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SOILS ACTIVITY MOBILITY STUDY: METHODOLOGY AND APPLICATION

NEVADA NATIONAL SECURITY SITE, NEVADA

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NEVADA NATIONAL SECURITY SITE, NEVADA

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF TABLES

TABLE OF CONTENTS (continued)

APPENDICES

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ACRONYMS AND ABBREVIATIONS

ac-ft	acre-feet
ac-ft/mi^2	acre-feet per square miles
AGWA	Automated Geospatial Watershed Assessment
AMCII	antecedent soil moisture condition II
CAS	Corrective Action Site
CAU	Corrective Action Unit
CCHE	National Center for Computational Hydroscience and Engineering
CCRFCD	Clark County Regional Flood Control District
cfs	cubic foot (feet) per second
CHAN-SED	Channel Sediment Transport
CN	curve number
DOE/NV	U.S. Department of Energy, Nevada Operations Office
DTM	Digital Terrain Model
ft	foot (feet)
ft^3	cubic foot (feet)
GIS	Geographic Information System
HEC-GeoHMS	Geospatial Hydrologic Modeling Extension
HEC-HMS	Hydrologic Engineering Center-Hydrologic Modeling System
HEC-RAS	Hydrologic Engineering Center-River Assessment System
KINEROS	Kinematic Runoff and Erosion
kt	kiloton(s)
mm	millimeter
mi^2	square miles
MUSLE	Modified Universal Soil Loss Equation
NOAA	National Oceanic and Atmospheric Administration
NNSS	Nevada National Security Site
PSD	particle size distribution
PSIAC	Pacific Southwest Interagency Committee
RUSLE	Revised Universal Soil Loss Equation
SCS	Soil Conservation Service

ACRONYMS AND ABBREVIATIONS (continued)

SWAT	Soil and Water Assessment Tool
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
USLE	Universal Soil Loss Equation
WEPP	Water Erosion Prediction Project
WGEW	Walnut Gulch Experimental Watershed

EXECUTIVE SUMMARY

This report presents a three-level approach for estimation of sediment transport to provide an assessment of potential erosion risk for sites at the Nevada National Security Site (NNSS) that are posted for radiological purposes and where migration is suspected or known to occur due to storm runoff. Based on the assessed risk, the appropriate level of effort can be determined for analysis of radiological surveys, field experiments to quantify erosion and transport rates, and long-term monitoring. The method is demonstrated at contaminated sites, including Plutonium Valley, Shasta, Smoky, and T-1.

The Pacific Southwest Interagency Committee (PSIAC) procedure is selected as the Level 1 analysis tool. The PSIAC method provides an estimation of the total annual sediment yield based on factors derived from the climatic and physical characteristics of a watershed. If the results indicate low risk, then further analysis is not warranted.

If the Level 1 analysis indicates high risk or is deemed uncertain, a Level 2 analysis using the Modified Universal Soil Loss Equation (MUSLE) is proposed. In addition, if a sediment yield for a storm event rather than an annual sediment yield is needed, then the proposed Level 2 analysis should be performed. MUSLE only provides sheet and rill erosion estimates. The U.S. Army Corps of Engineers Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) provides storm peak runoff rate and storm volumes, the inputs necessary for MUSLE. Channel Sediment Transport (CHAN-SED) I and II models are proposed for estimating sediment deposition or erosion in a channel reach from a storm event. These models require storm hydrograph associated sediment concentration and bed load particle size distribution data.

When the Level 2 analysis indicates high risk for sediment yield and associated contaminant migration or when there is high uncertainty in the Level 2 results, the sites can be further evaluated with a Level 3 analysis using more complex and labor- and data-intensive methods.

For the watersheds analyzed in this report using the Level 1 PSIAC method, the risk of erosion is low. The field reconnaissance surveys of these watersheds confirm the conclusion that the sediment yield of undisturbed areas at the NNSS would be low. The climate, geology, soils, ground cover, land use, and runoff potential are similar among these watersheds. There are no well-defined ephemeral channels except at the Smoky and Plutonium Valley sites. Topography seems to have the strongest influence on sediment yields, as sediment yields are higher on the steeper hill slopes. Lack of measured sediment yield data at the NNSS does not allow for a direct evaluation of the yield estimates by the PSIAC method.

Level 2 MUSLE estimates in all the analyzed watersheds except Shasta are a small percentage of the estimates from PSIAC because MUSLE is not inclusive of channel erosion. This indicates that channel erosion dominates the total sediment yield in these watersheds. Annual sediment yields for these watersheds are estimated using the CHAN-SEDI and CHAN-SEDII channel sediment transport models. Both transport models give similar results and exceed the estimates obtained from PSIAC and MUSLE. It is recommended that the total watershed sediment yield of watersheds at the NNSS with flow channels be obtained by adding the washload estimate (rill and inter-rill erosion) from MUSLE to that obtained from channel transport models (bed load and suspended sediment). PSIAC will give comparable results if factor scores for channel erosion are revised towards the high erosion level.

EXECUTIVE SUMMARY (continued)

Application of the Level 3 process-based models to estimate sediment yields at the NNSS cannot be recommended at this time. Increased model complexity alone will not improve the certainty of the sediment yield estimates. Models must be calibrated against measured data before model results are accepted as certain. Because no measurements of sediment yields at the NNSS are available, model validation cannot be performed. This is also true for the models used in the Level 2 analyses presented in this study.

The need to calibrate MUSLE to local conditions has been discussed. Likewise, the transport equations of CHAN-SEDI and CHAN-SEDII need to be calibrated against local data to assess their applicability under semi-arid conditions and for the ephemeral channels at the NNSS. Before these validations and calibration exercises can be undertaken, a long-term measured sediment yield data set must be developed.

Development of long-term measured sediment yield data cannot be overemphasized. Long-term monitoring is essential for accurate characterization of watershed processes. It is recommended that a long-term monitoring program be set up to measure watershed erosion rates and channel sediment transport rates.

1.0 INTRODUCTION

1.1 PURPOSE AND SCOPE

The U.S. Department of Energy, National Nuclear Security Administration Nevada Field Office Environmental Management Program has been addressing the remediation of surface and shallow subsurface soils at various Corrective Action Sites (CASs) at the Nevada National Security Site (NNSS) since 1989. Radiological contamination at these sites is due to atmospheric and underground nuclear weapons tests, chemical explosion tests of plutonium-bearing materials, safety experiments, and storage-transportation tests. Many CASs that have been characterized to date have been closed in place with administrative controls. The current extent of contamination has been determined at these sites, and the areas are controlled under a Real Estate Operations Permit and, where appropriate, fenced with signage. At sites that are posted for radiological purposes, radiological surveys are performed periodically to assess if migration of radionuclides is occurring. Although migration is known to occur due to storm runoff and the associated soil erosion and sediment transport, the following assessment questions are being raised:

- At what rate are radionuclides in surface soils migrating downstream with soil erosion due to storm runoff?
- What is the severity of erosion and sediment transport?
- Should CAS boundaries be revised based on erosion potential?
- Should the frequency of radiological surveys be changed?

The following activities are being undertaken to address these questions and to make remediation/closure and post-closure monitoring decisions:

- Modeling of erosion and sediment transport
- Analysis of ground radiological surveys over time
- Field experiments to quantify erosion and transport rates
- Long-term monitoring of erosion and sediment

This report addresses only the first activity, modeling of erosion and sediment transport. The modeling approach can provide a quick assessment of potential erosion risk, and based on the assessed risk, it can be used to determine the level of effort appropriate for the other three activities listed above at each CAS. Therefore, the study is undertaken to develop a modeling methodology that would assist the remediation and monitoring decisions at each CAS.

The scope of the study consists of the following:

- Identify a suite of erosion and sediment transport models applicable to the semi-arid setting of the NNSS.
- Develop a three-level modeling methodology to assess erosion risk, using models from simple to complex.
- Demonstrate the methodology at a few contaminated sites.
- Assess the methodology and make recommendations.

1.2 CONTENTS

This report contains the following sections:

Chapter 2, Methodology, presents a three-level modeling methodology, from simple to complex, to assess the erosion and sediment transport potential of watersheds at the NNSS. This study is limited to the detailed discussion and application of the Level 1 and Level 2 analysis methods. The Level 3 analysis models that have potential for use at the NNSS are identified and briefly described.

Chapter 3, Application of the Methodology, presents the application of the methodology to each of the contaminated sites at Plutonium Valley, Shasta, Smoky, and T-1. A summary of the physical characteristics of the NNSS is provided prior to presenting the application of the methodology for each site.

Chapter 4, Assessment of the Methodology, presents the comparisons of the watershed sediment yields derived from the Level 1 and Level 2 model applications, and discusses the merits and shortcomings of the methods based on the results of the site applications presented in Chapter 3.

Chapter 5, Recommendations, emphasizes the need for long-term monitoring and discusses the need for model calibration and validation with site-specific data to improve the validity and certainty of the sediment yield estimates at the NNSS watersheds.

Chapter 6, References, lists references cited in the text of this report.

Appendices to the document include details of the analysis and modeling tools for the Level 1 and Level 2 methods. Appendix A details the method of the Level 1 analysis and includes its EXCEL spreadsheet implementation, and Appendices B, C, and D discuss the equations and parameters of the Level 2 analysis tools and models developed in an EXCEL spreadsheet.

2.0 METHODOLOGY

Soil erosion caused by storm runoff is one of the primary mechanisms for the migration of radionuclides in surface soils at the contaminated sites of the NNSS. Radionuclides at these sites can attach to surface soils and move downstream with eroded sediment. Thus, remedial decisions about these contaminated sites can be supported by assessing the sediment yield potential of the watershed that includes each site.

Soil erosion is defined as detachment, transportation, and deposition of soil particles on the land surface under the influence of wind or water. Sediment refers to these soil particles. Sediment transport refers to the processes by which sediment is moved downstream by flowing water in channels. Erosion is a natural geologic process occurring over a landscape that can be accelerated by human activities. Sediment yield of a watershed refers to the quantity of sediment moving past a cross-section of a channel in a specified time interval. The main source of sediment transported in a channel is the upstream watershed. However, channel bed and banks can also be significant sources. Assessment of erosion and sediment yield of a watershed is a highly complex and uncertain endeavor.

The most reliable way to assess sediment yield is measurement. Soil erosion and sediment yield can be measured in the field using erosion pins, runoff plots, shrub mounds, measurement of sediment in ponds and reservoirs, and sediment concentration in rivers. For a reliable estimate of sediment yield, long-term data must be available that are often collected continuously over several decades. Where no such data exist for a particular site, modeling is the only method available for assessment. At the NNSS, there are no available measurements of sediment. Therefore, this assessment methodology proposes modeling and includes a suite of models from simple to complex.

The simple models proposed for this methodology are conceptual/empirical models originally developed by the U.S. Department of Agriculture (USDA) to assess loss of topsoil from farms across midwestern states and later extended for application to rangelands of the semi-arid southwestern states. Complex models range from watershed-wide hydrologic models that incorporate simple models of soil erosion and sediment transport in channel networks to physically based process models. The application of this assessment methodology is limited to simple models.

A three-level assessment is proposed. Level 1 and Level 2 analyses are screening-level analyses. A Level 3 analysis is proposed if previous analyses indicate a need for more rigorous analysis either because results indicate high erosion risk and/or because results remain highly uncertain.

2.1 LEVEL 1 ANALYSIS: FACTOR ANALYSIS

The Level 1 analysis tool selected for the NNSS is the watershed sediment yield rating procedure developed by the Pacific Southwest Interagency Committee (PSIAC, 1968). The PSIAC method was originally intended for use in planning-level studies, but it has been used in southwestern states by local and state agencies as well as engineering contractors in planning and design studies (Mussetter Engineering Inc., 2008).

The PSIAC method provides ranges of sediment yield estimates for a watershed based on factors derived from the watershed's climatic and physical characteristics, including geology, soils, climate, runoff, topography, ground cover, land use, upland erosion, and channel erosion/sediment transport. Each factor is assigned a numerical value corresponding to three sediment yield levels (high, moderate, and low). These numerical values are summed for all nine factors to define an overall rating. Annual sediment yield corresponding to rating is shown in Table 2-1.

TABLE 2-1. PSIAC ANNUAL SEDIMENT YIELD CLASSIFICATION

CLASSIFICATION	RATING	ANNUAL SEDIMENT YIELD	
		ACRE-FEET/SQUARE MILE	TONS/ACRE
1	>100	>3.0	10.1
2	75–100	1.0–3.0	3.4–10.1
3	50–75	0.5–1.0	1.7–3.4
4	25–50	0.2–0.5	0.7–1.7
5	0–25	<0.2	<0.7

A flowchart for Level 1 analysis using the PSIAC rating is shown in Figure 2.1. If the results of the factor analysis indicate low risk or low uncertainty, then further analysis is not warranted.

A successful application of this factor rating requires a good understanding of the regional and local hydrometeorology, hydrology, geology, soils, geomorphology, vegetation, ground cover, and land use. Quantitative data supporting this analysis include topographic maps, geologic maps, and streamflow information from the U.S. Geological Survey (USGS), precipitation and climatic data from the National Oceanic and Atmospheric Administration (NOAA), soils data from local soil surveys or the U.S. Department of Agriculture soil maps, field reconnaissance surveys of the watershed land use, vegetation and ground cover, upland erosion, erosion along the channel beds and slopes, and the formation of gullies.

The details of the methodology and its spreadsheet implementation are provided in Appendix A.

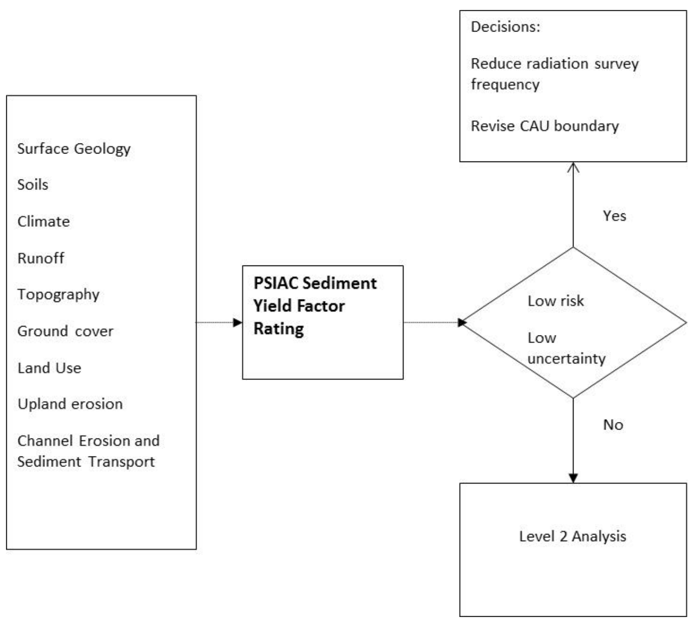

FIGURE 2-1. LEVEL 1 ANALYSIS FLOWCHART

2.2 LEVEL 2 ANALYSIS: EROSION AND SEDIMENT TRANSPORT EQUATIONS

If the annual sediment yield estimated using the Level 1 analysis (PSIAC method) indicates high risk or is deemed uncertain, a Level 2 analysis is proposed following the procedure shown in the flowchart of Figure 2-2. In addition, the PSIAC method provides only annual sediment yields; therefore, if a sediment yield for a storm event is needed, then the proposed Level 2 analysis should be performed. The Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt, 1972; Williams, 1975) is proposed for estimating the net sediment yield from the watershed for the site of interest for a given storm event. MUSLE provides an estimate of sheet and rill erosion from the watershed surfaces. MUSLE is described in Section 2.2.2. If the watershed outlet at the site of interest is a stream or arroyo, then the total sediment discharged should also include the bed material load eroded from the channels. In the proposed methodology, the bed material load transport in the channel is determined by the transport capacity of the channel, which depends on the hydraulic characteristics of the channel and the sediment sizes present in the channel bed. The sediment transport equations that are proposed in this methodology are described in Section 2.2.3. Storm peak runoff rate and storm volume are the two hydrologic inputs for estimating storm sediment yields using the Level 2 analysis. To estimate these storm data, watershed modeling is proposed, which is discussed in Section 2.2.1.

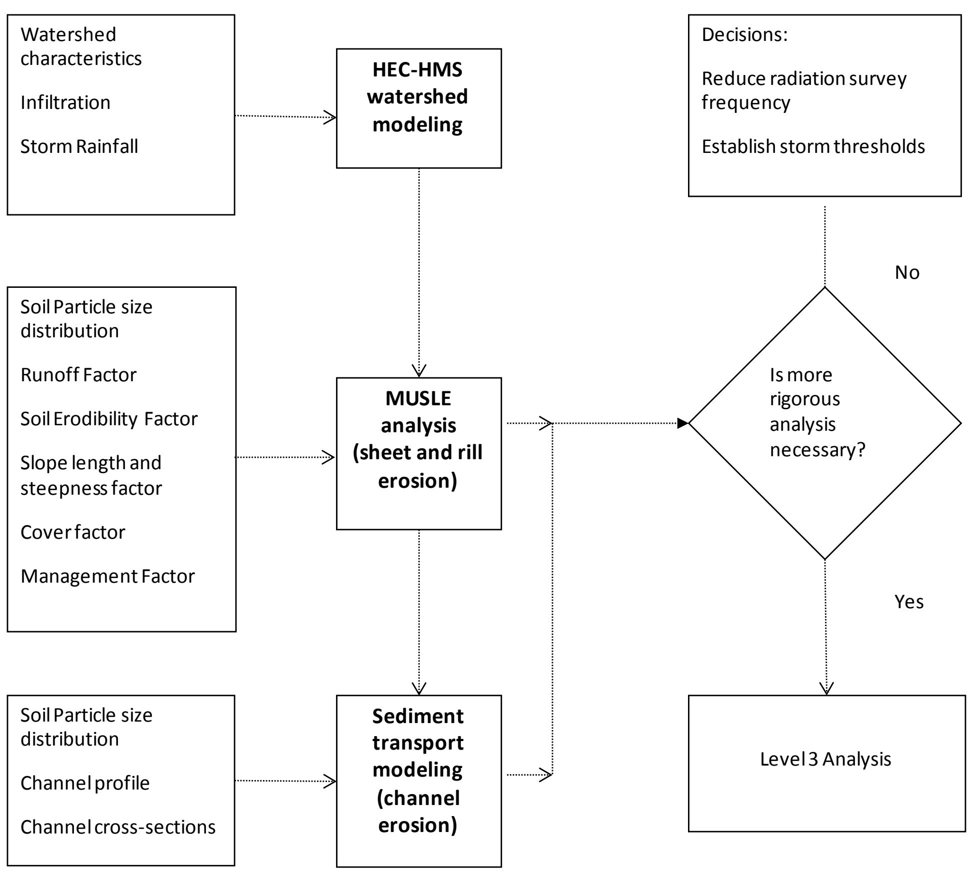

FIGURE 2-2. LEVEL 2 ANALYSIS FLOWCHART

2.2.1 Watershed Modeling using HEC-HMS

The proposed watershed model is the U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS). HEC-HMS is public domain software that is widely used to quantitatively assess the hydrologic response of a watershed to precipitation events (USACE, 2010a). HEC-HMS has been used for flood studies at the NNSS for 20 years. HEC-HMS includes a watershed module, a meteorological module, and a control specifications module. Features of these modules pertinent to the current work are briefly summarized. A watershed is defined by a number of sub-basins and a channel network to simulate runoff processes and channel flows from precipitation events. The model provides several infiltration models to choose from, including initial constant, Soil Conservation Service (SCS) curve number (CN), gridded SCS CN, exponential, and Green Ampt, to compute losses due to soil infiltration from given precipitation. Precipitation excess (precipitation minus losses) is then transformed into surface runoff using unit hydrograph methods such as the Clark, Snyder, and SCS techniques. A user-specified unit hydrograph or an S-graph can also be used. Simulating flow in open channels (channels with trapezoidal, rectangular, triangular, or circular cross sections) can be achieved by kinematic wave or Muskingum-Cunge routing methods.

A meteorological model is set up to represent the precipitation over sub-basins. Watershed precipitation is described by historical storm data at one or more gauges or by synthetic precipitation. Design storm precipitation for different durations and exceedance probabilities is obtained from the NOAA Atlas 14 for input to the model. Control specifications include a start date and time, end date and time, and time interval. A simulation run is created by combining a basin model, a meteorologic model, and control specifications.

A useful extension of HEC-HMS for large basin applications is its link to a geographic information system (GIS) called the Geospatial Hydrologic Modeling Extension (HEC-GeoHMS).

Currently, HEC-HMS is at Version 3.5. A future version is expected to include land surface erosion, channel sediment transport, water quality transport, and transformation capabilities. A recent beta version shows the MUSLE sediment yield equation is added to the basin module for basin erosion calculations. A simplified channel transport capability will also be added to simulate erosion and deposition within the channels.

HEC-HMS is well documented. A user’s manual, technical documentation, and application document are available to download at the HEC website.

HEC-HMS is proposed to provide the input necessary for sheet and rill erosion estimating using MUSLE and channel transport calculations.

2.2.2 Modified Universal Soil Loss Equation (MUSLE)

MUSLE is derived from the Universal Soil Loss Equation (USLE), a widely used empirical equation used to estimate annual sheet and rill erosion from a land surface as a product of several factors (rainfall energy factor, soil erodibility factor, steepness and overland slope factor, cover factor, and an erosion control management factor) (Williams and Berndt, 1972; Williams, 1975). In MUSLE, a storm runoff factor replaces the rainfall energy factor of USLE. The use of the runoff factor in MUSLE improves sediment yield prediction and eliminates the need for watershed delivery ratios. MUSLE is also applicable to individual storm events. In semi-arid southwestern states, a few short-duration, high-intensity storms generate the bulk of the annual sediment yield from watersheds. Therefore, the use of MUSLE is found appropriate in semi-arid southwestern watersheds (Mussetter Engineering Inc., 2008; Clark County Regional Flood Control District [CCRFCD], 1999). However, because the sites that are evaluated in this study are generally flat grasslands, it is possible that MUSLE may underestimate annual sediment yields.

The current version of the MUSLE equation is

$$Y = 95(Q * q_p)^{0.56} * K * LS * C * P$$

where

Y = sediment yield (tons)

Q = surface runoff volume (acre-feet [ac-ft])

q_p = peak flow (cubic feet per second [cfs])

K = soil erodibility factor

LS = topographic factor (length and slope of overland flow)

C = cover and management factor

P = support practice factor

MUSLE can also be used to estimate the average annual sediment yield of a watershed. Storm event sediment yields (V) are calculated for events of return periods from 2 to 100 years, and these yield estimates times their frequency of occurrences are summed to calculate the average annual sediment yield estimate (V_m). Using the trapezoidal rule for integration,

$$V_m = 0.01 * V_{100} + 0.01 * \frac{V_{100} + V_{50}}{2} + 0.02 * \frac{V_{50} + V_{25}}{2} + 0.06 * \frac{V_{25} + V_{10}}{2} + 0.1 * \frac{V_{10} + V_5}{2} + 0.3 * \frac{V_5 + V_2}{2} + 0.5 * \frac{V_2 + 0}{2}$$

2.2.3 Channel Sediment Transport (CHAN-SED)

Two alternate models are proposed for estimating sediment transport in channels. Both models estimate sediment transport in an open channel system based on a sediment continuity equation and different sediment transport equations. The sediment transport equation in CHAN-SEDI is developed by the Keck Laboratory of California Institute of Technology (Brownlie, 1981). The second model, CHAN-SEDII, was adopted from French (1996) and FORTRAN codes prepared for the U.S. Department of Energy, Nevada Operations Office (DOE/NV), dated April 24, 1996. The transport equations used in CHAN-SEDII are the Yang equation for sand and gravel (sediment particle sizes between 0.062 and 10 millimeters [mm]) and the Schoklistch equation for sediment sizes greater than 10 mm. Equations discussed above are located in Appendix C.

Both models require a storm hydrograph and an associated sediment concentration as inputs as well as a bed material particle size distribution (PSD). The models compute sediment deposition or erosion in a channel reach from a storm event. The volume of sediment deposited or eroded is the difference between the upstream sediment supply rate and the channel sediment transport rate. If the supply rate is greater than the transport rate, sediment will deposit in the reach, while if transport is greater than supply, the balance will be supplied by the reach by bed scouring and bank slumping.

The other input parameters for the models include the physical properties of water (gravitational acceleration, specific weight, and kinematic viscosity), the physical properties of sediment (specific weight of bed material, median particle size and geometric standard deviation of bed material distribution in CHAN-SEDI or PSD in CHAN-SEDII, sediment porosity, and the angle of repose of the side slopes in CHAN-SEDI). Channel reaches are defined by upstream and downstream elevations, channel bottom width, and channel reach length. CHAN-SEDII also requires an input value for channel roughness. Details of the model equations and input parameters are included in Appendices C and D for CHAN-SEDI and CHAN-SEDII, respectively.

2.3 Level 3 Analysis: Modeling Systems

When the Level 2 analysis indicates high risk for sediment yield and associated contaminant migration from the site or when there is high uncertainty in the Level 2 analysis results, the sites can be further evaluated using more complex and labor- and data-intensive methods. Models or modeling systems for a Level 3 sediment yield and transport analysis are discussed in four categories: (1) GIS-based models that incorporate simple sediment yield estimators such as USLE, revised USLE (RUSLE), or MUSLE; (2) physically based watershed erosion models; (3) sediment transport models; and (4) integrated erosion and sediment transport models.

Category 1 models integrate GIS and erosion modeling capability for watershed-based erosion and sediment yield estimation. They are widely used for developing erosion hazard maps and assessing the impact of different practices for managing soil losses. Wachal and Banks (2007) discuss estimating soil loss from well sites in North Central Texas through the integration of GIS and erosion modeling using RUSLE. Zhang et al. (2009) discuss the integration of MUSLE into ArcGIS® software.

Category 2 models include the empirical and physically based single storm event or continuous time simulation models such as the Soil and Water Assessment Tool (SWAT), the Water Erosion Prediction Project (WEPP) model, and the Kinematic Runoff and Erosion (KINEROS) model, all developed by the USDA. SWAT is a continuous simulation model used to estimate the long-term water and sediment yield of a watershed (Neitsch et al., 2011). SWAT simulates a number of physical processes in a watershed using either empirical or physically based equations. Erosion and sediment yield are estimated using the empirical equation MUSLE. For modeling purposes, a watershed is divided into homogeneous sub-basins or land segments that are connected with a network of channels. SWAT provides capabilities to simulate a watershed's weather (precipitation and energy inputs), its hydrologic cycle, sediment production, plant growth, nutrient and pesticide cycles on the land surface, and routing of water, sediment, nutrients, and pesticides in open channels. The WEPP model is similar to the SWAT model but employs a different sediment yield estimation procedure. WEPP was envisioned as a replacement for MUSLE and its derivatives. It can simulate temporal and spatial soil erosion, sediment deposition and delivery from hillslopes, detachment and deposition of sediment in gullies and channels, and hydraulic structures (Flanagan and Nearing, 1995). KINEROS is a physically based event model capable of simulating interception, infiltration, surface runoff, and erosion from a small watershed represented by a cascade of planes and channels (Woolhiser et al., 1990). Finite difference techniques are used to solve the partial differential equations describing overland flow, channel flow, erosion, and sediment transport. An updated version of the model, KINEROS2, can be found at http://www.tucson.ars.ag.gov/Kineros/.

