FIRST-ORDER CONCEPTUAL MODEL FOR FLUVIAL REMOBILIZATION OF TEPHRA ALONG FORTYMILE WASH, YUCCA MOUNTAIN, NEVADA

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ABSTRACT

A conceptual model is being formulated to address the remobilization of contaminated tephra following a probable volcanic eruption at the potential Yucca Mountain, Nevada, high-level radioactive waste repository site. Basaltic pyroclastic-fall deposits can be eroded from surrounding hillslopes, transported by infrequent rainfall events, and deposited in the Fortymile Wash drainage system. The proposed reasonably maximally exposed individual is located 18 km [11.2 mi] from the potential repository site in the vicinity of the Fortymile Wash alluvial fan. Fortymile Wash is an ephemeral stream for which hydrologic data and sediment transport data are lacking. Therefore, available perennial streamflow models of suspended load, bedload, or total sediment load are not applicable. Initial modeling efforts utilize a simplified mass-balance approach to evaluate the potential remobilization and redistribution of tephra or pyroclastic ejecta in the drainage system. Rates of erosion in arid regions are not well-constrained, however, a suitable range of values can be entered into a sediment budget to demonstrate the quantitative or mass flux relationship between such components as annual sediment transport rates (focusing on the tephra), discharge to the alluvial fan, balance of remaining tephra, and associated changes in sediment storage. This approach is tested by applying it to the tephra sheet or mantle from the 1943–1952 eruption of Parícutin volcano, Mexico. Parícutin serves as the principal analog for this study because of eruption type, nature of the deposit, and detailed documentation of posteruption erosion. The preeruption erosion rate at Parícutin has a relative sediment yield of 1.0, and for the model runs presented in this report, erosion rates were set to 10 m^3/km^2-yr [915 ft^3/mi^2-yr] for volume calculations. Preliminary results from the remobilization model for Fortymile Wash show <0.25 percent of the tephra was removed by erosion after the first 30 years. This result, however, is strongly dependent upon erosion rate and thickness of dispersed tephra within the watershed.

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: All CNWRA original data contained within this report were collected and analyzed to meet quality assurance requirements as described in the CNWRA Quality Assurance manual. Sources for all other data should be consulted to determine the level of quality of these data.

ANALYSES AND CODES: Although no CNWRA-developed codes were used to analyze data for this report, the commercially available spreadsheet and plotting software, KaleidaGraph® Version 3.0, was employed. Generation of figures was aided by the use of Adobe® Photoshop® Version 7.0.1.

1 INTRODUCTION

1.1 Background and Purpose

Yucca Mountain, Nye County, Nevada, has been identified as a potential site for underground storage of high-level waste derived from reprocessing uranium and plutonium, surplus plutonium, and other nuclear weapons materials and spent fuel from civilian nuclear power plants. The presence of basaltic volcanism near Yucca Mountain has led to more than 20 years of volcanic hazard studies sponsored by the U.S. Department of Energy, the U.S. Nuclear Regulatory Commission, and the State of Nevada. Recent reports addressing the technical basis for resolving the issue of igneous activity at Yucca Mountain include Hill and Connor (2000) and Detournay, et al. (2003). A key component of these studies is quantifying the likelihood that a new basaltic volcano will form at the potential repository site during the 10,000-year postclosure period. According to this scenario, there is the potential for the volcanic disruption of the waste packages. Waste could be entrained in the subvolcanic conduit and dispersed in the eruption plume; thereby enabling the airborne transport of radionuclides. Tephra (ash, lapilli, bombs, and blocks) dispersal associated with an explosive eruption depends on many factors, including height of the eruption column, particle size distribution, and structure of the winds aloft. Contaminated tephra-fall deposits would be affected by surface processes and remobilized. The tephra would be eroded by mass wasting (including creep and mudflows), by the combined effects of raindrop splash and sheet wash, by channel erosion (including rilling and gullying), and by deflation.

The ephemeral Fortymile Wash drainage system is the focus of sediment transport, deposition, and redistribution because it is a part of the fluvial system that affects the Yucca Mountain biosphere and drains the east side of Yucca Mountain. Estimating the erosion and contribution of sediment to dryland channel systems is difficult because many factors control the process and because accurate measurements are scarce. Rates of erosion in arid and semiarid areas are not well constrained, but an anticipated range of values can be entered into a sediment budget to demonstrate the quantitative relationship between such components as sediment transport rates (focusing on a hypothetical tephra deposit), discharge to the Fortymile Wash alluvial fan, balance of remaining tephra, dilution of contaminated tephra, and associated changes in sediment storage.

This report presents the progress of a first-order conceptual model that focuses on a simplified mass-balance approach to evaluate the remobilization of tephra in the Fortymile Wash drainage system. The methodology is tested by first applying it to the tephra deposit from the 1943–1952 eruption of Parícutin volcano, Mexico. As an analog, Parícutin aids model calibration and may serve as a proxy for some analyses. Erosional processes are mostly simplified in this first-order approach, but improvements in the model are anticipated.

1.2 Precipitation and Streamflow Characteristics at Yucca Mountain, Nevada

Fortymile Wash is an ephemeral stream that drains the rugged, arid terrain of southwestern Nevada. The time between streamflow events can be several years, and perennial surface water comes only from springs. Runoff is infrequent because of high evapotranspiration rates and a low annual precipitation of approximately 150 mm [6 in] per year. Modern climate

summaries for the Yucca Mountain area and western United States meteorological stations are located at:

- http://www/yuccamountain.dri.edu
- http://www.wrcc.dri.edu/climsum.html
- http://wwwsord.nv.doe.gov/SORD_Rain.html

Ephemeral streams, which tend to have wide channels, have a high ratio of sediment to water compared with humid-temperate rivers (Bull and Kirkby, 2002). Because streamflow is so uncommon, any flow locally may be considered to be a flood. When dryland rivers are in flood conditions, they are also more efficient erosional agents than perennial systems (Laronne and Reid, 1993). Infiltration losses are high, however. Sediment transport in dryland rivers tends to be more transport limited than supply limited (Graf, 1988).

Ephemeral streams on the east side of Yucca Mountain are tributary to Fortymile Wash, which heads on Pahute Mesa and flows southward through Fortymile Canyon nearly 40 km [25 mi] before flowing onto an alluvial fan in the Amargosa Desert near the town of Amargosa Valley, Nevada, and the U.S. Highway 95 crossing. During floods, the distributary system of Fortymile Wash may join the Amargosa River and flow into Death Valley in southeastern California. Prior to its decommissioning, the streamflow gaging network in the Yucca Mountain area consisted of continuous-record gaging stations, peak flow crest-stage gages, and miscellaneous sites (Pabst, et al., 1993; Kane, et al., 1994; Savard, 1998). The relevant streamflow gaging stations are described in Table 1-1.

The Fortymile Wash drainage basin can be divided into four sections or reaches, from north to south (Figure 1-1):

(1) Fortymile Canyon reach or the upper headwater area: upstream from Fortymile Wash at the Narrows (Station 10251250) to the Pah Canyon confluence, a distance of 7.1 km [4.4 mi]

(2) Upper Jackass Flats reach: the incised channel from the Narrows to near Well J–13 (Station 10251255), a distance of 10.1 km [6.3 mi]

(3) Lower Jackass Flats reach: the incised channel from near Well J–13 to Fortymile Wash near the settlement of Amargosa Valley (Station 10251258), a distance of 16.8 km [10.4 mi]

(4) Amargosa Desert reach: downstream from Fortymile Wash near the town of Amargosa Valley as part of a broad distributary network

1.3 Fortymile Wash Streamflow, 1969–1998

Streamflow data were collected by the U.S. Geological Survey following standard methods and procedures in various U.S. Geological Survey publications. Details regarding individual streamflow events can be found in Waddell, et al. (1984), Pabst, et al. (1993), Kane, et al. (1994), Beck and Glancy (1995), and Tanko and Glancy (2001). Peak discharges at stream gaging sites in the Fortymile Wash area are summarized in Appendix A. Squires and Young (1984) examined the flood potential of Fortymile Wash and its principle southwestern

Table 1-1. Selected Surface Water Data Collection Sites in the Fortymile Wash Drainage Basin near Yucca Mountain, Nevada*				
Station Number†	**Station Name**	**Latitude and Longitude**	**Drainage Area (km^2)**	**Site Type§ and Period of Record**
10251250	Fortymile Wash at Narrows, Nevada Test Site	36º53'13" 116º22'50"	668	C: 1982–1983 G: September 21, 1983–1997
10251252	Yucca Wash near mouth (tributary), Nevada Test Site	36º51'58" 116º23'38"	44.0	C: 1982–1995
10251254	Drillhole Wash at mouth (tributary), Nevada Test Site	36º49'13" 116º23'52"	42.2	C: 1983–1995
10251255	Fortymile Wash near Well J-13, Nevada Test Site	36º48'27" 116º24'01"	787	M: 1969 and 1983 G: November 30, 1983–1997
10251256	Dune Wash near Busted Butte (tributary), Nevada Test Site	36º47'35" 116º24'29"	17.5	C: 1982–1995
10251258	Fortymile Wash near Amargosa Valley, Nevada	36º40'18" 116º26'03"	815.3‡	M: 1969 C: 1982–1983 G: November 15, 1983–1997

*Sources: Pabst, M.E., D.A. Beck, P.A. Glancy, and J.A. Johnson. "Streamflow and selected Precipitation Data for Yucca Mountain and Vicinity, Nye County, Nevada, Water Years 1983–85." U.S. Geological Survey Open-File Report 93–438. p. 66. 1993; Savard, C.S. "Estimated Ground-Water Recharge from Streamflow in Fortymile Wash Near Yucca Mountain, Nevada." U.S. Geological Survey Water Resource Investigations Report 97–4273. p. 30. 1998; CRWMS M&O, 2000.
†Station numbers are assigned in downstream order from uppermost location.
‡U.S. Geological Survey publications use a drainage area of 818 km^2 [316 mi^2] [1 km^2 = 0.386 mi^2].
§C = crest-stage gage; G = continuous gaging station; M = miscellaneous site.

tributaries, and Glancy (1994) conducted a similar study for Coyote Wash. Savard (1998) estimated groundwater recharge from streamflow and calculated infiltration loss associated with the Fortymile Wash drainage system (Appendix B). Because recharge from streamflow was found to be relatively small, operation of the Fortymile Wash gaging stations was reduced to a low priority in the late 1990s, and the stations were decommissioned (CRWMS M&O, 2000; Tanko and Glancy, 2001).

