1, but about two orders of magnitude higher than the other soils (Backfill, Upper Vadose Zone, and Lower Vadose Zone).

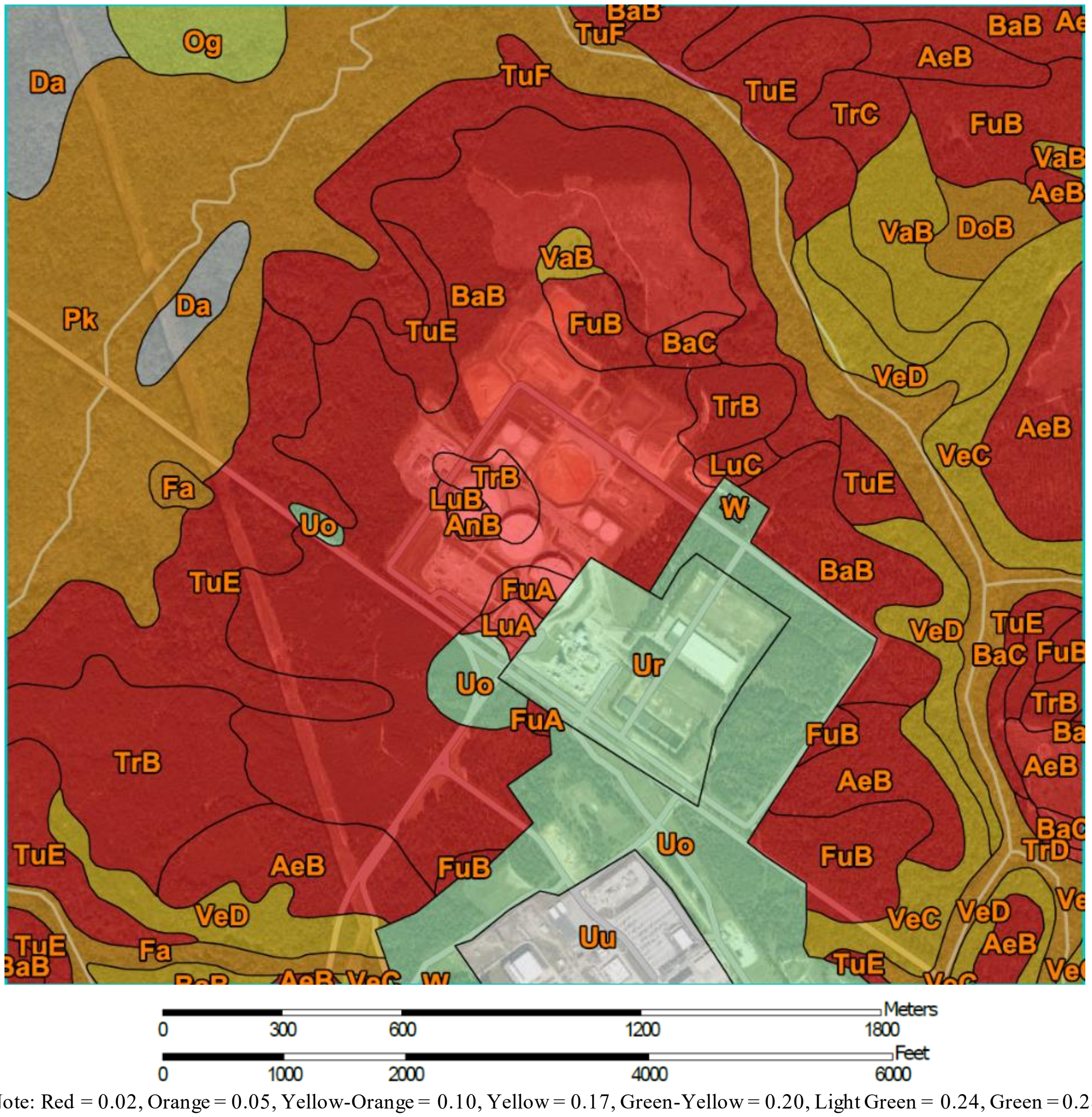
Table 3.3-3: Selected NRCS Soil Properties for Selected Soils Identified at Z Area (USDA Web Soil Survey)

Map Unit Symbol	Map Unit Name	Bulk Density (g/cm^3)	Saturated Hydraulic Conductivity (cm/s)	K Factor,	
				Surface	Depth Weighted
AeB	Ailey sand, 2 to 6 percent slopes, wet substratum	1.65	3.06E-03	0.02	0.28
BaB	Blanton sand, 0 to 6 percent slopes	1.52	6.47E-03	0.02	0.20
Da	Dorovan muck, frequently flooded	0.69	1.29E-03	Not Rated	0.28
Fa	Fluvaquents, frequently flooded	1.49	9.20E-03	0.10	0.10
FuB	Fuquay sand, 2 to 6 percent slopes	1.65	4.26E-03	0.02	0.17
Pk	Pickney sand, frequently flooded	1.41	9.20E-03	0.10	0.20
TrB	Troup sand, 0 to 6 percent slopes, Carolina and Georgia Sand Hills	1.63	6.53E-03	0.02	0.17
TuE	Troup and Lucy sands, 15 to 25 percent slopes	1.50	7.11E-03	0.02	0.24
TuF	Troup and Lucy sands, 25 to 40 percent slopes	1.50	7.11E-03	0.02	0.24
Uo	Udorthents, friable substratum	1.48	1.00E-03	0.28	0.28
Ur	Udorthents-Urban land complex, gently sloping	1.48	1.00E-03	0.28	0.28
Uu	Urban land	N/A	N/A	Not Rated	Not Rated
VeC	Vaucluse-Ailey complex, 6 to 10 percent slopes	1.72	2.24E-03	0.15	0.24
VeD	Vaucluse-Ailey complex, 10 to 15 percent slopes	1.72	2.24E-03	0.15	0.24

The K factor from Table 3.3-3 is a parameter used for estimating the rate of erosion using the Revised Universal Soil Loss Equation (RUSLE) from the United States Department of Agriculture (USDA-HDBK-703) (see Section 4.1). The first column of K factors provides surface-only values; these values are applicable when the surface soils are undisturbed. Figure 3.3-3 provides a graphical depiction of these values. In general, the "warmer" colors (e.g., reds and oranges) indicate lower K factor values, which indicate better resistance to erosion, and "cooler" colors (e.g., greens and blues) indicate higher K factor values, which indicate less resistance to erosion. As shown, for the surface soils most of the area surrounding the SDF is red, indicating a low K factor of 0.02.

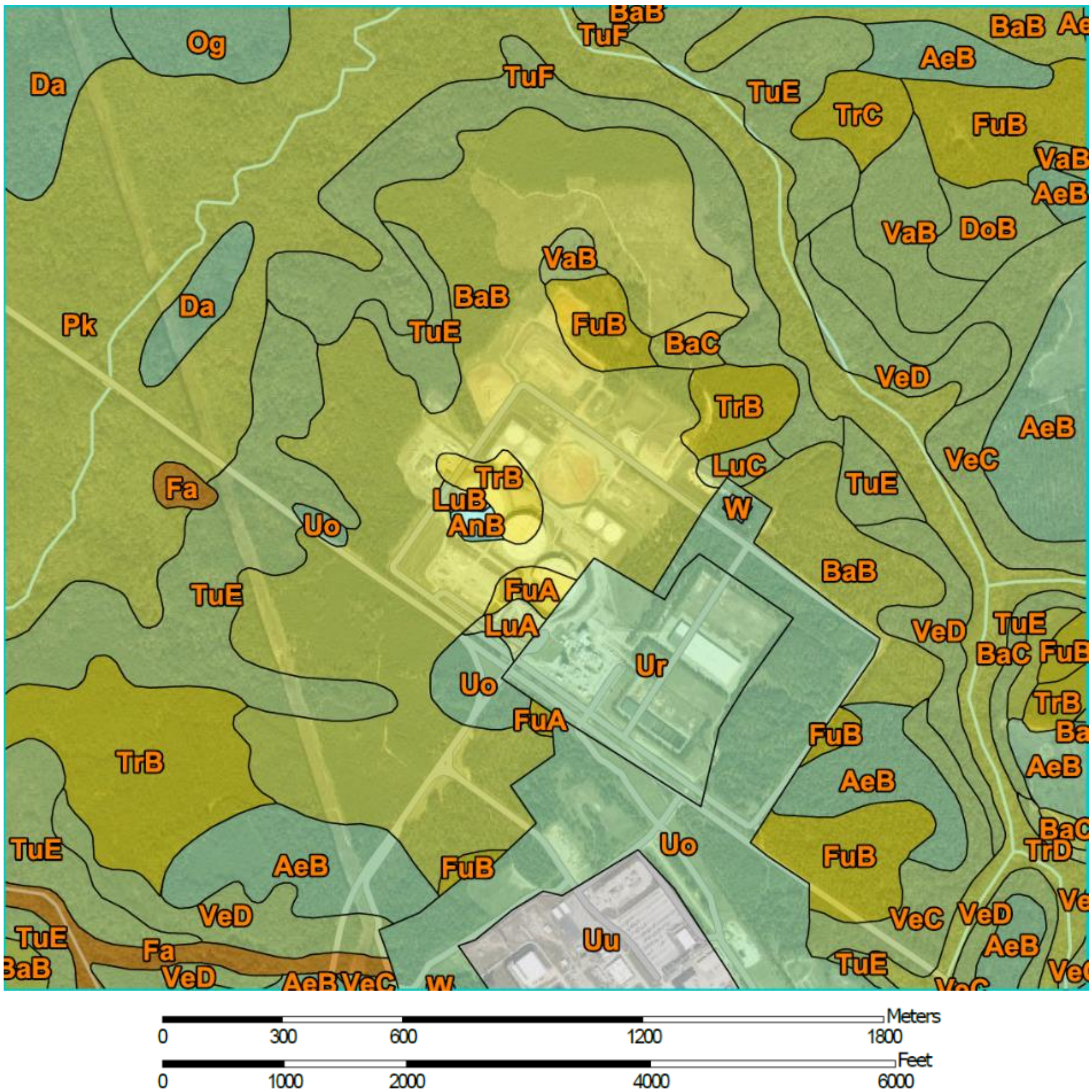
The second column of K factor values provides depth-weighted values; these values are applicable when the surface soils have been disturbed. Figure 3.3-4 provides a graphical depiction of these values. Around SDUs 1 and 4, the soils (Ur and Uo) have been disturbed by operations and construction activities, so both columns of Table 3.3-3 show the same values.