Representative examples of transport models of Category 3 include the USACE's Hydrologic Modeling Center-River Analysis System (HEC-RAS) and the one-, two-, and three-dimensional numerical models developed by the National Center for Computational Hydroscience and Engineering (CCHE) at the University of Mississippi, supported by the USDA Agricultural Research Service. The one-dimensional CCHE1D model simulates unsteady flow and non-uniform sediment transport in channel networks (Vieira and Wu, 2002). CCHE2D is a depth-averaged, two-dimensional model for flow and sediment transport. These models can be downloaded from http://www.ncche.olemiss.edu/sw_download.

Large amounts of data are required to set up and run these models. To model sediment yield and transport in a watershed is highly complex, and no single model can address all the specific issues involved. Therefore, geospatial tools are developed to manage data, perform data analysis, integrate various model components, and visualize model outputs. Category 4 models are the geospatial platforms designed to address such needs. An example of an integrated platform is the Automated Geospatial Watershed Assessment (AGWA) tool, a GIS interface jointly developed by the U.S. Environmental Protection Agency, the USDA Agricultural Research Service, and the University of Arizona (http://www.epa.gov/nerlesd1/land-sci/agwa/index.htm). AGWA currently integrates the SWAT and KINEROS2 hydrologic models to conduct hydrologic modeling and watershed assessments at multiple temporal and spatial scales.

To facilitate data input and output and data visualization, the HEC developed graphical user interfaces for HEC-HMS and HEC-RAS software. HEC-GeoRAS allows for processing geospatial data in ArcGIS using a graphical user interface (GUI) (http://www.hec.usace.army.mil/software/hec-georas). HEC-GeoRAS requires a digital terrain model (DTM) of the river system. DTMs are also required for most applications of the numerical models discussed above.

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3.0 APPLICATION

The methodology developed in Section 2.0 is applied to four sites located at the NNSS. Before the site applications are discussed, pertinent physical characteristics of the NNSS are summarized.

3.1 REGIONAL SETTING

The NNSS, which is approximately 1,360 square miles in area, is located in Nye County, Nevada, about 65 miles northwest of Las Vegas. It is located in the Basin and Range Physiographic Province, characterized by north-south trending mountain ranges and intervening valleys, and large volcanic calderas (Figure 3-1). The principal valleys in the NNSS are Frenchman Flat, Yucca Flat, and Jackass Flat. Frenchman Flat and Yucca Flat are closed basins with dry lake beds (playas) at their lowest elevations. Jackass Flat is an open basin drained by Fortymile Wash off the NNSS at its southern end. Pahute Mesa, Rainier Mesa, Timber Mountain, and Shoshone Mountain are the dominant highlands. Slopes of the highland areas are steep and dissected, while those in the valleys are mild and less eroded. The lowest elevation on the NNSS is at 2,700 feet (ft) in Jackass Flat in the southwest, and the highest elevation is 7,680 ft on Rainer Mesa in the north-central NNSS (Shott et al., 1998).

Mountains of the Basin and Range Physiographic Province are composed of primarily Proterozoic and Paleozoic sedimentary rocks. These rocks are mostly of marine origin, made up of carbonates, shales, sandstones, and conglomerates. These sedimentary rocks were folded and faulted during multiple periods of deformation. In the western part of the Basin and Range Physiographic Province, these sedimentary rocks were intruded by granitic rocks of Mesozoic age. The Proterozoic and Paleozoic sedimentary rock and the Mesozoic intrusions underwent erosion during the early Cenozoic Era. This period of erosion was followed by extensional faulting of the older rocks, resulting in the basin and range structure definitive of the province today. Volcanic rocks consisting of silicic tuffs and lavas and basaltic lavas were erupted in the province during the middle Cenozoic Era, forming overlapping calderas. These calderas are partially coincident with the mesas in the northwestern part of NNSS. Crustal extension, folding, and faulting continue to the present in the Basin and Range Physiographic Province. Erosion of the uplifted mountain ranges progressively filled the basins at the NNSS with up to approximately 3,900 ft of gravel, sand, and silt (Shott et al., 1998).

The surficial deposits are composed of alluvial, colluvial, eolian, and playa sediments. Alluvial fan and wash deposits form the bulk of the piedmont areas below mountains and hills and are composed predominantly of massive to moderately sorted, moderately to well stratified sands and gravels ranging from pebbles to boulders. Geomorphic mapping indicates that the age of the surfaces range from late Pleistocene (oldest) to late Holocene (youngest), with a predominant surface age from the middle Holocene to late Pleistocene. Late Holocene surfaces are present in the small active channels.

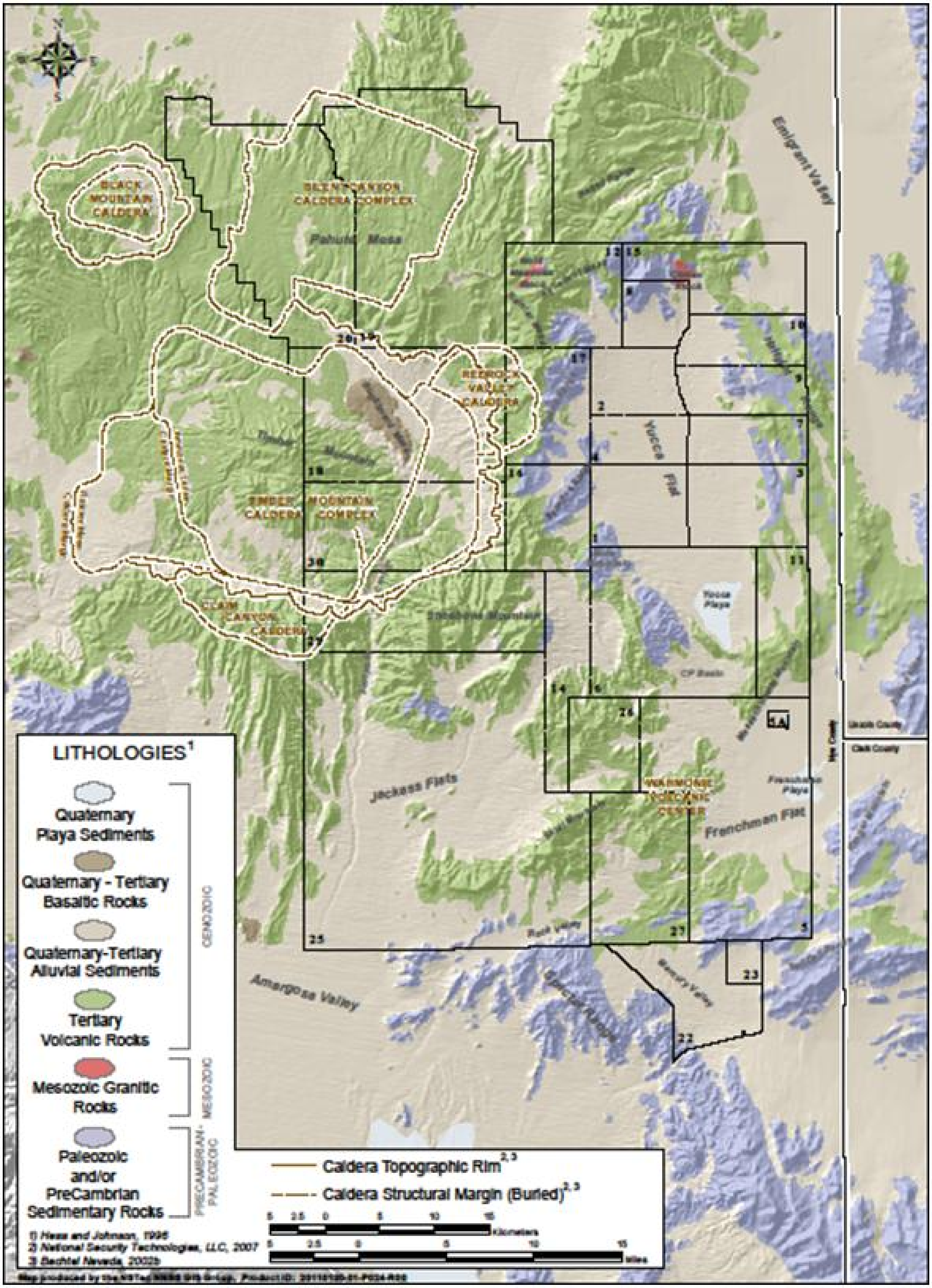

FIGURE 3-1. GEOLOGIC MAP OF THE NEVADA NATIONAL SECURITY SITE

Most of the soils on the NNSS have developed on alluvial deposits that contain unconsolidated parent materials of both sedimentary and volcanic origins. They have developed under conditions of high temperatures and low rainfall and display characteristics of desert soils: coarse texture, an accumulation of carbonates within a few feet of the surface contributing to the formation of a caliche layer, low organic matter content, and low carbon/nitrogen ratios. The soils are young and show little evidence of leached upper horizons. Much of the diversity in soil profiles reflects their mixed alluvial origin. Coarser fragments are found in soils developed near the base of mountains and hills, and finer textures are found towards the middle of valleys. If clay is present, it is usually found in B horizons in more level areas (Bechtel Nevada, 2001b).

The NNSS lies within a region of the southwestern U.S. known for its arid intermountain deserts. Orographic lifting of humid Pacific air masses by coastal mountain ranges to the west causes a majority of the moisture destined for the continent to fall on the intercoastal mountain ranges before reaching the interior. The NNSS lies in a region that is transitional between the Nevadan Desert and the Mojave Desert. The climate is characterized by a large number of cloudless days, low precipitation, and high daily temperatures, especially in the summer.

Mean annual precipitation totals on the NNSS range from approximately 13 inches over the high terrain in the northwestern part of the NNSS to less than 5 inches in Frenchman Flat (Soule, 2006). Rainfall varies markedly with the seasons as well as with elevation. The majority of rain falls during two seasons, with a larger peak in the winter and a smaller one occurring in the summer. This bimodal precipitation pattern results from two distinctive global weather patterns that develop during the summer and winter. During the summer, the lower Great Basin experiences frequent intrusions of warm moist tropical air due to the formation of a high-pressure ridge over the southern U.S. and northern Mexico. It is widely accepted that the clockwise rotation of the air mass brings warm, moist air up from the Gulf of Mexico to create a summer monsoon season characterized by local, high-intensity thunderstorm activity of relatively short duration. Much of this summer moisture may be credited to moisture driven up from the Pacific Ocean by way of the Gulf of California.

Precipitation during the winter months is governed by the formation of a high-pressure ridge in the Pacific and an accompanying low-pressure cell in the Gulf of Alaska known as the Aleutian low. This combination often forces cold, wet air masses from the Pacific Northwest over the Great Basin and Rocky Mountains. Although these storms are often longer in duration and less intense than their summer counterparts, they account for most of the annual moisture at the NNSS. Snowfall is frequently observed at elevations greater than approximately 5,500 ft.

The flora of the NNSS has been grouped into three major or regional communities: the Mojave Desert community of southern Nevada, the Great Basin Desert community of central Nevada, and a transitional community interspersed between the two (Figure 3-2). Mojave Desert communities occur over the southern third of the NNSS on the bajadas and mountain ranges at elevations below 4,000 ft and are dominated by *Larrea tridentuta* (creosote bush) and variable co-dominant shrubs. Shrub coverage varies from 7 to 23 percent for Mojave Desert communities. Great Basin Desert communities occur within basins and on mountains at elevations above 4,900 ft. These locations are less arid due to lower temperatures and greater precipitation. In comparison to Mojave Desert communities, Great Basin Desert communities tend to have more herbaceous perennials and fewer annuals. Shrub coverage in Great Basin communities averages 24 percent, with a range of 15 to 37 percent (Bechtel Nevada, 2000; 2001b).

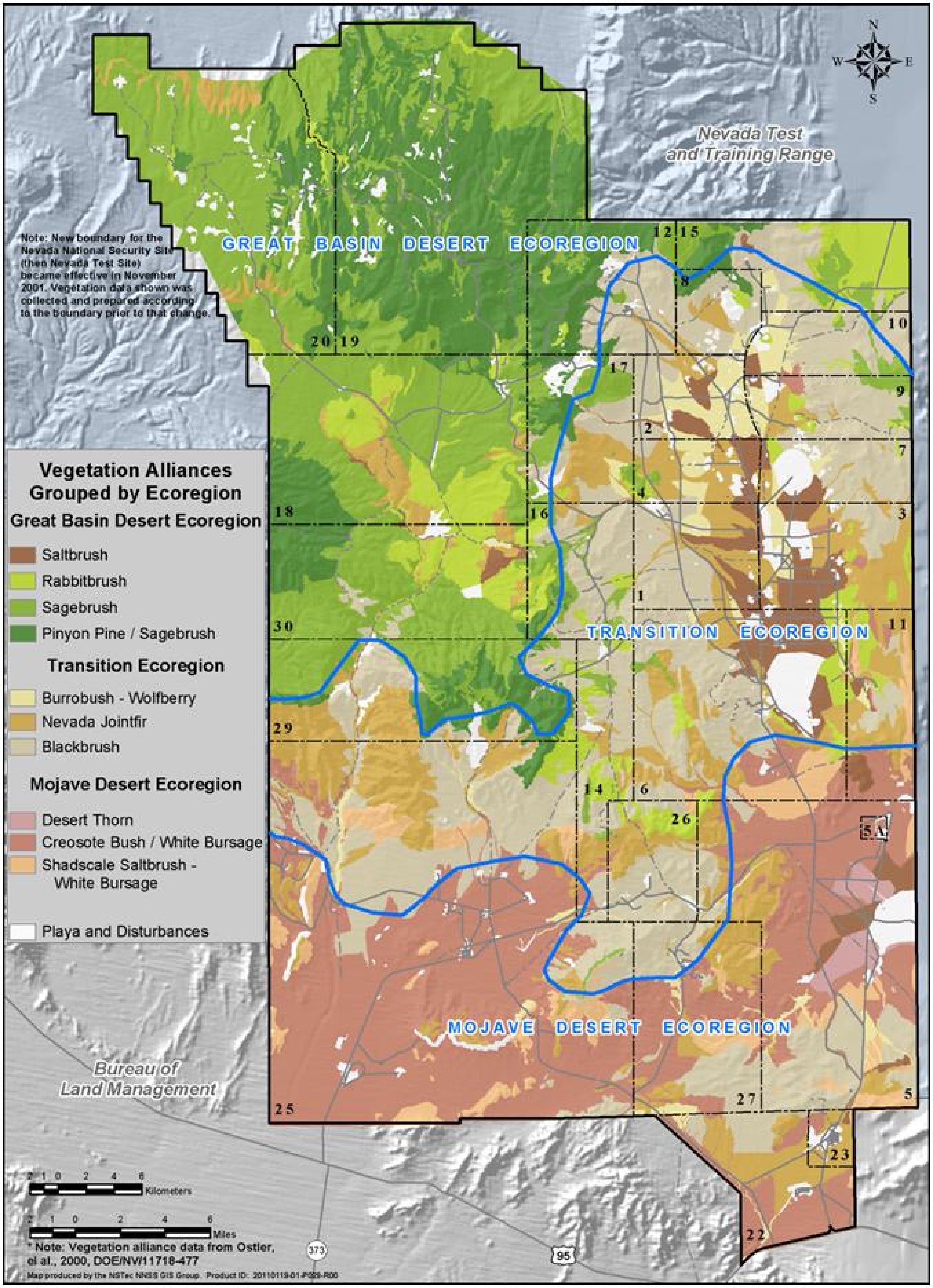

FIGURE 3-2. ECOREGIONS OF THE NEVADA NATIONAL SECURITY SITE

3.2 SOIL PARTICLE SIZE DISTRIBUTION

Soil PSD is required input for sediment yield estimation by both MUSLE and the channel transport models CHAN-SEDI and CHAN-SEDII. For this analysis, data from Lawrence Livermore National Laboratory are used to derive the PSDs for the four watersheds (Spriggs and Ray-Maitra, 2007). Spriggs and Ray-Maitra collected soil samples (containing a small amount of gravel) at approximately 140 locations at the NNSS. Using a combination of dry sieving techniques and hydrometric methods, the University of Arizona's Environmental Research Laboratory, Department of Soil, Water, and Environmental Science measured the PSDs of these soil samples. The PSD results obtained by the University of Arizona were normalized for gravel content, which was obtained by in situ measurements. The PSDs shown in Figure 3-3 are normalized distributions of averages of nearby samples for each of the watersheds.

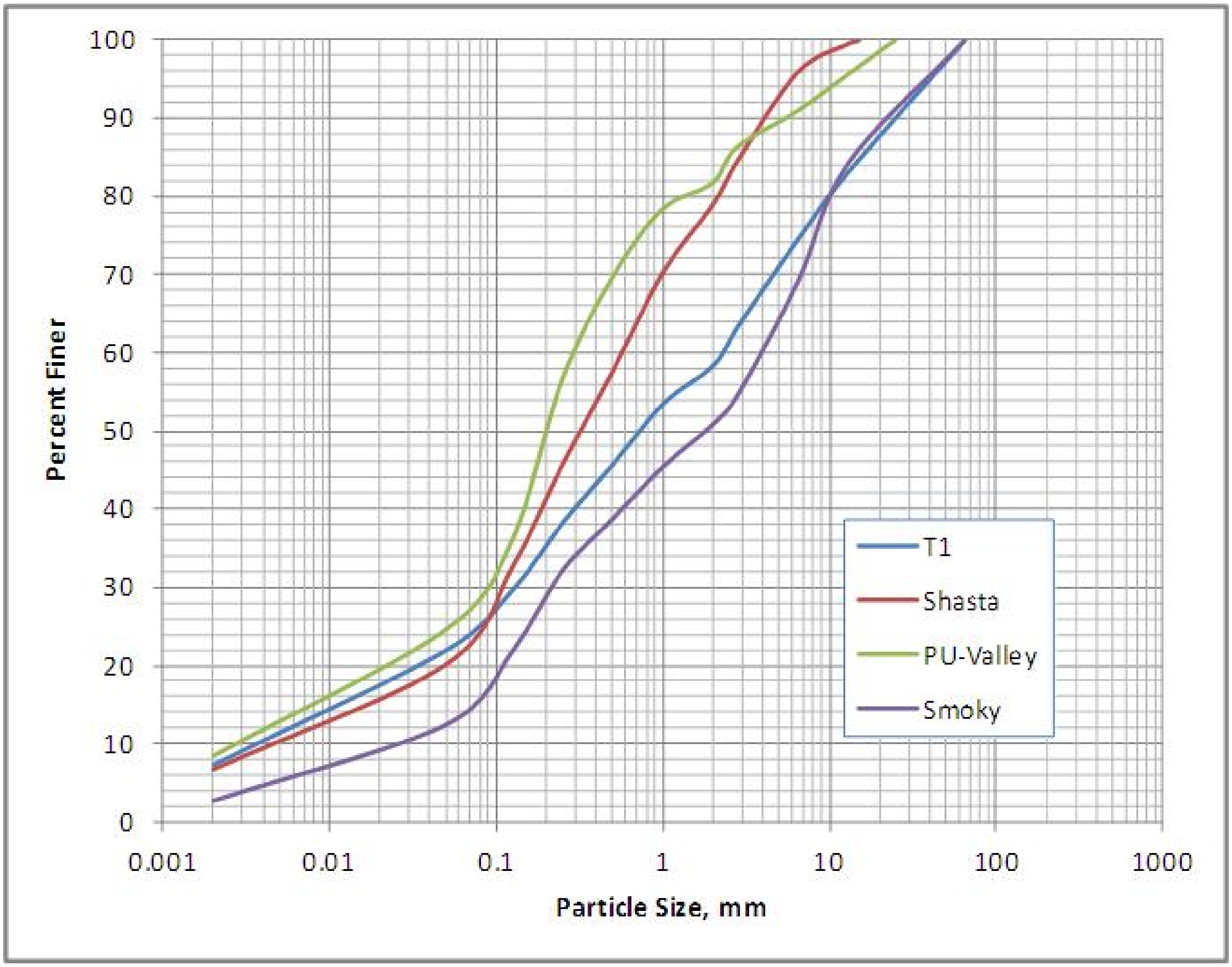

FIGURE 3-3. SOIL PARTICLE SIZE DISTRIBUTION

3.3 PLUTONIUM VALLEY

3.3.1 Site Characteristics

This site is located in the northern portion of Area 11 and consists of four test areas (identified as 11a, 11b, 11c, and 11d). The site was used to support safety experiments associated with Project 56 conducted in 1955 and 1956. Project 56 was the first test of a full-scale, completely assembled device to verify nuclear safety in the event of an accidental detonation (e.g., handling, fire, electrical discharge). The 11b, 11c, and 11d test areas are fenced and posted as High Contamination Areas, and all four test areas are located within a large, fenced site-encompassing posted Contamination Area.

Three watersheds at or near the contaminated sites are identified for the application of the methodology. These watersheds, designated as PV-1, PV-3, and PV-4 (Figure 3-4), have drainage areas of 0.78, 2.86, and 0.24 square miles (mi^2), respectively. Watershed elevations range from 4,100 to 4,300 ft in PV-1 and PV-4 and from 4,100 to 4,500 ft in PV-3. Overland slopes are approximately 6 percent in PV-1, 15 percent in PV-3, and 3 percent in PV-4. All watersheds drain through established channels. Average annual precipitation at Plutonium Valley is approximately 7.2 inches (Soule, 2006). Surface geology and the vegetation classification of Plutonium Valley are shown in Figures 3-5 and 3-6, respectively. Alluvial deposits and colluvium cover the middle and lower parts of these watersheds, while the uplands are predominantly covered with tuff. The overall plant cover is less than 30 percent and is composed mostly of transition ecoregion species such as Greene’s rabbitbrush and Nevada jointfir.