1.4 Volcanological Setting

Strombolian eruptive activity, the type most relevant to disruptive magmatism at Yucca Mountain, is characterized by mildly explosive bursts of solidified and partly solidified ash

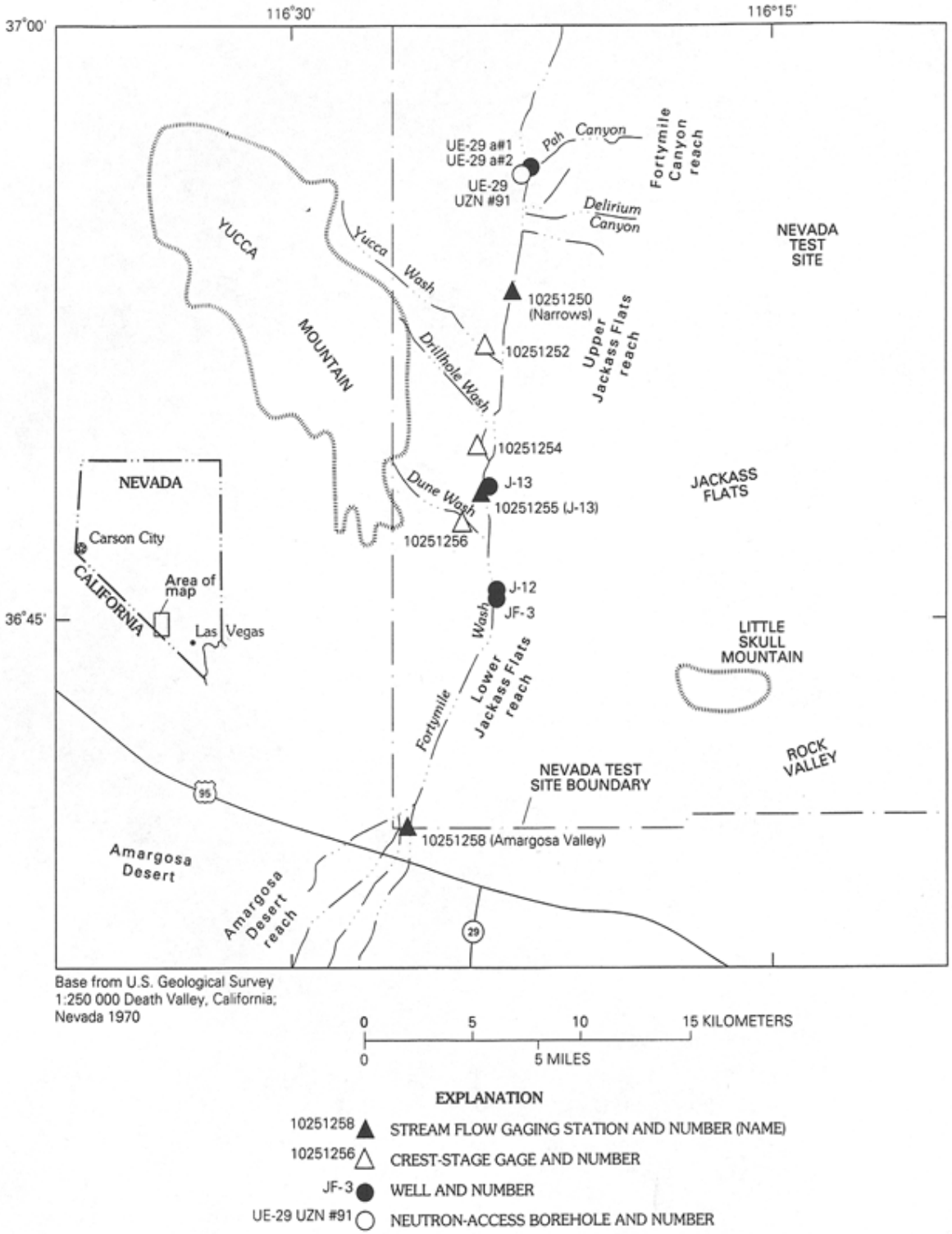

Figure 1-1. Location of Selected Streamflow Gaging Stations, Crest-Stage Gages, Neutron-Access Boreholes, and Wells in the Fortymile Wash Drainage Basin Near Yucca Mountain, Nevada (from Savard, 1998)

{<2 mm [0.08 in]}, lapilli {2–64 mm [0.08–2.5 in]}, and blocks and bombs {>64 mm [2.5 in]}. Most pyroclasts are lapilli-size. More violent explosions tend to produce smaller fragments. Scoria-fall deposits of limited areal extent and volume are emplaced around and downwind from the vent. Most of the pyroclasts fall ballistically around the vent and build up a scoria or cinder cone. These scoria cones tend to be relatively small for volcanic landforms and occur in groups or clusters in which individual cones may overlap one another. Strombolian eruptions are generally basaltic or near-basaltic in composition and may be accompanied by the ejection of relatively fluid lava spatter and the simultaneous effusion of lava. The grain-size distribution; direction, thickness, and extent of the tephra-fall deposit; and the tendency of scoria cones to occur in groups, all have important ramifications for understanding issues related to igneous activity at Yucca Mountain.

2 CONCEPTUAL MODEL

2.1 Outline of the Conceptual Model

Yucca Mountain, Nevada, has been selected as a potential site for an underground repository of high-level radioactive waste. A conceptual model is formulated to estimate the remobilization and redistribution of contaminated tephra following a potential volcanic eruption at this site. Basaltic pyroclastic-fall or scoria-fall deposits can be eroded from surrounding hillsides, transported by infrequent rainfall events, and deposited in the Fortymile Wash drainage system, which is the main drainage outlet for the eastern slope of Yucca Mountain. The proposed reasonably maximally exposed individual is located 18 km [11.2 mi] from the potential repository on the alluvial fan section of Fortymile Wash, an area that water and wind can deposit and erode contaminated tephra (Figure 2-1). Few data on sediment transport are available to evaluate these remobilization processes in detail. Fortymile Wash and its tributaries are normally dry streambeds that flow only after infrequent rainstorms or occasionally after snowmelt. Therefore, typical perennial streamflow models of suspended load, bedload, or total sediment load are not applicable. Even models portraying sediment transport by floods (Komar, 1988) are only marginally applicable to these conditions. To resolve these difficulties, this first-order conceptual model will utilize a simplified mass-balance approach to evaluate the remobilization of tephra in the Fortymile Wash drainage system.

2.2 Analog Sites for Model Development

The 1943–1952 eruption of Parícutin volcano in central Mexico, which produced a well-defined tephra sheet and cinder cone, serves as the principal analog for this study. Although Parícutin resides on a high plateau and receives more annual rainfall than Yucca Mountain, it is a reasonable analog site because of the eruption type, nature of the deposit, and thorough documentation of subsequent erosion. Parícutin is discussed further in Chapter 4. Other possible analog sites are discussed below.

Sunset Crater in the San Francisco volcanic field of Arizona erupted approximately 1,000 years ago, and traces of the scoria-fall deposit are still present 20 km [12.4 mi] from the vent (Amos, 1986). This region of north-central Arizona is semiarid, and previous studies focusing on the erosion of the Sunset Crater tephra sheet are nonexistent. Future field work concentrating on the degradation of the tephra sheet could provide valuable model input.

Nahal Eshtemoa is a gravel-bed ephemeral stream draining a basin of 119 km^2 [46 mi^2] on the southwestern flanks of the Hebron Hills in the northern Negev Desert, Israel. Powell, et al. (1996) and Reid, et al. (1998) describe the area, watershed characteristics, and results from their sediment yield measurements from the Nahal Eshtemoa. The river valley is incised with steep slopes that often include free faces. Rainfall averages between 220–350 mm [8.7–13.8 in] per year and is seasonal, falling mainly between November and March. Soils are thin and stony, and there are extensive areas of bare rock over the major portion of the catchment basin. The installation of a fully automatic sediment monitoring station in an ephemeral channel allowed the measurement of suspended and bedload yield for this dryland stream. From this detailed data, the mass per unit volume of discharge is calculated. Although this region does not have volcanic deposits, Nahal Eshtemoa serves as a well-documented example of fluvial processes in an ephemeral dryland stream.