Figure 3.3-3: Surface Values for Soil Erodibility (K Factor) Values (USDA Web Soil Survey)



Note: Red = 0.02, Orange = 0.05, Yellow-Orange = 0.10, Yellow = 0.17, Green-Yellow = 0.20, Light Green = 0.24, Green = 0.28

Figure 3.3-4: Depth Averaged Values for Soil Erodibility (K Factor) Values (USDA Web Soil Survey)



Note: Red = 0.02, Orange = 0.05, Yellow-Orange = 0.10, Yellow = 0.17, Green-Yellow = 0.20, Light Green = 0.24, Green = 0.28

The use of the K factor is described further in Section 4.0. Based on the NRCS soil data, a value of 0.28 is conservatively assumed. This is consistent with previous analyses (WSRC-STI-2008-000244) and with similar recommendations based on an equivalent analysis performed for H-Area soils (SRR-CWDA-2021-00023).

3.4 Land Usage

The SDF is located within Z Area, which is centrally on site to support waste processing activities (i.e., it is located near HTF, FTF and SWPF so low-level waste may be transferred to the SPF). Construction of future SDUs is ongoing. These concrete structures are used to isolate low-level radioactive waste. In addition to the SDUs and the waste processing facilities, the GSA currently supports space for offices and paved roads.

Once closure activities are completed and the closure cap is constructed, the land use at Z Area will shift to grassy reclaimed lands with minimal disturbance and no paved features that could lead to higher runoff rates due to their impermeable properties. All runoff and erosion will occur over the reclaimed lands with no outside influencers.

It is noted that the U.S. federal government plans to own and maintain control of SRS in perpetuity per the *Savannah River Site Land Use Plan* (SRNS-RP-2014-00537). As such, it is possible that maintenance and erosion prevention measures may take place post closure; however, the analyses described within this report take no credit for any potential erosion control practices that may be deployed after an initial 100 year institutional control period.

4.0 METHODS FOR ASSESSING EROSION AND STABILITY

The discussions in the previous section provide estimates for weather extremes extending out to 10,000 years. These estimates are based on available and historic weather data, and thus cannot guarantee future conditions that might change due to unprecedented factors. The following discusses methods for addressing uncertainties associated with sediment loss due to future runoff events.

4.1 Potential Sheet and Rill Erosion Analysis

The average annual rate of soil loss due to erosion is commonly estimated using a form of the USDA's Universal Soil Loss Equation (USLE). For this analysis, the Revised Universal Soil Loss Equation (RUSLE) from the USDA's Agricultural Handbook: *Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE)* (USDA-HDBK-703) shall be used. The RUSLE is an updated version of the USLE used to determine soil loss. RUSLE estimates sedimentation rates caused by climate factors, sheet flow, and rill erosion. RUSLE is based on several theories of erosion processes, data from rainfall records, and rainfall simulations.

RUSLE determines erosion effectively for reclaimed lands and simulates such rates on an annual basis. It is unable to determine point-event erosion. The soil loss calculated by RUSLE does not capture any impacts from gullying that may occur on the cover, so this must be calculated separately. The RUSLE formula (USDA-HDBK-703) is given as:

$$A = R \times K \times L \times S \times C \times P \qquad \text{Eq. 4-1}$$

Where:

A = Computed spatial average soil loss and temporal average soil loss per unit of area, expressed in the units selected for K and for the period selected for R. In practice, these are usually selected so that A is expressed in ton/acre/year.

R = Rainfall-runoff erosivity factor: the rainfall erosion index plus a factor for any significant runoff from snowmelt.

K = Soil erodibility factor: the soil-loss rate per erosion index unit for a specified soil as measured on a standard plot, which is defined as a 72.6-ft (22.1-m) length of uniform 9% slope in continuous clean-tilled fallow.

L = Slope length factor: the ratio of soil loss from the field slope length to soil loss from a 72.6-ft length under identical conditions.

S = Slope steepness factor: the ratio of soil loss from the field slope gradient to soil loss from a 9% slope under otherwise identical conditions.

C = Cover-management factor: the ratio of soil loss from an area with specified cover and management to soil loss from an identical area in tilled continuous fallow.

P = Erosion control practice factor: the ratio of soil loss with a support practice like contouring, strip-cropping, or terracing to soil loss with straight-row farming up and down the slope.

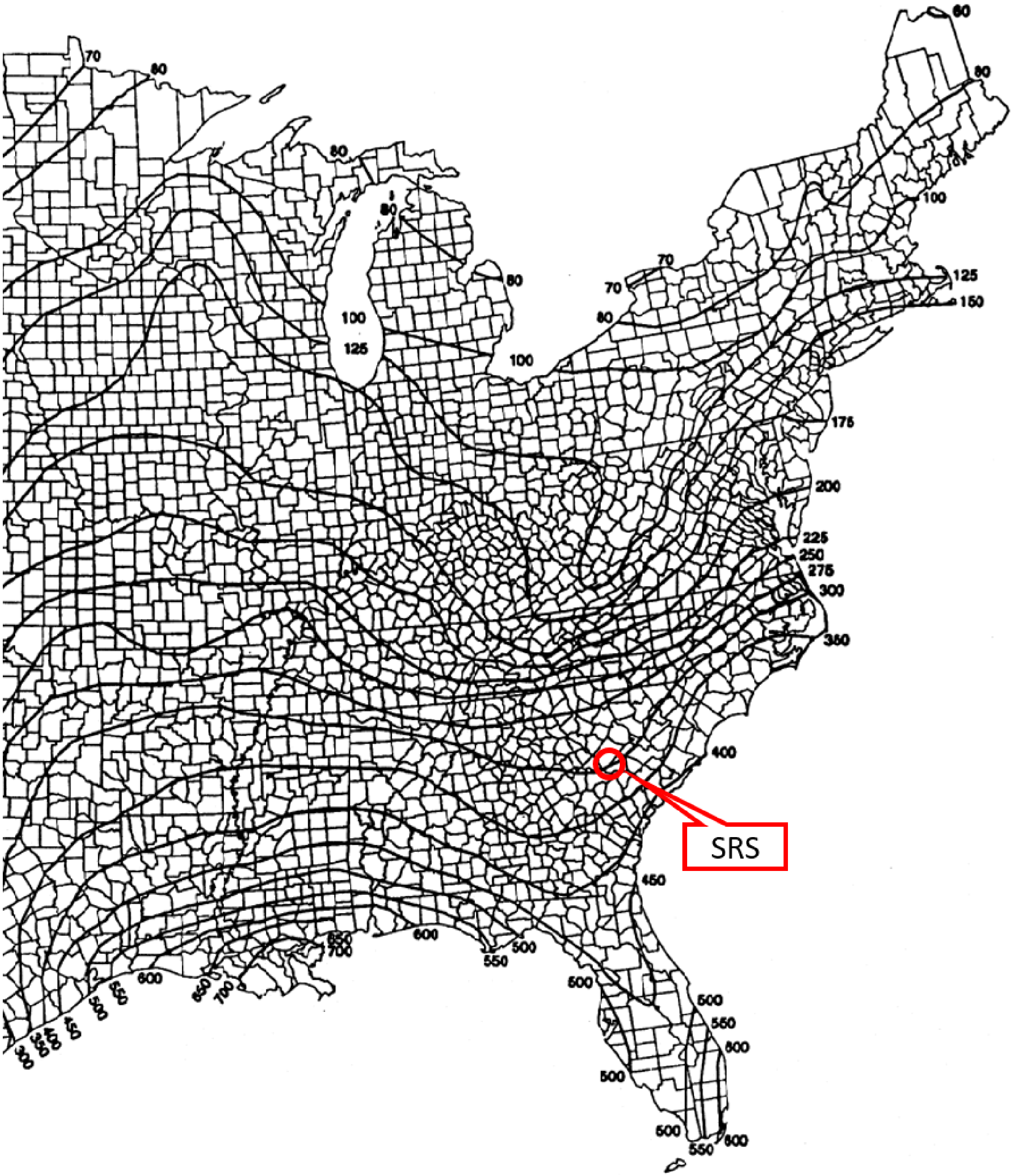
Using the A values from RUSLE it is possible to infer the thickness of cover soil at the end of design life or maintenance period for the closure cap. In the case of SDF, the annual soil loss value will be multiplied by the control period timeframe to ensure that the top layer will protect the lower layers of the closure cap.

The **rainfall-runoff erosivity factor (*R*)** is estimated as a function of rainfall. Specifically, when factors other than rainfall are held constant, data indicates that soil losses are proportional to the product total storm energy storm intensity (USDA-HDBK-703). The value for R is selected from isoerodent maps, which show that values can vary from less than 8 hundreds of (ft·tonf·in)/(acre·hr·yr) in the drier Western region of the United States to over 800 hundreds of (ft·tonf·in)/(acre·hr·yr) in coastal Louisiana.

Figure 4.1-1 shows an isoerodent map for the eastern United States from USDA-HDBK-703. Based on this figure, the location of SRS has a rainfall-runoff erosivity value of approximately 300 hundreds of (ft·tonf·in)/(acre·hr·yr). Similarly, the Federal Highway Administration developed an alternative isoerodent map for South Carolina (Figure 4.1-2). [FHWA-RD-77-159] Based on their map, the location of SRS has an rainfall-runoff erosivity value of approximately 350 hundreds of (ft·tonf·in)/(acre·hr·yr). Assuming the higher value would yield faster erosion rates; therefore, the value of 350 hundreds of (ft·tonf·in)/(acre·hr·yr) shall be used even though the map from USDA-HDBK-703 was published more recently (1997 as opposed to 1977).