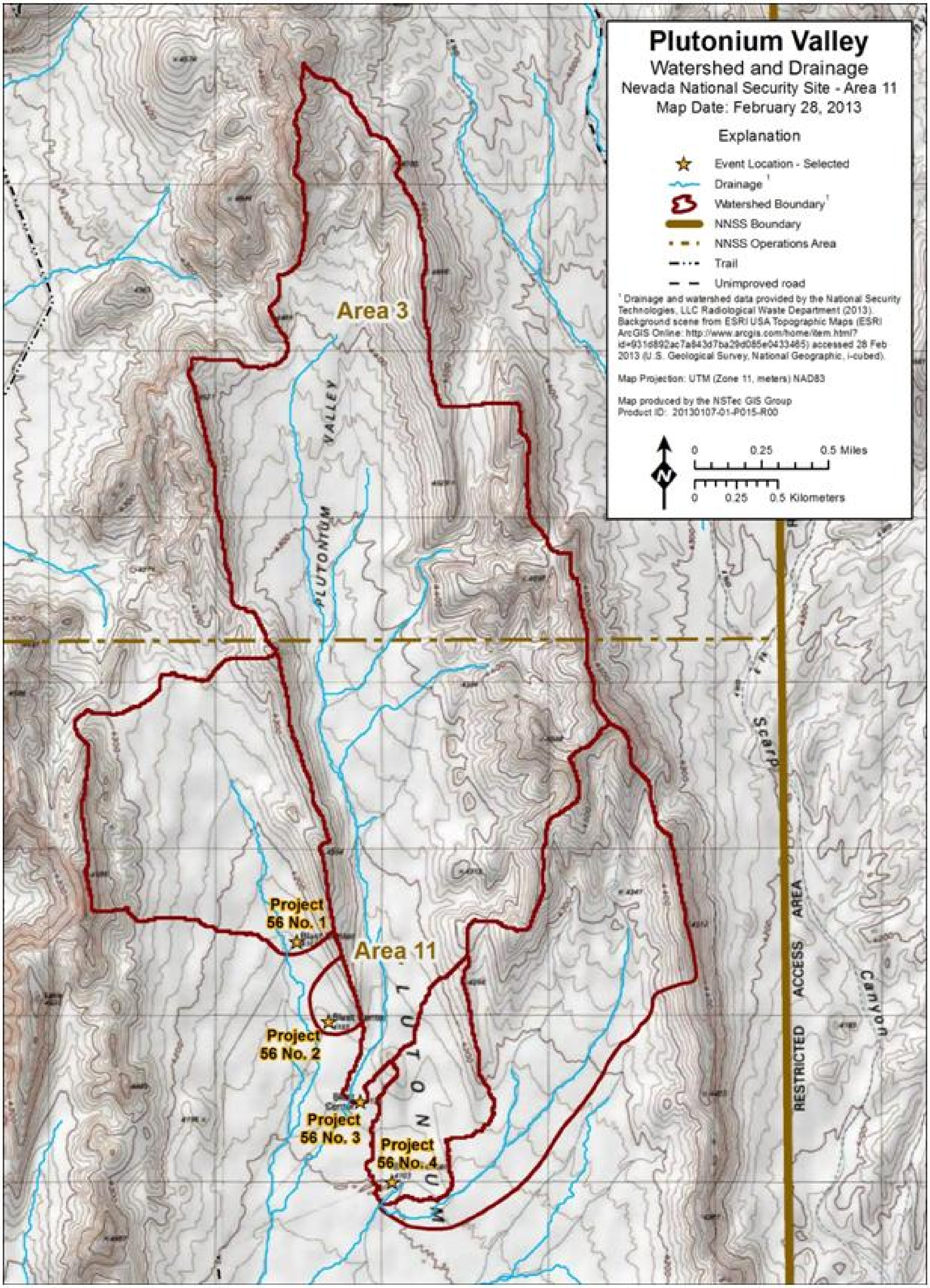

FIGURE 3-4. PLUTONIUM VALLEY WATERSHEDS

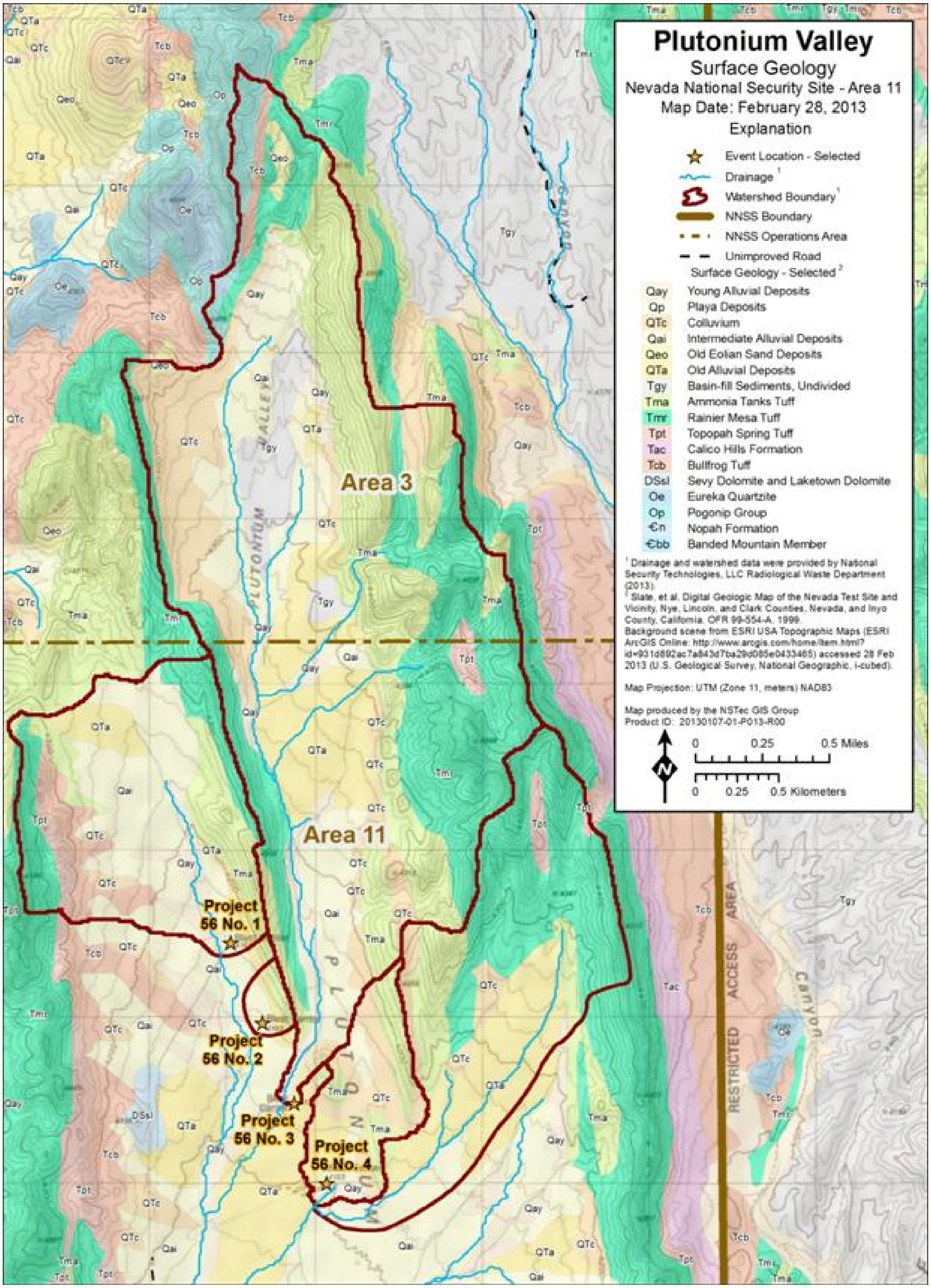

FIGURE 3-5. PLUTONIUM VALLEY SURFACE GEOLOGY

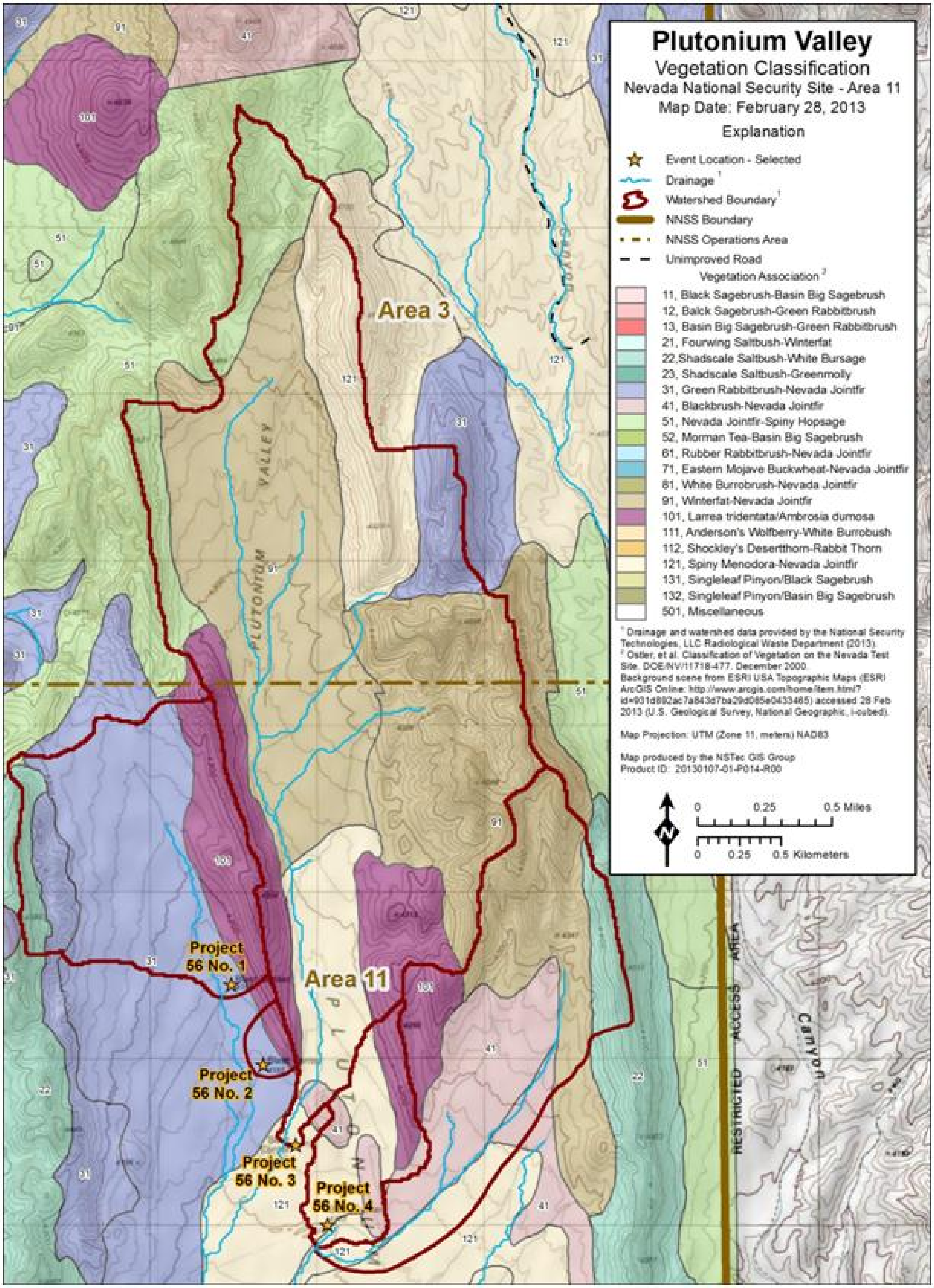

FIGURE 3-6. PLUTONIUM VALLEY VEGETATION CLASSIFICATION

3.3.2 Storm Runoff Modeling

The HEC-HMS model was set up and run to generate storm runoff data (peak flow rates, storm runoff volumes, and runoff hydrographs) for the Plutonium Valley watersheds using design storm precipitation of return periods from 2 to 100 years. The precipitation data were obtained from the NOAA's Hydrometeorological Design Studies Center website at http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=nv, accessed on February 14, 2013. The storm depth-duration-frequency data are shown in Table 3-1 and Figure 3-7. The precipitation values are reported in inches.

TABLE 3-1. PLUTONIUM VALLEY STORM PRECIPITATION DATA

DURATION	RETURN PERIOD, YEARS					
	2	5	10	25	50	100
5 minutes	0.16	0.22	0.27	0.36	0.43	0.51
10 minutes	0.24	0.34	0.42	0.54	0.65	0.77
15 minutes	0.3	0.41	0.52	0.67	0.8	0.96
30 minutes	0.4	0.56	0.7	0.9	1.08	1.29
60 minutes	0.49	0.69	0.86	1.12	1.34	1.6
2 hours	0.55	0.76	0.95	1.24	1.49	1.78
3 hours	0.62	0.85	1.04	1.33	1.58	1.87
6 hours	0.8	1.07	1.3	1.63	1.9	2.22

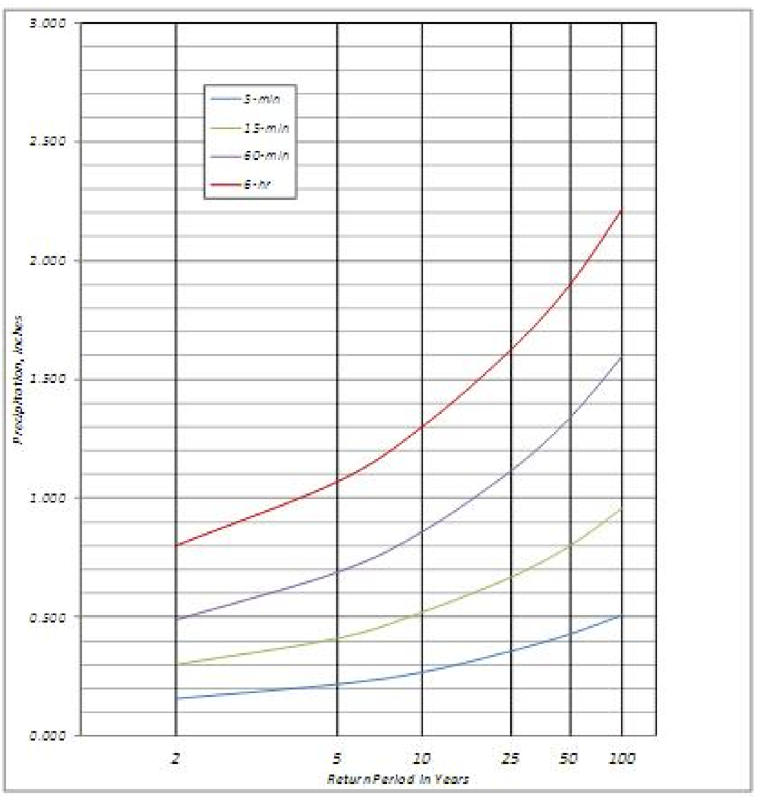

FIGURE 3-7. PLUTONIUM VALLEY PRECIPITATION DEPTH-DURATION-FREQUENCY

The SCS CN loss model was used to compute excess precipitation, and the SCS unit hydrograph procedure was used for runoff generation. Model parameters are shown in Table 3-2. CN values are for semi-arid rangelands with desert shrub of poor coverage and soil groups B and C (USACE, 2010a). The CN values were developed using antecedent soil moisture condition II (AMCII), which is the local standard, for the initial soil moisture condition for all storm events. The CN values in Table 3-2 are also composite values, derived for the basins to account for the variability in basin surface soil type, land slope, and cover. The simulated peak flow and storm runoff volumes are listed in Table 3-3 for a 6-hour storm duration.

TABLE 3-2. HEC-HMS PARAMETERS FOR THE PLUTONIUM VALLEY WATERSHEDS

BASIN	AREA (MI^2)	L (MI)	L_C (MI)	SLOPE (FT/MI)	LAG (MIN)	CN (AMCII)
PV-1	0.78	1.29	0.79	84	23	77
PV-2	2.86	4.08	1.91	75	46	77
PV-3	0.24	0.76	0.44	161	14	77

L: length of the longest watercourse
L_c: length along the watercourse from basin outlet to a point opposite the centroid of the basin
Slope: average slope of the longest watercourse
Lag: lag time between the centroid of the storm rainfall excess and the peak of the unit hydrograph
CN: curve number
AMCII: antecedent soil moisture condition II

TABLE 3-3. HEC-HMS MODELING RESULTS FOR THE PLUTONIUM VALLEY WATERSHEDS

RETURN PERIOD	PV-1		PV-3		PV-4	
	PEAK FLOW (CFS)	RUNOFF VOLUME (AC-FT)	PEAK FLOW (CFS)	RUNOFF VOLUME (AC-FT)	PEAK FLOW (CFS)	RUNOFF VOLUME (AC-FT)
2 years	58.1	5.39	135.9	19.84	23.6	1.67
5 years	119.6	10.79	279.9	39.69	48.2	3.34
10 years	182.8	16.18	426.0	59.53	74.0	5.01
25 years	282.5	23.65	658.0	87.00	114.4	7.33
50 years	373.1	30.71	870.3	112.95	151.0	9.51
100 years	490.4	39.42	1,141.7	145.01	198.8	12.21

3.3.3 PSIAC Factor Analysis

The ratings and scores for the drainage basin characteristics are shown in Tables 3-4 through 3-6 for the PV-1, PV-3, and PV-4 watersheds. The scores for geology, soils, topography, and ground cover are based on site watershed maps for Plutonium Valley. Soule (2006), was the source for climate and runoff factors. Land use factors were scored considering no cultivation. Upland erosion and channel erosion scores were based on field observations.

The computed annual sediment yields for these watersheds are between 0.2 and 0.5 ac-ft/mi^2.

TABLE 3-4. PSIAC FACTOR ANALYSIS FOR THE PV-1 WATERSHED

DRAINAGE BASIN CHARACTERISTICS	HIGH RATING	MEDIUM RATING	LOW RATING	SCORE
Surface Geology	10: marine shales and related mudstones and siltstones	5: rocks of medium hardness, moderately weathered, and fractured	0: massive, hard formations	8
Soils	10: fine textured and easily dispersed or single grain salts and fine sands	5: medium textured, occasional rock fragments, or caliche crusted layers	0: frequent rock fragments, aggregated clays, or high organic content	8
Climate	10: frequent intense convective storms	5: infrequent convective storms, moderate intensity	0: humid climate with low intensity rainfall, arid climate with low intensity rainfall, or arid climate with rare convective storms	5
Runoff	10: high flows or volume per unit area	5: moderate flows or runoff volume per unit area	0: low flows or volume per unit area or rare runoff events	1
Topography	20: steep slopes (in excess of 30%), high relief, little or no flood plain development	10: moderate slopes (about 20%), moderate flood plain development	0: gentle slopes (less than 5%), extensive flood plain development	2
Ground Cover	10: ground cover less than 20%, no rock or organic litter in surface soil	0: ground cover less than 40%, noticeable organic litter in surface soil	(-10): area completely covered by vegetation, rock fragments, organic litter with little opportunity for rainfall to erode soil	10
Land Use	10: more than 50% cultivated, sparse vegetation, and no rock in surface soil	0: less than 25% cultivated, less than 50% intensively grazed	(-10): no cultivation, no recent logging, and only low intensity grazing, if any	-10
Upland Erosion	25: rill, gully, or landslide erosion over more than 50% of the area	10: rill, gully, or landslide erosion over about 25% of the area	0: no apparent signs of erosion	5
Channel Erosion	25: continuous or frequent bank erosion, or active headcuts and degradation in tributary channels	10: occasional channel erosion of bed or banks	0: wide, shallow channels with mild gradients, channels in massive rock, large boulders, dense vegetation, or artificially protected channels	10
			Total Rating	**39**

Risk	Class	Sediment Yield (ac-ft/mi^2)	Rating
Very High	1	>3.0	>100
High	2	1.0–3.0	75–100
Medium	3	0.5–1.0	50–75
Low	4	0.2–0.5	25–50
Very Low	5	<0.2	0–25
Calculated Risk	**Low**	**Calculated Yield (ac-ft/mi^2)**	**0.32**

TABLE 3-5. PSIAC FACTOR ANALYSIS FOR THE PV-3 WATERSHED

DRAINAGE BASIN CHARACTERISTICS	HIGH RATING	MEDIUM RATING	LOW RATING	SCORE
Surface Geology	10: marine shales and related mudstones and siltstones	5: rocks of medium hardness, moderately weathered, and fractured	0: massive, hard formations	6
Soils	10: fine textured and easily dispersed or single grain salts and fine sands	5: medium textured, occasional rock fragments, or caliche crusted layers	0: frequent rock fragments, aggregated clays, or high organic content	6
Climate	10: frequent intense convective storms	5: infrequent convective storms, moderate intensity	0: humid climate with low intensity rainfall, arid climate with low intensity rainfall, or arid climate with rare convective storms	5
Runoff	10: high flows or volume per unit area	5: moderate flows or runoff volume per unit area	0: low flows or volume per unit area or rare runoff events	1
Topography	20: steep slopes (in excess of 30%), high relief, little or no flood plain development	10: moderate slopes (about 20%), moderate flood plain development	0: gentle slopes (less than 5%), extensive flood plain development	5
Ground Cover	10: ground cover less than 20%, no rock or organic litter in surface soil	0: ground cover less than 40%, noticeable organic litter in surface soil	(-10): area completely covered by vegetation, rock fragments, organic litter with little opportunity for rainfall to erode soil	10
Land Use	10: more than 50% cultivated, sparse vegetation, and no rock in surface soil	0: less than 25% cultivated, less than 50% intensively grazed	(-10): no cultivation, no recent logging, and only low intensity grazing, if any	-10
Upland Erosion	25: rill, gully, or landslide erosion over more than 50% of the area	10: rill, gully, or landslide erosion over about 25% of the area	0: no apparent signs of erosion	10
Channel Erosion	25: continuous or frequent bank erosion, or active headcuts and degradation in tributary channels	10: occasional channel erosion of bed or banks	0: wide, shallow channels with mild gradients, channels in massive rock, large boulders, dense vegetation, or artificially protected channels	10
			Total Rating	**43**

Risk	**Class**	**Sediment Yield (ac-ft/mi^2)**	**Rating**
Very High	1	>3.0	>100
High	2	1.0–3.0	75–100
Medium	3	0.5–1.0	50–75
Low	4	0.2–0.5	25–50
Very Low	5	<0.2	0–25
Calculated Risk	**Low**	**Calculated Yield (ac-ft/mi^2)**	**0.37**

Table 3-6. PSIAC Factor Analysis for the PV-4 Watershed

Drainage Basin Characteristics	High Rating	Medium Rating	Low Rating	Score
Surface Geology	10: marine shales and related mudstones and siltstones	5: rocks of medium hardness, moderately weathered, and fractured	0: massive, hard formations	9
Soils	10: fine textured and easily dispersed or single grain salts and fine sands	5: medium textured, occasional rock fragments, or caliche crusted layers	0: frequent rock fragments, aggregated clays, or high organic content	9
Climate	10: frequent intense convective storms	5: infrequent convective storms, moderate intensity	0: humid climate with low intensity rainfall, arid climate with low intensity rainfall, or arid climate with rare convective storms	5
Runoff	10: high flows or volume per unit area	5: moderate flows or runoff volume per unit area	0: low flows or volume per unit area or rare runoff events	1
Topography	20: steep slopes (in excess of 30%), high relief, little or no flood plain development	10: moderate slopes (about 20%), moderate flood plain development	0: gentle slopes (less than 5%), extensive flood plain development	0
Ground Cover	10: ground cover less than 20%, no rock or organic litter in surface soil	0: ground cover less than 40%, noticeable organic litter in surface soil	(-10): area completely covered by vegetation, rock fragments, organic litter with little opportunity for rainfall to erode soil	10
Land Use	10: more than 50% cultivated, sparse vegetation, and no rock in surface soil	0: less than 25% cultivated, less than 50% intensively grazed	(-10): no cultivation, no recent logging, and only low intensity grazing, if any	-10
Upland Erosion	25: rill, gully, or landslide erosion over more than 50% of the area	10: rill, gully, or landslide erosion over about 25% of the area	0: no apparent signs of erosion	0
Channel Erosion	25: continuous or frequent bank erosion, or active headcuts and degradation in tributary channels	10: occasional channel erosion of bed or banks	0: wide, shallow channels with mild gradients, channels in massive rock, large boulders, dense vegetation, or artificially protected channels	10
			Total Rating	**34**

Risk	Class	Sediment Yield (ac-ft/mi^2)	Rating
Very High	1	>3.0	>100
High	2	1.0–3.0	75–100
Medium	3	0.5–1.0	50–75
Low	4	0.2–0.5	25–50
Very Low	5	<0.2	0–25
Calculated Risk	**Low**	**Calculated Yield (ac-ft/mi^2)**	**0.27**

3.3.4 MUSLE Sediment Yield Estimates

Sediment yields for design storms from 2- to 100-year return periods were estimated using MUSLE. The factor values and storm sediment yield estimates are shown in Table 3-7. The storm runoff volume and peak flow rate are from the HEC-HMS modeling results. Soil PSD data for Plutonium Valley in Section 3.2 were used to drive the soil erodibility factor. The watershed overland slopes and lengths derived from the topographic map of the watersheds shown in Figure 3-4 were used to compute the slope and length factor.

TABLE 3-7. MUSLE SEDIMENT YIELD ANALYSIS FOR THE PLUTONIUM VALLEY WATERSHEDS

PV-1 WATERSHED						
FACTORS	**STORM RETURN PERIOD**					
	2 YEARS	**5 YEARS**	**10 YEARS**	**25 YEARS**	**50 YEARS**	**100 YEARS**
Overland length and slope, LS	1.42	1.42	1.42	1.42	1.42	1.42
Soil erodibility, K	0.12	0.12	0.12	0.12	0.12	0.12
Cover factor, C	0.3	0.3	0.3	0.3	0.3	0.3
Conservation practice factor, P	1.00	1.00	1.00	1.00	1.00	1.00
Peak flow rate, cfs	58.10	119.60	182.80	282.50	373.10	490.40
Storm runoff volume, ac-ft	5.39	10.79	16.18	23.65	30.71	39.42
Yield, ac-ft/mi^2	**0.04**	**0.08**	**0.13**	**0.21**	**0.28**	**0.38**
PV-3 WATERSHED						
FACTORS	**STORM RETURN PERIOD**					
	2 YEARS	**5 YEARS**	**10 YEARS**	**25 YEARS**	**50 YEARS**	**100 YEARS**
Overland length and slope, LS	5.34	5.34	5.34	5.34	5.34	5.34
Soil erodibility, K	0.12	0.12	0.12	0.12	0.12	0.12
Cover factor, C	0.3	0.3	0.3	0.3	0.3	0.3
Conservation practice factor, P	1.00	1.00	1.00	1.00	1.00	1.00
Peak flow rate, cfs	135.90	279.90	426.00	659.00	870.30	1,140.70
Storm runoff volume, ac-ft	19.84	39.69	59.53	87.00	112.95	145.00
Yield, ac-ft/mi^2	**0.07**	**0.14**	**0.23**	**0.36**	**0.49**	**0.65**
PV-4 WATERSHED						
FACTORS	**STORM RETURN PERIOD**					
	2 YEARS	**5 YEARS**	**10 YEARS**	**25 YEARS**	**50 YEARS**	**100 YEARS**
Overland length and slope, LS	0.58	0.58	0.58	0.58	0.58	0.58
Soil erodibility, K	0.12	0.12	0.12	0.12	0.12	0.12
Cover factor, C	0.3	0.3	0.3	0.3	0.3	0.3
Conservation practice factor, P	1.00	1.00	1.00	1.00	1.00	1.00
Peak flow rate, cfs	23.60	48.20	74.00	114.40	151.00	198.80
Storm runoff volume, ac-ft	1.67	3.34	5.01	7.32	9.51	12.21
Yield, ac-ft/mi^2	**0.02**	**0.05**	**0.08**	**0.13**	**0.18**	**0.24**

3.3.5 Transport Modeling

For demonstration purposes, the channel sediment transport EXCEL models CHAN-SEDI and CHAN-SEDII were used to estimate storm-based sediment yields from the PV-3 sub-watershed. A 3.5-mile-long, wide rectangular channel with an average slope of 1.5 percent was divided into three reaches with varying slopes derived from the topographic map of Plutonium Valley. The channel bed material in the CHAN-SEDI model is represented by the geometric mean and geometric standard deviation of the PSD for Plutonium Valley shown in Figure 3-3. The geometric mean is 0.17 mm, and the geometric standard deviation is 19.05 mm. The entire PSD of Figure 3-3 for Plutonium Valley was input to the CHAN-SEDII model. The parameters common to both models are shown in Table 3-8. For each storm event, the time series of storm flows with 5-minute time intervals, derived from the HEC-HMS modeling, were input to both models. Inflow was assumed to be sediment-free. Table 3-9 lists the estimated sediment yields.

TABLE 3-8. COMMON PARAMETERS FOR THE CHANNEL TRANSPORT MODELS

PARAMETER	VALUE
Gravitational acceleration, ft/s^2	32.2
Specific weight of water, lb/ft^3	62.4
Kinematic viscosity of water, ft^2/s	1.22E-05
Specific gravity of sediment	2.65
Porosity of settled material	0.4

TABLE 3-9. PV-3 STORM SEDIMENT YIELDS IN AC-FT/MI^2

RETURN PERIOD	CHAN-SEDI	CHAN-SEDII
2 years	0.11	0.14
5 years	0.33	0.42
10 years	0.61	0.75
25 years	1.17	1.36
50 years	1.77	1.96
100 years	2.65	2.79
Yearly average	**0.27**	**0.33**

3.3.6 Discussion of Results

The PSIAC average annual sediment yield estimates are 0.32, 0.37, and 0.27 ac-ft/mi^2 for the PV-1, PV-3, and PV-4 watersheds, respectively. Using MUSLE, they are 0.06, 0.1, and 0.04 ac-ft/mi^2. MUSLE only provides sediment yield estimates for rill and inter-rill erosion and does not account for sediment from other sources such as flow channels. If channel erosion accounts for a large portion of a watershed's sediment yield, MUSLE would underestimate the total sediment yield from a watershed. For the Plutonium Valley watersheds, sediment eroded from the channels must be added to the rill and inter-rill erosion from land surfaces provided by MUSLE. CCRFCD (1999) advocates this methodology. The total sediment yield for a watershed is estimated by adding the MUSLE estimate (wash load coming into the channels) to the bed material load estimate (suspended sediment load plus bed load), which is estimated using a sediment transport equation. For the PV-3 watershed, the annual sediment yield estimates from the CHAN-SEDI and CHAN-SEDII models are 0.27 and 0.33 ac-ft/mi^2. When these are added to the MUSLE result of 0.1 ac-ft/mi^2, the resulting total annual sediment yields are 0.37 and

0.43 ac-ft/mi^2. These estimates compare well with the estimate provided by the PSIAC method, which is 0.37 ac-ft/mi^2.

The storm sediment yield estimates from CHAN-SEDI and CHAN-SEDII transport models are similar even though these models employ different transport equations and the bed material size is specified differently.

3.4 SHASTA

3.4.1 Site Characteristics

The Shasta atmospheric test was detonated at Site T-2A. This atmospheric detonation was part of Operation Plumbbob, designed as a weapons-related test with a yield of 17 kilotons (kt). The test was performed on August 18, 1957, from a 500 ft tower (DOE/NV, 2000). The Shasta site is posted as a Radioactive Material Area.