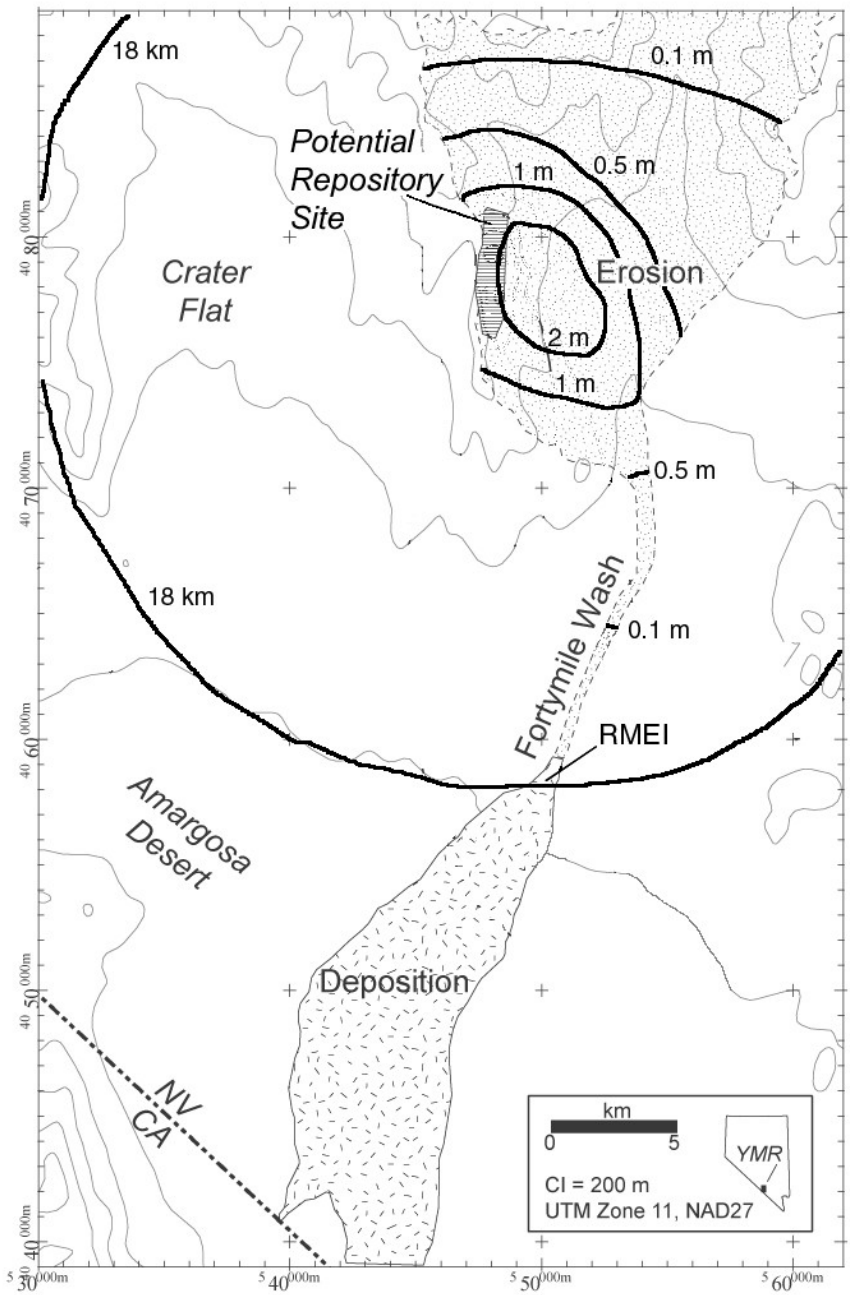

Figure 2-1. Scoping Calculation for the Remobilization of Tephra Following a Large-Volume Volcanic Eruption at the Potential Repository Site [Figure Redrawn from Hill and Connor (2000); data from Hill (2001)]. Erosional and Depositional Zones are Shown Along Fortymile Wash, but the Northern Portion of the Watershed is Truncated in This Figure. Reasonably Maximally Exposed Individual (= RMEI) Is Located 18 km [11.2 mi] from the Potential Repository. Partial Heavy Dark Lines Represent the Thickness of Tephra from the Modeled Eruption in Meters [1 m = 3.3 ft]. Erosional and Depositional Outlines Determined from U.S. Geological Survey 7.5' Topographic Maps [1 km = 0.62 mi].

2.3 Tasks

The completed initial steps in developing the conceptual model for tephra remobilization include the following:

- Review previous studies of arid to semiarid drainage systems to estimate sediment transport rates and sediment yield from similar dryland channel systems.
- Acquire hydrologic data for Fortymile Wash, Nevada, from gaging stations, including peak discharge, duration, and streamflow volume.
- Use published studies to determine the rate of erosion of the tephra deposit at Parícutin volcano, Mexico.
- Construct a simplified mass-balance approach to estimate remobilization of tephra following the Parícutin eruption.
- Apply the first-order remobilization model to Fortymile Wash for preliminary analysis of potential deposits.
- Perform initial analyses with the remobilization model to determine rates of fluvial transport and deposition, as well as areal concentration, dilution, and thickness of the potentially redistributed tephra deposit on the Fortymile Wash alluvial fan (site of the reasonably maximally exposed individual).
- Complete report on progress of model development (this report).

Future tasks and work-in-progress include the following:

- Calculate diffusion coefficients (as a measure of hillslope degradation) for each study site to constrain the range of erosion rates and sediment yields.
- Develop an abstracted model for downslope erosion of tephra using an empirical diffusion process.
- Revisit the topic of sediment transport in ephemeral streams from the perspective of stream power and efficiency (probably as a function of stream capacity); update the model as warranted.
- Incorporate, as needed, the recently published results from studies of gravel-bed ephemeral streams in the Negev Desert of Israel.
- Conduct field work at study sites.
- Revise empirical model parameters based on newly acquired field data.
- Evaluate the contribution of slope angle on erosion rate and remobilization; update the model as warranted.

- Plot the flood-frequency curve for Fortymile Wash to evaluate the recurrence interval (the limited historical record of flood occurrences hinders this analysis, however, flood estimates have been calculated by U.S. Geological Survey hydrologists).

- Achieve at least a first-order understanding of soil stabilization at Yucca Mountain to determine the effects on long-term remobilization processes.

- Incorporate at least a first-order approximation (or an abstracted model) of eolian processes into the model for fluvial remobilization of tephra; integrate approximation into performance assessment.

- Use either a previously derived or empirically derived diminution coefficient to address hypothetical tephra breakage, downstream fining, and fines enrichment/depletion processes in Fortymile Wash (results will be incorporated into inhalation studies).

- Assess the remobilization model as an integrated sediment budget for the entire drainage system; refine the terms for sediment yield, sediment storage, erosion rate, and volumetric analysis; and compare with past activity in the Fortymile Wash drainage system.

- Integrate the results of tephra remobilization processes into Total-system Performance Assessment (TPA Version 5.1 Code), including revised risk calculations, converting ash deposit fluxes into airborne mass-load decay functions and calculating inhalation doses from the airborne mass loads.

- Complete model integration and testing; produce the final range of output.

3 SEDIMENT TRANSPORT AND EROSION

3.1 Modeling Sediment in Natural Streams

The physics of sediment transport is complex. A thorough treatment of the hydraulics of sediment transport can be found in Graf (1971), while the mechanics of sediment-laden flows are succinctly addressed in a more recent text by Julien (1998). The complexity lies in describing the mechanics of a two-phase flow of water and sediment. The interface between flowing mixture of water and sediment particles and granular medium can move as a result of a continuous exchange of sediment particles. Fine particles are brought into suspension when turbulent velocity fluctuations are large enough to maintain the particles within the mass of fluid without frequent contact with the bed. Clay and silt particles generally enter suspension. Noncohesive bed particles enter motion as soon as the shear stress applied on the bed material exceeds the critical shear stress. Therefore, when hydraulic forces exerted on sediment particles exceed the threshold condition for beginning of motion, coarse sediment particles move in contact with the bed surface. Ordinarily, sand- and gravel-sized particles roll and slide in a thin layer near the streambed. This bedload is generally considered a minor component of the total sediment load, usually <15 percent (Knighton, 1998), but most measurements are from rivers in temperate climates. Concentrations of suspended load and bedload can vary significantly as flow conditions range from dilute discharge to dense concentrations almost verging on a debris flow.

No single approach is likely to describe all relationships between stream discharge, sediment transport, and particle entrainment in the natural river system. The general form of an equation for sediment transport is given by (Selby, 1993):

$$q_s = \frac{kQ_w^a \sin\beta^b}{n^c D_{50}} \tag{3-1}$$

where q_s is the net sediment transport, Q_w is the discharge of water, β is the slope angle of the streambed, n is the resistance to particle entrainment, D_{50} is the median particle diameter, and k, a, b, and c have empirically derived values.

Sediment transport through dryland fluvial systems can be treated from an areal perspective as either a drainage basin or as sediment yield from slope units. Sediment yield at the basin outlet is commonly much less than the gross erosion on its upstream watershed. Temporary stores of sediment, such as colluvium, alluvium, and gravel bars, are often extensive. Therefore, sediment yield is generally measured at the mouth of the basin and is usually expressed in units of weight (mass) per unit area or volume per unit area. The difference between erosion and sediment yield is termed the sediment delivery ratio, and while such terms as denudation, sediment yield, and rate of erosion are similar, they are not necessarily synonymous. Furthermore, it is commonly observed that sediment yield per unit area and sediment delivery ratio both decrease from small to large basins (Walling and Kleo, 1979). If the ratio equals 1.0, the amount of material removed from hillslopes equals the amount leaving the basin as fluvial sediment yield. Because of the lack of data regarding erosion rates and fluvial sediment load in arid or dryland basins, these sediment delivery ratios can be only estimated (Walling and Kleo,

1979). Relevant works by Graf (1988) and Bull and Kirkby (2002) specifically discuss fluvial processes in dryland rivers.

3.2 Erosion Rates

A steady stream of publications reports the measured rates of surface processes. In a milestone publication, Saunders and Young (1983) summarized results from 270 publications and collated this with another 149 publications they previously reviewed. Their compilation later appeared in chapter form following the 1985 Binghampton (New York) Symposium in Geomorphology (Young and Saunders, 1986). Their data are classified by major climatic zone, normal or steep relief, and consolidated or unconsolidated rocks. The surface processes measured include soil creep, surface wash, slope retreat, dissolution, cliff retreat, and total denudation. Total denudation is mainly produced by surface wash (Saunders and Young, 1983). These researchers adopted a simple and highly generalized classification of climate in which southwestern Nevada would be arid with less than 10 in [250 mm] of precipitation, and central Mexico (Parícutin region) would be categorized as temperate continental. All results for ground lowering were presented as Bubnoff units (B) where 1 B = 1 mm per 1,000 years [0.04 in per 1,000 years], equivalent to 1 m per million years [3.3 ft per million years]. Average rates of denudation may be converted to volume or mass of material removed by this relationship: 1 mm [0.04 in] of ground lowering equals the removal of 1.0 m^3/km^2-yr [91.5 ft^3/mi^2-yr] (Selby, 1993). Hence, volume can be converted to mass by multiplying by the bulk density of soil, sediment, or rock. For example, alluvial channel sediment has a bulk density of roughly 1,600 kg/m^3 [100 lb/ft^3] (Leopold, et al., 1966); thus, a 1 B denudation rate yields 1.6 t/km^2 [9,138 lb/mi^2] of sediment per year, where *t* = 1,000 kg or 1 metric ton (or tonne) [1 metric ton = 2,204.6 lb].

The denudation rate in central Mexico would range between 10 B [0.4 in per 1,000 years] (minimum) and 100 B [4 in per 1,000 years] (maximum) according to the compilations by Saunders and Young (1983) and Young and Saunders (1986). Studies from arid regions are lacking, thus a typical range for rate of denudation is poorly constrained. Saunders and Young (1983) only report a minimum denudation rate of 10 B or 10 mm per 1,000 years [0.4 in per 1,000 years]. This is also equivalent to a denudation or erosion rate of 10 m^3/km^2-yr [915 ft^3/mi^2-yr]. At Parícutin volcano, Fries (1953) measured the weight (mass) per unit volume of freshly deposited ash to be 1.7 metric tons per cubic meter or 1,700 kg/m^3 [106 lb/ft^3]. After converting to a mass measurement, the sediment production rate now becomes 17 t/km^2-yr [9.7 x 10^4 lb/mi^2]. Because of this overlap in the predominant range of denudation rates, a 10 B value (or 17 t/km^2-yr) will be used for the calculations presented in this report since this is common to both arid and temperate continental climate settings. It may represent the minimum denudation rate for both sites.