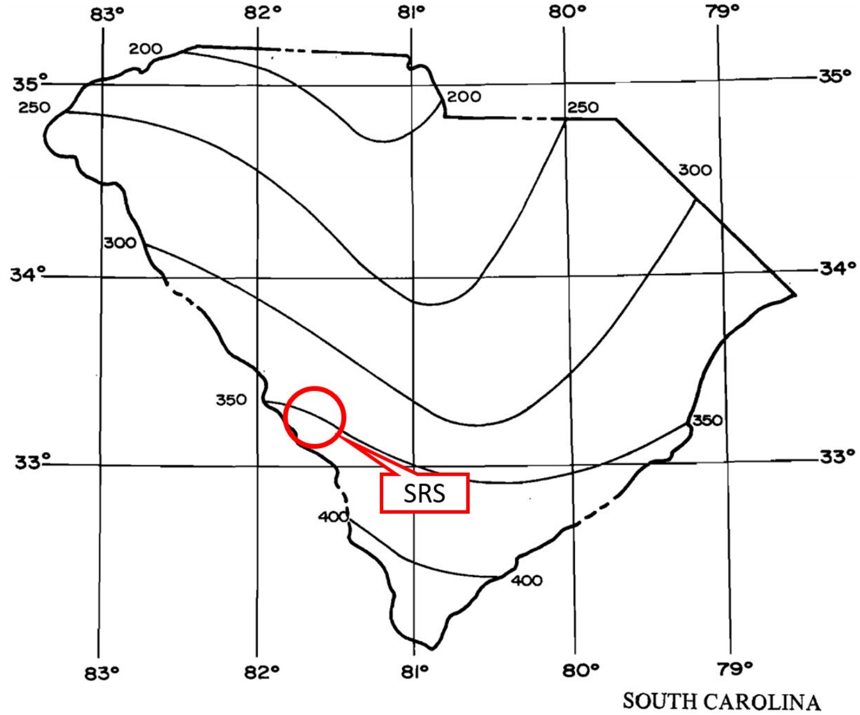
Note that the *Performance Assessment for the Saltstone Disposal Facility at the Savannah River Site* (SRR-CWDA-2019-00001) used 300 hundreds of (ft·tonf·in)/(acre·hr·yr) from USDA-HDBK-703. Both values are higher than the values recommended as part of the *SRS Engineering Standards Manual for Civil Site Design Criteria* (WSRC-TM-95-1-01110), which recommends rainfall-runoff erosivity values of 250 hundreds of (ft·tonf·in)/(acre·hr·yr) for Aiken County and 275 hundreds of (ft·tonf·in)/(acre·hr·yr) for Barnwell County.

Figure 4.1-1: Isoerodent Map of Eastern United States, Modified from USDA-HDBK-703



[Figure 2-1 from USDA-HDBK-703, modified to show approximate location of SRS.
Units are hundreds of (ft·tonf·in)/(acre·hr·yr).]

Figure 4.1-2: Isoerodent Map of South Carolina, Modified from FHWA-RD-77-159



[Appendix C-45 from FHWA-RD-77-159, modified to show approximate location of SRS. Units are hundreds of (ft·tonf·in)/(acre·hr·yr).]

The **soil erodibility factor (*K*)** is an empirical measure of soil erodibility based on the physical characteristics of soil. The main soil properties used in developing a K value include soil texture, such as the percentages of sand, silt, and clay, organic matter, soil structure, and the permeability of soils. Clay soils have low K values due to their resistance to detachment. Sandy soils also have low K values attributed to their high infiltration rates and lower runoff. Silt and loam type soils have moderate to high K values due to their ease of detachment and low infiltration contributing to higher runoff. Silt soils have the highest K values because they easily clump and detach, causing large amounts of sediment to be transported.

This is the same K factor discussed in Section 3.3, which showed that locally this parameter varies between 0.02 tons/acre per unit of *R* and 0.28 tons/acre per unit of *R*. Based on this range, the value of 0.28 tons/acre per unit of *R* is assumed.

The **slope length factor (*L*)** and the **slope steepness factor (*S*)** are combined into a single unitless topographic factor (*LS*). RUSLE uses these topographic factors to determine the effects of rill erosion caused by surface runoff that increases downslope. *L* is defined as the distance between the upslope starting point on the slope to the downslope point where deposition begins. Erosion rates increase as the slope steepness, *S*, increases.

For the *Performance Assessment for the Saltstone Disposal Facility at the Savannah River Site* (SRR-CWDA-2019-00001) a value of 0.59 was assumed based on extrapolating data from Table 4-1 from USDA-HDBK-703, using a 3% surface slope and an assumed slope length of 1,170 ft.

Note that the closure cap design, as described in Section 2.2 has a maximum slope of 1,020 ft (Figure 2.2-1); the 1,170 ft was based an alternative closure cap design with a 1.5% surface slope. The higher slope length (based on the alternative design) was assumed for greater defensibility. The resulting LS value was 0.59; however, the difference between using 1,170 feet versus using 1,020 feet for this parameter is negligible, as using the design slope length would change the LS value from 0.59 to 0.57. Therefore, to maintain consistency with the design, the value of 0.57 shall be used.

The **cover-management factor (C)** represents cover management and the impact of land use on erosion. It describes the relationship between vegetation communities, tillage systems, and mulches. The C factor is an amalgamation of canopy cover, ground cover, surface roughness, rooting networks in soil, and organic matter. In the Southern United States, erosivity is mostly static throughout the year, with more variability between the seasons in the Midwest and Pacific Coast. Values for C can range from nearly zero for well-protected soil to 1.5 for finely tilled, ridged surfaces that leave soil vulnerable to rill erosion (USDA-HDBK-703).

The cover-management factor (C) has been a subject of scrutiny due to the variability in potential values. Specifically, in *Technical Review: Hydraulic Performance and Erosion Control of the Planned Saltstone Disposal Facility Closure Cap and Adjacent Area (Docket No. PROJ0734)*, technical staff from the U.S. Nuclear Regulatory Commission suggested that defining the cover-management factor (C) using more "recent publications may provide additional information as to the correct range of C factors" (ML18002A545). In 2015, Panagos et al. provided recommended values for C based on literature reviews, statistical analyses, and biophysical attributes derived from remote sensing across the European Union. Table 4.1-1 shows the ranges of values defined by Panagos et al. (2015).

Most of the land surrounding the SDF at SRS would be classified as either "coniferous forest" or "mixed forest," both with a range of C values from 0.0001 to 0.003 per Table 4.1-1. This is the most likely anticipated end-state for the vegetative cover, and the appropriate range of values to assume for the Z Area Hills Slopes. However, the SDF closure cap and the Z Area Hilltops will likely be vegetated with grasses prior to any forest succession, which would suggest a higher value for C: 0.05 to 0.15 for pastures per Table 4.1-1. Prior to forestation, as an intermediate stage, the "transitional woodland shrub," with C values of 0.003 to 0.05 would be appropriate.

Jones and Phifer (2008) recommended a succession timeline for the growth of pine trees at SRS which would begin approximately 40 years after the end of the institutional control prior (140 years after SDF closure) and would take 320 years to complete (460 years after SDF closure) (WSRC-STI-2008-00244). Based on this recommendation, the cover-management factor (C) should be implemented as follows:

- From 0 to 140 years after closure, C = 0.05 to 0.15,
- From 140 to 460 years after closure, C = 0.003 to 0.05, and
- At 460 years after closure and beyond, C = 0.0001 to 0.003.

With respect to handling the ranges for these values, Panagos et al. (2015) recommended applying the range of values as a function of the fractional abundance of bare soil versus ground cover:

$$C = \mathrm{Min}(C_{LandUse}) + \mathrm{Range}(C_{LandUse}) \times (1 - F_{cover}) \quad \text{Eq. 4-2}$$

Where:

C = the value to use for the cover-management factor,

$C_{LandUse}$ = the values from Table 4.1-1, and

F_{Cover} = the fraction of ground covered by vegetation.

The greatest challenge in imposing this approach is the lack of data for appropriate F_{Cover} values, especially with respect to predicting such values into the future. For simplicity and maximum defensibility, F_{cover} is assumed to be 0 which means the maximum value of C is assumed within each range (values starting at 0.15 for grasses, then 0.05 for transitional woodland shrub, then 0.003 for forest, based on the assumed evolution). This is assumption is expected to overpredict erosion, especially because satellite and aerial imagery of the Savannah River Site indicate that much of the surface is heavily vegetated.

In the *Performance Assessment for the Saltstone Disposal Facility at the Savannah River Site* (SRR-CWDA-2019-00001), three values were considered, for three separate vegetation scenarios: 0.001 for pinewood forests, 0.004 for Bahiagrass, and 0.007 for unmanaged undergrowth.

Table 4.1-1: C-Factors for Non-arable Land Covers from Panagos et al. (2015)

Group	Detailed class	Description	C-factor values
Permanent crops	Vineyards	Areas planted with vines	0.15–0.45
	Fruit trees & berry plantations	Parcels planted with fruit trees or shrubs: single/mixed fruit species, fruit trees associated with permanently grassed surfaces.	0.1–0.3
	Olive groves	Areas planted with olive trees	0.1–0.3
Pastures	Pastures	Dense, predominantly graminoid grass cover, of floral composition, not under a rotation system. Mainly used for grazing.	0.05–0.15
Hetero-geneous agricultural areas	Annual crops associated with permanent crops	Non-permanent crops (arable land or pasture) associated with permanent crops on the same land parcel (non-associated annual crops represent less than 25%)	0.07–0.35
	Complex cultivation patterns	Juxtaposition of small parcels of diverse annual crops, pasture and/or permanent crops (arable land, pasture and orchards each occupy less than 75% of the total surface area of the land unit)	0.07–0.2
	Land principally used for agriculture, with significant areas of natural vegetation	Areas principally used for agriculture, interspersed with significant natural areas (agricultural land occupies between 25 and 75% of the total surface of the land unit)	0.05–0.2
	Agro-forestry areas	Annual crops or grazing land under the wooded cover of forest species	0.03–0.13
Forests	Broad-leaved forest	Vegetation formation composed principally of trees, including shrub and bush understories, where broadleaved species predominate.	0.0001–0.003
	Coniferous forest	Vegetation formation composed principally of trees, including shrub and bush understories, where coniferous species predominate.	0.0001–0.003
	Mixed forest	Vegetation formation composed principally of trees, including shrub and bush understories, where broadleaved and coniferous species co-dominate.	0.0001–0.003
Scrub and/or herbaceous vegetation associations	Natural grasslands	Low productivity grassland. Often situated in areas of rough and uneven ground	0.01–0.08
	Moors and heathland	Vegetation with low and closed cover, dominated by bushes, shrubs and herbaceous plants (heath, briars, broom, gorse, laburnum)	0.01–0.1
	Sclerophyllous vegetation	Bushy sclerophyllous vegetation. Includes maquis (dense vegetation composed of numerous shrubs) and garrige (oak, arbutus, lavender, thyme, cistus)	0.01–0.1
	Transitional woodland-shrub	Bushy or herbaceous vegetation with scattered trees. Can represent either woodland degradation or forest regeneration/colonisation. [*stet*]	0.003–0.05
Open spaces with little or no vegetation	Beaches, dunes, sands	Beaches, dunes and expanses of sand or pebbles in coastal or continental areas	0
	Bare rocks	Scree, cliffs, rocks and outcrops	0
	Sparsely vegetated areas	Includes steppes, tundra and badlands. Scattered high-altitude vegetation	0.1–0.45
	Burnt areas	Areas affected by recent fires, still mainly black	0.1–0.55
	Glaciers and perpetual snow	Land covered by glaciers or permanent snowfields	0

The **erosion control practice factor (P)** represents supporting maintenance for land including contouring, slopes, terraces, basins, and subsurface drainage. These features support erosion control by redirecting runoff on the slope or slowing down runoff. The erosion control practice factor (P) factor assumes runoff rates are a function of location, soil, management practice, erosivity and transport capacity of runoff related to slope gradient and hydraulic roughness of surface, and sediment size (USDA-HDBK-703).