Shasta is located in Area 2 of the NNSS, and the upstream watershed lies in both Areas 2 and 17 (Figure 3-8). The drainage area above the site is 2.98 mi^2. Elevations range from 4,300 to 6,800 ft. The longitudinal slopes are 9 to 12 percent in the upper sub-watersheds and approximately 4 percent in the lower watershed. Hillslopes in the upper watersheds are steep, with overland slopes about 34 percent. Average annual precipitation in the Shasta watershed is about 9.6 inches (Soule, 2006). Surface geology and the vegetation classification of the watershed are shown in Figures 3-9 and 3-10, respectively. Young alluvial deposits cover the entire lower watershed. Upper watersheds are mostly covered with rocks of Elena formation, with colluvium in about 5 percent. The overall plant cover is less than 30 percent and is composed mostly of transition ecoregion plants, predominantly black sagebrush in upper sub-watersheds and white burrobrush in the lower sub-watershed.

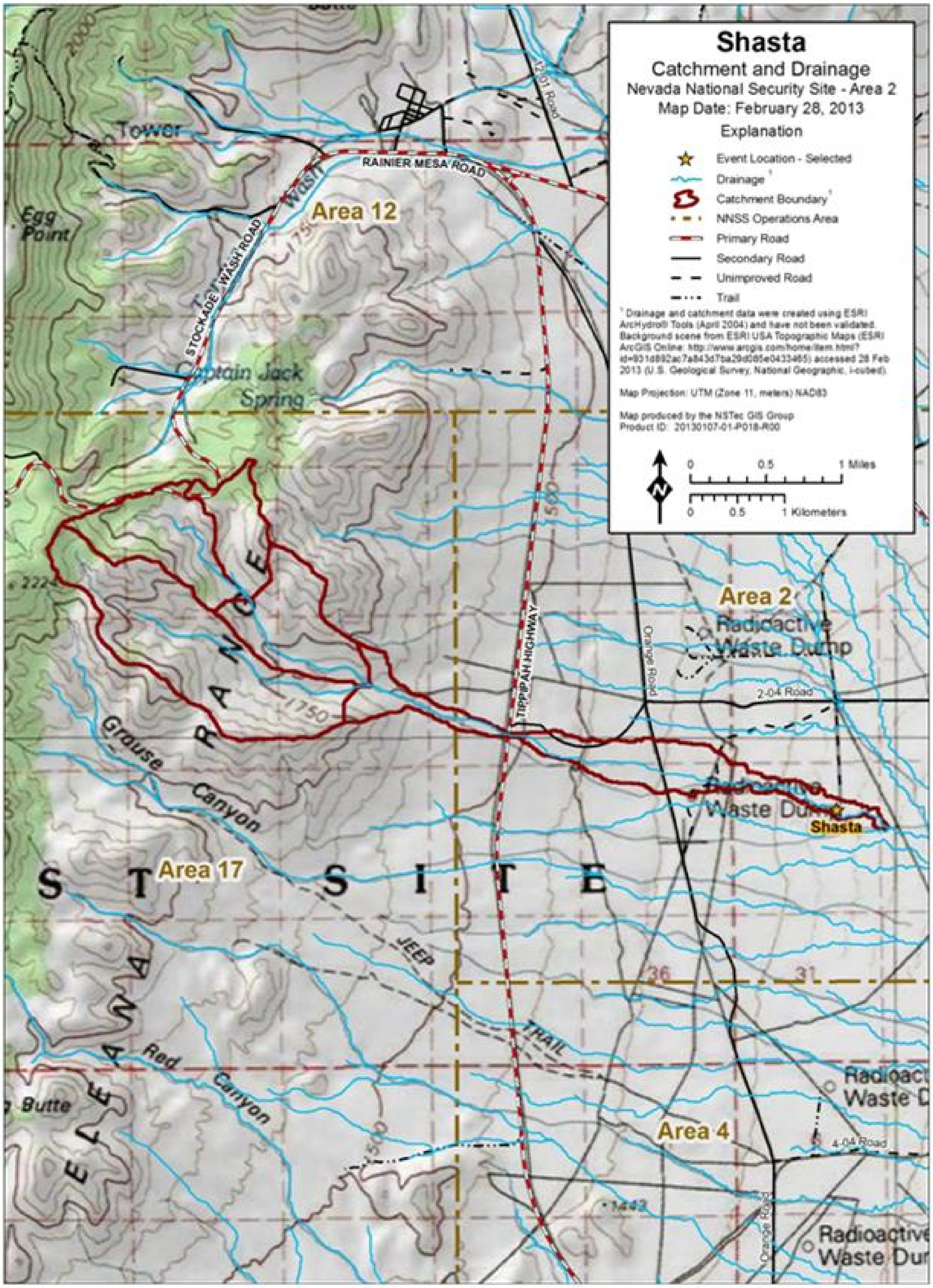

FIGURE 3-8. SHASTA WATERSHED

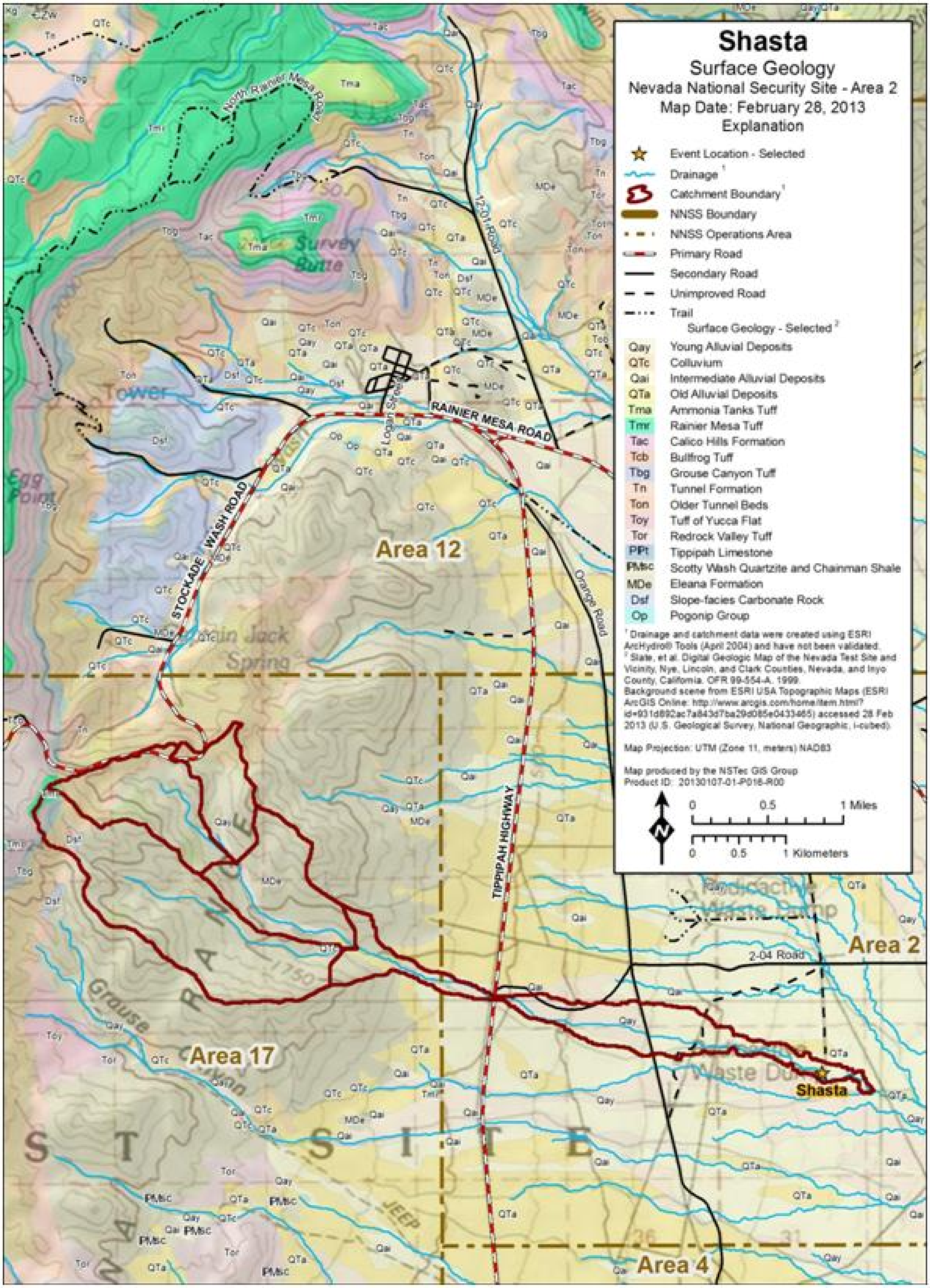

FIGURE 3-9. SHASTA SURFACE GEOLOGY

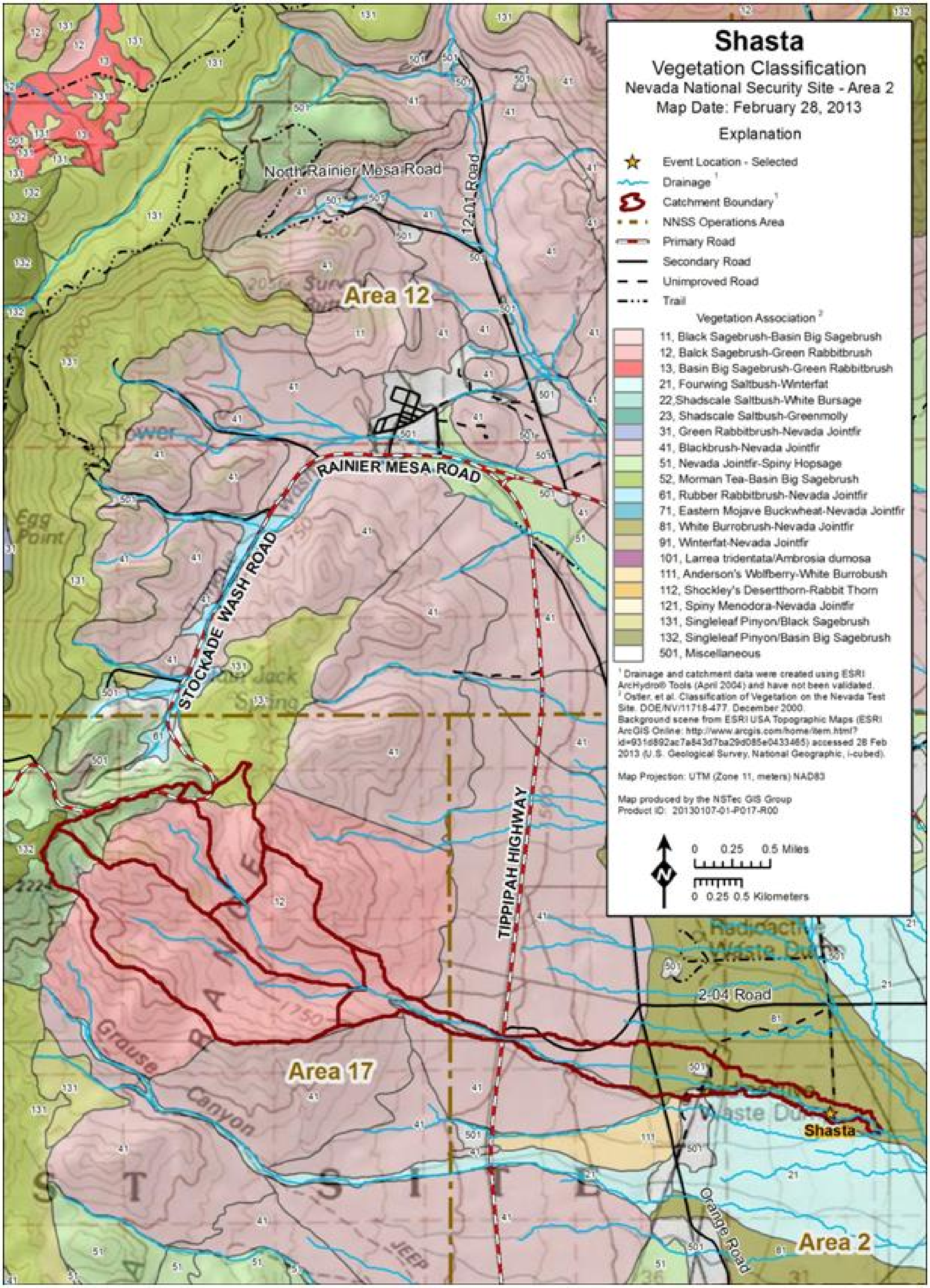

FIGURE 3-10. SHASTA VEGETATION CLASSIFICATION

3.4.2 Storm Runoff Modeling

The HEC-HMS model was set up and run to generate storm runoff data (peak flow rates, storm runoff volumes, and runoff hydrographs) for the Shasta watershed using design storm precipitation of return periods from 2 to 100 years. The precipitation data were obtained from the NOAA's Hydrometeorological Design Studies Center website at http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=nv, accessed on February 14, 2013. The storm depth-duration-frequency data are shown in Table 3-10 and Figure 3-11. The precipitation values are reported in inches.

TABLE 3-10. SHASTA STORM PRECIPITATION DATA

DURATION	RETURN PERIOD, YEARS					
	2	5	10	25	50	100
5 minutes	0.19	0.26	0.32	0.41	0.49	0.57
10 minutes	0.29	0.4	0.49	0.63	0.74	0.88
15 minutes	0.36	0.49	0.61	0.78	0.92	1.08
30 minutes	0.48	0.67	0.82	1.05	1.24	1.46
60 minutes	0.6	0.83	1.01	1.29	1.53	1.81
2 hours	0.68	0.94	1.16	1.5	1.79	2.12
3 hours	0.8	1.07	1.31	1.67	1.97	2.33
6 hours	1.1	1.46	1.76	2.18	2.54	2.94

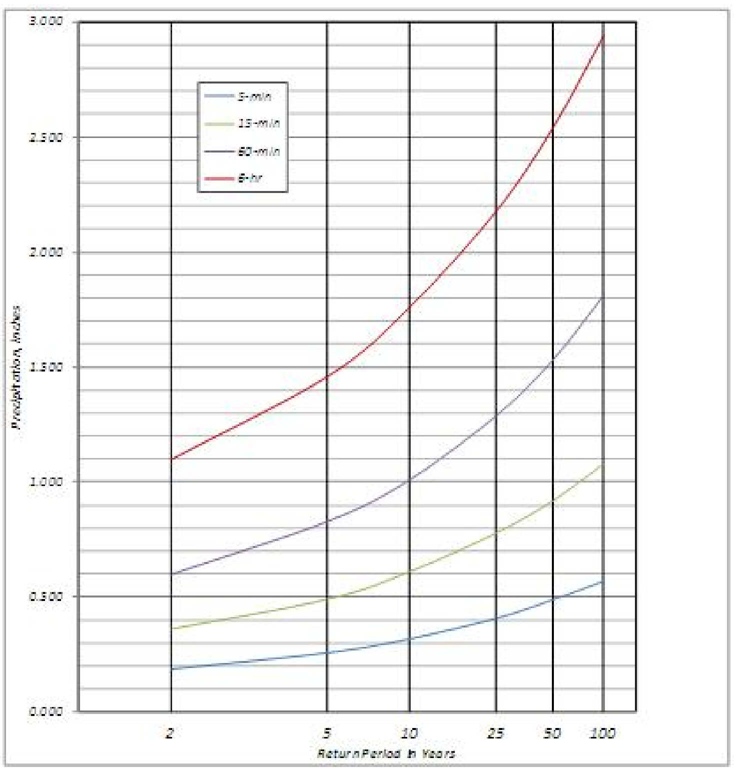

FIGURE 3-11. SHASTA PRECIPITATION DEPTH-DURATION-FREQUENCY

The SCS CN loss model was used to compute excess precipitation, and the SCS unit hydrograph procedure was used for runoff generation. Model parameters are shown in Table 3-11. CN values are for semi-arid rangelands with desert shrub of poor coverage and soil groups B and C (USACE, 2010a). The CN values were developed using AMCII, which is the local standard, for the initial soil moisture condition for all storm events. The CN values in Table 3-11 are also composite values, derived for the basins to account for the variability in basin surface soil type, land slope, and cover. The simulated peak flow and storm runoff volumes are listed in Table 3-12 for a 6-hour storm duration.

TABLE 3-11. HEC-HMS PARAMETERS FOR SHASTA

BASIN	AREA (MI^2)	L (MI)	L_C (MI)	SLOPE (FT/MI)	LAG (MIN)	CN (AMCII)
North Branch	1.18	2.29	1.33	479	25	85
South Branch	1.08	2.25	1.19	624	23	88
Lower Branch	0.72	3.51	1.79	210	36	85

L: length of the longest watercourse
L_c: length along the watercourse from basin outlet to a point opposite the centroid of the basin
Slope: average slope of the longest watercourse
Lag: lag time between the centroid of the storm rainfall excess and the peak of the unit hydrograph
CN: curve number
AMCII: antecedent soil moisture condition II

TABLE 3-12. HEC-HMS MODELING RESULTS FOR SHASTA

RETURN PERIOD	NORTH BRANCH		SOUTH BRANCH		LOWER BRANCH		OUTLET	
	PEAK FLOW (CFS)	RUNOFF VOLUME (AC-FT)	PEAK FLOW (CFS)	RUNOFF VOLUME (AC-FT)	PEAK FLOW (CFS)	RUNOFF VOLUME (AC-FT)	PEAK FLOW (CFS)	RUNOFF VOLUME (AC-FT)
2 years	195.3	21.40	218.9	23.02	94.2	13.05	504.9	57.19
5 years	370.3	39.02	405.5	40.86	179.0	23.79	947.4	103.26
10 years	528.8	54.12	572.1	55.82	255.1	33.01	1,343.4	142.97
25 years	762.4	75.52	813.2	77.11	368.1	46.05	1,923.9	198.57
50 years	966.0	93.77	1,020.1	94.95	466.8	57.18	2,426.8	246.23
100 years	1,207.8	115.17	1,263.4	115.09	584.5	70.23	3,022.0	300.24

3.4.3 PSIAC Factor Analysis

The ratings and scores for the drainage basin characteristics for Shasta are shown in Table 3-13. The scores for geology, soils, topography, and ground cover are based on site watershed maps for Shasta. Soule (2006) was the source for climate and runoff factors. Land use factors were scored considering no cultivation. Upland erosion and channel erosion scores were based on field observations.

The computed annual sediment yield for Shasta is 0.53 ac-ft/mi^2.

TABLE 3-13. PSIAC FACTOR ANALYSIS FOR SHASTA

DRAINAGE BASIN CHARACTERISTICS	HIGH RATING	MEDIUM RATING	LOW RATING	SCORE
Surface Geology	10: marine shales and related mudstones and siltstones	5: rocks of medium hardness, moderately weathered, and fractured	0: massive, hard formations	6
Soils	10: fine textured and easily dispersed or single grain salts and fine sands	5: medium textured, occasional rock fragments, or caliche crusted layers	0: frequent rock fragments, aggregated clays, or high organic content	6
Climate	10: frequent intense convective storms	5: infrequent convective storms, moderate intensity	0: humid climate with low intensity rainfall, arid climate with low intensity rainfall, or arid climate with rare convective storms	5
Runoff	10: high flows or volume per unit area	5: moderate flows or runoff volume per unit area	0: low flows or volume per unit area or rare runoff events	4
Topography	20: steep slopes (in excess of 30%), high relief, little or no flood plain development	10: moderate slopes (about 20%), moderate flood plain development	0: gentle slopes (less than 5%), extensive flood plain development	9
Ground Cover	10: ground cover less than 20%, no rock or organic litter in surface soil	0: ground cover less than 40%, noticeable organic litter in surface soil	(-10): area completely covered by vegetation, rock fragments, organic litter with little opportunity for rainfall to erode soil	10
Land Use	10: more than 50% cultivated, sparse vegetation, and no rock in surface soil	0: less than 25% cultivated, less than 50% intensively grazed	(-10): no cultivation, no recent logging, and only low intensity grazing, if any	-10
Upland Erosion	25: rill, gully, or landslide erosion over more than 50% of the area	10: rill, gully, or landslide erosion over about 25% of the area	0: no apparent signs of erosion	8
Channel Erosion	25: continuous or frequent bank erosion, or active headcuts and degradation in tributary channels	10: occasional channel erosion of bed or banks	0: wide, shallow channels with mild gradients, channels in massive rock, large boulders, dense vegetation, or artificially protected channels	15
			Total Rating	**53**

Risk	Class	Sediment Yield (ac-ft/mi^2)	Rating
Very High	1	>3.0	>100
High	2	1.0–3.0	75–100
Medium	3	0.5–1.0	50–75
Low	4	0.2–0.5	25–50
Very Low	5	<0.2	0–25
Calculated Risk	**Medium**	**Calculated Yield (ac-ft/mi^2)**	**0.53**

3.4.4 MUSLE Sediment Yield Estimates

Sediment yields for design storms from 2- to 100-year return periods were estimated using MUSLE. The factor values and storm sediment yield estimates are shown in Table 3-14. The storm runoff volume and peak flow rate are from the HEC-HMS modeling results for Shasta. Soil PSD data for Shasta in Section 3.2 were used to drive the soil erodibility factor. The watershed overland slopes and lengths were derived from the topographic map of the watershed shown in Figure 3-8 to compute the slope and length factor.

TABLE 3-14. MUSLE SEDIMENT YIELD ANALYSIS FOR SHASTA

FACTORS	STORM RETURN PERIOD					
	2 YEARS	5 YEARS	10 YEARS	25 YEARS	50 YEARS	100 YEARS
Overland length and slope, LS	15.39	15.39	15.39	15.39	15.39	15.39
Soil erodibility, K	0.12	0.12	0.12	0.12	0.12	0.12
Cover factor, C	0.3	0.3	0.3	0.3	0.3	0.3
Conservation practice factor, P	1.00	1.00	1.00	1.00	1.00	1.00
Peak flow rate, cfs	504.90	947.40	1,343.40	1,923.90	2,426.80	3,022.00
Storm runoff volume, ac-ft	57.19	103.23	142.97	198.57	246.23	300.24
Yield, ac-ft/mi^2	**0.33**	**0.65**	**0.95**	**1.40**	**1.80**	**2.27**

3.4.5 Transport Modeling

For demonstration purposes, the channel sediment transport EXCEL models CHAN-SEDI and CHAN-SEDII were used to estimate storm-based sediment yields from the Shasta watershed. A 1.62-mile-long, wide rectangular channel with an average slope of 2.9 percent was divided into three reaches with varying slopes derived from the topographic map of the Shasta watershed. The channel bed material in the CHAN-SEDI model is represented by the geometric mean and geometric standard deviation of the PSD for Shasta shown in Figure 3-3. The geometric mean is 0.24 mm, and the geometric standard deviation is 14.9 mm. The entire PSD of Figure 3-3 for Shasta was input to the CHAN-SEDII model. The parameters common to both models are shown in Table 3-8. For each storm event, the time series of storm flows with 5-minute time intervals, derived from the HEC-HMS modeling, were input to both models. Inflow was assumed to be sediment-free. The estimated sediment yields are shown in Table 3-15.

TABLE 3-15. SHASTA STORM SEDIMENT YIELDS IN AC-FT/MI^2

RETURN PERIOD	CHAN-SEDI	CHAN-SEDII
2 years	0.89	1.02
5 years	2.28	2.49
10 years	3.89	3.96
25 years	6.74	6.24
50 years	9.73	8.31
100 years	13.83	10.86
Yearly average	**1.75**	**1.76**

3.4.6 Discussion of Results

The PSIAC average annual sediment yield estimate is 0.53 ac-ft/mi^2 for Shasta. Using MUSLE, the estimate is 0.46 ac-ft/mi^2. These two estimates are similar. However, MUSLE only provides sediment yield estimates for rill and inter-rill erosion and does not account for sediment from other sources such as flow channels. If channel erosion accounts for a large portion of a watershed's sediment yield, MUSLE would underestimate the total sediment yield from a watershed. For Shasta, sediment eroded from the channels must be added to the rill and inter-rill erosion from the land surfaces provided by MUSLE. CCRFCD (1999) advocates this methodology. The total sediment yield for a watershed is estimated by adding the estimate from MUSLE (wash load coming into the channels) to the estimate of the bed material load (suspended sediment load plus bed load), which is estimated using a sediment transport equation. For Shasta, the annual sediment yield estimates from the CHAN-SEDI and CHAN-SEDII models are 1.75 and 1.76 ac-ft/mi^2. When these estimates are added to the MUSLE result of 0.46 ac-ft/mi^2, the resulting total annual sediment yields are 2.21 and 2.22 ac-ft/mi^2. These annual sediment yield estimates exceed the estimate provided by the PSIAC method, which is 0.53 ac-ft/mi^2. Further field observations of Shasta would be necessary to verify that the erosion from channels may indeed account for a significant portion of the total annual sediment yield. The application of the PSIAC to Shasta assumed no significant channel erosion.

The storm sediment yield estimates from CHAN-SEDI and CHAN-SEDII transport models are similar even though these models employ different transport equations and the bed material size is specified differently.

3.5 SMOKY

3.5.1 Site Characteristics

Smoky is located in Area 8 of the NNSS (Figure 3-12). One weapons-related atmospheric tower test (Smoky) and three tower safety experiments (Oberon, Ceres, and Titania) were conducted in this area. Smoky was conducted on August 31, 1957, from a 700 ft tower as part of Operation Plumbbob and had a yield of 44 kt. Smoky was also used to study the blast effects produced on missiles, vehicles, and unmanned tanks. Oberon was a zero-yield safety experiment detonated from a tower at 25 ft on October 22, 1958. Ceres was a safety experiment with a yield of 0.7 tons detonated from a tower at 25 ft on October 26, 1958. Titania was a safety experiment with a yield of 0.2 tons detonated from a tower at 25 ft on October 30, 1958 (DOE/NV, 2000). The present Contamination Area fence was constructed in 1998 to enclose the safety experiment test ground zeros using soil-based removable contamination data.

The drainage area above the site is 0.32 mi^2. Elevations range from 4,400 to 4,900 ft. The longitudinal slope of the watershed is approximately 5.5 percent. Overland slopes are approximately 15 percent. Average annual precipitation in the Smoky watershed is about 7.6 inches (Soule, 2006). Surface geology and the vegetation classification of the watershed are shown in Figures 3-13 and 3-14, respectively. Young alluvial deposits cover the entire lower watershed. Upper watersheds are mostly covered with rocks of Nopah formation, with alluvial deposits and colluvium in about 5 percent. The overall plant cover is less than 30 percent and is composed mostly of transition ecoregion plants, predominantly black sagebrush and Nevada jointfir in 40 percent of the area and other desert plants in the remaining 60 percent of the area.