4 PARÍCUTIN VOLCANO, MEXICO

4.1 Setting

Parícutin volcano, Michoacán, Mexico, began erupting on February 20, 1943, and ceased activity on March 4, 1952. The eruption occurred on a high volcanic plateau at approximately 2,400 m [7,874 ft]. The climate is humid subtropical with a mean annual temperature of roughly 15 °C [59 °F] and a mean annual precipitation between 1,800–2,000 mm [71–79 in], depending on elevation (Inbar, et al., 1994). Hilly terrain, including older volcanoes, is generally covered by a dense forest; the plains are often cultivated. The eruption of this scoria or cinder cone volcano was well documented, and the case history is a reasonable analog for tephra removal processes that may occur in the event of a possible eruption in the Yucca Mountain region.

Explosive volcanic eruptions disrupt watershed hydrology and geomorphologic processes. Erosional response to severe volcanic disturbance is commonly rapid and dramatic; as a consequence, posteruption sediment yields can greatly exceed preeruption yields. Based on measurements made during the eruption, Fries (1953) published estimates of volume and mass for pyroclastic material and lava at Parícutin. Segerstrom (1950, 1960, 1961, and 1966) made extensive observations of tephra erosion at Parícutin. He addressed the degree of compaction, redeposition, and stripping of the ash mantle; the amount of new plant growth on lava flows and tephra deposits; and the overall deceleration of erosion. Segerstrom (1961) noted that erosion and redeposition in the Parícutin area may have slowed down for two principal reasons: (i) the most vulnerable deposits in stream channels and on the steepest slopes largely have been stripped away, and (ii) areas covered by ash or new alluvial deposits are becoming rapidly vegetated. In his final publication on the aftermath of the eruption, Segerstrom (1966) concluded that, by 1965, an approach toward stability was evident in the devastated area. Where the forest was not killed by the eruption, stabilization of the ash mantle has been even more rapid.

4.2 Volume and Mass of the Parícutin Tephra Mantle

The volume of air-fall deposits can be calculated in various ways from isopach maps. In the summer of 1946, Segerstrom (1950, Plate 1) made a series of ash thickness measurements around Parícutin and prepared a map showing ash thickness in the vicinity of the cone out to the 25-cm [10-in] isopach. From a few measurements at selected points beyond the 25-cm [10-in] isopach, he then inferred the 8-cm [3.1-in], 1-cm [0.4-in], and 1-mm [0.04-in] isopachs to be confocal to the 25-cm [10-in] isopach. He drew the 1-mm [0.04-in] isopach through Guadalajara, although Fries (1953) notes this is speculative. Despite this supposition, Segerstrom (1950, Table 4) estimated the area enclosed by the 1-mm [0.04-in] isopach to be 60,000 km^2 [23,166 mi^2]. He also assigned the 1-cm [0.4-in] isopach an area of 6,000 km^2 [2,316.6 mi^2]. By means of planimetric measurements of the area enclosed by each isopach and reconstruction of the areas out to the 8-cm [3.1-in], 1-cm [0.4-in], and 1-mm [0.04-in] isopachs, Fries (1953, Table 6) recalculated the volume of ash and presented the results as annual volume and mass increments. From these computations, he determined the area enclosed by the 1-mm [0.4-in] isopach to be 58,682 km^2 [22,657 mi^2]. The Fries (1953) value of 58,682 km^2 [22,657 mi^2] is believed to be more accurate than the Segerstrom (1950) value and is the area term used in this report when referring to the area enclosed by the 1-mm [0.04-in] isopach.

Based on his field observations and measurements made during and after the eruption, Segerstrom (1961) then plotted the relative volume of material eroded at Parícutin for the 1940–1960 time period. His diagram is replotted in Figure 4-1 of this report, with the assumption the estimated erosion in 1940–1942 was drawn to represent the average, preeruption erosion rate. Fries (1953) measured the weight (mass) per unit volume of ash deposited to be 1,700 kg/m^3 or 1.7 metric tons per cubic meter [106 lb/ft^3] and used this value to convert his volume measurements to mass measurements for erupted materials (ash and lava) from 1943 through 1951. Fries (1953, Table 6) did not include in his table his estimate of 40 million metric tons [8.82 × 10^{10} lb] of ash and lava erupted in 1952. Because the ratio of ash to lava erupted was similar during the final 3 full years of activity (1949–1951), a pro-rated value of 5.9 × 10^6 m^3 [2.08 x 10^8 ft^3] and 1.0 × 10^7 t (metric tons) [2.2 x 10^{10} lb] of ash can be approximated for 1952.

4.3 Model Procedure

The study in which Segerstrom (1961) estimated the deceleration of erosion at Parícutin volcano ended with the year 1960 (see Figure 4-1). The erosion rate peaked in 1944, the second year of the eruption, with a relative sediment yield seven times greater than the preeruption rate. Inbar, et al. (1994) attempted to extrapolate Segerstrom's plot, but they used manual curve-fitting. For this report, however, the Segerstrom (1961) data were extrapolated using a logarithmic curve fit (Figure 4-2). Based on this extrapolation, the Parícutin area should return to a normal, preeruption sediment yield in 1972, 30 years after the start of the eruption. The erosion of the tephra sheet proceeds according to the rate set by the relative sediment yield. All erosive processes are lumped into this annual measure of sediment yield.

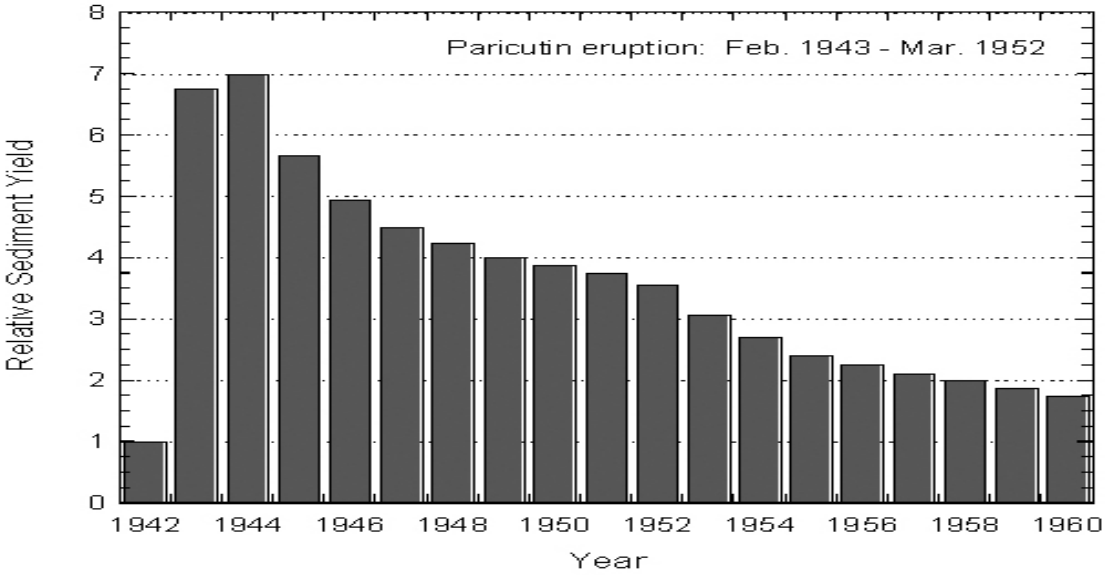

Figure 4-1. Erosion Rates at Parícutin Volcano, Mexico, 1942–1960 (Modified from Segerstrom, 1961)

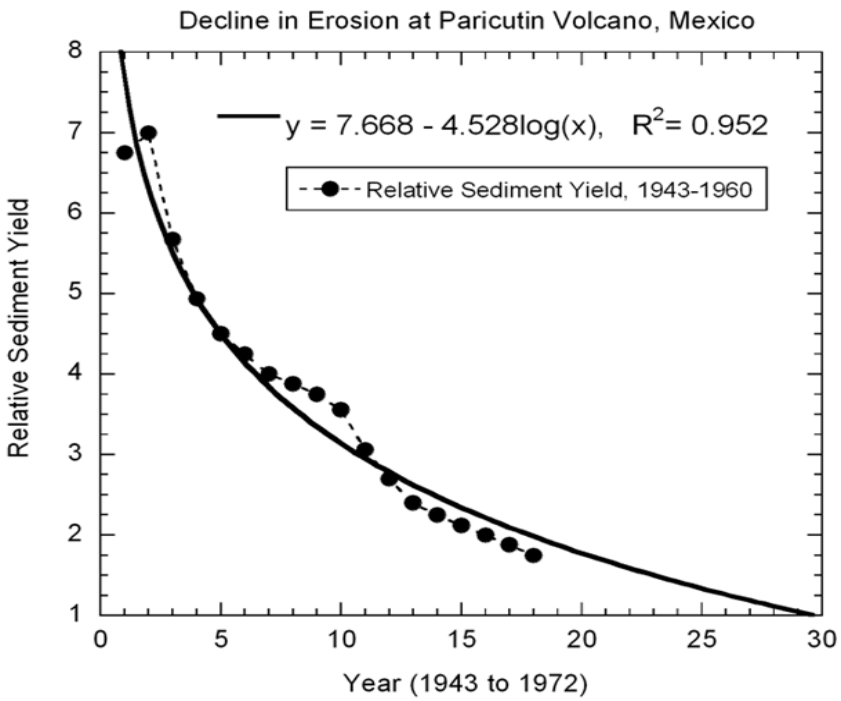

Figure 4-2. Decline in Erosion Rate at Parícutin, Mexico

The normal or preeruption erosion rate has a relative sediment yield of 1.0 and, for the model runs presented in this report, was set to 10 m^3/km^2-yr (or 10 B) [915 ft^3/mi^2-yr] for volume and 17 t/km^2-yr [9.7 x 10^4 lb/mi^2] for mass. The remobilization model enlists the following procedure.

(1) Erosion is controlled by the relative sediment yield, which lumps all erosive processes into a single annual term.

(2) Erupted tephra is estimated from isopach maps and expressed as mass or volume.

(3) Annual erosion is calculated by multiplying the relative sediment yield by the erosion rate (equations are presented with the data in each appendix of this report).

(4) Mass or volume of eroded tephra is determined by multiplying the measure of annual erosion by the area affected by tephra fall (or drainage basin area).

(5) Eroded and erupted tephra are summed.

(6) Eroded tephra is subtracted from the erupted tephra to determine the amount of remaining volcanic material (i.e., the sedimentary budget is updated).