Although the U.S. federal government will own and maintain control of SRS in perpetuity, (per the *Savannah River Site Land Use Plan* (SRNS-RP-2014-00537)), no credit is assumed for any potential erosion control practices that may be deployed; therefore, a value of 1 shall be assumed for the **erosion control practice factor (P)**. This is consistent with regulatory guidance in the Department of Energy (DOE) Standard: *Disposal Authorization Statement and Tank Closure Documentation* (DOE-STD-5002-2017), which recommends that institutional control of a facility be assumed for the first 100 years after closure, and any active maintenance beyond this period must be justified.

Table 4.1-2 provides a summary of the recommended parameter values for RUSLE based on the previous discussions.

Table 4.1-2: Summary of Recommended Values for RUSLE Parameters

Parameter	**Recommended Values(s)**	**Condition(s) (if Applicable)**
Rainfall-runoff erosivity factor (R)	350 hundreds of (ft·tonf·in)/(acre·hr·yr)	Not Applicable.
Soil erodibility factor (K)	0.28 tons/acre per unit of R	Not Applicable.
Slope length factor (L) and the Slope steepness factor (S)	0.57	Not Applicable.
Cover-management factor (C)	0.15	0 to 140 yrs (grass)
	0.05	140 to 460 yrs (mix)
	0.003	460 yrs and beyond (forest)
Erosion control practice factor (P)	1	Not Applicable.

Once the value for the spatial average soil loss and temporal average soil loss per unit of area (A) in tons/acre/yr is found using the RUSLE formula (Eq. 4-1), it may be converted into a depth of soil loss per year by dividing the value by the average bulk density of the soil. Table 3.3-1 and Table 3.3-3 indicate that the Z Area soils have bulk densities that vary between 1.41 g/cm^3 and 1.72 g/cm^3. For this analysis a nominal value of 1.56 g/cm^3 will be assumed.

It should be noted that the RUSLE formula is not a dynamic representation of long-term conditions but is being applied here a simplification based on shorter term erosion studies. This is expected to over-predict erosion because over time, as mass is transported via erosion, it is expected that the steepness of the surface of the slope would gradually decrease. As the steepness of the closure cap decreases, so would the slope steepness factor and the resulting rate of soil loss. However, given the uncertainties associated with this process, no credit it taken for this aspect of the evolution of the system.

4.2 Potential for Gullying Analysis

The concentration of runoff over a vegetated cover system or closure cap can cause various deformations on the top layer resulting in a potential growth for gullies if left unchecked. Gullying is the most severe type of erosion that can occur on a cover system, leading to deep cracks exposing multiple layers. In addition to this, gullying occurs more often on reclaimed surfaces than on materials in-situ. Gully formation is dynamic and can occur anywhere throughout a cover system. The consensus of the geotechnical engineering community is that research is needed to develop better methods for predicting gully development. However, there are methods for predicting the potential for gully development.

Physical stability requirements for the final closure cap design shall be established according to stability calculations equivalent to those presented in Appendix A of *Saltstone Disposal Facility Closure Cap Concept and Infiltration Estimates* (WSRC-STI-2008-00244) and were developed based on the NRC's *Design of Erosion Protection for Long-Term Stabilization* (NUREG-1623).

As defined in Appendix A of *Saltstone Disposal Facility Closure Cap Concept and Infiltration Estimates* (WSRC-STI-2008-00244), the slope is considered stable if the maximum permissible velocity is greater than the calculated actual velocity. The maximum permissible velocity is the highest velocity at which water can be transported without significant sediment attachment occurring. If the computed actual velocity is less than the permissible velocity, gullying should not occur. The equation showing this final calculation is shown as:

$$V_a < V_p \qquad \text{Eq. 4-3}$$

Where:

- V_a = the actual velocity (see Eq. 4-4) of flow over a given surface with a defined slope during a PMP event, and
- V_p = the permissible velocity (see Eq. 4-10) of flow over a given surface with a defined slope during a PMP event.

4.2.1 Calculations to Determine Actual Velocity

The first step is determining the actual velocity:

$$V_a = \frac{Q}{y} \qquad \text{Eq. 4-4}$$

Where:

- V_a = the actual velocity of flow over a given surface with a defined slope,
- Q = the peak flow rate (see Eq. 4-5), and
- y = the flow depth (see Eq. 4-9).

The **peak flow rate (Q)** is calculated as the product of four input values, as shown in Eq. 4-5, which is also known as the Rational Method formula:

$$Q = F \times C \times I \times A \qquad \text{Eq. 4-5}$$

Where:

Q = the peak flow rate (ft^3/s),

F = the flow concentration factor (see discussion below),

C = runoff coefficient (see discussion below),

I = rainfall intensity (see Eq. 4-6), and

A = drainage area (see Eq. 4-8).

The **flow concentration factor (F)** is used to adjust for uncertainty in the geometric influence of tributary discharge. Possible values range from 1.0 for overland sheet flow, 2.0 for a high probability of concentrated flow, or 3.0 for a high probability of channelized flow (NUREG/CR-4651, Vol. 2, Section 7.1). Per NUREG-1623, (page A-4, Step 3) the default recommended value is 3.0, which is the most conservative value; however, other values may be used if appropriately justified. For vegetated surfaces, the factor should be between 2 and 3, so a value of 2.5 shall be assumed herein.

Due to the assumed rural nature of the site, the **runoff coefficient (C)** is calculated based on relief, soil infiltration, vegetal cover, and surface storage. Runoff coefficients can be determined based on Table 4.2-1 (below), from Thomason (2019).

For the SDF closure cap, the variable selections are shown below based on design characteristics.

- Relief: Low, 0.14
- Soil infiltration: Normal, 0.08
- Vegetal Cover: Low, 0.06
- Surface Storage: High, 0.10

The runoff coefficient is calculated by adding the above factors together for a coefficient of 0.38.

Table 4.2-1: Runoff Coefficients for Rural Watersheds

Watershed characteristic	Extreme	High	Normal	Low
Relief (C_r)	0.28-0.35 Steep, rugged terrain with average slopes above 30%	0.20-0.28 Hilly, with average slopes of 10-30%	0.14-0.20 Rolling, with average slopes of 5-10%	0.08-0.14 Relatively flat land, with average slopes of 0-5%
Soil infiltration (C_i)	0.12-0.16 No effective soil cover; either rock or thin soil mantle of negligible infiltration capacity	0.08-0.12 Slow to take up water, clay or shallow loam soils of low infiltration capacity or poorly drained	0.06-0.08 Normal; well drained light or medium textured soils, sandy loams	0.04-0.06 Deep sand or other soil that takes up water readily; very light, well-drained soils
Vegetative Cover C_v)	0.12-0.16 No effective plant cover, bare or very sparse cover	0.08-0.12 Poor to fair; clean cultivation, crops or poor natural cover, less than 20% of drainage area has good cover	0.06-0.08 Fair to good; about 50% of area in good grassland or woodland, not more than 50% of area in cultivated crops	0.04-0.06 Good to excellent; about 90% of drainage area in good grassland, woodland, or equivalent cover
Surface Storage (C_s)	0.10-0.12 Negligible; surface depressions few and shallow, drainageways steep and small, no marshes	0.08-0.10 Well-defined system of small drainageways, no ponds or marshes	0.06-0.08 Normal; considerable surface depression, e.g., storage lakes and ponds and marshes	0.04-0.06 Much surface storage, drainage system not sharply defined; large floodplain storage, large number of ponds or marshes
The total runoff coefficient based on the 4 runoff components is $C = C_r + C_i + C_v + C_s$				

The next parameter to determine for Eq. 4-5 is the rainfall intensity (I), which is a function of the PMP value from Section 3.2.5. Rainfall intensity is estimated as:

$$I = \frac{PMP}{t_c} \qquad \text{Eq. 4-6}$$

Where:

I = rainfall intensity (in inches per hour),

PMP = the probable maximum precipitation event (PMP) in inches (see Section 3.2.5, and

t_c = time of concentration (in hours) (see Eq. 4-7).

This time of concentration (t_c) can be estimated using Equation D-2 from NUREG-1623 [ML022530043]:

$$t_c = \left(11.9 \times \frac{{L_{mi}}^3}{(L_{ft} \times S)}\right)^{0.385} \qquad \text{Eq. 4-7}$$

Where:

t_c = time of concentration (in hours),

L_{mi} = the maximum drainage length (in miles),

L_{ft} = the maximum drainage length (in feet), and

S = percent-slope.

The selection of the appropriate PMP value to use in Eq. 4-6 is also determined based on the time of concentration (t_c) from Eq. 4-7, where t_c = the PMP measurement interval. For example, if t_c equals 15 minutes, then the appropriate PMP value to use for evaluating performance over a 10,000-year period of recurrence would be the PMP value developed from the 15-minute measurement intervals for the 10,000-year period (see Section 3.2.5). In most cases, the t_c value will not align with a specific PMP measurement interval, so it is necessary to interpolate or extrapolate values based on the PMP measurement intervals provided in Table 3.2-9. Since the shortest PMP interval in Table 3.2-9 is 15 minutes, if the time of concentration (t_c) is less than 15 minutes, then the PMP value for a 5-minute interval will be assumed to be equal to half the PMP value for the 15-minute interval to support interpolation.

Note that according to the Washington State Department of Transportation *Hydraulics Manual* (M 23-03.06), a time of concentration of less than 5 minutes (0.0833 hr) should never be used. This is because PMP data less than 5 minutes may be unreliable, and because rainfall takes time to generate runoff, thus it would not be realistic to have less than 5 minutes for a time of concentration. [M 23-03.06]

Next, to complete Eq. 4-5 the drainage area (A) is found:

$$A = \frac{L_{ft}}{43{,}560} \qquad \text{Eq. 4-8}$$

Where:

A = drainage area (in acres) and

L_{ft} = the maximum drainage length (in feet) (1,020 feet based on the closure cap design described in Section 2.2).

The value of 43,560 is the unit conversion factor for square feet per acre from NUREG-1623 [ML022530043], Equation D-2.

Next, to complete Eq. 4-4, the flow depth (y) is calculated based on NUREG-1623 [ML022530043], Equation A-3:

$$y = \left(\frac{Qn}{1.486 \times S^{0.5}}\right)^{\left(3/5\right)} \qquad \text{Eq. 4-9}$$

Where:

y = the flow depth,

Q = the peak flow rate (see Eq. 4-5),

n = the Manning coefficient of roughness (described below), and

S = percent-slope (3% based on the closure cap design described in Section 2.2).