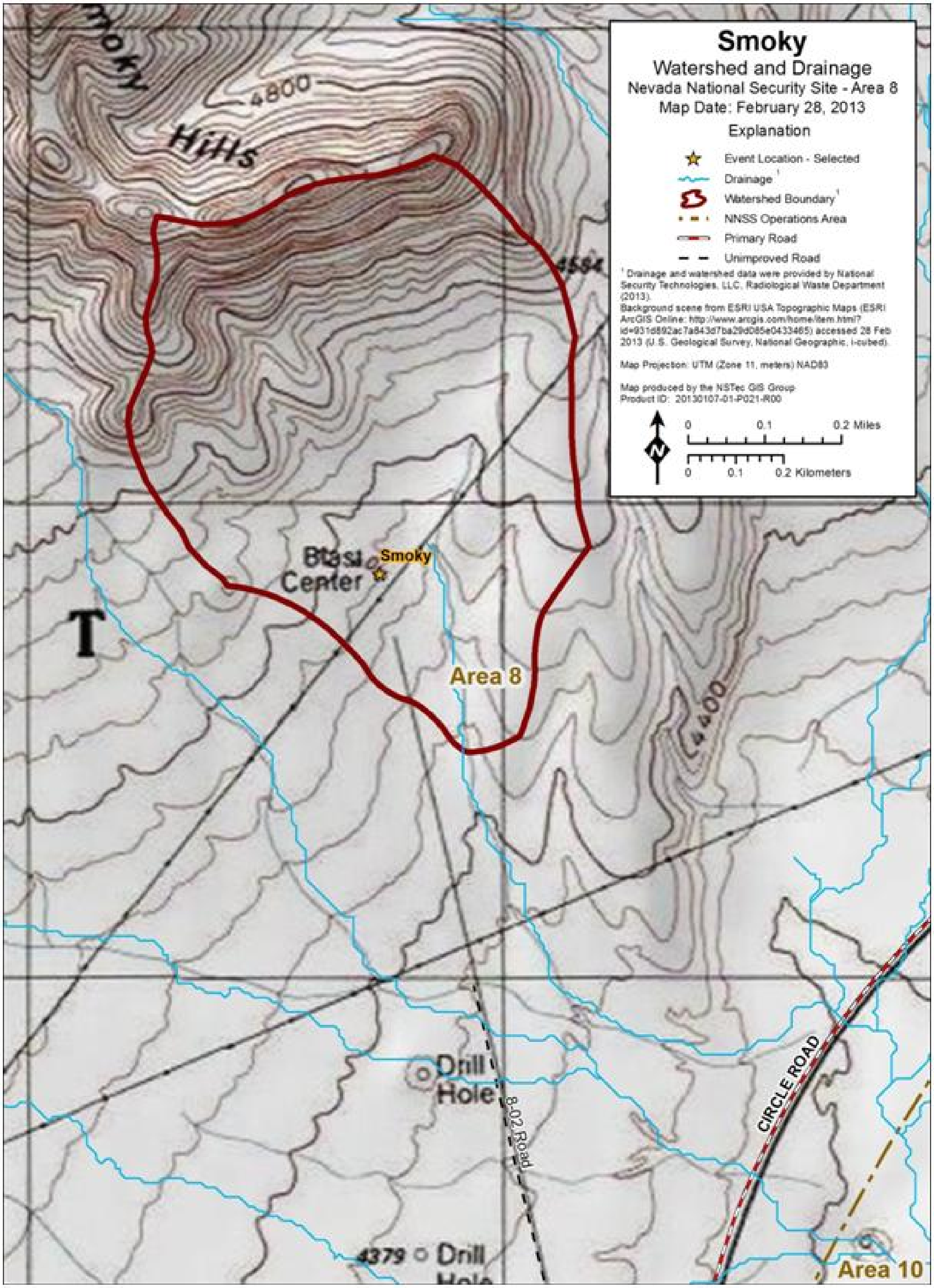

FIGURE 3-12. SMOKY WATERSHED

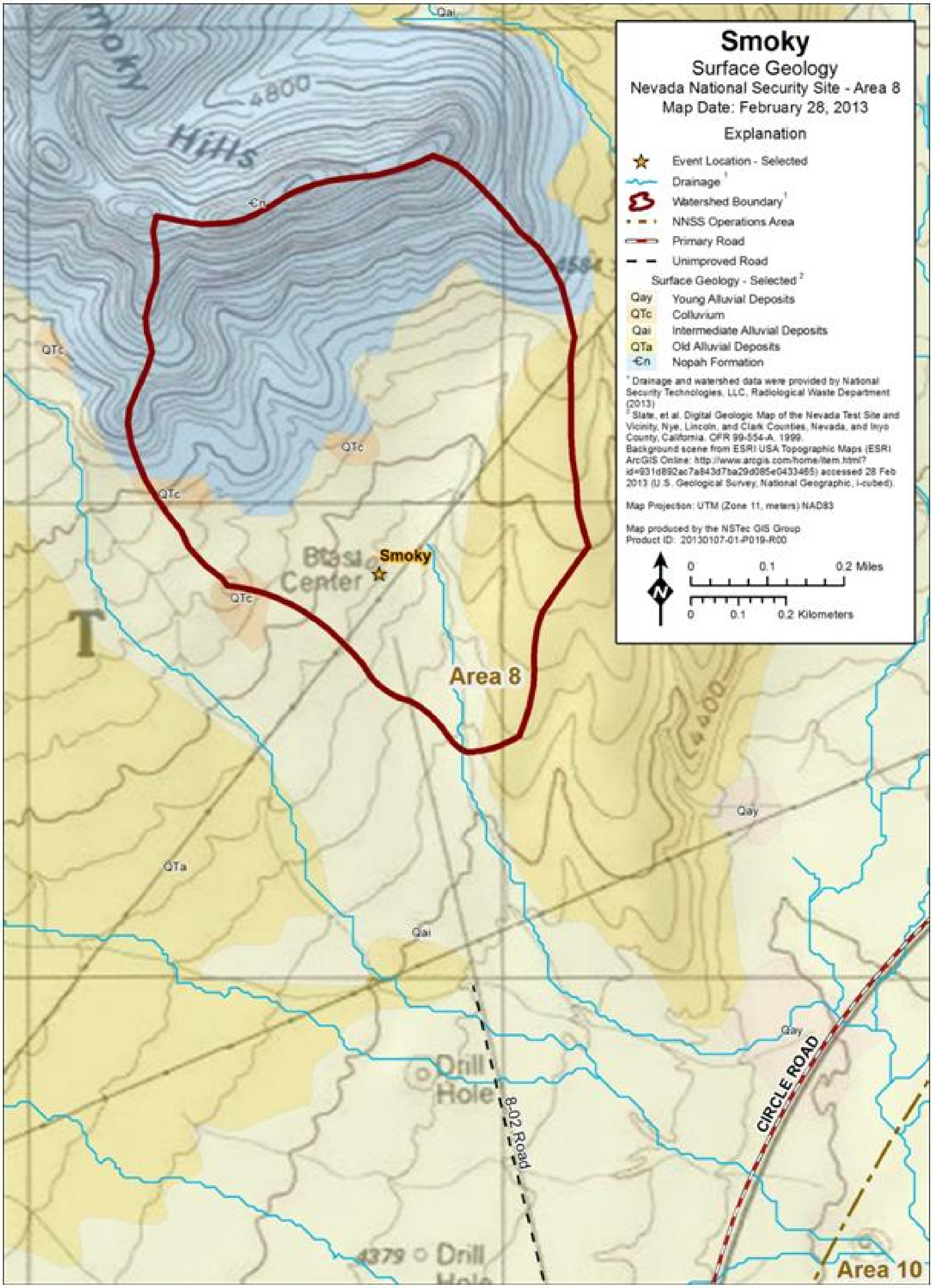

FIGURE 3-13. SMOKY SURFACE GEOLOGY

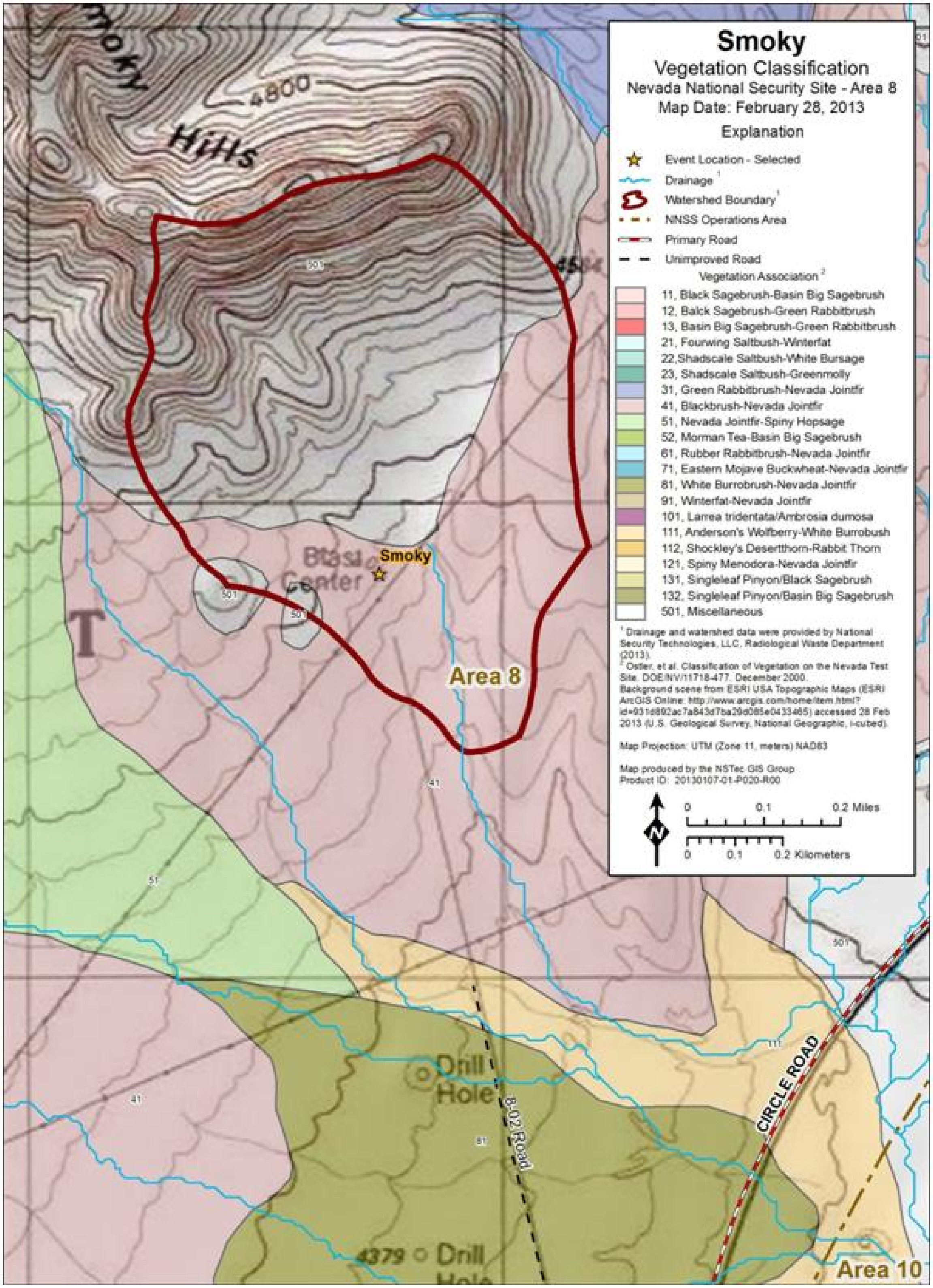

FIGURE 3-14. SMOKY VEGETATION CLASSIFICATION

3.5.2 Storm Runoff Modeling

The HEC-HMS model was set up and run to generate storm runoff data (peak flow rates, storm runoff volumes, and runoff hydrographs) for the Smoky watershed using design storm precipitation of return periods from 2 to 100 years. The precipitation data were obtained from the NOAA's Hydrometeorological Design Studies Center website at http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=nv, accessed on February 14, 2013. The storm depth-duration-frequency data are shown in Table 3-16 and Figure 3-15. The precipitation values are reported in inches.

TABLE 3-16. SMOKY STORM PRECIPITATION DATA

DURATION	RETURN PERIOD, YEARS					
	2	5	10	25	50	100
5 minutes	0.17	0.23	0.28	0.37	0.44	0.52
10 minutes	0.25	0.35	0.43	0.56	0.67	0.79
15 minutes	0.31	0.43	0.54	0.69	0.82	0.98
30 minutes	0.42	0.58	0.72	0.93	1.11	1.32
60 minutes	0.52	0.72	0.89	1.15	1.37	1.63
2 hours	0.57	0.80	0.99	1.28	1.54	1.84
3 hours	0.66	0.89	1.09	1.40	1.66	1.96
6 hours	0.86	1.15	1.39	1.73	2.02	2.35

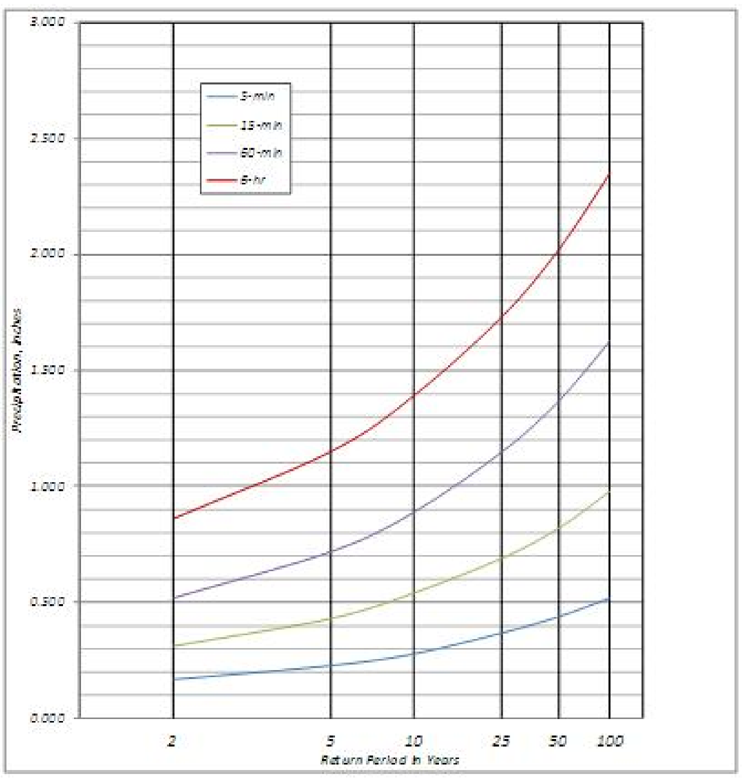

FIGURE 3-15. SMOKY PRECIPITATION DEPTH-DURATION-FREQUENCY

The SCS CN loss model was used to compute excess precipitation, and the SCS unit hydrograph procedure was used for runoff generation. Model parameters are shown in Table 3-17. CN values are for semi-arid rangelands with desert shrub of poor coverage and soil groups B and C (USACE, 2010a). The CN values were developed using AMCII, which is the local standard, for the initial soil moisture condition for all storm events. The CN values in Table 3-17 are also composite values, derived for the basins to account for the variability in basin surface soil type, land slope, and cover. The simulated peak flow and storm runoff volumes are listed in Table 3-18 for a 6-hour storm duration.

TABLE 3-17. HEC-HMS PARAMETERS FOR SMOKY

BASIN	AREA (MI^2)	L (MI)	L_C (MI)	SLOPE (FT/MI)	LAG (MIN)	CN (AMCII)
Smoky	0.32	0.85	0.51	293	14	85

L: length of the longest watercourse
L_c: length along the watercourse from basin outlet to a point opposite the centroid of the basin
Slope: average slope of the longest watercourse
Lag: lag time between the centroid of the storm rainfall excess and the peak of the unit hydrograph
CN: curve number
AMCII: antecedent soil moisture condition II

TABLE 3-18. HEC-HMS MODELING RESULTS FOR SMOKY

RETURN PERIOD	OUTLET	
	PEAK FLOW (CFS)	RUNOFF VOLUME (AC-FT)
2 years	52.3	3.93
5 years	102.3	7.17
10 years	150.3	10.24
25 years	221.4	14.68
50 years	284.5	18.43
100 years	363.2	22.87

3.5.3 PSIAC Factor Analysis

The ratings and scores for the drainage basin characteristics for Smoky are shown in Table 3-19. The scores for geology, soils, topography, and ground cover are based on site watershed maps for Smoky. Soule (2006) was the source for climate and runoff factors. Land use factors were scored considering no cultivation. Upland erosion and channel erosion scores were based on field observations.

The computed annual sediment yield for Smoky is 0.39 ac-ft/mi^2.

TABLE 3-19. PSIAC FACTOR ANALYSIS FOR SMOKY

DRAINAGE BASIN CHARACTERISTICS	HIGH RATING	MEDIUM RATING	LOW RATING	SCORE
Surface Geology	10: marine shales and related mudstones and siltstones	5: rocks of medium hardness, moderately weathered, and fractured	0: massive, hard formations	6
Soils	10: fine textured and easily dispersed or single grain salts and fine sands	5: medium textured, occasional rock fragments, or caliche crusted layers	0: frequent rock fragments, aggregated clays, or high organic content	6
Climate	10: frequent intense convective storms	5: infrequent convective storms, moderate intensity	0: humid climate with low intensity rainfall, arid climate with low intensity rainfall, or arid climate with rare convective storms	5
Runoff	10: high flows or volume per unit area	5: moderate flows or runoff volume per unit area	0: low flows or volume per unit area or rare runoff events	2
Topography	20: steep slopes (in excess of 30%), high relief, little or no flood plain development	10: moderate slopes (about 20%), moderate flood plain development	0: gentle slopes (less than 5%), extensive flood plain development	5
Ground Cover	10: ground cover less than 20%, no rock or organic litter in surface soil	0: ground cover less than 40%, noticeable organic litter in surface soil	(-10): area completely covered by vegetation, rock fragments, organic litter with little opportunity for rainfall to erode soil	10
Land Use	10: more than 50% cultivated, sparse vegetation, and no rock in surface soil	0: less than 25% cultivated, less than 50% intensively grazed	(-10): no cultivation, no recent logging, and only low intensity grazing, if any	-10
Upland Erosion	25: rill, gully, or landslide erosion over more than 50% of the area	10: rill, gully, or landslide erosion over about 25% of the area	0: no apparent signs of erosion	10
Channel Erosion	25: continuous or frequent bank erosion, or active headcuts and degradation in tributary channels	10: occasional channel erosion of bed or banks	0: wide, shallow channels with mild gradients, channels in massive rock, large boulders, dense vegetation, or artificially protected channels	10
			Total Rating	**44**

Risk	Class	Sediment Yield (ac-ft/mi^2)	Rating
Very High	1	>3.0	>100
High	2	1.0–3.0	75–100
Medium	3	0.5–1.0	50–75
Low	4	0.2–0.5	25–50
Very Low	5	<0.2	0–25
Calculated Risk	**Low**	**Calculated Yield (ac-ft/mi^2)**	**0.39**

3.5.4 MUSLE Sediment Yield Estimates

Sediment yields for design storms from 2- to 100-year return periods were estimated using MUSLE. The factor values and storm sediment yield estimates are shown in Table 3-20. The storm runoff volume and peak flow rate are from the HEC-HMS modeling results for Smoky. Soil PSD data for Smoky in Section 3.2 were used to drive the soil erodibility factor. The watershed overland slopes and lengths derived from the topographic map of the watershed shown in Figure 3-12 were used to compute the slope and length factor.

TABLE 3-20. MUSLE SEDIMENT YIELD ANALYSIS FOR SMOKY

FACTORS	STORM RETURN PERIOD					
	2 YEARS	5 YEARS	10 YEARS	25 YEARS	50 YEARS	100 YEARS
Overland length and slope, LS	4.88	4.88	4.88	4.88	4.88	4.88
Soil erodibility, K	0.07	0.07	0.07	0.07	0.07	0.07
Cover factor, C	0.3	0.3	0.3	0.3	0.3	0.3
Conservation practice factor, P	1.00	1.00	1.00	1.00	1.00	1.00
Peak flow rate, cfs	52.30	102.30	150.30	221.40	284.50	363.20
Storm runoff volume, ac-ft	3.93	7.17	10.24	14.68	18.43	22.87
Yield, ac-ft/mi^2	**0.08**	**0.17**	**0.25**	**0.39**	**0.50**	**0.65**

3.5.5 Transport Modeling

For demonstration purposes, the channel sediment transport EXCEL models CHAN-SEDI and CHAN-SEDII were used to estimate storm-based sediment yields from the Smoky watershed. A 0.44-mile-long, wide rectangular channel with an average slope of 3.7 percent was divided into four reaches with varying slopes derived from the topographic map of the Smoky watershed. The channel bed material in the CHAN-SEDI model is represented by the geometric mean and geometric standard deviation of the PSD for Smoky shown in Figure 3-3. The geometric mean is 1.04 mm, and the geometric standard deviation is 24.3 mm. The entire PSD of Figure 3-3 for Smoky was input to the CHAN-SEDII model. The parameters common to both models are as shown in Table 3-8. For each storm event, the time series of storm flows with 5-minute time intervals, derived from the HEC-HMS modeling, were input to both models. Inflow was assumed to be sediment-free. The estimated sediment yields are shown in Table 3-21.

TABLE 3-21. SMOKY STORM SEDIMENT YIELDS IN AC-FT/MI^2

RETURN PERIOD	CHAN-SEDI	CHAN-SEDII
2 years	0.06	0.25
5 years	0.18	1.19
10 years	0.32	2.44
25 years	0.58	4.81
50 years	0.86	7.19
100 years	1.26	10.38
Yearly average	**0.14**	**0.99**

3.5.6 Discussion of Results

Using the PSIAC method, the average annual sediment yield estimate is 0.39 ac-ft/mi^2 for Smoky. Using MUSLE, the estimate is 0.12 ac-ft/mi^2. These estimates differ. MUSLE only provides sediment yield estimates for rill and inter-rill erosion and does not account for sediment from other sources such as flow channels. If channel erosion accounts for a large portion of a watershed's sediment yield, MUSLE would underestimate the total sediment yield from a watershed. For Smoky, sediment eroded from the channels must be added to the rill and inter-rill erosion from the land surfaces provided by MUSLE. CCRFCD (1999) advocates this methodology. The total sediment yield for a watershed is estimated by adding the estimate from MUSLE (wash load coming into the channels) to the estimate of the bed material load (suspended sediment load plus the bed load), which is estimated using a sediment transport equation. For Smoky, the annual sediment yield estimates from the CHAN-SEDI and CHAN-SEDII models are 0.14 and 0.99 ac-ft/mi^2. When these estimates are added to the MUSLE result of 0.46 ac-ft/mi^2, the resulting total annual sediment yields are 0.26 and 1.11 ac-ft/mi^2. The CHAN-SEDI estimate is close to the estimate from the PSIAC method, which is 0.39 ac-ft/mi^2. Further field observations of Smoky would be necessary to verify that the erosion from channels may indeed account a significant portion of the total annual sediment yield. The application of the PSIAC to Smoky assumed no significant channel erosion.

The storm sediment yield estimates from CHAN-SEDI and CHAN-SEDII transport models are dissimilar. This is primarily due to the different transport equations used by the models and the different ways the bed material size distribution was input to the models.

3.6 T-1

3.6.1 Site Characteristics

T-1 is located in Area 1 of the NNSS (Figure 3-16). Four weapons-related tower tests were conducted in this area, Easy, Simon, Apple-2, and Galileo. Easy was conducted from a 300 ft tower on May 7, 1952, as part of Operation Tumbler-Snapper and had a yield of 12 kt. Simon was conducted from a 300 ft tower on April 25, 1953, as part of Operation Upshot-Knothole and had a yield of 43 kt. Apple-2 was conducted from a 500 ft tower on May 5, 1955, as part of Operation Teapot and had a yield of 29 kt. Galileo was conducted from a 500 ft tower on September 2, 1957, as part of Operation Plumbbob and had a yield of 11 kt (DOE/NV, 2000). The T-1 site is posted as a Radioactive Material Area.

The drainage area above the site is 0.69 mi^2. Elevations range from 4,400 to 4,500 ft. The longitudinal slope of the watershed is about 1.1 percent. Overland slopes are also about 1.1 percent. Average annual precipitation in the T-1 watershed is about 7.1 inches (Soule, 2006). Surface geology and the vegetation classification of the watershed are shown in Figures 3-17 and 3-18, respectively. Intermediate alluvial deposits cover most of the watershed areas, with about 25 percent of the upper watershed covered with old alluvial deposits. The overall plant cover is less than 30 percent, and is composed mostly of transition ecoregion plants, with black sagebrush and Nevada jointfir in 50 percent of the area (middle watershed), miscellaneous desert plants in 20 percent of the area (upper watershed), and white burrobrush and Nevada jointfir in 30 percent of the area (lower watershed).