(7) The percentage of tephra removed by erosion is computed by dividing the sum of eroded tephra by the sum of the erupted tephra.

4.4 Model Results

The annual sediment yield (see Figures 4-1 and 4-2) and the erupted volume and mass from the Parícutin (Mexico) eruption were entered into the remobilization procedure and the output is found in Appendixes C through E. Appendix C presents the total mass of pyroclastic material erupted at Parícutin and the mass of remobilized tephra. Appendix D is similar and lists the total volume of pyroclastic material erupted at Parícutin and the volume of remobilized tephra. Appendix E has the same format as Appendix D, but uses the 1-cm [0.4-in] isopach with a 6,000-km^2 [2,316.6-mi^2] area rather than the 1-mm [0.04-in] isopach with an area of 58,682 km^2 [22,657 mi^2] used in Appendixes C and D. Because this area is smaller, the total amount of eroded material is less.

These model runs serve as examples of a simplified mass-balance model to measure remobilization of tephra following the Parícutin eruption. After the first year, 6.73 × 10^6 t [1.48 x 10^{10} lb] and 3.96 × 10^6 m^3 [1.40 × 10^8 ft^3] of tephra or ash were eroded (Appendix C and D Column C5). This assumes all eroded material is tephra. Because the relative sediment yield increased during the second year, the amount of eroded material also increased to 6.98 × 10^6 t [1.54 x 10^{10} lb] and 4.11 × 10^6 m^3 [1.45 × 10^8 ft^3] for the second year. The percentage of total tephra removed by erosion or remobilized is initially 0.66 after the first year and increases to 3.72 percent after 1972, 30 years after the eruption began (Figure 4-3). Although not shown in this report, if a 100 m^3/km^2-yr [9,150 ft^3/mi^2-yr] or 100 B erosion rate was used, these values increase to 6.6 percent and 37.2 percent.

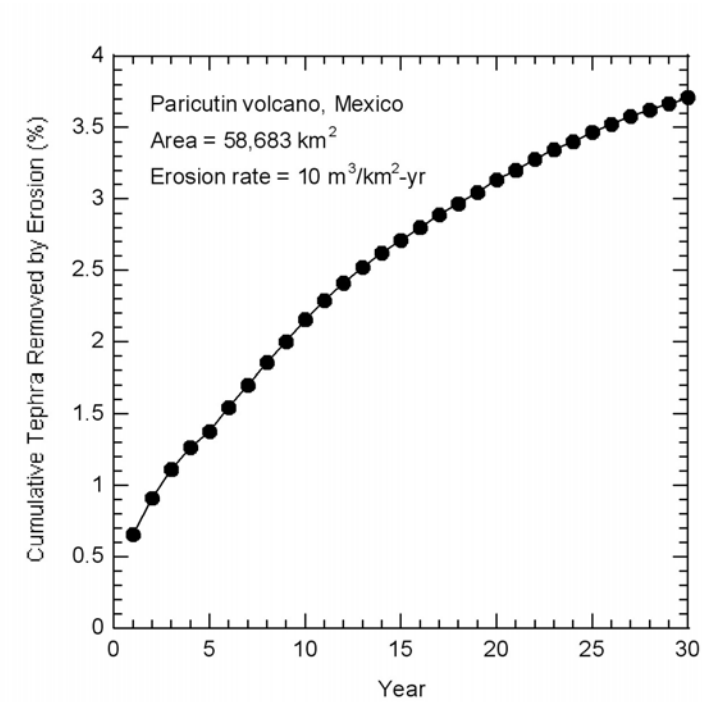

Figure 4-3. Percentage of Tephra Removed by Erosion at Parícutin Volcano (Mexico) During the First 30 Years after Deposition. The Area of 58,682 km^2 [22,657 mi^2] is for the 1-mm [0.04-in] Isopach and the Percentage of Eroded Material is the Same Whether the Calculations Use Mass or Volume [10 m^3/km^2-yr = 915 ft^3/mi^2-yr].

5 FORTYMILE WASH, YUCCA MOUNTAIN, NEVADA

5.1 Evaluation of Erosion at Yucca Mountain, Nevada

In the future, it is probable that a strombolian eruption will occur in close proximity to Yucca Mountain and the potential repository site. Depending on the actual vent location and wind direction, some amount of tephra will be deposited on slopes that are part of the Fortymile Wash drainage system. If the erupted material is contaminated by high-level waste, reworking by wind and water will spread the contaminated tephra-fall deposit beyond the area of original deposition. Therefore, contaminated tephra may be deposited at a site, such as a population center, as an air-fall deposit, or it may be transported to the site by erosional processes. Any material in the confined channel of Fortymile Wash will be removed rapidly by subsequent streamflow and transported south away from Yucca Mountain. Long-term sediment deposition begins just north of U.S. Highway 95 where the steep-sided channel changes to a broad, braided fan system. Sediment deposition and alluvial aggradation continue south into the Amargosa Desert and, most importantly, overlap the location of the reasonably maximally exposed individual.

Running water is still the primary agent for sediment transport in a dryland setting, but it may be limited to widely spaced episodes. Chemical weathering and mass movements such as creep are dominant geomorphic processes in humid climates. These processes play a less significant role in an arid climate. Desiccation and wind action such as deflation are more consequential in an arid region than in a humid region.

Hillslopes in the Yucca Mountain area of Nevada are a combination of exposed bedrock and bedrock mantled by coarse-grained, bouldery colluvium and fine-grained eolian deposits. The boulder deposits are commonly coated with a dark rock varnish, and the minimal vegetation cover provides little resistance to erosion caused by intense precipitation and the resultant runoff. With hillslopes lacking an abundance of readily available sediment for transport, the Yucca Mountain area can be considered sediment starved. A fresh blanket of tephra obviously would change this condition to a sediment choked system.

Varnished colluvial surfaces are believed to represent stable surfaces. Cation-ratio and Cl-36 age estimates of varnished, relict, colluvial-boulder, hillslope deposits in the Yucca Mountain region range from approximately 150 ka to 1.2 Ma [0.15 to 1.2 million years] (Whitney and Harrington, 1993). Coe, et al. (1997) estimate long-term average rates of slope degradation at Yucca Mountain ranging from 0.2 to 7 mm [0.008-0.3 in] per 1,000 years. On the basis of area and thickness estimates of Late Pleistocene and Holocene surficial deposits on the east side of Yucca Mountain, they report minimum degradation rates for hillslope colluvium that range from 25 to 28 mm [1-1.1 in] per 1,000 years for the last 25,000 years. In another study, long-term, average erosion rates have been calculated from dated hillslope deposits using rock varnish cation-ratio dating (Yucca Mountain Site Characterization Project, 1993). These rates range from <1 mm [<0.04 in] to 6 mm [0.24 in] per 1,000 years for hillslopes in the Yucca Mountain area. Erosion rates on Yucca Mountain are low, averaging 1.9 mm [0.07 in] per 1,000 years. Although the dating methodology for these studies may contain large uncertainties, what can be established is the erosion rate for the Yucca Mountain area is low. Humid temperate climates also show low minimum and possibly the lowest maximum rates of denudation; soil creep is slow and slope wash is low because of dense vegetation cover (Saunders and Young, 1983).

Another exercise can be conducted to examine erosion rates in southern Nevada. Only trace amounts of tephra-fall deposit remain within 3 km [1.9 mi] of the approximately 80,000-year old Lathrop Wells cone near Yucca Mountain (Hill and Connor, 2000). If a scoria-fall deposit with a thickness of 1 to 2 m [3.3 to 6.6 ft] in the proximal zone is assumed, the complete removal of this material in 80,000 years would aid in constraining erosion and transport rates. Therefore, 2 m [6.6 ft or 2,000 mm] of tephra would erode in 80,000 years at a rate of 25 mm [1 in] per 1,000 years. If a bounding value of 1 m [3.3 ft] is used, this rate drops to 12.5 mm [0.5 in] per 1,000 years. These erosion rates are slightly higher than anticipated for a southern Nevada climatic setting, but are still within the expected range of values. With the exception of trace amounts trapped in surface irregularities on associated lava flows, all remaining tephra has been eroded from the other Yucca Mountain region volcanoes (Hill and Connor, 2000). This indicates a thorough removal of the fall deposit and a hillslope erosion rate that may seem higher than anticipated. The apparent contradiction may arise because the tephra covering does not easily stabilize in an arid region and is, therefore, easily eroded by sporadic rainfall events and wind action. Patterns of degradation at other volcanoes (Segerstrom, 1966; Collins and Dunne, 1986; Major, et al., 2000) typically show the accelerated erosion rate peaks soon after the tephra is deposited, usually within 2 to 3 years and then declines rapidly. These studies imply this decline is not just caused by a recovery of vegetation, but also by (i) decreased erodibility because of changes in the infiltration capacity of the tephra layer, (ii) exposure of less erodible substrates, and (iii) development of a stable rill network. Fresh volcanic debris erodes through rapid extension of drainage networks. Erosion rates and sediment yields decline as drainage networks extend, integrate, and diminish hydrologic contributing areas and slope gradients.

5.2 Results

Remobilization and redistribution of tephra surrounding Yucca Mountain would primarily affect one major drainage system, Fortymile Wash. Hill (2001) used standard geographic and spatial applications to measure the extent of the drainage system and determined the northern basin has an area of 815.3 km^2 [314.8 mi^2], while the aggrading southern fan (the unconfined fan south of U.S. Highway 95) has an area of 135.5 km^2 [52.3 mi^2]. Hill (2001) used the 1975 Tolbachik eruption in Kamchatka as an analog model for a strombolian eruption that could occur in close proximity to Yucca Mountain. He then used conditions in Hill, et al. (1998) to calculate how much tephra from a Tolbachik-type eruption would fall on a remobilized surface if this hypothetical eruption was centered over the potential repository site at Yucca Mountain, Nevada (see Figure 2-1). Of the 815.3 km^2 [314.8 mi^2] in the northern basin, only 262.8 km^2 [101.5 mi^2] would receive tephra fall {using the 1-cm [0.4-in] isopach}. Note that the entire northern basin is not shown in Figure 2-1. Hill (2001) calculated a total tephra volume of 1.811×10^8 m^3 [6.4×10^9 ft^3], however, only 55.2 percent or 9.993×10^7 m^3 [3.5×10^9 ft^3] would fall within the northern or nondepositional portion of the Fortymile Wash drainage system.