The **Manning's coefficient of roughness (n)** is an empirical, unitless coefficient for sheet flow related to velocity, hydraulic radius, and vegetative cover. Table 4.2-2 provides a summary of the Manning's coefficient of roughness (n) for excavated or dredged channels, lined channels, and natural streams that was compiled by Chow (1959). For this analysis, a Manning's coefficient of roughness (n) of 0.265 is assumed as the midpoint in the 0.030 to 0.50 range for a vegetated lining.

Table 4.2-2: Manning's Roughness Coefficients

Type of channel	Manning's n	
A. Excavated or dredged channels		
1. Earth, straight and uniform	Minimum	Maximum
a. Clean, recently completed	0.016	0.020
b. Clean, after weathering	0.018	0.025
c. Gravel, uniform section, clean	0.022	0.030
d. With short grass, few weeds	0.022	0.033
2. Earth, winding and sluggish	Minimum	Maximum
a. No vegetation	0.023	0.030
b. Grass, some weeds	0.025	0.033
c. Deep weeds or aquatic plants in deep channels	0.030	0.040
d. Earth bottom and rubble sides	0.028	0.035
e. Stony bottom and weedy banks	0.025	0.040
f. Cobble bottom and clean sides	0.030	0.050
g. Winding, sluggish, stony bottom, weedy banks	0.025	0.040
h. Dense weeds as high as flow depth	0.050	0.120
3. Dragline-excavated or dredged	Minimum	Maximum
a. No vegetation	0.025	0.033
b. Light brush on banks	0.035	0.060
4. Rock cuts	Minimum	Maximum
a. Smooth and uniform	0.025	0.040
b. Jagged and irregular	0.035	0.050
5. Unmaintained channels	Minimum	Maximum
a. Dense weeds, high as flow depth	0.050	0.120
b. Clean bottom, brush on sides	0.040	0.080
c. Clean bottom, brush on sides, highest stage	0.045	0.110
d. Dense brush, high stage	0.080	0.140
B. Lined channels		
1. Asphalt	0.013	0.016
2. Brick (in cement mortar)	0.012	0.018
3. Concrete	Minimum	Maximum
a. Trowel finish	0.011	0.015
b. Float finish	0.013	0.016
c. Unfinished	0.014	0.020
d. Gunite, regular	0.016	0.023
e. Gunite, wavy	0.018	0.025
4. Riprap (n-value depends on rock size)	0.020	0.035
5. Vegetal lining	0.030	0.500

Table 4.2-2: Manning's Roughness Coefficients (Continued)

Type of channel	Manning's n	
C. Natural streams		
1. Minor streams (top width at flood stage < 100 ft)	Minimum	Maximum
a. Clean, straight, full, no rifts or deep pools	0.025	0.033
b. Same as a, but more stones and weeds	0.030	0.040
c. Clean, winding, some pools and shoals	0.033	0.045
d. Same as c, but some weeds and stones	0.035	0.050
e. Same as d, lower stages, more ineffective	0.040	0.055
f. Same as d, more stones	0.045	0.060
g. Sluggish reaches, weedy, deep pools	0.050	0.080
h. Very weedy, heavy stand of timber and underbrush	0.075	0.150
i. Mountain streams with gravel and cobbles, few boulders on bottom	0.030	0.050
j. Mountain streams with cobbles and large boulders on bottom	0.040	0.070
2. Floodplains	Minimum	Maximum
a. Pasture, no brush, short grass	0.025	0.035
b. Pasture, no brush, high grass	0.030	0.050
c. Cultivated areas, no crop	0.020	0.040
d. Cultivated areas, mature row crops	0.025	0.045
e. Cultivated areas, mature field crops	0.030	0.050
f. Scattered brush, heavy weeds	0.035	0.070
g. Light brush and trees in winter	0.035	0.060
h. Light brush and trees in summer	0.040	0.080
i. Medium to dense brush in winter	0.045	0.110
j. Medium to dense brush in summer	0.070	0.160
k. Trees, dense willows summer, straight	0.110	0.200
l. Trees, cleared land with tree stumps, no sprouts	0.030	0.050
m. Trees, cleared land with tree stumps, with sprouts	0.050	0.080
n. Trees, heavy stand of timber, few down trees, flood stage below branches	0.080	0.120
o. Trees, heavy stand of timber, few down trees, flood stage reaching branches	0.100	0.160
3. Major streams (top width at flood stage > 100 ft)	Minimum	Maximum
a. Regular section with no boulders or brush	0.025	0.060
b. Irregular rough section	0.035	0.100

Source: Adapted from Chow, 1959, Table 5-6.

4.2.2 Calculations to Determine Permissible Velocity

The final step is determining the permissible velocity (V_p) to identify potential gully formation using the Permissible Velocity Method for Vegetated Surfaces (Chow, 1959). Flow velocity should be less than the permissible velocity for the vegetated cover. Flow velocity is found using Eq. 4-5.

$$V_p = MPV \times CF \qquad \text{Eq. 4-10}$$

Where:

V_p = the permissible velocity of flow over a vegetative soil cover with a defined slope during a PMP event.

MPV = the maximum permissible velocity (see Table 4.3 3), and

CF = the velocity correction factor (discussed below).

Table 4.2-3 provides the maximum permissible velocities (MPV) for channels lined with vegetation, as adapted from the USDA's *Handbook of Channel Design for Soil and Water Conservation* (SCS-TP-61). As a simplifying assumption, any channels that form are assumed to be vegetated with Bahiagrass, which is common throughout the Southeast United States (per Figure 2.1-1). With a slope of less than 5%, and assuming the SDF closure cap soils will be easily eroded, the maximum permissible velocity is equal to 5 ft/s.

Table 4.2-3: Maximum Permissible Velocities in Channels Lined with Vegetation

Cover	Slope Range (%)	Maximum Permissible Velocity (MPV) (ft/s)	
		Erosion Resistant Soils	Easily Eroded Soils
Bermudagrass	<5	8	6
	5 to 10	7	5
	> 10	6	4
Bahiagrass Buffalo grass Kentucky bluegrass Smooth brome Blue grama Tall fescue	<5	7	5
	5 to 10	6	4
	> 10	5	3
Grass mixture Reed canary grass	<5	5	4
	5 to 10	4	3
Sericea lespedeza Weeping love grass Yellow bluestem Kudzu Redtop Alfalfa Red fescue Crab grass	<5	3.5	2.5
Common lespedeza Sudan grass	<5	3.5	2.5

[Reference: Adapted from Table 3 from SCS-TP-61.]

The velocity correction factor (CF) may be interpolated from values in Table 4.2-4, which is from page A-5 of NUREG-1623.

Table 4.2-4: Velocity Correction Factors

Flow Depth (ft)	Velocity Correction Factor
≥ 3	1.0
1.9	0.9
1.0	0.8
0.65	0.7
0.4	0.6
≤ 0.25	0.5

5.0 RESULTS

Section 5.1 provides the results from the RUSLE formula used to estimate sheet and rill erosion, as described in Section 4.1. Section 5.2 provides a summary of the slope stability analyses based on similar studies performed for other SRS facilities with similar closure cap designs. Finally Section 5.3 provides the results of the potential for gullying analyses based on the approach described in Section 4.2.

5.1 Potential Sheet and Rill Erosion Results

Modeling the evolution of the SDF closure cap from initial closure to 10,000 years into the future assumes three transitional periods of vegetative cover factor C. The initial pasture (grassed cover) period occurs from 0 to 140 years post-closure. The next period covers 140 years to 460 years post-closure and assumes transitional woodland-shrub. The final cover assumes a coniferous forest cover spanning from 460 years post-closure onward. These changes in vegetation reflect the natural changes anticipated to vegetation after final closure and monitoring based on analyses by Jones and Phifer (2008) [WSRC-STI-2008-00244], as described in Section 4.1. The remaining RUSLE factors remain constant in the analysis. Table 5.1-1 provides a summary of the RUSLE factors used for this analysis.