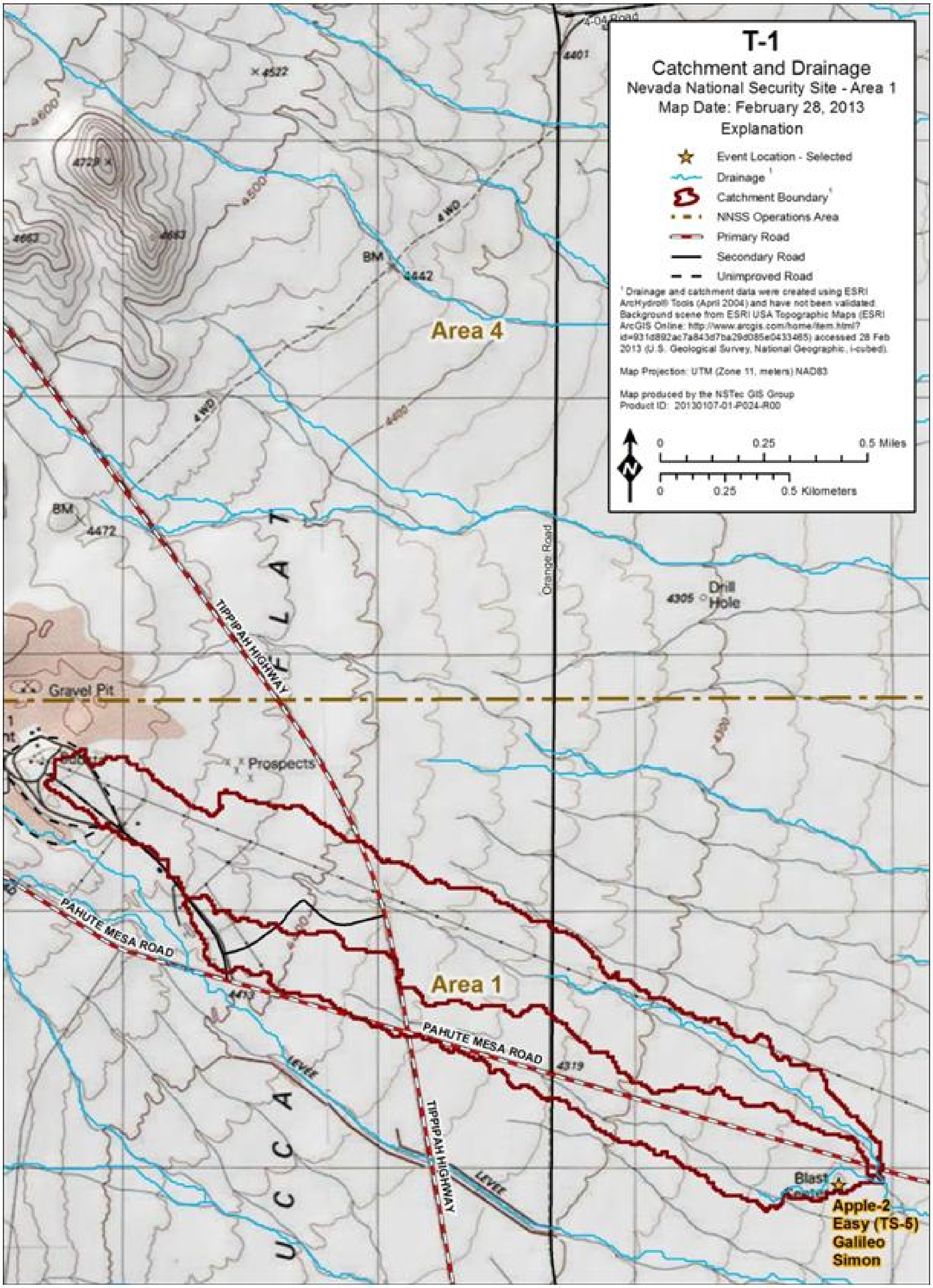

FIGURE 3-16. T-1 WATERSHED

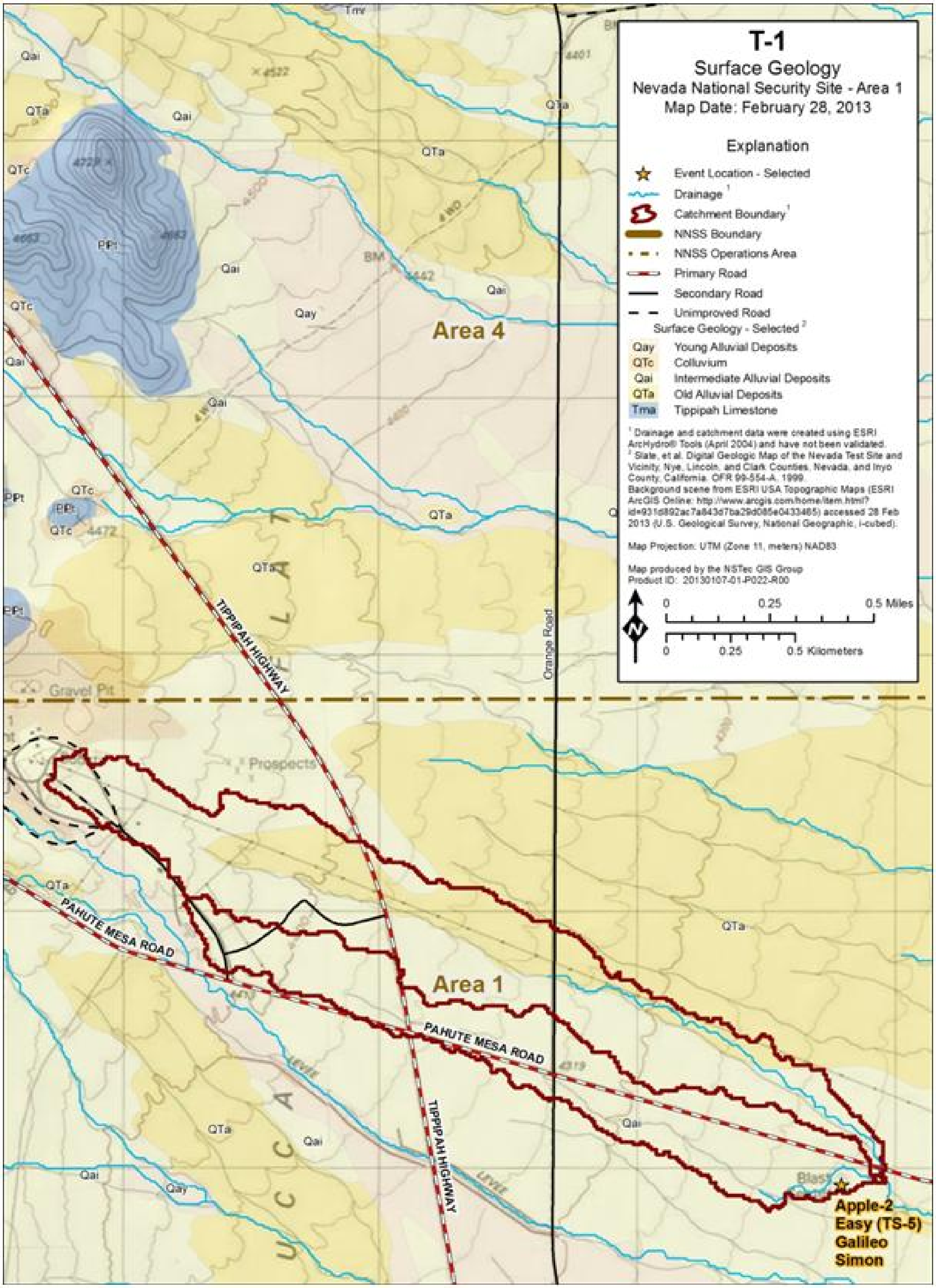

FIGURE 3-17. T-1 SURFACE GEOLOGY

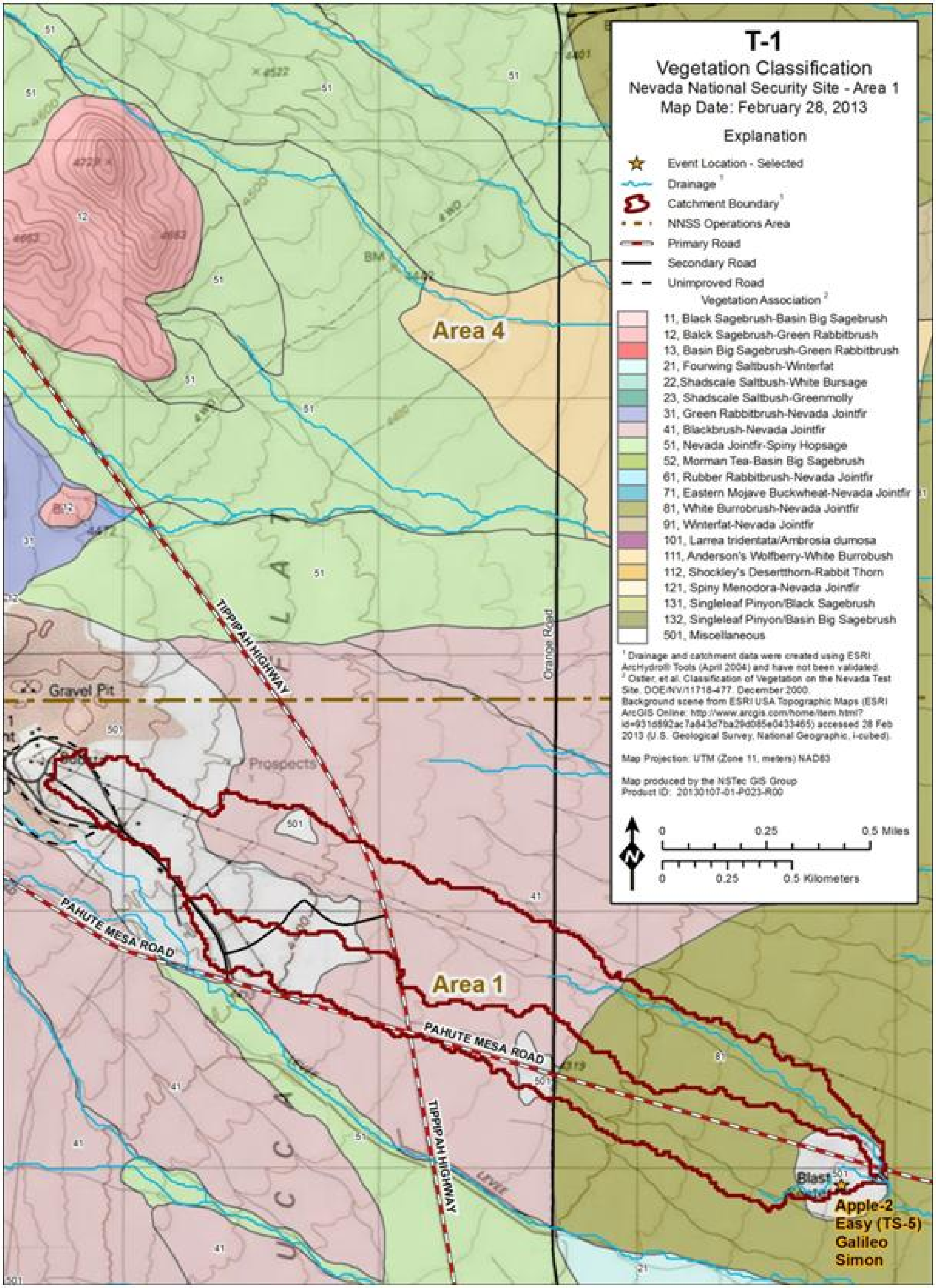

FIGURE 3-18. T-1 VEGETATION CLASSIFICATION

3.6.2 Storm Runoff Modeling

The HEC-HMS model was set up and run to generate storm runoff data (peak flow rates, storm runoff volumes, and runoff hydrographs) for the T-1 watershed using design storm precipitation of return periods from 2 to 100 years. The precipitation data were obtained from the NOAA's Hydrometeorological Design Studies Center website at http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=nv, accessed on February 14, 2013. The storm depth-duration-frequency data are shown in Table 3-22 and Figure 3-19. The precipitation values are reported in inches.

TABLE 3-22. T-1 STORM PRECIPITATION DATA

DURATION	RETURN PERIOD, YEARS					
	2	5	10	25	50	100
5 minutes	0.15	0.22	0.27	0.36	0.42	0.50
10 minutes	0.24	0.33	0.41	0.53	0.63	0.76
15 minutes	0.29	0.41	0.51	0.66	0.79	0.94
30 minutes	0.39	0.55	0.68	0.88	1.06	1.26
60 minutes	0.49	0.68	0.84	1.09	1.31	1.56
2 hours	0.54	0.75	0.93	1.22	1.47	1.75
3 hours	0.61	0.83	1.02	1.31	1.56	1.85
6 hours	0.79	1.07	1.30	1.62	1.89	2.21

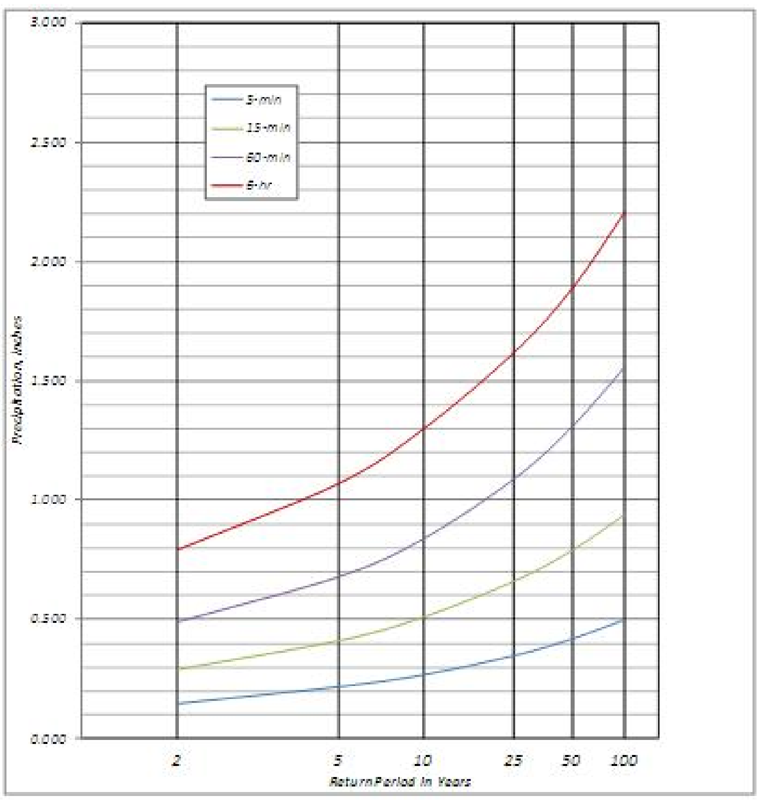

FIGURE 3-19. T-1 PRECIPITATION DEPTH-DURATION-FREQUENCY

The SCS CN loss model was used to compute excess precipitation, and the SCS unit hydrograph procedure was used for runoff generation. Model parameters are shown in Table 3-23. CN values are for semi-arid rangelands with desert shrub of poor coverage and soil groups B and C (USACE, 2010a). The CN values were developed using AMCII, which is the local standard and gives composite CN values that reflect variability in soils, slopes, covers, etc., within the basins. The simulated peak flow and storm runoff volumes are listed in Table 3-24 for a 6-hour storm duration.

TABLE 3-23. HEC-HMS PARAMETERS FOR T-1

BASIN	AREA (MI^2)	L (MI)	L_C (MI)	SLOPE (FT/MI)	LAG (MIN)	CN (AMCII)
T-1 North	0.42	4.00	2.08	59	49	77
T-1 North	0.27	3.39	1.70	57	44	77

L: length of the longest watercourse
L_c: length along the watercourse from basin outlet to a point opposite the centroid of the basin
Slope: average slope of the longest watercourse
Lag: lag time between the centroid of the storm rainfall excess and the peak of the unit hydrograph
CN: curve number
AMCII: antecedent soil moisture condition II

TABLE 3-24. HEC-HMS MODELING RESULTS FOR T-1

RETURN PERIOD	T-1 NORTH		T-1 NORTH		OUTLET	
	PEAK FLOW (CFS)	RUNOFF VOLUME (AC-FT)	PEAK FLOW (CFS)	RUNOFF VOLUME (AC-FT)	PEAK FLOW (CFS)	RUNOFF VOLUME (AC-FT)
2 years	18.7	2.91	7.2	1.01	25.9	4.05
5 years	38.8	5.82	15.5	2.16	54.1	8.10
10 years	58.6	8.74	23.9	3.31	82.3	12.14
25 years	90.1	12.77	37.9	5.04	127.7	17.66
50 years	119.6	16.35	51.4	6.62	170.6	23.18
100 years	156.6	21.06	68.9	8.64	224.9	29.81

3.6.3 PSIAC Factor Analysis

The ratings and the scores for the drainage basin characteristics for T-1 are shown in Table 3-25. The scores for geology, soils, topography, and ground cover are based on site watershed maps for the T-1 site. Soule (2006) was the source for climate and runoff factors. Land use factors were scored considering no cultivation. Upland erosion and channel erosion scores were based on field observations.

The computed annual sediment yield for the T-1 watershed is 0.2 ac-ft/mi^2.

TABLE 3-25. PSIAC FACTOR ANALYSIS FOR T-1

DRAINAGE BASIN CHARACTERISTICS	HIGH RATING	MEDIUM RATING	LOW RATING	SCORE
Surface Geology	10: marine shales and related mudstones and siltstones	5: rocks of medium hardness, moderately weathered, and fractured	0: massive, hard formations	10
Soils	10: fine textured and easily dispersed or single grain salts and fine sands	5: medium textured, occasional rock fragments, or caliche crusted layers	0: frequent rock fragments, aggregated clays, or high organic content	10
Climate	10: frequent intense convective storms	5: infrequent convective storms, moderate intensity	0: humid climate with low intensity rainfall, arid climate with low intensity rainfall, or arid climate with rare convective storms	5
Runoff	10: high flows or volume per unit area	5: moderate flows or runoff volume per unit area	0: low flows or volume per unit area or rare runoff events	1
Topography	20: steep slopes (in excess of 30%), high relief, little or no flood plain development	10: moderate slopes (about 20%), moderate flood plain development	0: gentle slopes (less than 5%), extensive flood plain development	0
Ground Cover	10: ground cover less than 20%, no rock or organic litter in surface soil	0: ground cover less than 40%, noticeable organic litter in surface soil	(-10): area completely covered by vegetation, rock fragments, organic litter with little opportunity for rainfall to erode soil	5
Land Use	10: more than 50% cultivated, sparse vegetation, and no rock in surface soil	0: less than 25% cultivated, less than 50% intensively grazed	(-10): no cultivation, no recent logging, and only low intensity grazing, if any	-10
Upland Erosion	25: rill, gully, or landslide erosion over more than 50% of the area	10: rill, gully, or landslide erosion over about 25% of the area	0: no apparent signs of erosion	0
Channel Erosion	25: continuous or frequent bank erosion, or active headcuts and degradation in tributary channels	10: occasional channel erosion of bed or banks	0: wide, shallow channels with mild gradients, channels in massive rock, large boulders, dense vegetation, or artificially protected channels	5
			Total Rating	**26**

Risk	**Class**	**Sediment Yield (ac-ft/mi^2)**	**Rating**
Very High	1	>3.0	>100
High	2	1.0–3.0	75–100
Medium	3	0.5–1.0	50–75
Low	4	0.2–0.5	25–50
Very Low	5	<0.2	0–25
Calculated Risk	**Low**	**Calculated Yield (ac-ft/mi^2)**	**0.20**

3.6.4 MUSLE Sediment Yield Estimates

Sediment yields for design storms from 2- to 100-year return periods were estimated using MUSLE. The factor values and storm sediment yield estimates are shown in Table 3-26. The storm runoff volume and peak flow rate are from the HEC-HMS modeling results for T-1. Soil PSD data for T-1 in Section 3.2 were used to drive the soil erodibility factor. The watershed overland slopes and lengths were derived from the topographic map of the watersheds shown in Figure 3-16 to compute the slope and length factor.

TABLE 3-26. MUSLE SEDIMENT YIELD ANALYSIS FOR T-1

FACTORS	STORM RETURN PERIOD					
	2 YEARS	5 YEARS	10 YEARS	25 YEARS	50 YEARS	100 YEARS
Overland length and slope, LS	0.17	0.17	0.17	0.17	0.17	0.17
Soil erodibility, K	0.12	0.12	0.12	0.12	0.12	0.12
Cover factor, C	0.3	0.3	0.3	0.3	0.3	0.3
Conservation practice factor, P	1.00	1.00	1.00	1.00	1.00	1.00
Peak flow rate, cfs	25.9	54.10	82.30	127.70	170.60	224.90
Storm runoff volume, ac-ft	4.05	8.10	12.14	17.66	23.18	29.81
Yield, ac-ft/mi^2	**0.01**	**0.01**	**0.02**	**0.03**	**0.04**	**0.06**

3.6.5 Transport Modeling

For demonstration purposes, the channel sediment transport EXCEL models CHAN-SEDI and CHAN-SEDII were used to estimate storm-based sediment yields from the T-1 watershed. A 1.61-mile-long, wide rectangular channel with an average slope of 1.0 percent was divided into three reaches with varying slopes derived from the topographic map of the T-1 watershed. The channel bed material in the CHAN-SEDI model is represented by the geometric mean and geometric standard deviation of the PSD for T-1 shown in Figure 3-3. The geometric mean is 0.59 mm, and the geometric standard deviation is 37.8 mm. The entire PSD of Figure 3-3 for T-1 was input to the CHAN-SEDII model. The parameters common to both models are as shown in Table 3-8. For each storm event, the time series of storm flows with 5-minute time intervals, derived from the HEC-HMS modeling, were input to both models. Inflow was assumed to be sediment-free. The estimated sediment yields are shown in Table 3-27.

TABLE 3-27. T-1 STORM SEDIMENT YIELDS IN AC-FT/MI^2

RETURN PERIOD	CHAN-SEDI	CHAN-SEDII
2 years	0.007	0.02
5 years	0.02	0.06
10 years	0.05	0.12
25 years	0.09	0.21
50 years	0.14	0.36
100 years	0.21	0.57
Yearly average	**0.02**	**0.05**

3.6.6 Discussion of Results

Using the PSIAC method, the average annual sediment yield estimate is 0.2 ac-ft/mi^2 for T-1. Using MUSLE, the estimate is 0.01 ac-ft/mi^2. These two estimates differ. MUSLE only provides sediment yield estimates for rill and inter-rill erosion and does not account for sediment from other sources such as flow channels. If channel erosion accounts for a large portion of a watershed's sediment yield, MUSLE would underestimate the total sediment yield from a watershed. For T-1, sediment eroded from the channels must be added to the rill and inter-rill erosion from the land surfaces provided by MUSLE. CCRFCD (1999) advocates this methodology. The total sediment yield for a watershed is estimated by adding the estimate from MUSLE (wash load coming into the channels) to the estimate of the bed material load (suspended sediment load plus the bed load), which is estimated using a sediment transport equation. For T-1, the annual sediment yield estimates from the CHAN-SEDI and CHAN-SEDII models are 0.02 and 0.05 ac-ft/mi^2. When these estimates are added to the MUSLE result of 0.01 ac-ft/mi^2, the resulting total annual sediment yields are 0.02 and 0.06 ac-ft/mi^2, which compare well with the PSIAC method's estimate for T-1 of 0.2 ac-ft/mi^2.

The storm sediment yield estimates from CHAN-SEDI and CHAN-SEDII transport models are similar even though these models employ different transport equations and the bed material size distribution is specified differently.

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4.0 ASSESSMENT

The PSIAC factor analysis method provides a robust estimation of the total annual sediment yield of watersheds at the NNSS. For the watersheds analyzed in this report, the risk of erosion is low, and the annual sediment yields of the watersheds as shown in Table 4-1 vary within a narrow range between 0.2 and 0.41 ac-ft/mi^2. The field reconnaissance surveys of these watersheds confirm the conclusion that the sediment yield of undisturbed areas at the NNSS would be low. The climate, geology, soils, ground cover, land use, and runoff potential are similar among these watersheds. There are no permanent channels except at Smoky and Plutonium Valley. There are no gullies upstream of the watersheds. Topography seems to have the strongest influence on sediment yields, as sediment yields are higher on the steeper hillslopes.

TABLE 4-1. PSIAC FACTORS AND WATERSHED SEDIMENT YIELDS

PSIAC FACTORS	WATERSHEDS					
	PV-1	PV-2	PV-4	SHASTA	SMOKY	T-1
Surface Geology	8	6	9	3	6	10
Soils	8	6	9	3	6	10
Climate	5	5	5	5	5	5
Runoff	1	1	1	2	2	1
Topography	2	5	0	8	5	0
Ground Cover	10	10	10	10	10	5
Land Use	-10	-10	-10	-10	-10	-10
Upland Erosion	5	10	10	10	10	0
Channel Erosion	10	10	10	15	10	5
Total Score	**39**	**43**	**43**	**46**	**44**	**26**
Calculated Yield, ac-ft/mi^2	**0.32**	**0.37**	**0.37**	**0.41**	**0.39**	**0.20**

Lack of measured watershed sediment yield data at the NNSS does not allow for a direct evaluation of the yield estimates by the PSIAC method. Measured sediment yield data for semi-arid rangeland watersheds are rare. However, the long-term sediment yield data at the USDA Agricultural Research Center Walnut Gulch Experimental Watershed (WGEW) in Arizona can be used as a proxy record for such a comparison. Nichols (2006) provides annual sediment yield estimates ranging from 0.1 to 0.6 ac-ft/mi^2, with a mean yield of 0.29 ac-ft/mi^2 and a standard deviation of 0.21 ac-ft/mi^2, based on 30 to 47 years of sediment accumulation records from sub-watersheds of 87 to 394 acres within the 57.9 mi^2 WGEW. These sub-watersheds are located at about 4,100 to 6,200 ft above mean sea level with annual precipitation rates ranging from 11.9 to 13.3 inches. WGEW is located in a transition zone between the Sonoran and Chihuahuan Deserts, with surface soils of gravelly to cobbly loams and ground cover of desert shrubs, predominantly creosote (Nichols, 2006). WGEW and the NNSS watersheds are similar in these respects, but WGEW precipitation is about twice that of the NNSS. The annual sediment yields for the NNSS watersheds shown in Table 4-1 are within the range of measured sediment yields presented in Nichols (2006). Therefore, these estimates made by the PSIAC method are considered reasonable.

PSIAC (1968) indicates that the method should be used for watersheds greater than 10 mi^2. All the watersheds evaluated in this report are less than 10 mi^2. Therefore, caution should be exercised in applying the method for small watersheds. Another shortcoming of the method is that it does not provide sediment yields for storm events. If the need for storm event estimates arises, a Level 2 analysis should be performed.

The storm event sediment yield estimates using MUSLE are shown in Figure 4-1. For the purposes of this study, all storms are assumed to occur over a 6-hour period, distributed to preserve 5-minute, 15-minute, 30-minute, etc. intensities.

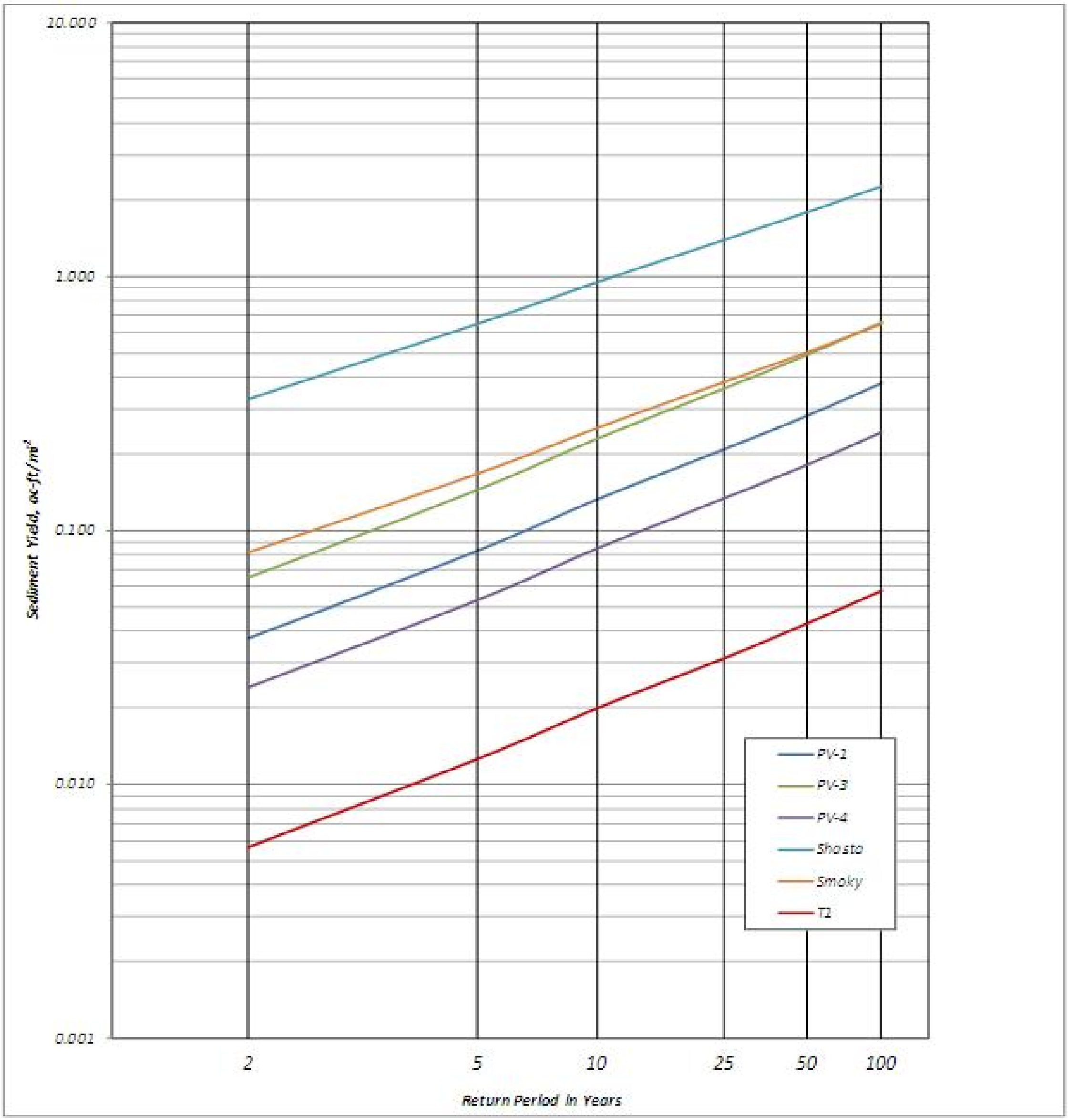

FIGURE 4-1. STORM EVENT SEDIMENT YIELD ESTIMATES

As shown in Figure 4-1, high intensity (longer return periods) precipitation events produce higher sediment yield estimates. Estimates for Shasta and Smoky are higher due to the steeper overland slopes of these watersheds. MUSLE results are substantially lower than the PSIAC results for these watersheds. This is expected because MUSLE provides rill and inter-rill erosion estimates from watersheds and does not account for erosion from gullies and channels. PSIAC provides for sediment yield estimates from all sources of erosion.