The pertinent parameters for area and volume of this hypothetical tephra sheet were entered into the remobilization model using the same Parícutin relative sediment yield values for calibration (Appendix F). The normal or preeruption erosion rate has a relative sediment yield of 1.0 and for the model runs presented in this report was set to 10 m^3/km^2-yr [915 ft^3/mi^2-yr] for volume. All erosive processes were again lumped into this annual measure of sediment yield. After 30 years, the sum or total of eroded tephra was estimated to be 2.188×10^5 m^3 [7.7×10^6 ft^3] or only 0.219 percent of the total erupted tephra due to the low erosion rate. This result is strongly dependent on erosion rate and thickness of dispersed tephra within the watershed. If

all this material was remobilized and deposited with a uniform thickness in the southern depositional part of the basin {area = 135.5 km^2 [52.3 mi^2]}, the remobilized deposit would be 0.16 cm [0.06 in] thick. It is unlikely, however, this contaminated tephra would be deposited over the entire alluvial fan. If it was spread over 40 km^2 [15.4 mi^2], perhaps in the vicinity of U.S. Highway 95 and the reasonably maximally exposed individual location, this result changes to a 0.55-cm [0.22-in] thick remobilized deposit.

If the fitted equation in Figure 4-2 is used, the volume (V) of cumulative eroded tephra from column C6 (Appendix F) can be expressed as:

$$\mathrm{V} = \int_0^T y(t) \mathrm{x} E \ \mathrm{x} A \, dt = 7.668 \, E \mathrm{x} A \mathrm{x} T - 4.528 \, E \mathrm{x} A \{ T \log T - T \} \qquad (5\text{-}1)$$

If E = 10 m^3/km^2-yr, A = 262.8 km^2, and T = 30 years (Appendix F), then after 30 years the cumulative volume of eroded tephra from this equation is equal to 4.34×10^5 m^3 [1.53×10^7 ft^3] compared with 2.188×10^5 m^3 [7.7×10^6 ft^3] from Appendix F, column C6. This difference may reflect discretization error or error in reading Figure 4-2.

Because the assumption in this example is that tephra contaminated by high-level waste is deposited over 262.8 km^2 [101.5 mi^2] of the Fortymile Wash watershed, the remaining 552.5 km^2 [213.2 mi^2] contributes noncontaminated sediment at the normal erosion rate of 10 m^3/km^2-yr [915 ft^3/mi^2-yr]. The ratio of contaminated tephra versus regular sediment is presented as a simple model of dilution in Figure 5-1. Details of the calculations can be found in Appendix G. Initially, 76 percent of the sediment yield is contaminated tephra, however, the percentage decreases for the 30-year period. This mixture is now from two sources, so there is an increase in the total volume of material (sediment) reaching the depositional basin near U.S. Highway 95. The area, thickness, and volume of dispersed tephra within the watershed again will influence strongly the rate and percentage of dilution.

5.3 Conclusion

The first-order model presented in this report depicts a simplified analysis. Future analyses could use the fundamental insights gained on remobilization processes to introduce more realism and complexity into the remobilization model. Insights gained through these preliminary numerical results will be beneficial for future field work.

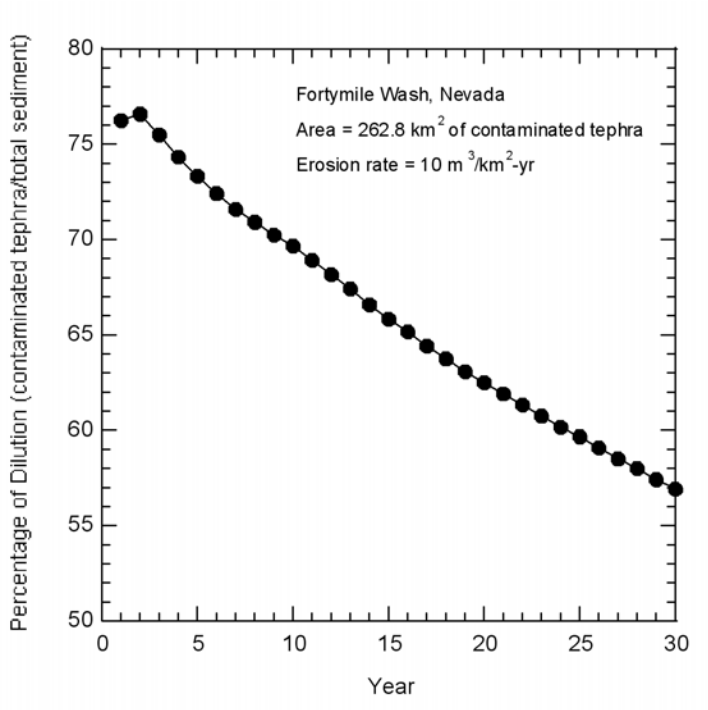

Figure 5-1. Dilution of Contaminated Sediment Expressed as a Ratio of Contaminated Tephra Versus Total Sediment. Area of Tephra Contaminated by High-Level Radioactive Waste is 262.8 km^2 [101.5 mi^2] and Area of Noncontaminated Sediment is 552.5 km^2 [213.2 mi^2]. Normal or Nonaccelerated Erosion Rate is 10 m^3/km^2-yr [915 ft^3/mi^2-yr].

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APPENDIX A

Table A. Peak Discharges at Stream Gaging Sites in the Fortymile Wash Area*						
Peak Discharge (m^3/s) [1 m^3/s = 35.3 ft^3/s]						
Date	10251250–Fortymile Wash at Narrows	10251252–Yucca Wash near Mouth (Tributary)	10251254–Drillhole Wash at Mouth (Tributary)	10251255–Fortymile Wash near Well J–13	10251256–Dune Wash near Busted Butte (Tributary)	10251258–Fortymile Wash near Amargosa Valley
January 25, 1969	—†	—	—	—	—	42.5
February 24–26, 1969	—	—	—	570	—	93.5
March 3, 1983	43.0	2.83	—	16.1	—	11.3
July 21–23, 1984	20.7	26.6	22.4	52.7	—	40.5
August 14–16, 1984	1.42	—	—	—	—	—
August 18–20, 1984	19.3	0.88	1.22	24.4	0.40	10.5
July 19–20, 1985	0.33	0.0003	0.48	0.17	2.66	0.09
February 23, 1987	—	—	—	—	—	0.02
May 7, 1987	—	<0.003	—	—	—	—
November 6, 1987	—	—	—	—	—	0.02
September 23, 1990	—	—	—	—	—	0.02
August 12–13, 1991	—	—	—	—	—	—
September 7, 1991	—	—	—	—	0.12	—
February 12–15, 1992	0.68	0.42	—	—	0.04	—
March 30–31, 1992	—	<0.03	—	—	0.03	—

Table A. Peak Discharges at Stream Gaging Sites in the Fortymile Wash Area (Continued)						
Peak Discharge (m^3/s) [1 m^3/s = 35.3 ft^3/s]						
Date	**10251250–Fortymile Wash at Narrows**	**10251252–Yucca Wash near Mouth (Tributary)**	**10251254–Drillhole Wash at Mouth (Tributary)**	**10251255–Fortymile Wash near Well J–13**	**10251256–Dune Wash near Busted Butte (Tributary)**	**10251258–Fortymile Wash near Amargosa Valley**
January 17–19, 1993	1.50	2.26	—	—	—	—
February 9, 1993	—	—	—	—	—	—
February 23, 1993	—	—	—	—	—	—
January 25–27, 1995	0.20	5.24	—	—	0.08	—
March 11–13, 1995	85.0	—	0.003	85.0	0.08	34.0
February 23–24, 1998 ‡	5.7	6.2	0.7	5.7	nd§	9.6

*Sources: CRWMS M&O,. "Surface Water Hydrology (Section 7)." TDR–CRW–GS–000001. Rev. 01 ICN 01. North Las Vegas, Nevada: DOE, Yucca Mountain Site Characterization Office. 2000; Tanko, D.J. and P.A. Glancy. "Flooding in the Amargosa River Drainage Basin, February 23–24, 1998, Southern Nevada and Eastern California, Including the Nevada Test Site." U.S. Geological Survey Fact Sheet FS–036–01. p. 4. 2001.
†Dash symbol (—) means either no streamflow recorded or site was not operating during period of streamflow.
‡Cumulative streamflow volumes for the 1995 and 1998 storm runoffs were estimated differently because most of the streamflow gaging stations were discontinued prior to the 1998 flood.
§Site disturbed by road crews prior to measurements (nd = not determined).

APPENDIX B

Table B. Measured and Estimated Volumes (in Cubic Meters) of Streamflow and Infiltration Losses for the Four Reaches of Fortymile Wash*

Volume (m^3) [1 m^3/s = 35.3 ft^3/s]									
Date	Estimated Fortymile Canyon Infiltration Loss†	Measured Narrows Gage (10251250)	Estimated Upper Jackass Flats Tributary Inflow	Estimated Upper Jackass Flats Infiltration Loss	Measured Well J–13 Gage (10251255)	Estimated Lower Jackass Flats Tributary Inflow	Estimated Lower Jackass Flats Infiltration Loss	Measured Amargosa Valley Gage (10251258)	Estimated Amargosa Desert Infiltration Loss
Jan. 25, 1969	**51,800**	—	—	**73,700**	—	—	**123,000**	—	**280,000**
Feb. 24–26, 1969	**51,800**	—	—	**73,700**	—	—	**123,000**	—	**440,000**
March 3, 1983	**51,800**	—	—	**73,700**	—	—	**123,000**	—	**128,000**
July 21–23, 1984	**51,800**	162,000	108,000	**73,700**	196,000	0	**123,000**	273,000	**273,000**
Aug. 14–16, 1984	**51,800**	10,500	—	**10,500**	3,600	—	**3,600**	1,200	**1,200**
Aug. 18–20, 1984	**51,800**	140,000	51,700	**73,700**	118,000	133,000	**123,000**	128,000	**128,000**
July 19–20, 1985	**4,800**	980	8,130	**8,280**	830	22,140	**22,730**	240	**240**
Feb. 23, 1987	**0**	0	0	**0**	0	0	**1,000**	100	**100**
May 7, 1987	**0**	0	100	**100**	0	0	**0**	0	**0**
Nov. 6, 1987	**0**	0	0	**0**	0	0	**500**	50	**50**
Sept. 23, 1990	**0**	0	0	**0**	0	0	**1,000**	100	**100**
Aug. 12–13, 1991	**100**	0	0	**0**	0	0	**0**	0	**0**
Sept. 7, 1991	**0**	0	0	**0**	0	1,000	**1,000**	0	**0**
Feb. 12–15, 1992	**42,300**	8,070	4,300	**12,400**	0	400	**400**	0	**0**