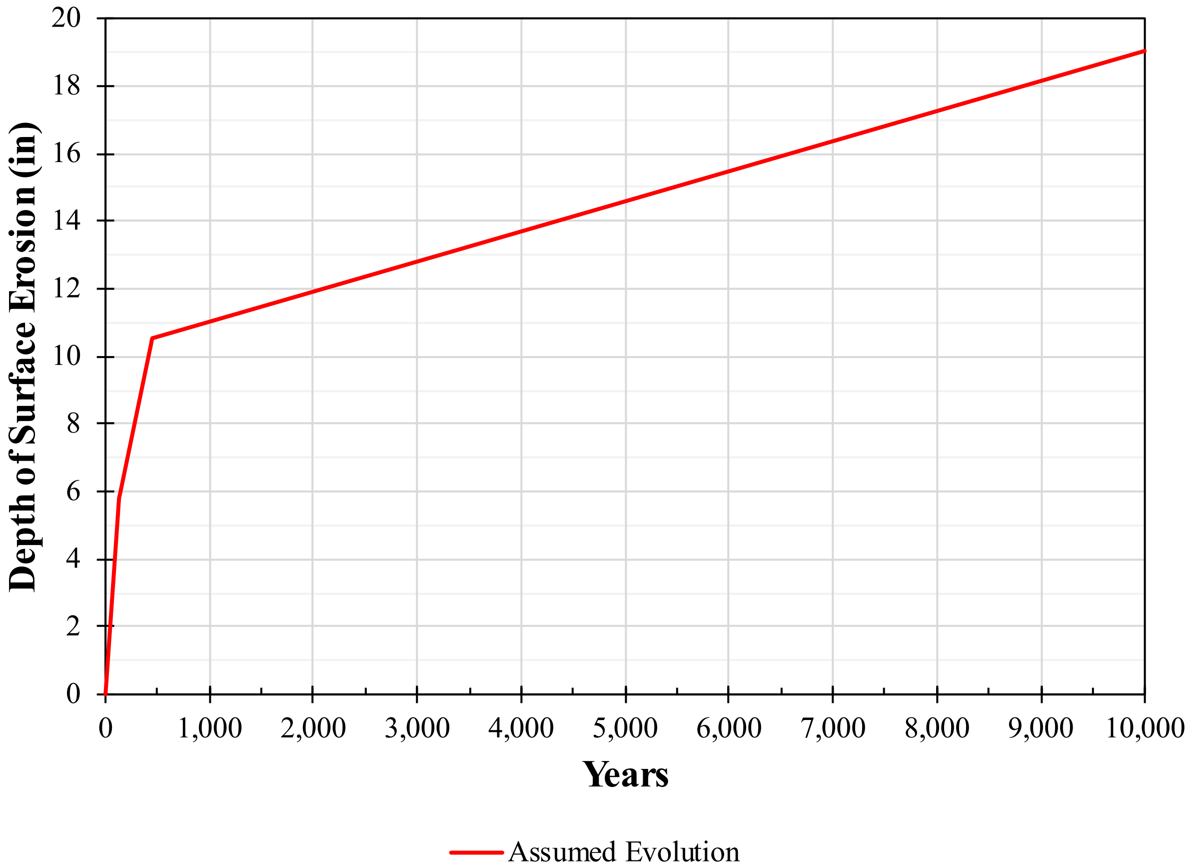
Table 5.1-1: RUSLE Inputs

<table>
<tr><th>Variable</th><th>Description</th><th colspan="2">Value</th><th>Units</th></tr>
<tr><td>R</td><td>rainfall and runoff factor by geographic location</td><td colspan="2">350</td><td>hundreds of (ft·tonf·in)/(acre·hr-yr)</td></tr>
<tr><td>K</td><td>soil erodibility factor</td><td colspan="2">0.28</td><td>(ton/acre) per R</td></tr>
<tr><td>L</td><td>length</td><td colspan="2">1020</td><td>ft</td></tr>
<tr><td>S</td><td>slope</td><td colspan="2">3%</td><td>%</td></tr>
<tr><td>LS</td><td>slope-length factor</td><td>0.57</td><td>Based on L and S</td><td>Unitless</td></tr>
<tr><td rowspan="3">C</td><td rowspan="3">crop and vegetation factor</td><td>0.15</td><td>0-140 yr</td><td rowspan="3">Unitless</td></tr>
<tr><td>0.05</td><td>140-460 yr</td></tr>
<tr><td>0.0003</td><td>460 or more yr</td></tr>
<tr><td>P</td><td>support practice factor</td><td colspan="2">1</td><td>Unitless</td></tr>
</table>

Based on these values, and the assumed 1.56 g/cm^3 bulk density of the soil, it is estimated that the loss rate will initially be approximately 0.045 in/yr, then as pine succession begins, the rate will slow to approximately 0.015 in/yr, and finally, once the SDF closure cap is vegetated by forest vegetation, the rate will be less than 0.001 in/yr.

The cumulative effects of these loss rates are visually depicted by Figure 5.1-1. This depth of soil loss curve shows that the anticipated erosion depth for the SDF closure cap is anticipated to be approximately 19 in over a period of 10,000 years. Based on the thicknesses of the SDF closure cap layers from Table 2.2-1, this indicates that soil losses will not reach the erosion control barrier during this period.

Figure 5.1-1: Depth of Erosion Results Based on RUSLE



It is noted that the rate of soil loss is strongly controlled by the assumed vegetative evolution from pastures, woodland-shrub, and coniferous forest. This is because of the changes to the C factor values in Table 5.1-1. However, it is also noted that the maximum C factor for each vegetative condition was assumed; had lower values within each range of potential values been assumed, the rates would be slower, and the cumulative depth of surface erosion would be less than 19 in. If midpoint values for the vegetative evolution range of C factors are used, the depth of surface erosion is lowered to 13 inches after 10,000 years.

5.2 Slope Stability Analysis Results

A slope stability analysis has been performed for the SDF closure cap (K-CLC-Z-00002), which determined that the SDF closure cap would have factors of safety below the minimum values indicating the slopes would be stable; however, that analysis was performed for an earlier closure cap design that was developed prior to the construction of any cylindrical SDUs, so this earlier analysis is no longer applicable.

A similar slope stability analysis was recently performed to evaluate the closure caps planned for the SRS tank farms (K-CLC-G-00111). While not directly the same as the SDF closure cap, it has enough similarities that it offers insights relative to slope stability for the current SDF closure cap. These similarities include the use of the same material layers for the closure cap, the same side slope gradient (3H:1V), and the same side slope features (with benches at approximately 25-ft vertical intervals). All of these facilities are expected to be subjected to the same or similar environmental conditions (rainfall, subsurface soil profiles, seismic stresses, etc.).

The key differences are that the top slopes vary slightly, wherein the closure caps for the tank farms assume a 4% gradient while the closure caps for the SDF assume a 3% gradient. Also, the SDF closure caps also cover a larger area, with a maximum slope length of 1,020 feet while the tank farms have a maximum slope length of less than 600 feet. These differences are expected to be minor relative to the similarities with respect to long-term slope stability. Therefore, the conclusions from K-CLC-G-00111 are presented here and assumed to be applicable to the SDF closure cap.

For the slope stability analyses for the tank farm closure caps, more than 10 cases were considered that evaluated system responses to various seismic stresses and static loads, using numerous conservative assumptions. For each case, "factors of safety" were estimated by dividing the forces resisting movement by the forces driving movement; in general, if a factor of safety is less than 1.0, the slope is unstable (so a higher value is more desirable). Table 5.2-1 provides the results of the slope stability analyses from K-CLC-G-00111.

Table 5.2-1: Summary of Minimum Factors of Safety for Slope Stability

Case No.	Description	Seismic Coefficient (g) kh	Seismic Coefficient (g) kv	Factor of Safety FTF	Factor of Safety HTF	Minimum Factor of Safety
1	Static	0	0	2.183	2.174	1.5
2	Seismic (H)	0.20	0	1.269	1.243	1.0 to 1.1
3	Seismic (+V)	0	0.20	2.155	2.152	1.0 to 1.1
4	Seismic (-V)	0	-0.20	2.192	2.208	1.0 to 1.1
5	Seismic (H, +V)	0.20	0.08	1.308	1.279	1.0 to 1.1
6	Seismic (H, -V)	0.20	-0.08	1.225	1.203	1.0 to 1.1
7	Seismic (V, H)	0.08	0.20	1.757	1.732	1.0 to 1.1
8	Seismic (-V, H)	-0.08	-0.20	1.628	1.619	1.0 to 1.1
9a	Seismic (H, -V), total stress, 0.20g	0.20	-0.08	1.225	0.915	1.0 to 1.1
9b	Seismic (H, -V), total stress, 0.16g	0.16	-0.064	n/a	1.015	1.0 to 1.1
9c	Seismic (H, -V), total stress, 0.10g	0.10	-0.04	n/a	1.213	1.0 to 1.1
10	Static, total stress	0	0	2.183	1.752	1.5

Source: K-CLC-G-00111, Table 1.

These results show that all except two cases met the minimum factors of safety. The two cases that did not reach the minimum factors of safety were Cases 9a and 9b for the HTF. The factors of safety for these two cases were marginal, which means that while the values were below the minimum, they were still relatively close. Case 9c was developed to further evaluate these cases, demonstrating that a satisfactory factor of safety "can be obtained by reducing the conservative factors that occur in the parameters" (K-CLC-G-00111).

5.3 Potential for Gullying Results

Table 5.3-1 shows the applied parameter values and the analytical results for the gullying analysis described in Section 4.2.

Using the maximum permissible velocity of 5 ft/s (from Table 4.2-3) and an interpolated velocity correction factors of 0.715 and 0.741 (for the 1,000-year and the 10,000-year return periods, respectively), the permissible velocities are 3.58 ft/s and 3.71 ft/s. The calculated actual flow velocity is 0.77 ft/s for the 1,000-year return period and 0.83 ft/s for the 10,000-year return period. This indicates that the flow velocity from runoff is expected to be less than the recommended permissible velocity for top vegetation. As such, the design for the SDF closure cap is unlikely to experience gullying. Since the flow velocity for a PMP storm-event is lower than the maximum stress, erosion severe enough to result in deep scours or gullying will likely not occur.

Table 5.3-1: Potential for Gullying Analysis

Parameter	Units	Inputs or Results		Basis
		1,000 Yr PMP	10,000 Yr PMP	
Flow Concentration Factor (F)	Unitless	2.5	2.5	Assumed value based on vegetated surfaces being between 2 and 3.
Runoff Coefficient (C)	Unitless	0.38	0.38	Based on interpretation of Table 4.2-1.
Rainfall Intensity (I)	in/hr	24.3	29.7	Eq. 4-6
15-minute PMP	in	2.700	3.300	Section 3.2.5
Assumed 5-minute PMP	in	1.350	1.650	Assumed to be half of the 15-minute PMP.
Time of Concentration (tc)	hr	0.104	0.104	Eq. 4-7
Slope (S)	ft/ft	3%	3%	Based on design in Section 2.2.
Maximum Drainage Length (Lft)	ft	1,020	1,020	Based on design in Section 2.2.
Maximum Drainage Length (Lmi)	mi	0.193	0.193	Unit conversion.
Drainage Area (A)	acres	0.023	0.023	Eq. 4-8
Peak flow rate (Q)	ft^3/s	0.54	0.66	Eq. 4-5
Manning's Coefficient of Roughness (n)	Unitless	0.265	0.265	Based on interpretation of Table 4.2-2.
Flow Depth (y)	ft	0.704	0.794	Eq. 4-9
Actual Flow Velocity (Va)	ft/s	0.77	0.83	Eq. 4-4
Velocity Correction Factor (CF)	Unitless	0.715	0.741	Based on interpretation of Table 4.2-4.
Maximum Permissible Velocity (MPV)	ft/s	5.00	5.00	Based on interpretation of Table 4.2-3.
Permissible Velocity (Vp)	ft/s	3.58	3.71	Eq. 4-10
Will Erosion Occur?	n/a	No Erosion	No Erosion	Eq. 4-3

6.0 CONCLUSIONS AND RECOMMENDATIONS

The PMP event for a 15-minute rainfall duration is estimated to be 2.7 inches for a 1,000-year return period and 3.3 inches for a 10,000-year return period to address potential climatic uncertainty. These values were used to assess long-term erosion.

Results for gullying and for the RUSLE formula both indicate that it is unlikely that the SDF closure cap will experience significant rates of erosion over a 10,000-year period. The RUSLE results indicate that sediment loss on the top of the cover will not reach low enough to interact with the erosion barrier. Gullying is also minimized on the 3% slope and the estimate of the actual velocity is significantly lower than the limit established by the permissible velocity. By accounting for evolution over time in the closure cap's life, these results take into account any ecological or climatic shifts that may occur.

A strong plant and root network will help dissipate rainfall energy on the closure cap and minimize the impact of surface flow. Regardless, it is imperative for the success of the closure cap to select a vegetation type, like Bahiagrass, that will have a better chance of thriving, deterring animals, and be resistant to weather extremes. It is important for the topsoil layer to be chemically and physically supportive of a complex root system. Six inches is adequate to promote a successful plant network.