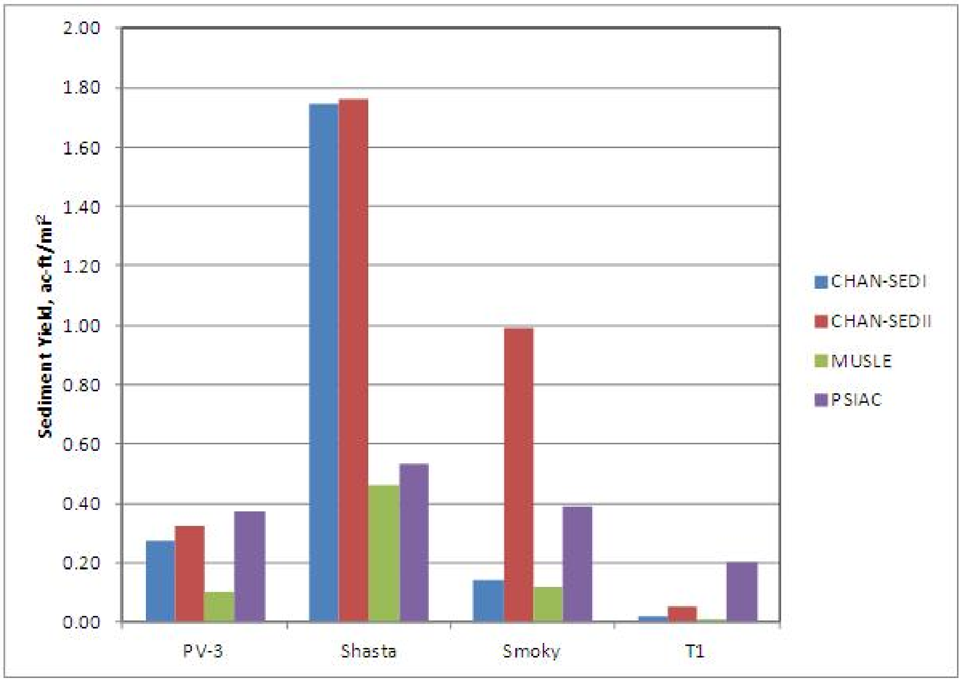

FIGURE 4-2. ANNUAL SEDIMENT YIELD ESTIMATES

Annual yield estimates from both of these methods are similar for Shasta, indicative of equal contribution of channel and gully erosion to the total watershed sediment yield in Shasta. MUSLE estimates in other watersheds are a small percentage of the estimates from PSIAC. This can be interpreted as indicating that channel erosion dominates the total sediment yield in these watersheds. However, there are no significant channels or gullies in these watersheds, except Smoky and Plutonium Valley watersheds. Therefore, one may conclude that MUSLE underestimates sediment yields of these watersheds. Mussetter Engineering Inc. (2008) states in the Sediment and Erosion Design Guide for the Southern Sandoval County Arroyo Flood Control Authority that MUSLE underestimates sediment yields by a factor of 3 in the Albuquerque area in New Mexico. On the other hand, CCRFCD (1999) makes the statement that MUSLE provides reasonable sediment yield estimates in Clark County, Nevada. However, no documentation is provided to support this claim.

Annual sediment yields for these watersheds were estimated using the CHAN-SEDI and CHAN-SEDII channel sediment transport models, assuming that watershed outlets are through an arroyo or channel. Both transport models give similar results despite the different sediment transport equations used in these models. Figure 4-2 shows that channel transport estimates far exceed the estimates obtained from PSIAC and MUSLE. CCRFCD (1999) indicates that the total watershed sediment yield should be obtained by adding the washload estimate (rill and inter-rill erosion) from MUSLE to that obtained from channel transport equations (bed load and suspended sediment).

It is recommended that the sediment yields of watersheds in NNSS with flow channels should be estimated in a Level 2 analysis by combining the estimates from channel transport models and the estimates from MUSLE. PSIAC will give comparable results if factor scores for channel erosion are revised towards the high erosion level.

Regression equations have been developed from reservoir sediment accumulation data to estimate sediment yield as a function of watershed area. The Erosion and Sedimentation Manual by the U.S. Department of the Interior Bureau of Reclamation (2006) includes two such equations. The Strand equation below was developed for semi-arid watersheds in Arizona, New Mexico, and California.

$$Q_s = 2.4 * A_d^{-0.229}$$

where

Q_s = annual sediment yield in ac-ft/mi^2

A_d = watershed area in mi^2

The following Strand and Pemberton equation was developed for the semi-arid southwestern United States.

$$Q_s = 1.84 * A_d^{-0.24}$$

The annual sediment yield estimates using these equations are shown in Figure 4-3. Estimates by these equations far exceed the estimates by the Level 1 and Level 2 methods used in this study. This leads to the conclusion that watershed area alone is not the sole factor in estimating sediment yield from watersheds, and such regression equations should be used with caution.

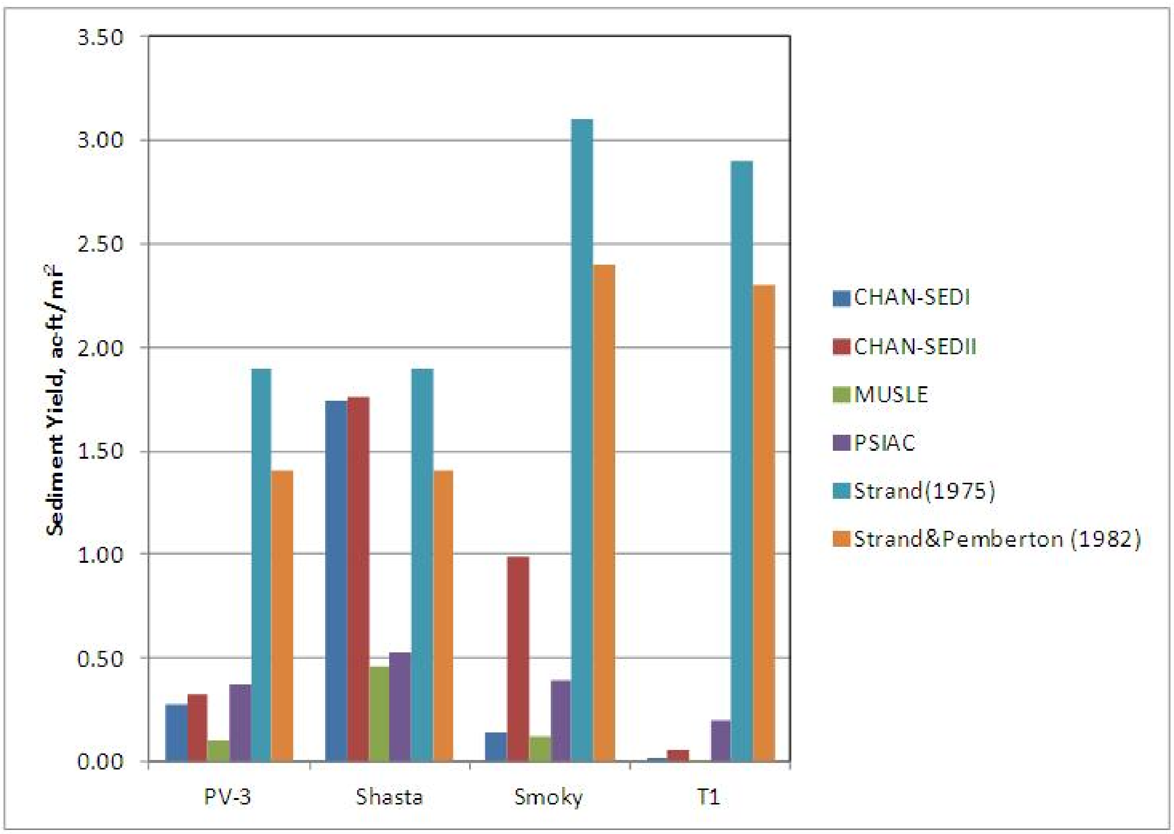

FIGURE 4-3. ANNUAL SEDIMENT YIELD ESTIMATES WITH REGRESSION EQUATIONS

5.0 RECOMMENDATIONS

Application of the Level 3 process-based models to estimate sediment yields at the NNSS cannot be recommended at this time. Increased model complexity alone will not improve the certainty of the sediment yield estimates. Models must be validated or calibrated against measured data before model results are accepted as certain. Because there are no measurements of sediment yields at the NNSS, model validation cannot be performed. This is true as well for the models used in the Level 2 analyses presented in this study.

The need to calibrate MUSLE to local conditions has been discussed in the past because the model runoff erodibility factor coefficients of 95 and 0.56 were based on data from watersheds in Texas and Nebraska (Mussetter Engineering Inc., 2008). Likewise, the transport equations of CHAN-SEDI and CHAN-SEDII need to be calibrated against local data to assess their applicability under semi-arid conditions and for the ephemeral channels at the NNSS. Before these validations, calibration exercises, can be undertaken, a long-term measured sediment yield data set must be developed.

Development of long-term measured sediment yield data cannot be overemphasized. Polyakov et al. (2010) conclude that long-term monitoring is essential for accurate characterization of watershed processes. Polyakov et al. analyzed 34 years of precipitation, runoff, and sediment data from eight small semi-arid rangeland watersheds in southern Arizona (the Santa Rita Experimental Range). They observed that between 6 and 22 percent of measured sediment yield for the 34-year period was from the single largest event. Therefore, it can be claimed that underestimation of the sediment yields is more likely with short records.

It is recommended that a long-term monitoring program be set up to measure watershed erosion rates and channel sediment transport rates.

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APPENDIX A

PSIAC FACTOR ANALYSIS

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APPENDIX A: PSIAC FACTOR ANALYSIS

The following is adopted from the Pacific Southwest Inter-Agency Committee (PSIAC) Report of the Water Management Subcommittee on Factors Affecting Sediment Yield in the Pacific Southwest Area and Selection and Evaluation of Measures for Reduction of Erosion and Sediment Yield (1968).

Sediment Yield Classification

PSIAC recommends that sediment yields in the Pacific Southwest be divided into five classes of average annual yield in acre-feet per square mile. These are listed in Table A-1.

TABLE A-1. PSIAC SEDIMENT YIELD CLASSES

CLASS	ACRE-FEET PER SQUARE MILE
1	> 3.0
2	1.0–3.0
3	0.5–1.0
4	0.2–0.5
5	< 0.2

Each class is derived from a total yield rating, as listed in Table A-2.

TABLE A-2. PSIAC SEDIMENT YIELD CLASSIFICATION

TOTAL YIELD RATING	CLASS
> 100	1
75–100	2
50–75	3
25–50	4
0–25	5

The total yield rating is obtained by assigning a numerical value to each of nine factors and summing those nine values. The factors used in determining sediment yield include geology, soils, climate, runoff, topography, ground cover, land use, upland erosion, and channel erosion and sediment transport, as listed in Table A-3. Characteristics of each of the nine factors give a factor of high, moderate, or low sediment yield. The sediment yield characteristic of each factor is assigned a numerical value representing its relative significance in the yield rating.

Guidelines that accompany the factors in Table A-3 describe the characteristics that influence sediment yield. To avoid complexity, the factors are described as independently influencing the yield. The variable impact of a factor is the result of influence by the others. To account for this variable influence in an area would require more intensive investigational procedures than those available for broad planning purposes.

To illustrate the interdependence of the factors, ground cover is used as an example. If there is no vegetation, litter, or rock protecting the surface, the rock, soil, and topography express their uniqueness on erosion and sediment yield. If the surface is protected by cover, the other factors are obscured. Similarly, an arid region has a high potential for erosion and sediment yield due to little or no ground cover, sensitive soils, and rugged topography. Given low intensity rainfall and rare intervals of runoff, the sediment yield could nevertheless be low.

TABLE A-3. PSIAC SEDIMENT YIELD FACTOR RATINGS

DRAINAGE BASIN CHARACTERISTICS	HIGH RATING	MEDIUM RATING	LOW RATING	SCORE
Surface Geology (A)	10: marine shales and related mudstones and siltstones	5: rocks of medium hardness, moderately weathered, and fractured	0: massive, hard formations	
Soils (B)	10: fine textured and easily dispersed or single grain salts and fine sands	5: medium textured, occasional rock fragments, or caliche crusted layers	0: frequent rock fragments, aggregated clays, or high organic content	
Climate (C)	10: frequent intense convective storms	5: infrequent convective storms, moderate intensity	0: humid climate with low intensity rainfall, arid climate with low intensity rainfall, or arid climate with rare convective storms	
Runoff (D)	10: high flows or volume per unit area	5: moderate flows or runoff volume per unit area	0: low flows or volume per unit area or rare runoff events	
Topography (E)	20: steep slopes (in excess of 30%), high relief, little or no flood plain development	10: moderate slopes (about 20%), moderate flood plain development	0: gentle slopes (less than 5%), extensive flood plain development	
Ground Cover (F)	10: ground cover less than 20%, no rock or organic litter in surface soil	0: ground cover less than 40%, noticeable organic litter in surface soil	(-10): area completely covered by vegetation, rock fragments, organic litter with little opportunity for rainfall to erode soil	
Land Use (G)	10: more than 50% cultivated, sparse vegetation, and no rock in surface soil	0: less than 25% cultivated, less than 50% intensively grazed	(-10): no cultivation, no recent logging, and only low intensity grazing, if any	
Upland Erosion (H)	25: rill, gully, or landslide erosion over more than 50% of the area	10: rill, gully, or landslide erosion over about 25% of the area	0: no apparent signs of erosion	
Channel Erosion (I)	25: continuous or frequent bank erosion, or active headcuts and degradation in tributary channels	10: occasional channel erosion of bed or banks	0: wide, shallow channels with mild gradients, channels in massive rock, large boulders, dense vegetation, or artificially protected channels	
			Total Rating	

Risk	**Class**	**Sediment Yield (ac-ft/mi^2)**	**Rating**
Very High	1	>3.0	>100
High	2	1.0–3.0	75–100
Medium	3	0.5–1.0	50–75
Low	4	0.2–0.5	25–50
Very Low	5	<0.2	0–25
Calculated Risk		**Calculated Yield (ac-ft/mi^2)**	

Note: Adopted from the PSIAC Report of the Water Management Subcommittee on Factors Affecting Sediment Yield in the Pacific Southwest Area and Selection and Evaluation of Measures for Reduction of Erosion and Sediment Yield (1968)

Each of the nine factors listed in Table A-3 has paired influences with the exception of topography. That is, geology and soils are directly related as are climate and runoff, ground cover and land use, and upland and channel erosion. Ground cover and land use have a negative influence under average or better conditions. Their impact on sediment yield is therefore indicated as a negative influence when affording better protection than this average.

It is recommended that the sum of the factors from A through G be compared with the sum of H and I. In most instances, high values in the former should correspond to high values in the latter. If not, either special erosion conditions exist or factors A through G should be re-evaluated.

Although only the high, moderate, and low sediment yield levels are shown in Table A-3, interpolation between these levels may be made.

Although not in the original PSIAC procedure, the following sediment yield equation is derived by fitting an exponential function to the rating-sediment yield data:

$$Sediment\ yield, \frac{ac-ft}{mi^2} = 0.0816 * e^{0.0353 * rating}$$

A discussion of each of the nine PSIAC factors is provided in the following sections.

Surface Geology

Over much of the Pacific Southwest, the effect of surface geology on erosion is readily apparent. The weaker, softer rocks more easily erode and generally yield more sediment than harder, more resistant types. Sandstones and similar coarse-textured rocks that disintegrate to form permeable soils erode less than shales and related mudstones and siltstones under the same precipitation conditions. On the other hand, due to the absence of cementing agents in some soils derived from sandstone, large storms may produce high sediment yields.

The widely distributed marine shales, such as the Mancos and shale members of the Moenkopi Formation, constitute a group of highly erodible formations. The very large areal extent of the shales and their outwash deposits gives them a rank of special importance in relation to erosion. Few of the shale areas are free from erosion. Occasionally, because of slope or cover conditions, metamorphic rocks and highly fractured, deeply weathered granites and granodiorites produce high sediment yields. Limestone and volcanic outcrop areas are among the most stable found in western areas. The principal reason for this appears to be excellent infiltration characteristics, which allow most precipitation to percolate into the underlying rocks.

In some areas, geologic formations are covered with alluvial or colluvial material that may have no relation to the underlying geology. In such areas, the geologic factor would have no influence and should be assigned a score of 0.

Soils

Soil formation in the Pacific Southwest has not generally been conducive to rapid development. Therefore, the soils are in an immature stage of development and consist of physically weathered rock materials. The presence of sodium carbonate (black alkali) in soil tends to cause the soil particles to disperse and renders it susceptible to erosion. Three inorganic properties (sand, silt, and clay) give soil its physical characteristics. Organic substances plus clay provide the binding material that tends to hold the soil together and form aggregates. Aggregate formation and stability of these aggregates are the resistant properties of soil against erosion.

Unstable aggregates or single grain soil materials can be very erodible. Climate and living organisms acting on parent material, as conditioned by relief or topography over a period of time, are the essential factors for soil development. Any one of these factors may overshadow or depress another and cause a difference in soil formation. For instance, climate determines what type of vegetation and animal population will be present in an area, and this will influence or determine the type of soil that evolves. For example, soils developing under a forest canopy are different from soils developing in a grassland community.

The raw, shaley areas (marine shales) of the Pacific Southwest have very little, if any, solid development. Colluvial-alluvial fan areas are usually present at lower extremities of steeper sloping shale areas. Infiltration and percolation are usually minimal in these areas due to the fine textured nature of the soil material. This material is easily dispersed and has a high shrink-swell capacity. Vegetation is generally sparse, and consists of salt desert shrubs.

Areas are present that contain soils with definite profile development and stony soils that contain few fines, which constitutes an improved physical condition for infiltration and plant growth over the fine textured shaley areas. These areas usually occur at moist, higher elevations where bare, hard crystalline rocks provide the soil parent material. Vegetation and other ground cover under these circumstances provide adequate protection against the erosive forces and thus low sediment yield results.

In arid and semi-arid areas, an accumulation of rock fragments (desert pavement) or calcareous material (caliche) is not uncommon. These layers can offer substantial resistance to erosion processes.

The two extreme conditions of sediment yield areas have been described. Intermediate situations contain some features of the two extremes. One such situation might be an area of predominately good soil development that contains small areas of badlands. This combination would result in an intermediate classification.

Climate and Runoff

Climate is paramount in soil and vegetal development and determines runoff quantity and discharge rate. Climatic factors constitute the forces that cause erosion and result in sediment yield. Likewise, temperature, precipitation, and the distribution of precipitation during the growing season affect the quantity and quality of ground cover and soil development. The quantity and intensity of precipitation determine the amount and discharge rates of runoff, resultant detachment of soil, and transport media for sediment yield. The intensity of prevailing and seasonal winds affects precipitation patterns, snow accumulation, and evaporation rates. Snow appears to have a minor effect on upland slope erosion because raindrop impact is absent and runoff associated with snow melt is generally only present in resistant mountain systems.

Frontal storms with moderate to high intensity precipitation produce high sediment yields. In humid and sub-humid areas, frontal storms may impact sediment on upland slopes and unstable geologic areas where slides and other downhill soil movement can readily occur.

Convective thunderstorms influence erosion and sedimentation in Arizona, New Mexico, and portions of the adjoining states. Intense rainfall on low density cover or easily dispersed soils produces high sediment yields. The average annual sediment yield is usually kept within moderate bounds by infrequent occurrence of thunderstorms.

High runoff of rare frequency may cause an impact on average annual sediment yield for a long period of time in a watershed that is sensitive to erosion, or it may have little effect in an insensitive watershed. For example, sediment that has been collecting in the bottom of a canyon and on side slopes for many years of low and moderate flows may be swept out during the rare event, creating a large change in the indicated sediment yield rate for the period of record.

In some areas the action of freezing and thawing becomes important in the erosion process. Impermeable ice usually forms in areas of fine textured soils where a supply of moisture is available before the advent of cold weather. Under these conditions the ice often persists throughout the winter and is still present when the spring thaw occurs. In some instances water tends to run over the surface of the ice and not detach soil particles, but it is possible for the ice in a surface layer to thaw during a warm period and create a very erodible situation. Spring rains with ice at shallow depth may wash away the loose material on the surface.

In some areas of the Pacific Southwest, particularly those underlain by marine shale, freezing and thawing alters the texture of surface soil, thus changing infiltration characteristics. These areas generally do not receive enough snow nor have cold enough temperatures to build a snow pack for spring melt. Later in the year, soil in a loosened condition can absorb a large part of the early rainfall. As rains occur in the summer, soil becomes compacted on the surface, allowing more water to run off and affording a greater chance for erosion.

Topography

Watershed slopes, relief, floodplain development, drainage patterns, orientation, and size are items to consider in connection with topography. However, their influence is closely associated with geology, soils, and cover. Generally, steep slopes result in rapid runoff. The rimrock and badlands, common in the Pacific Southwest, consist of steep slopes of soft shales usually maintained by overlying cap rock. As the soft material is eroded, the cap rock is undercut and falls, exposing more soft shales to be carried away. However, high sediment yields from these areas are often modified by temporary deposition of sediment on the intermediate floodplains.

The high mountain ranges, although having steep slopes, produce varying quantities of sediment depending on the type of parent materials, soil development, and cover, which directly affect the erosion processes. Southerly exposed slopes generally erode more rapidly than northerly exposed slopes due to greater fluctuation of air and soil temperatures, more frequent freezing and thawing cycles, and less ground cover.

The size of the watershed may or may not affect the sediment yield per unit area. Generally, the sediment yield is inversely related to the watershed size because larger areas usually have less overall slope, smaller proportions of upland sediment sources, and more opportunity for the deposition of upstream-derived sediments on floodplains and fans. In addition, large watersheds are less affected by small convective storms. However, under other conditions, the sediment yield may not decrease as the watershed size increases. There is little change in mountainous areas of relatively uniform terrain. There may be an increase of sediment yield as the watershed size increases if downstream watersheds or channels are more susceptible to erosion than upstream areas.

Ground Cover

Ground cover includes anything on or above the ground surface that alters the effect of precipitation. Ground cover includes vegetation, litter, and rock fragments. A good ground cover dissipates the energy of rainfall before it strikes the soil surface, delivers water to the soil at a relatively uniform rate, impedes the flow of water, and promotes infiltration by the action of roots. Conversely, the absence of ground cover, whether through natural growth habits or the effect of overgrazing or fire, leave the land surface open to the effects of storms.

In some areas, small rocks or rock fragments may be so numerous on the surface that they afford protection for underlying fine material. These rocks absorb the energy of falling rain and are resistant enough to prevent cutting by flowing water.

The Pacific Southwest is made up of land with all classes of ground cover. The high mountain areas generally have the most vegetation, while many areas in desert regions have very little or none. The abundance of vegetation is related to precipitation. If vegetative ground cover is destroyed in areas where precipitation is high, high erosion rates may occur.

Differences in vegetative type have a variable effect on erosion and sediment yield, even though percentages of total ground cover may be the same. For instance, the absence of understory in pinion-juniper stands would allow a higher erosion rate than areas of grass.

Land Use

Land use has a variable impact on sediment yield, depending on the susceptibility of the soil and rock to erosion, the amount of stress exerted by climatic factors, and the type and intensity of use. In most instances, land use either removes or reduces natural vegetative cover. Activities that remove vegetation include cultivation, urban development, and road construction. Grazing, logging, mining, and fires artificially induce permanent or temporary reduction in cover density.

Land use that reduces cover density on a steep slope with erodible soils and severe climatic conditions will strongly affect sediment yield. The extent of this effect will depend on the area and intensity of use relative to the availability of sediment from other causes. Construction of roads or urban development with numerous cut and fill slopes through a large area of widespread sheet or gully erosion will most likely change the sediment yield classification. Similar construction and continued disturbance in an area of good vegetative response to a favorable climate can raise yield by one or more classifications.

Land use has the greatest potential impact on sediment yield where a delicate balance exists under natural conditions. Alluvial valleys of fine, easily dispersed soils from shales and sandstones are highly vulnerable to erosion where intensive grazing and trailing by livestock have occurred. Valley trenching has developed in many of these valleys and provides a large part of the sediment in high yield classes from these areas.

A decline in vegetative density is not the only effect of livestock on erosion and sediment yield. Studies at Badger Wash, Colorado, which is underlain by Mancos shale, have indicated that sediment yield from ungrazed watersheds is appreciably less than from those that are grazed. This difference is attributed to the absence of soil trampling in the ungrazed areas because the density of vegetation has not noticeably changed since exclusion began. The arid and semi-arid portions of the Southwest that are surfaced by desert pavement are less sensitive to grazing and other use because the pavement affords a substitute for vegetative cover.