Table B. Measured and Estimated Volumes (in Cubic Meters) of Streamflow and Infiltration Losses for the Four Reaches of Fortymile Wash (Continued)*

Volume (m^3) [1 m^3/s = 35.3 ft^3/s]									
Date	Estimated Fortymile Canyon Infiltration Loss†	Measured Narrows Gage (10251250)	Estimated Upper Jackass Flats Tributary Inflow	Estimated Upper Jackass Flats Infiltration Loss	Measured Well J–13 Gage (10251255)	Estimated Lower Jackass Flats Tributary Inflow	Estimated Lower Jackass Flats Infiltration Loss	Measured Amargosa Valley Gage (10251258)	Estimated Amargosa Desert Infiltration Loss
Mar. 30–31, 1992	**14,100**	0	100	**100**	0	400	**400**	0	**0**
Jan. 17–19, 1993	**51,800**	24,700	37,900	**62,600**	0	0	**0**	0	**0**
Feb. 9, 1993	**17,300**	0	0	**0**	0	0	**0**	0	**0**
Feb. 23, 1993	**10,400**	0	0	**0**	0	0	**0**	0	**0**
Jan. 25–27, 1995	**51,800**	1,500	38,000	**39,500**	0	0	**0**	0	**0**
Mar. 11–13, 1995	**51,800**	597,000	40,700	**73,700**	564,000	0	**123,000**	441,000	**440,000**
Feb. 23–24, 1998	—	—	—	—	—	—	—	—	—

*Sources: Savard, C.S. "Estimated Ground-Water Recharge from Streamflow in Fortymile Wash Near Yucca Mountain, Nevada." U.S. Geological Survey Water Resources Investigations Report 97–4273. p. 30. 1998 (Table 3); Tanko, D.J. and P.A. Glancy. "Flooding in the Amargosa River Drainage Basin, February 23–24, 1998, Southern Nevada and Eastern California, Including the Nevada Test Site." U.S. Geological Survey Fact Sheet FS–036–01. p. 4. 2001

†All infiltration calculations (in bold) use a 7,300 m^3/km [4.15×10^5 ft^3/mi] streamflow volume loss factor (Savard, 1998)

APPENDIX C

Table C. Total Mass of Pyroclastic Material Erupted at Parícutin (Mexico) and Mass of Remobilized Tephra								
Year (C1)	**Relative Sediment Yield (C2)**	**Erupted Tephra (t, Metric Tons) (C3)**	**Annual Erosion (t/km^2-yr) (C4)**	**Mass of Eroded Tephra (t/yr) (C5)**	**Cumulative Eroded Tephra (t) (C6)**	**Cumulative Erupted Tephra (t) (C7)**	**Remaining Tephra (t) (C8)**	**Removed by Erosion (%) (C9)**
1943	6.75	1.022×10^9	114.75	6.73×10^6	6.73×10^6	1.022×10^9	1.015×10^9	0.66
1944	7	4.75×10^8	119	6.98×10^6	1.37×10^7	1.50×10^9	1.48×10^9	0.92
1945	5.67	2.52×10^8	96.4	5.66×10^6	1.94×10^7	1.75×10^9	1.73×10^9	1.1
1946	4.94	1.75×10^8	84	4.93×10^6	2.43×10^7	1.92×10^9	1.90×10^9	1.26
1947	4.5	1.67×10^8	76.5	4.49×10^6	2.88×10^7	2.09×10^9	2.06×10^9	1.38
1948	4.25	4.8×10^7	72.2	4.24×10^6	3.30×10^7	2.14×10^9	2.11×10^9	1.54
1949	4	3.6×10^7	68	4.0×10^6	3.70×10^7	2.18×10^9	2.14×10^9	1.7
1950	3.88	2.7×10^7	66	3.87×10^6	4.09×10^7	2.20×10^9	2.16×10^9	1.86
1951	3.75	2.4×10^7	63.75	3.74×10^6	4.46×10^7	2.23×10^9	2.18×10^9	2
1952	3.56	1.0×10^7*	60.5	3.55×10^6	4.82×10^7	2.24×10^9	2.19×10^9	2.15
1953	3.06	0	52	3.05×10^6	5.12×10^7	2.24×10^9	2.18×10^9	2.29
1954	2.7	0	45.9	2.69×10^6	5.39×10^7	2.24×10^9	2.18×10^9	2.41
1955	2.4	0	40.8	2.39×10^6	5.63×10^7	2.24×10^9	2.18×10^9	2.52
1956	2.25	0	38.25	2.24×10^6	5.86×10^7	2.24×10^9	2.18×10^9	2.62
1958	2	0	34	2.0×10^6	6.27×10^7	2.24×10^9	2.17×10^9	2.8
1959	1.88	0	32	1.88×10^6	6.46×10^7	2.24×10^9	2.17×10^9	2.88
1960	1.75	0	29.75	1.74×10^6	6.63×10^7	2.24×10^9	2.17×10^9	2.96
1957	2.12	0	36	2.11×10^6	6.07×10^7	2.24×10^9	2.18×10^9	2.71

Table C. Total Mass of Pyroclastic Material Erupted at Parícutin (Mexico) and Mass of Remobilized Tephra (Continued)								
Year (C1)	**Relative Sediment Yield (C2)**	**Erupted Tephra (t, Metric Tons) (C3)**	**Annual Erosion (t/km^2-yr) (C4)**	**Mass of Eroded Tephra (t/yr) (C5)**	**Cumulative Eroded Tephra (t) (C6)**	**Cumulative Erupted Tephra (t) (C7)**	**Remaining Tephra (t) (C8)**	**Removed by Erosion (%) (C9)**
1961	1.88	0	32	1.88×10^6	6.82×10^7	2.24×10^9	2.17×10^9	3.05
1962	1.78	0	30.3	1.78×10^6	7.0×10^7	2.24×10^9	2.17×10^9	3.13
1963	1.68	0	28.6	1.68×10^6	7.16×10^7	2.24×10^9	2.16×10^9	3.2
1964	1.59	0	27	1.59×10^6	7.32×10^7	2.24×10^9	2.16×10^9	3.27
1965	1.5	0	25.5	1.5×10^6	7.47×10^7	2.24×10^9	2.16×10^9	3.34
1966	1.42	0	24.1	1.42×10^6	7.61×10^7	2.24×10^9	2.16×10^9	3.4
1967	1.34	0	22.8	1.34×10^6	7.75×10^7	2.24×10^9	2.16×10^9	3.46
1968	1.26	0	21.4	1.26×10^6	7.87×10^7	2.24×10^9	2.16×10^9	3.52
1969	1.19	0	20.2	1.19×10^6	8.0×10^7	2.24×10^9	2.16×10^9	3.57
1970	1.12	0	19	1.12×10^6	8.10×10^7	2.24×10^9	2.16×10^9	3.62
1971	1.05	0	17.8	1.05×10^6	8.21×10^7	2.24×10^9	2.16×10^9	3.67
1972	1	0	17	9.98×10^5	8.31×10^7	2.24×10^9	2.15×10^9	3.72
Eq.	—	—	C4 = C2•E†	C5 = C4•A‡	C6 = $\sum$ (C5)	C6 = $\sum$ (C3)	C8 = C7−C6	C9 = C6/C7•100

*Estimated from Fries, C. "Volumes and Weights of Pyroclastic Material, Lava, and Water Erupted by Parícutin Volcano, Michoacan, Mexico." Transactions, American Geophysical Union. Vol. 34, No. 4. pp. 603–616. 1953. (see text)
†E = 17 t/km^2-yr [9.7×10^4 lb/mi^2-yr] (erosion) for this model run
‡A = 58,682 km^2 [22,657 mi^2] (area) for the 1-mm [0.04-in] isopach (see text)

APPENDIX D

Table D. Total Volume of Pyroclastic Material Erupted at Parícutin (Mexico) and Volume of Remobilized Tephra								
Year (C1)	**Relative Sediment Yield (C2)**	**Erupted Tephra (m^3) (C3)**	**Annual Erosion (m^3/km^2-yr) (C4)**	**Volume of Eroded Tephra (m^3/yr) (C5)**	**Cumulative Eroded Tephra (m^3) (C6)**	**Cumulative Erupted Tephra (m^3) (C7)**	**Remaining Tephra (m^3) (C8)**	**Removed by Erosion (%) (C9)**
1943	6.75	6.01×10^8	67.5	3.96×10^6	3.96×10^6	6.01×10^8	5.97×10^8	0.66
1944	7	2.80×10^8	70	4.11×10^6	8.07×10^6	8.81×10^8	8.73×10^8	0.92
1945	5.67	1.48×10^8	56.7	3.33×10^6	1.14×10^7	1.03×10^9	1.02×10^9	1.1
1946	4.94	1.03×10^8	49.4	2.90×10^6	1.43×10^7	1.13×10^9	1.12×10^9	1.26
1947	4.5	9.8×10^7	45	2.64×10^6	1.69×10^7	1.23×10^9	1.21×10^9	1.38
1948	4.25	2.8×10^7	42.5	2.49×10^6	1.94×10^7	1.26×10^9	1.24×10^9	1.54
1949	4	2.1×10^7	40	2.35×10^6	2.17×10^7	1.28×10^9	1.26×10^9	1.70
1950	3.88	1.6×10^7	38.8	2.28×10^6	2.40×10^7	1.30×10^9	1.27×10^9	1.86
1951	3.75	1.4×10^7	37.5	2.20×10^6	2.62×10^7	1.31×10^9	1.28×10^9	2.0
1952	3.56	5.9×10^6*	35.6	2.09×10^6	2.83×10^7	1.31×10^9	1.29×10^9	2.15
1953	3.06	0	30.6	1.80×10^6	3.01×10^7	1.31×10^9	1.28×10^9	2.29
1954	2.7	0	27	1.58×10^6	3.17×10^7	1.31×10^9	1.28×10^9	2.41
1955	2.4	0	24	1.41×10^6	3.31×10^7	1.31×10^9	1.28×10^9	2.52
1956	2.25	0	22.5	1.32×10^6	3.44×10^7	1.31×10^9	1.28×10^9	2.62
1957	2.12	0	21.2	1.24×10^6	3.57×10^7	1.31×10^9	1.28×10^9	2.71
1958	2	0	20	1.17×10^6	3.69×10^7	1.31×10^9	1.28×10^9	2.80
1959	1.88	0	18.8	1.10×10^6	3.80×10^7	1.31×10^9	1.28×10^9	2.88
1960	1.75	0	17.5	1.03×10^6	3.90×10^7	1.31×10^9	1.28×10^9	2.96
1961	1.88	0	18.8	1.10×10^6	4.01×10^7	1.31×10^9	1.27×10^9	3.05
1963	1.68	0	16.8	9.86×10^5	4.21×10^7	1.31×10^9	1.27×10^9	3.2
1964	1.59	0	15.9	9.33×10^5	4.31×10^7	1.31×10^9	1.27×10^9	3.27
1965	1.5	0	15	8.80×10^5	4.39×10^7	1.31×10^9	1.27×10^9	3.34
1962	1.78	0	17.8	1.04×10^6	4.11×10^7	1.31×10^9	1.27×10^9	3.13