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APPENDIX A. PMP DATA FOR UPDATED ELIASSON METHOD

This appendix provides the data used for updating the Eliasson Method for estimating the SRS PMP values as discussed in Section 3.2.

Table A-1 provides a summary of the rainfall data stations that were used for these PMP analyses. Six rainfall data stations were used to develop the 15-minute PMP estimates. Figure A-1 shows that these six stations are in relatively close proximity to SRS.

The National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) does not provide data for rainfall events with durations shorter than 15 minutes.

Table A-1: Rainfall Data Stations Used to Update PMP Estimates

Station	Latitude	Longitude	Elevation (m above mean sea level)	Years of Record [a]
Clarks Hill, SC	33.66667	-82.1833	116.1	1979 to 2014
Wagener, SC	33.65	-81.3667	128.0	1971 to 2014
St. Matthews, SC	33.66667	-80.7333	82.0	1971 to 2014
St. George, SC	33.18333	-80.5833	31.1	1971 to 2007
Sylvania, GA	32.75	-81.65	77.4	1971 to 2008
Louisville, GA	33.0125	-82.3914	98.1	1971 to 2014

Notes: (a) The years of record includes some years with incomplete data. As such the AMS values do not include values for every year with recorded values.

Table A-2 shows the annual maximum rainfall values for 15-minute rainfall durations for each of these stations. Similarly, Table A-3 and Table A-4 show similar values for 1-hour rainfall durations and 1-day rainfall durations, respectively. For the daily rainfall totals, the on-site (SRS) precipitation records described in Section 3.1 were used.

Figure A-1: Map of Rainfall Data Stations Used to Develop 15-Minute PMP Estimates

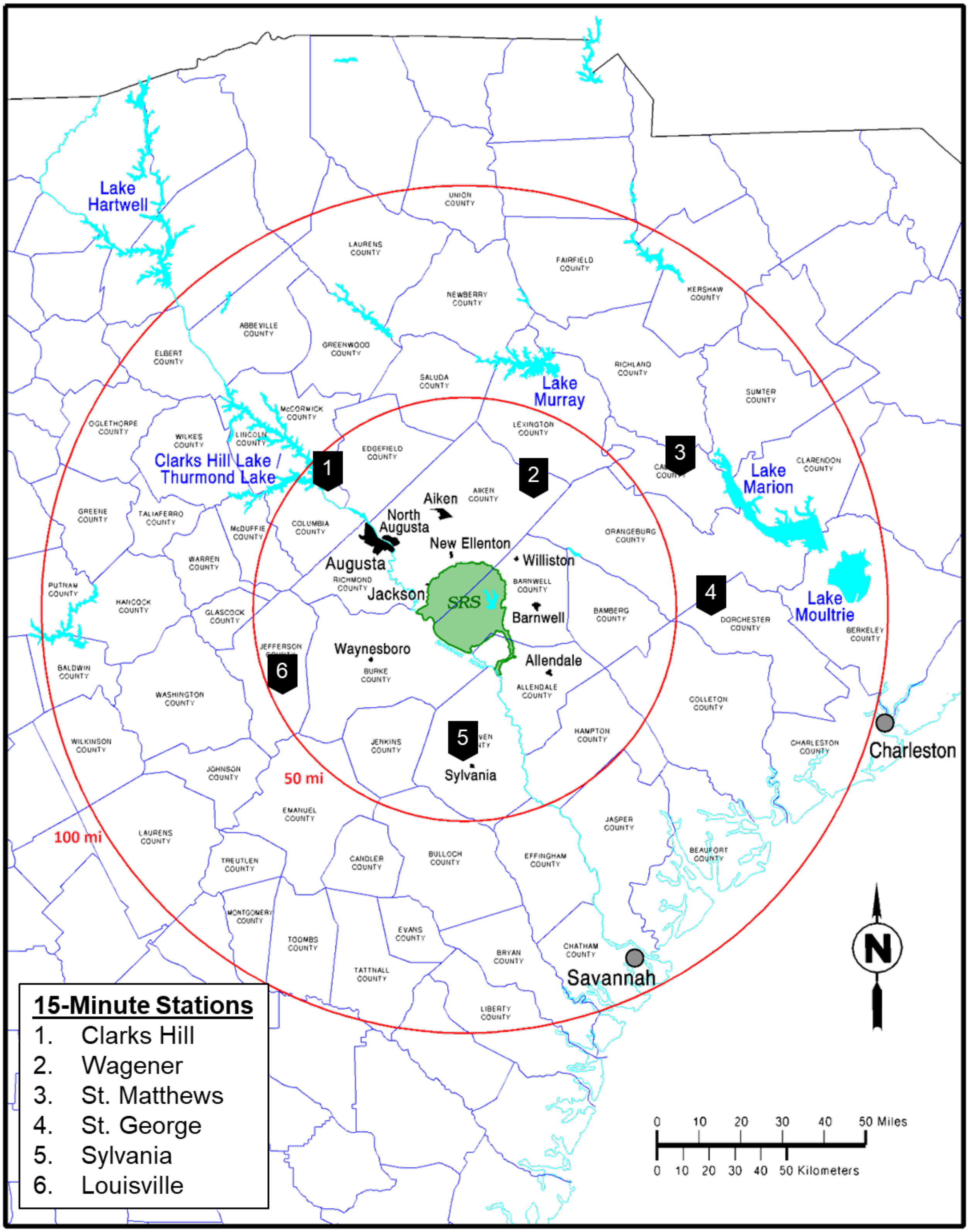

Table A-2: Annual Maximum Series (AMS) 15-minute Rainfall Totals (in)

Year	Clarks Hill, SC	Wagener, SC	St. Matthews, SC	St. George, SC	Sylvania, GA	Louisville, GA
1971	NA	1.00	1.00	1.70	NA	0.70
1972	NA	0.60	0.60	0.90	0.90	0.80
1973	NA	1.50	1.00	1.10	0.90	0.50
1974	NA	0.90	1.40	1.10	1.20	0.70
1975	NA	1.20	0.50	1.10	0.70	0.90
1976	NA	1.10	0.60	1.00	1.10	0.80
1977	NA	0.90	0.90	1.40	0.70	0.90
1978	NA	1.30	1.10	1.00	0.70	0.80
1979	0.70	0.60	0.70	0.80	1.40	1.10
1980	0.50	1.00	0.60	1.00	0.90	0.60
1981	0.90	1.30	1.00	1.10	0.60	0.80
1982	0.90	1.00	0.50	1.00	1.00	0.70
1983	0.60	1.00	0.90	1.70	0.60	0.50
1984	0.60	1.00	0.80	0.70	0.90	0.70
1985	0.80	1.10	1.40	1.00	1.80	1.30
1986	1.00	0.60	1.00	1.10	1.00	0.80
1987	0.70	0.90	0.60	1.10	1.00	0.90
1988	0.80	0.40	1.20	1.20	1.40	0.80
1989	0.90	1.10	1.10	1.10	0.70	1.00
1990	1.10	0.80	1.00	0.70	0.90	1.20
1991	0.70	1.10	1.10	1.10	1.70	0.80
1992	0.70	0.80	1.10	0.50	1.20	1.00
1993	0.60	0.70	1.00	0.60	1.00	1.30
1994	0.60	0.90	0.70	NA	1.30	1.00
1995	0.60	0.60	1.00	1.00	1.10	1.00
1996	0.90	1.00	1.10	0.90	0.70	1.00
1997	1.00	0.50	0.70	NA	0.80	1.10
1998	0.90	1.00	0.80	1.10	0.80	0.60
1999	0.70	0.80	0.60	NA	0.70	0.80
2000	0.50	0.70	0.80	NA	0.40	1.10
2001	NA	0.50	0.60	NA	1.20	0.40
2002	0.60	0.50	0.70	NA	0.70	0.80
2003	1.30	0.40	0.70	NA	0.50	1.00
2004	0.90	0.20	0.90	NA	NA	1.00
2005	0.70	0.90	0.70	NA	NA	0.70
2006	0.60	0.40	0.80	NA	NA	0.70
2007	0.70	0.70	0.70	NA	NA	0.90
2008	0.90	0.90	0.50	NA	NA	0.90
2009	1.30	1.00	1.00	NA	NA	0.80
2010	0.60	NA	1.20	NA	NA	1.10
2011	0.80	NA	0.80	NA	NA	0.70
2012	1.10	0.20	0.60	NA	NA	1.00
2013	0.90	0.90	1.10	NA	NA	1.20
2014	NA	NA	NA	NA	NA	NA

NA = Not available (or the incomplete annual data was not included).

Table A-3: Annual Maximum Series (AMS) 1-Hour Rainfall Totals (in)

Year	Clarks Hill, SC	Wagener, SC	St. Matthews, SC	St. George, SC	Sylvania, GA	Louisville, GA
1948	NA	1.13	1.56	1.47	1.19	2.69
1949	NA	2.10	1.40	1.53	1.16	2.17
1950	NA	2.26	1.68	1.00	2.85	1.45
1951	NA	1.33	0.91	1.70	1.02	1.70
1952	1.81	1.67	1.13	1.64	0.97	0.90
1953	2.50	1.33	1.58	1.25	1.74	0.90
1954	1.38	1.69	1.70	1.23	1.80	0.95
1955	1.77	0.58	2.07	1.40	1.85	0.97
1956	1.06	1.09	1.20	1.10	1.66	1.33
1957	1.56	1.80	1.92	1.40	1.60	0.93
1958	1.23	1.15	1.21	1.40	1.01	1.57
1959	1.96	1.60	1.38	0.94	2.40	2.43
1960	1.38	1.79	2.56	0.92	2.39	2.61
1961	1.27	1.38	1.26	1.19	1.88	1.67
1962	1.04	1.71	0.95	1.76	2.15	2.33
1963	0.93	1.72	1.28	1.27	0.87	1.60
1964	1.47	1.49	2.56	1.52	1.33	0.89
1965	1.60	1.56	2.06	2.20	1.37	2.00
1966	0.87	2.95	1.27	1.73	1.29	1.00
1967	0.94	2.94	2.22	1.22	1.59	0.91
1968	1.46	1.25	1.16	1.60	0.88	2.94
1969	0.94	2.44	1.67	2.00	1.63	1.09
1970	1.24	1.05	1.20	0.90	1.15	2.80
1971	1.40	2.50	1.90	2.30	1.46	2.00
1972	1.50	1.10	1.30	1.40	1.30	1.60
1973	1.59	2.30	1.50	2.40	1.60	1.10
1974	1.29	1.60	2.10	1.30	1.80	1.20
1975	1.26	1.60	1.10	1.80	1.70	1.70
1976	1.24	1.60	1.00	1.30	1.50	1.90
1977	2.27	1.20	1.50	2.20	1.20	1.20
1978	0.80	1.80	1.60	1.30	1.10	1.60
1979	1.50	1.00	1.70	1.50	2.00	1.30
1980	1.00	1.20	1.30	2.10	1.30	0.90
1981	2.70	1.70	1.00	1.50	2.00	1.30
1982	3.20	1.80	1.30	1.50	1.80	1.00
1983	1.40	1.90	1.60	1.90	0.60	1.20
1984	0.90	1.70	1.40	1.40	1.30	1.10
1985	1.50	2.30	2.80	1.80	1.80	2.00
1986	2.10	1.00	1.90	1.40	1.70	1.60
1987	1.00	1.50	1.30	1.70	1.70	1.30
1988	1.30	0.60	2.10	1.90	1.40	1.40
1989	1.90	2.00	1.40	2.00	1.10	1.30
1990	2.70	2.10	2.20	1.40	1.20	3.80
1991	2.00	2.30	2.20	2.60	3.90	1.10
1992	1.10	1.80	2.00	0.70	2.00	2.00
1993	1.40	1.00	1.20	1.10	1.30	2.00
1994	0.90	1.40	0.80	0.60	2.70	1.40
1995	1.20	0.90	1.50	2.30	1.30	1.70
1996	1.10	2.50	1.90	1.50	1.40	1.40
1997	2.10	0.90	0.90	0.80	1.60	2.70
1998	1.60	1.40	1.40	1.60	1.20	1.40
1999	1.20	2.00	1.30	1.10	1.40	2.20
2000	0.80	1.30	0.90	NA	0.70	1.40