In some instances, the loss or deterioration of vegetative cover may have little noticeable onsite impact but may increase offsite erosion by acceleration of runoff. This could be evident below urbanized areas where accelerated runoff from pavement and rooftops has increased the stress on downstream channels. Widespread destruction of cover by poor logging practices or brush and timber fires frequently increases channel erosion and erosion on directly affected watershed slopes. On the other hand, cover disturbances under favorable conditions, such as a cool, moist climate, frequently result in a healing of erosion sources within a few years.

Upland Slope Erosion

Upland slope erosion occurs on sloping watersheds beyond the confines of valleys. Sheet erosion, which involves the removal of a thin layer of soil over an extensive area, is not usually visible. This erosion form is evidenced by the formation of rills. Soil loss from rill erosion can be seen if it amounts to approximately 5 tons per acre or more. This is equivalent in volume per square mile to approximately 2 acre-feet.

Wind erosion from upland slopes and the deposition of eroded material in stream channels may be a factor. The material deposited in channels is readily moved by subsequent runoff. Downslope soil movement due to creep can be an important factor in sediment yield on steep slopes underlain by unstable geologic formations.

Significant gully erosion as a sediment contributor is evidenced by the presence of numerous raw cuts along hill slopes. Deep soils on moderately steep to steep slopes usually provide an environment for gully development. Processes of slope erosion must be considered in light of factors that contribute to its development.

Channel Erosion and Sediment Transport

If a stream is ephemeral, runoff that traverses the dry alluvial bed may be reduced by transmission losses (absorption by channel alluvium). This decrease in flow volume results in a decreased potential to move sediment. Sediment may be deposited in the streambed from one or a series of relatively small flows only to be picked up and moved on in a subsequent larger flow. Sediment concentrations, as determined by field measurements at consecutive stations, have generally been shown to increase in instances of no tributary inflow. Thus, although water yield per unit area decreases with increasing drainage area, the sediment yield per unit area may remain nearly constant or may even increase with increasing drainage area.

In instances of convective precipitation in a watershed with perennial flow, the role of transmission losses is not as significant as in watersheds with ephemeral flow, but other channel factors, such as the shape of the channel, may be important.

Frontal storm durations are generally longer than convective storms, and runoff is often generated from the entire basin. In such instances, sediment removed from surfaces is generally carried out of the area by runoff. Stream channel degradation and/or aggradation must be considered in such cases, as well as bank scour.

Because many stream beds in the Pacific Southwest are composed of fine-grained alluvium in well defined channels, the potential for sediment transport is limited only by the amount and duration of runoff. Large volumes of sediment may be moved by frontal storms because of long flow durations.

Frontal storms of long duration with high intensity and limited extent convective activity will generally be in the highest class for sediment movement in channels. This type of storm produces the high peak flows and long durations necessary for maximum sediment transport.

Sediment yield may be substantially affected by the degree of channel development in a watershed. This development can be described by the channel cross sections and by geomorphic parameters such as drainage density, channel gradients, and width-depth ratio. The effect of these geomorphic parameters is difficult to evaluate, primarily because of the scarcity of sediment transport data in the Pacific Southwest.

If flow is kept within defined banks, then upstream sediment is generally transported to a downstream point without significant losses. Confinement of the flow within alluvial banks can result in high erosional capability of a flood flow, especially the flows with long return periods. In most channels with wide floodplains, deposition on the floodplain during floods is often significant, and the transport is less than that within a bank flow. The effect of this transport capability can be explained in terms of tractive force, which signifies the hydraulic stress exerted by the flow on the stream bed. This average bed-shear stress is obtained as the product of the specific weight of the fluid, hydraulic radius, and energy gradient slope. Thus, greater depth results in greater bed shear and greater potential for moving sediment. Steep slopes (the energy slope and bed slope are assumed to be equivalent) also result in high bed shear stress.

The boundary between sediment yield classifications in much of the Pacific Southwest may be at the mountain front, with the highest yield designation on the alluvial plain if there is extensive channel erosion. In contrast, many mountain streams emerge from canyon reaches and then spread over fans or valley flats. Water depths can decrease from many feet to only a few inches in short distances with a resultant loss of the capacity to transport sediment. High sediment yield can drop in such a transition from a confined channel to one that has no definition.

Channel bank and bed composition may influence the sediment yield of a watershed. In many areas in the Pacific Southwest, channels in valleys dissect unconsolidated material that may contribute significantly to the stream sediment load. Bank sloughing during periods of flow and during dry periods, piping, and bank scour generally add to the sediment load of the stream and often increase the sediment yield classification of the watershed. Field examination for areas of head cutting, aggradation or degradation, and bank cutting are generally necessary prior to classification of the transport expectancy of a stream. Geology plays a significant role in such an evaluation. Geologic controls in channels can greatly affect the stream regimen by limiting degradation and head cuts. Thus, the transport capacity may be present, but the supply of sediment from this source is limited.

Man-made structures can also affect the transport characteristics of the stream. For example, channel straightening can temporarily upset the channel equilibrium and cause an increase in channel gradient and in the stream velocity and shear stress. Thus, the sediment transport capacity of the stream may be temporarily increased. Structures such as debris dams, lined channels, drop spillways, and detention dams may drastically reduce the sediment transport.

APPENDIX B

MUSLE

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APPENDIX B: MUSLE

The Modified Universal Soil Loss Equation (MUSLE) is:

$Y = R * K * LS * C * P$

where

Y = sediment yield (tons)

R = runoff factor = $95 * (Q * q_p)^{0.56}$

Q = surface runoff volume (acre-feet [ac-ft])

q_p = peak flow (cubic feet per second [cfs])

K = soil erodibility factor

LS = topographic factor (length and slope of overland flow)

C = cover and management factor

P = erosion control practice factor

Williams (1975) describes MUSLE and introduces the runoff factor to replace the rainfall energy factor of USLE. Factors K, LS, C, and P are described in Wischmeier and Smith (1978). These factors can be obtained from nomographs, tables, and figures provided in USDA Handbook 537 with site-specific information on soils, overland slope and length, surface cover, and support practices. An EXCEL spreadsheet is used to implement MUSLE. The following equations are used to compute the soil erodibility factor (K), and length and slope factor (LS).

Soil erodibility factor (K) (Wischmeier and Smith, 1978):

$K = (0.00021 * (12 - \%O) * M^{1.14} + 3.25 * (SI - 2) + 2.5 * (PI - 3)) * 0.001$

$M = (\% \text{ sand} + \% \text{ silt}) * (100 - \% \text{ clay})$

%O = percent organic carbon

SI = soil structure index: 1, very fine granular; 2, fine granular; 3, medium or coarse granular; 4, blocky, platy, or massive

PI = permeability index: 1, rapid; 2, moderate to rapid; 3, moderate; 4, slow to moderate; 5, slow; 6, very slow

Length and slope factor (LS) (Haan et al., 1994):

Θ = slope in radians

For $\sin(\Theta) < 0.09$: $S_{factor} = 10.8 * \sin(\Theta) + 0.03$

Otherwise: $S_{factor} = 16.8 * \sin(\Theta) - 0.5$

$L_{factor} = (L/72.6)^a$

$a = f\beta/(1+f\beta)$

es = erosion susceptibility: 1, low; 2, moderate; 3, high

For es = 1: $f\beta = \beta/2$

For es = 2: $f\beta = \beta$

For es = 3: $f\beta = 2 - \beta$

$LS = L_{factor} * S_{factor}$

The cover and management factor (C) can be obtained from Table B-1, which provides factors for pasture, range, idle land, and grazed woodland (Wischmeier and Smith, 1978). The erosion-control practice factor (P) accounts for the effect of conservation practices such as contouring, strip cropping, and terracing on erosion. This factor has no significance for range and wildland areas at the Nevada National Security Site, and can be set at 1.0.

TABLE B-1. MUSLE COVER FACTORS

VEGETATIVE COVER		COVER THAT CONTACTS THE SOIL SURFACE[1]						
Type and Height[2]	**Percent Cover[3]**	**Type[4]**	**Percent Ground Cover**					
			0	**20**	**40**	**60**	**80**	**95+**
No appreciable canopy		G	0.45	0.20	0.10	0.042	0.013	0.003
		W	0.45	0.24	0.15	0.091	0.043	0.011
Tall weeds or short brush with average drop fall height of 20 inches	25	G	0.36	0.17	0.09	0.038	0.013	0.003
		W	0.36	0.20	0.13	0.083	0.041	0.011
	50	G	0.26	0.13	0.07	0.035	0.012	0.003
		W	0.26	0.16	0.11	0.076	0.039	0.011
	75	G	0.17	0.10	0.06	0.032	0.011	0.003
		W	0.17	0.12	0.09	0.068	0.038	0.011
Appreciable brush or brushes with average drop fall height of 6.5 feet	25	G	0.40	0.18	0.09	0.040	0.013	0.003
		W	0.40	0.22	0.14	0.087	0.042	0.011
	50	G	0.34	0.16	0.08	0.038	0.012	0.003
		W	0.34	0.19	0.13	0.082	0.041	0.011
	75	G	0.28	0.14	0.08	0.036	0.012	0.003
		W	0.28	0.17	0.12	0.078	0.040	0.011
Trees, but no appreciable low brush, and average drop fall height of 13 feet	25	G	0.42	0.19	0.10	0.041	0.013	0.003
		W	0.42	0.23	0.14	0.089	0.042	0.011
	50	G	0.39	0.18	0.09	0.040	0.013	0.003
		W	0.39	0.21	0.14	0.087	0.042	0.011
	75	G	0.36	0.17	0.09	0.039	0.012	0.003
		W	0.36	0.20	0.13	0.084	0.041	0.011

[1] The listed C values assume that vegetation and mulch are randomly distributed over the entire area.
[2] Canopy height is measured as the average fall height of water drops falling from the canopy to the ground. Canopy effect is inversely proportional to drop fall height and is negligible if fall height exceeds 33 feet.
[3] Portion of total area surface that would be hidden from view by canopy in a vertical projection (a bird's eye view).
[4] G: cover at surface is grass, grass-like plants, decaying compacted duff, or litter at least 2 inches deep.
W: cover at surface is mostly broadleaf herbaceous plants (as weeds with little lateral-root network near surface) or undecayed residues or both.

An example EXCEL spreadsheet is shown in Table B-2.

TABLE B-2. MUSLE STORM EVENT EROSION ESTIMATES

PV-1 WATERSHED	2-YEAR STORM EVENT
Parameters	**Input Values**
Determination of Length and Slope Factor (LS)	
Drainage area	
mi^2	0.78
ft^2	21,745,152
Overland Flow Length	
Length of channels, ft	7,000
Overland flow length, ft	400
Overland Slope	
Slope, ft/ft	0.06
Slope, degrees	3.43
Sin (slope)	0.06
S_{factor}	0.68
β	0.76
Susceptibility to erosion	2
$F\beta$	0.76
Exponent	0.43
L_{factor}	2.09
LS	**1.42**
Determination of Soil Erodibility Factor (K)	
Very fine sand, percent	12.5
Silt, percent	13.4
Clay, percent	6.6
Organic matter, percent	1
Structure index	2
Permeability index	1
M	2,419.06
K	**0.116**
Cover and Management Factor (C)	0.3
Conservation Practice Factor (P)	1
Determination of Runoff Factor (R)	
Q_v, ac-ft	5.39
Q_p, cfs	58.1
a	95
B	0.56
R	**2,373.30**
Sediment Yield = R * K * LS * C * P	
tons	63
pounds	126,463
cubic feet	1,277
ac-ft/mi²	**0.04**

Reference: Design Hydrology and Sedimentology for Small Catchments, Academic Press, Inc., 1994

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Haan, C. T., B. J. Barfield, and J. C. Hayes, 1994. *Design Hydrology and Sedimentology for Small Catchments*. Academic Press, Inc.

Williams, J. R., 1975. *Sediment Yield Prediction with Universal Equation Using Runoff Energy Factor*. U.S. Department of Agriculture, Agricultural Research Service. ARS-S-40.

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APPENDIX C

CHAN-SEDI

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APPENDIX C: CHAN-SEDI

An EXCEL spreadsheet model was developed to estimate sediment transport in an open channel system based on the sediment continuity equation and the sediment transport equations developed by the Keck Laboratory of the California Institute of Technology (Brownlie, 1981). The model computes sediment deposition or erosion in a channel reach from a storm event. The volume of sediment deposited or eroded is the difference between the upstream sediment supply rate and the channel sediment transport rate. If the supply rate is greater than the transport rate, sediment will deposit in the reach. If transport is greater than supply, the balance will be supplied by the reach by bed scouring and bank slumping. A study channel can be divided into up to six reaches in the current model. An upstream sediment supply reach is usually assigned as a boundary condition to account for sediment inflow from the upstream watershed (storm hydrograph and sediment concentration).

The input parameters for the model include the physical properties of water (gravitational acceleration, specific weight, and kinematic viscosity of water), the physical properties of sediment (specific weight of bed material, the median particle size and geometric standard deviation of bed material distribution, sediment porosity, and the angle of repose of the side slopes). Channel reaches are defined by upstream and downstream elevations, channel bottom width, and channel reach length.

Brownlie (1981) provides a few definitions related to the sediment transport equations developed for sand-bed channels. The total sediment load, which can be divided into wash load and bed material load, is the material being transported. The wash load is the sediment load finer than 0.062 millimeters, which does not depend on channel hydraulics, brought into the channel from an upstream watershed. The bed material load is the material found on the bed, which can be further subdivided into bed load (portion moving near the bed) and the suspended load (that portion of the load moving in suspension). The transport equations are for the bed material load, and sediment concentration refers to the bed material load concentration. Brownlie equations and the model input parameters are described below.

Properties of Water

- Specific weight of water, S_w (typical value = 62.4 pounds per cubic foot)
- Kinematic viscosity of water, N_u (typical value = 1.217e-5 square feet per second)

Bed Material Properties

- Median bed material particle size, D_{50}
- Geometric standard deviation of particle size distribution, σ

The model input includes the cumulative distribution of the particle sizes. The above two parameters are calculated assuming the bed material distribution is lognormal.

- Specific gravity of bed material, S_g (typical value = 2.65)
- Porosity, por
- Angle of repose of bank material, Ø

Channel Properties

- Channel bottom width, B (ft)
- Channel reach length, X_1 (ft)
- Channel slope, S (ft/ft), computed from upstream and downstream elevations (Z1, Z2) of the reach and its length

Inflow flow and sediment hydrographs are specified as flow rate (Q in cfs) and concentration at fixed time intervals, Δt (minutes).

Calculation of Flow Parameters

Flow per unit channel width (ft^2/s), $q = \frac{Q}{B}$

Dimensionless flow, $q_* = \frac{q}{\sqrt{g * D_{50}^3}}$

Slope, $S = \frac{Z1 - Z2}{X1}$

Flow Depth:

$$upper\ regime, Y_n = D_{50} * (0.2836 * q_*^{0.6248} * \sigma^{0.08013} * S^{-0.2877})\ \ if\ S > 0.006$$

$$lower\ regime, Y_n = D_{50} * (0.3724 * q_*^{0.6539} * \sigma^{0.105} * S^{-0.2542})\ \ otherwise$$

Flow velocity (ft/s), $V = \frac{q}{Y_n}$

Flow Froude number, $F_r = \frac{V}{\sqrt{g * Y_n}}$

Grain Froude number, $F_g = \frac{V}{\sqrt{(S_g - 1) * g * D_{50}}}$

Grain Froude number threshold for slopes less than 0.006, $F_{gp} = \frac{1.74}{S^{0.333}}$

$$if\ \ F_g > F_{gp}\ \ upper\ regime\ flow\ depth\ equation\ is\ used.$$

Calculation of Sediment Discharge

Grain Reynolds number, $R_g = \frac{\sqrt{g * D_{50}^3}}{N_u}$

Critical shear stress,

$$Y = \left(\sqrt{S_g - 1} * R_g\right)^{-0.6}$$

$$\tau_* = 0.22 * Y + 0.06 * 10^{-7.7 * Y}$$

Critical grain Froude number,

$$F_{go} = \frac{4.596 * \tau_*^{0.5293}}{S^{0.1405} * \sigma^{0.1606}}$$

$$\Delta F_g = F_g - F_{go}$$

Sediment concentration,

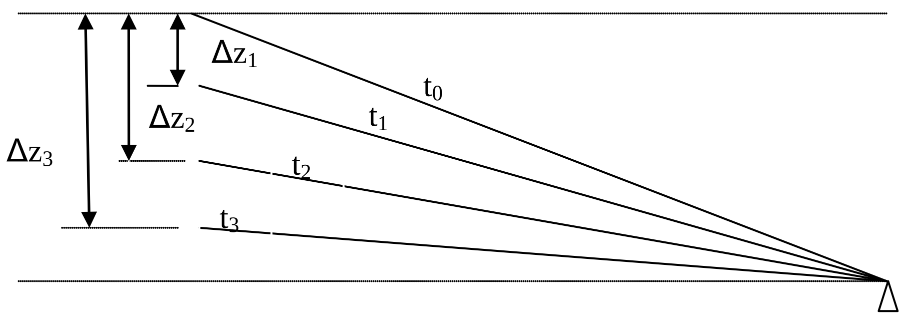
$$C = 7115 * (1.268) * \Delta F_g^{\ 1.978} * S^{\ 0.6601} * Y_d^{\ -0.33}$$

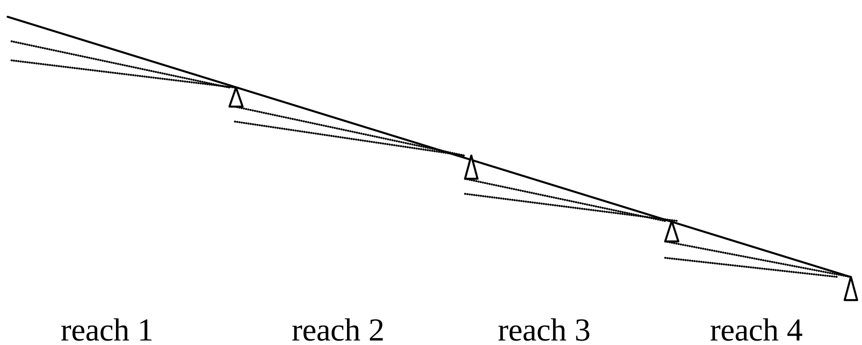
Sediment discharge (ft^2/s),

$$Q_{sv} = \frac{C * q * 10^{-6}}{S_g}$$

Channel Degradation and Sediment Discharge from Side Slope Slumping (optional):

The following figures define how channel degradation is assumed to occur for a single reach and for multiple reaches.



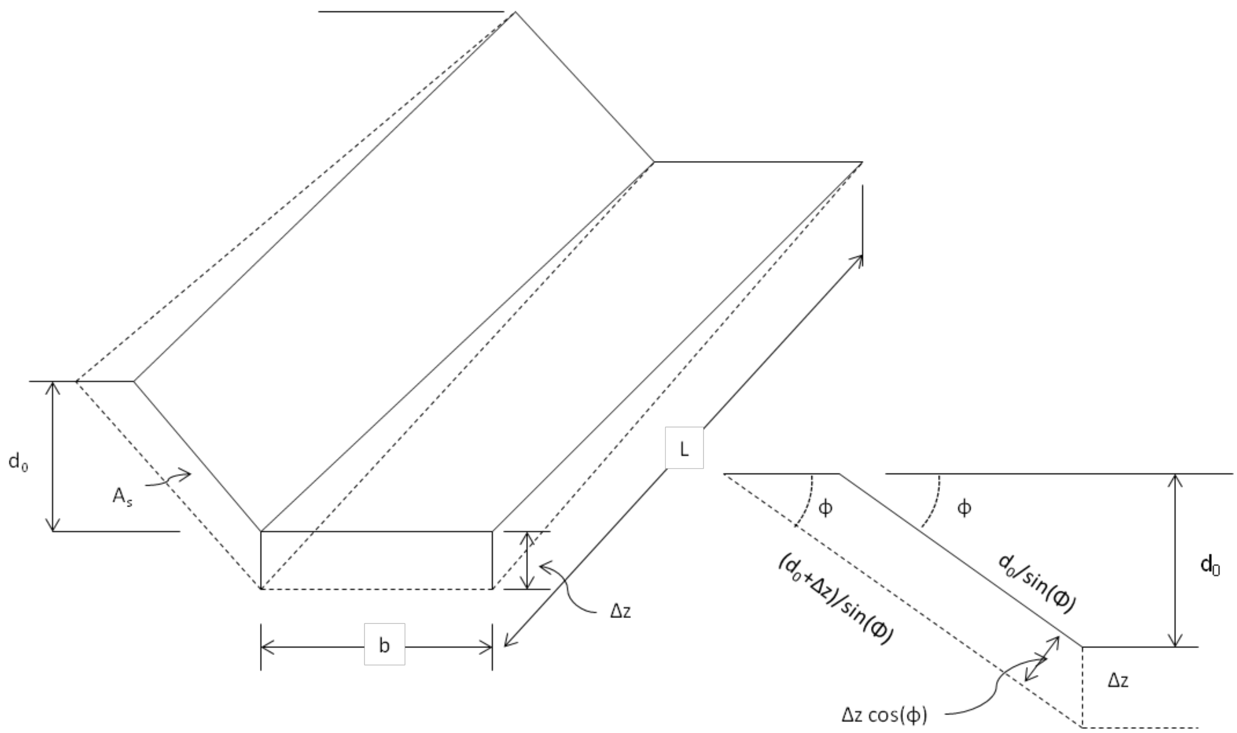


Bed scour for a cascading system of reaches is computed as follows:

$$\Delta z = \frac{2}{X}\left[\frac{(Q_{svin} - Q_{svout}) * \Delta t}{1 - por}\right]$$

where X is the reach length and *por* is the porosity of the channel material.

The bank slumping from one side of the channel is calculated with reference to the schematic below.



The derivation of the volume of material removed from the channel side involves integrating A_s along the channel reach length L. This volume is then considered in the sediment budget for each time step of the simulation in deriving the bed scour depth, Δz.

$$\Delta z = 2 * \Delta t * \frac{Q_{svin} + Q_{svside} - Q_{svout}}{L * (1 - por)}$$

The derivation leads to the following (ft):

$$\Delta z = \frac{-(-B + \sqrt{B^2 - 4 * C})}{2}$$

where

$$B = 3 * (d_0 + b * \tan(\emptyset))$$
$$C = -3 * b * \tan(\emptyset) * \Delta z$$

Sediment discharge from bank slumping,

$$Q_{svs} = \frac{-\Delta z * \left(d_0 - \frac{\Delta z}{3}\right)}{2 * \tan(\emptyset) * b * \Delta t} * L * (1 - por) \qquad \left(\frac{ft^2}{s}\right)$$

Reference

Brownlie, W. R., 1981. *Prediction of Flow Depth and Sediment Discharge in Open Channels.* Report No. KH-R-43A, W. M. Keck Laboratory of Hydraulics and Water Resources, California Institute of Technology. Pasadena, CA.

APPENDIX D

CHAN-SEDII

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APPENDIX D: CHAN-SEDII

A CHAN-SEDII spreadsheet model in EXCEL was adopted from French (1996) and FORTRAN codes prepared for the U.S. Department of Energy, Nevada Operations Office, dated April 24, 1996. The CHAN-SEDII spreadsheet model is similar to CHAN-SEDI with a few exceptions. CHAN-SEDII uses different transport equations, performs transport for ten classes of particle sizes ranging from very fine sand to very coarse gravel and integrates them to derive the total bed material transport, and allows for several options for channel hydraulics. Channel scour/deposition for multiple reaches is modeled as in CHAD-SEDI.

Both models require a storm hydrograph and an associated sediment concentration as inputs as well as a bed material particle size distribution. The transport equations used in AFSED are the Yang equation for sand and gravel (sediment particle sizes between 0.062 and 10 millimeters) and the Schoklistch equation for sediment sizes greater than 10 millimeters. Four options are provided for the computation of channel hydraulics parameters: two options for flow cut channels as defined in the Federal Emergency Response Agency alluvial fan model (critical depth assumption of Dawdy and normal depth assumption of Edwards and Thielman), channels with fixed geometry, and sheet flow (very wide channels). The transport equations are described below.

Yang Sediment Transport Equation

Input parameters:

- Average velocity, V (ft/s)
- Discharge, Q (ft^3/s)
- Hydraulic radius, R (ft)
- Slope, S (ft/ft)
- Unit weight of water, γ_w (lb/ft^3)
- Kinematic viscocity of water, ν (ft^2/s)
- Median particle diameter, d (mm)
- Specific gravity of sediment, s
- Acceleration of gravity, g (ft/s^2)

Calculations:

Shear velocity (ft/s),

$$u_* = \sqrt{g * R * S}$$

Particle fall velocity using Rubey's equation,

$$\omega_s = \frac{\sqrt{0.67 * (s-1) * d^3 + 36 * \nu^2} - 6 * \nu}{d}$$

Shear Reynold's number,

$$R_s = \frac{u_* * d}{\nu}$$

Critical velocity,

$$V_{cr} = \omega_s * \left[\frac{2.5}{log_{10}(R_s) - 0.06} + 0.66\right] \quad if\ R_s < 70$$
$$= \omega_s * 2.05 \qquad if\ R_s > 70$$

Log_{10} of concentration,

$$log_{10}(C) = 5.435 - 0.286 * log_{10}\left(\frac{\omega * d}{\nu}\right) - 0.457 * log_{10}\left(\frac{u_*}{\omega}\right) + \left[1.799 - 0.409 * log_{10}\left(\frac{\omega * d}{\nu}\right) - 0.314 * log_{10}\left(\frac{u_*}{\omega}\right)\right] * log_{10}\left(\frac{V * S}{\omega} - \frac{V_{cr}}{\omega}\right) \quad if\ d < 2\ mm$$
$$log_{10}(C) = 6.681 - 0.633 * log_{10}\left(\frac{\omega * d}{\nu}\right) - 4.816 * log_{10}\left(\frac{u_*}{\omega}\right) + \left[2.784 - 0.305 * log_{10}\left(\frac{\omega * d}{\nu}\right) - 0.282 * log_{10}\left(\frac{u_*}{\omega}\right)\right] * log_{10}\left(\frac{V * S}{\omega} - \frac{V_{cr}}{\omega}\right) \quad if\ 2 < d < 10\ mm$$

Concentration (ppm), $C = 10^{log_{10}(C)}$

Sediment discharge (lb/s), $G = \gamma_w * Q * C * 10^{-6}$

Schoklitsch sediment transport equation

Median particle size = d_{50} in inches

Critical discharge at which movement of particles of diameter d_{50} starts, $q_0 = 0.00532 * \frac{d_{50}}{S^{4/3}}$

Unit discharge, q

Sediment discharge, q_b (lb/s)

$$q_b = \frac{86.7}{\sqrt{d_{50}}} * S^{1.5} * (q - q_0) * B$$
$$where\ B = width\ of\ the\ water\ surface\ in\ the\ channel\ in\ ft$$

Sediment discharge (tons/day), $G = \frac{86000}{2000} * q_b$

The total discharge is then computed as the sum of the sediment discharge of each of the ten particle size classes weighted by its weight percentage.

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