Year	Clarks Hill, SC	Wagener, SC	St. Matthews, SC	St. George, SC	Sylvania, GA	Louisville, GA
2001	0.50	1.60	1.00	1.00	3.10	0.70
2002	0.80	0.60	1.20	NA	0.90	1.10
2003	2.70	0.60	0.90	NA	0.90	1.50
2004	1.70	0.20	1.70	NA	NA	1.70
2005	1.20	1.50	1.50	NA	NA	1.10
2006	1.00	1.00	2.00	NA	NA	1.00
2007	1.20	0.90	1.60	NA	NA	1.00
2008	1.30	1.20	0.80	NA	NA	1.60
2009	1.50	1.40	2.30	NA	NA	1.60
2010	1.60	NA	2.30	NA	NA	1.60
2011	1.40	NA	1.60	NA	NA	1.00
2012	1.80	0.50	1.10	NA	NA	1.70
2013	1.60	1.20	1.60	NA	NA	3.70
2014	NA	NA	NA	NA	NA	NA
2015	NA	NA	NA	NA	NA	NA

NA = Not available (or the incomplete annual data was not included).

Table A-4: Annual Maximum Series (AMS) 1-Day Rainfall Totals (in)

Year	700-A	BARR2	BARR3	BARR5	100-C	400-D	200-F	200-H	100-K	100-L	MOX	100-P	SRTC
1961	3.77	3.25	NA	NA	NA	NA	4.00	NA	NA	3.76	NA	NA	8.20
1962	3.59	4.90	NA	NA	NA	NA	3.04	NA	NA	4.28	NA	NA	6.52
1963	3.14	3.30	NA	NA	NA	NA	3.20	NA	NA	4.78	NA	NA	8.42
1964	7.05	5.30	2.88	NA	NA	NA	5.35	NA	NA	6.00	NA	NA	12.34
1965	2.54	NA	2.00	NA	NA	NA	3.75	NA	NA	2.66	NA	NA	2.50
1966	2.46	NA	2.10	NA	NA	NA	2.96	NA	NA	4.00	NA	NA	2.56
1967	4.87	NA	4.76	NA	NA	NA	4.40	NA	NA	4.50	NA	NA	6.75
1968	2.15	NA	3.75	NA	NA	NA	NA	NA	NA	2.30	NA	NA	4.35
1969	1.96	NA	2.20	NA	NA	NA	2.22	NA	NA	NA	NA	2.10	2.00
1970	3.43	NA	2.50	2.50	NA	NA	3.50	NA	NA	NA	NA	2.75	4.02
1971	4.00	NA	4.00	4.95	NA	NA	4.30	NA	NA	NA	NA	4.75	5.50
1972	2.58	NA	2.80	2.89	NA	NA	3.12	NA	NA	NA	NA	2.90	2.90
1973	2.90	4.62	3.85	5.15	NA	3.40	3.00	NA	NA	NA	NA	3.45	2.83
1974	1.60	2.35	1.76	2.50	NA	2.74	3.45	NA	NA	NA	NA	2.48	2.28
1975	3.00	3.10	2.00	2.63	NA	3.15	3.27	NA	NA	NA	NA	2.35	2.73
1976	6.53	4.75	4.50	3.75	NA	4.75	5.25	NA	NA	NA	NA	2.90	6.48
1977	2.15	2.83	3.10	2.48	NA	2.25	2.15	NA	NA	NA	NA	2.60	2.37
1978	3.00	2.60	2.25	2.60	NA	2.45	2.30	NA	NA	NA	NA	2.48	3.15
1979	4.35	3.90	4.45	5.00	NA	3.60	4.35	NA	NA	NA	NA	3.85	4.88
1980	2.80	3.02	3.50	3.78	NA	3.60	3.40	NA	NA	NA	NA	3.05	3.60
1981	4.30	4.60	2.40	2.81	NA	3.25	3.48	NA	NA	NA	NA	2.25	5.04
1982	2.85	3.35	3.00	2.30	NA	2.75	3.25	NA	NA	NA	NA	2.50	3.22
1983	2.76	2.46	2.00	2.55	NA	2.25	2.78	NA	NA	NA	NA	2.25	2.93
1984	3.38	2.70	2.50	2.00	1.85	4.50	2.72	2.74	2.40	1.60	NA	2.75	3.69
1985	3.03	3.04	2.78	3.75	2.75	3.20	3.10	3.50	3.00	3.00	NA	2.74	3.04
1986	4.35	5.00	2.75	1.90	2.45	3.00	1.75	4.00	3.00	3.15	NA	2.50	4.45
1987	2.30	2.25	3.20	3.00	3.25	2.00	2.48	2.30	2.25	2.75	NA	2.50	2.90
1988	2.75	3.00	3.50	2.00	2.25	2.80	2.51	2.85	3.50	3.00	NA	3.90	2.71
1989	5.05	3.38	3.74	3.00	4.50	4.25	4.50	3.85	4.00	4.00	NA	4.25	2.55
1990	5.25	5.72	4.25	7.15	5.25	6.75	6.10	6.00	5.50	5.00	NA	6.40	5.60
1991	3.75	3.00	5.25	2.75	5.25	3.25	4.65	4.95	5.25	5.60	NA	5.75	3.91
1992	2.50	1.75	2.75	3.25	3.75	2.27	2.76	2.50	2.25	3.00	NA	2.75	2.50
1993	3.00	3.50	3.40	2.75	3.25	4.80	3.30	3.50	5.76	5.80	NA	4.20	3.25
1994	2.75	2.75	2.80	3.50	3.60	2.50	2.50	2.25	2.50	2.74	NA	2.80	3.00
1995	3.75	3.25	3.85	3.25	3.00	3.25	4.50	3.25	3.75	3.25	NA	3.25	3.50
1996	2.00	3.20	2.25	3.50	2.25	2.25	2.50	2.00	2.75	3.25	NA	3.50	2.45
1997	2.50	2.25	1.90	3.50	2.20	3.50	2.50	2.75	3.15	3.00	NA	3.25	2.50
1998	5.25	5.00	4.35	3.50	4.50	4.75	4.55	3.90	4.25	3.50	NA	4.25	5.20
1999	2.26	2.52	3.50	2.75	2.50	4.35	2.75	4.00	3.25	3.25	NA	4.00	2.43
2000	3.75	3.50	4.25	5.00	3.86	5.65	3.76	4.22	5.25	5.52	NA	4.66	3.80
2001	2.25	3.26	2.25	4.05	2.90	2.35	2.50	2.25	2.50	2.40	NA	2.30	3.05
2002	2.30	2.25	3.25	3.00	1.78	1.80	2.75	2.40	1.75	1.25	NA	1.25	2.70
2003	3.75	3.25	3.15	3.40	3.25	3.26	3.00	3.60	3.50	3.75	NA	3.25	3.65
2004	4.00	4.00	3.75	3.25	3.60	2.70	4.25	4.40	4.00	3.55	NA	2.75	3.10
2005	2.90	2.75	2.50	3.23	2.85	3.30	3.00	2.76	2.85	2.80	NA	2.28	2.25
2006	2.25	3.75	3.50	4.94	2.25	3.00	3.50	3.90	3.50	3.00	NA	3.50	3.95
2007	2.77	2.25	5.25	3.25	2.80	2.85	2.75	3.50	5.50	3.00	NA	3.20	2.90
2008	2.25	3.00	2.70	3.25	2.25	2.50	2.60	3.95	2.75	2.50	NA	2.75	2.90
2009	4.00	3.50	3.30	2.48	2.52	3.50	3.75	4.00	3.00	2.52	NA	3.00	4.75
2010	2.25	2.70	2.00	3.20	2.10	3.25	3.10	2.73	2.50	3.25	NA	2.70	2.40
2011	2.60	3.25	3.25	2.00	2.40	2.00	2.60	2.50	2.27	2.40	2.70	3.00	3.25
2012	2.52	3.00	2.90	6.15	3.10	3.75	3.85	4.25	3.75	4.25	3.80	3.75	2.50
2013	4.76	5.50	2.75	4.15	3.00	2.08	3.50	2.75	3.30	2.77	3.60	3.22	2.68
2014	2.75	4.00	3.50	NA	3.00	3.28	NA	2.25	2.40	3.10	NA	2.80	3.10
2015	3.64	3.25	4.25	NA	3.15	2.59	NA	3.00	3.50	2.77	NA	3.10	3.51

2016	4.90	4.25	6.00	NA	5.74	5.47	NA	5.50	7.00	6.25	NA	6.25	5.36
2017	5.30	4.50	5.60	NA	5.00	5.14	1.78	5.25	4.50	5.20	NA	5.60	4.70
2018	2.75	2.75	2.76	NA	2.85	2.05	3.37	4.00	3.75	3.75	NA	2.65	3.13
2019	4.25	3.25	4.50	NA	2.25	2.21	2.14	3.25	2.00	2.25	NA	2.23	4.14
2020	4.02	3.91	3.21	1.93	3.47	2.84	3.93	3.93	4.00	5.00	NA	5.70	3.99

NA = Not available (or the incomplete annual data was not included).