Table D. Total Volume of Pyroclastic Material Erupted at Parícutin (Mexico) and Volume of Remobilized Tephra (Continued)								
Year (C1)	**Relative Sediment Yield (C2)**	**Erupted Tephra (m^3) (C3)**	**Annual Erosion (m^3/km^2-yr) (C4)**	**Volume of Eroded Tephra (m^3/yr) (C5)**	**Cumulative Eroded Tephra (m^3) (C6)**	**Cumulative Erupted Tephra (m^3) (C7)**	**Remaining Tephra (m^3) (C8)**	**Removed by Erosion (%) (C9)**
1966	1.42	0	14.2	8.33×10^5	4.48×10^7	1.31×10^9	1.27×10^9	3.4
1967	1.34	0	13.4	7.86×10^5	4.56×10^7	1.31×10^9	1.27×10^9	3.46
1968	1.26	0	12.6	7.39×10^5	4.63×10^7	1.31×10^9	1.27×10^9	3.52
1969	1.19	0	11.9	6.98×10^5	4.70×10^7	1.31×10^9	1.27×10^9	3.57
1970	1.12	0	11.2	6.57×10^5	4.77×10^7	1.31×10^9	1.27×10^9	3.62
1971	1.05	0	10.5	6.16×10^5	4.83×10^7	1.31×10^9	1.27×10^9	3.67
1972	1	0	10	5.87×10^5	4.89×10^7	1.31×10^9	1.27×10^9	3.72
Eq.	—	—	C4 = C2•E†	C5 = C4•A‡	C6 = $\sum$(C5)	C7 = $\sum$(C3)	C8 = C7−C6	C9 = (C6/C7)•100

*Estimated from Fries, C. "Volumes and Weights of Pyroclastic Material, Lava, and Water Erupted by Parícutin Volcano, Michoacan, Mexico." Transactions, American Geophysical Union. Vol. 34, No. 4. pp. 603–616. 1953. (see text)
†E = 10 m^3/km^2-yr [915 ft^3/mi^2-yr] (erosion) for this model run
‡A = 58,682 km^2 [22,657 mi^2] (area) for the 1-mm [0.04 = in] isopach (see text)

APPENDIX E

Table E. Total Volume of Pyroclastic Material Erupted at Parícutin (Mexico) and Volume of Remobilized Tephra {Using 1-cm [0.4-in] Isopach or 6,000-km^2 [2,316.6-mi^2] Area}

Year (C1)	Relative Sediment Yield (C2)	Erupted Tephra (m^3) (C3)	Annual Erosion (m^3/km^2-yr) (C4)	Volume of Eroded Tephra (m^3/yr) (C5)	Cumulative Eroded Tephra (m^3) (C6)	Cumulative Erupted Tephra (m^3) (C7)	Remaining Tephra (m^3) (C8)	Removed by Erosion (%) (C9)
1943	6.75	6.01×10^8	67.5	4.05×10^5	4.05×10^5	6.01×10^8	6.00×10^8	0.067
1944	7	2.80×10^8	70	4.20×10^5	8.25×10^5	8.81×10^8	8.80×10^8	0.094
1945	5.67	1.48×10^8	56.7	3.40×10^5	1.16×10^6	1.03×10^9	1.03×10^9	0.11
1946	4.94	1.03×10^8	49.4	2.96×10^5	1.46×10^6	1.13×10^9	1.13×10^9	0.13
1947	4.5	9.8×10^7	45	2.70×10^5	1.73×10^6	1.23×10^9	1.23×10^9	0.14
1948	4.25	2.8×10^7	42.5	2.55×10^5	1.99×10^6	1.26×10^9	1.26×10^9	0.16
1949	4	2.1×10^7	40	2.40×10^5	2.23×10^6	1.28×10^9	1.28×10^9	0.17
1950	3.88	1.6×10^7	38.8	2.33×10^5	2.46×10^6	1.30×10^9	1.29×10^9	0.19
1951	3.75	1.4×10^7	37.5	2.25×10^5	2.68×10^6	1.31×10^9	1.31×10^9	0.2
1952	3.56	$5.9 \times 10^{6*}$	35.6	2.14×10^5	2.90×10^6	1.31×10^9	1.31×10^9	0.22
1953	3.06	0	30.6	1.84×10^5	3.09×10^6	1.31×10^9	1.31×10^9	0.23
1954	2.7	0	27	1.62×10^5	3.24×10^6	1.31×10^9	1.31×10^9	0.25
1955	2.4	0	24	1.44×10^5	3.39×10^6	1.31×10^9	1.31×10^9	0.26
1956	2.25	0	22.5	1.35×10^5	3.52×10^6	1.31×10^9	1.31×10^9	0.27
1957	2.12	0	21.2	1.27×10^5	3.65×10^6	1.31×10^9	1.31×10^9	0.28
1958	2	0	20	1.20×10^5	3.77×10^6	1.31×10^9	1.31×10^9	0.29
1959	1.88	0	18.8	1.13×10^5	3.88×10^6	1.31×10^9	1.31×10^9	0.3
1960	1.75	0	17.5	1.05×10^5	3.99×10^6	1.31×10^9	1.31×10^9	0.3
1961	1.88	0	18.8	1.13×10^5	4.10×10^6	1.31×10^9	1.31×10^9	0.31
1962	1.78	0	17.8	1.07×10^5	4.21×10^6	1.31×10^9	1.31×10^9	0.32
1963	1.68	0	16.8	1.01×10^5	4.31×10^6	1.31×10^9	1.31×10^9	0.33
1964	1.59	0	15.9	9.54×10^4	4.40×10^6	1.31×10^9	1.31×10^9	0.33
1965	1.5	0	15	9.0×10^4	4.49×10^6	1.31×10^9	1.31×10^9	0.34

Table E. Total Volume of Pyroclastic Material Erupted at Parícutin (Mexico) and Volume of Remobilized Tephra {Using 1-cm [0.4-in] Isopach or 6,000-km^2 [2,316.6-mi^2] Area} (Continued)

Year (C1)	Relative Sediment Yield (C2)	Erupted Tephra (m^3) (C3)	Annual Erosion (m^3/km^2-yr) (C4)	Volume of Eroded Tephra (m^3/yr) (C5)	Cumulative Eroded Tephra (m^3) (C6)	Cumulative Erupted Tephra (m^3) (C7)	Remaining Tephra (m^3) (C8)	Removed by Erosion (%) (C9)
1966	1.42	0	14.2	8.52×10^4	4.58×10^6	1.31×10^9	1.31×10^9	0.35
1967	1.34	0	13.4	8.04×10^4	4.66×10^6	1.31×10^9	1.31×10^9	0.35
1968	1.26	0	12.6	7.56×10^4	4.73×10^6	1.31×10^9	1.31×10^9	0.36
1969	1.19	0	11.9	7.14×10^4	4.81×10^6	1.31×10^9	1.31×10^9	0.36
1970	1.12	0	11.2	6.72×10^4	4.87×10^6	1.31×10^9	1.31×10^9	0.37
1971	1.05	0	10.5	6.30×10^4	4.94×10^6	1.31×10^9	1.31×10^9	0.38
1972	1	0	10	6.0×10^4	5.0×10^6	1.31×10^9	1.31×10^9	0.38
Eq.	—	—	C4 = C2•E†	C5 = C4•A‡	C6 = ∑(C5)	C7 = ∑(C3)	C8 = C7−C6	C9 = (C6/C7)•100

*Estimated from Fries, C. "Volumes and Weights of Pyroclastic Material, Lava, and Water Erupted by Parícutin Volcano, Michoacan, Mexico." Transactions, American Geophysical Union. Vol. 34, No. 4. pp. 603–616. 1953. (see text)
†E = 10 m^3/km^2-yr [915 ft^3/mi^2-yr] (erosion) for this model run
‡A = 6,000 km^2 [2,316.6 mi^2] (area) for the 1-cm [0.4-in] isopach (see text)

APPENDIX F

Table F. Application of Observed Rate of Erosion at Parícutin (Me×ico) to Potential Remobilized Tephra at Fortymile Wash (Nevada)

Year (C1)	Relative Sediment Yield (C2)	Erupted Tephra Volume (m^3) (C3)	Annual Erosion (m^3/km^2-yr) (C4)	Volume of Eroded Tephra (m^3/yr) (C5)	Cumulative Eroded Tephra (m^3/yr) (C6)	Cumulative Erupted Tephra (m^3) (C7)	Remaining Tephra (m^3) (C8)	Removed by Erosion (%) (C9)
1	6.75	9.993×10^7*	67.5	1.774×10^4	1.774×10^4	9.993×10^7	9.991×10^7	0.0178
2	7	0	70	1.840×10^4	3.614×10^4	9.993×10^7	9.989×10^7	0.0362
3	5.67	0	56.7	1.490×10^4	5.104×10^4	9.993×10^7	9.988×10^7	0.0511
4	4.94	0	49.4	1.298×10^4	6.402×10^4	9.993×10^7	9.987×10^7	0.0641
5	4.5	0	45	1.183×10^4	7.584×10^4	9.993×10^7	9.985×10^7	0.0759
6	4.25	0	42.5	1.117×10^4	8.701×10^4	9.993×10^7	9.984×10^7	0.0871
7	4	0	40	1.051×10^4	9.752×10^4	9.993×10^7	9.983×10^7	0.0976
8	3.88	0	38.8	1.020×10^4	1.077×10^5	9.993×10^7	9.982×10^7	0.108
9	3.75	0	37.5	9.855×10^3	1.176×10^5	9.993×10^7	9.981×10^7	0.118
10	3.56	0	35.6	9.356×10^3	1.269×10^5	9.993×10^7	9.980×10^7	0.127
11	3.06	0	30.6	8.042×10^3	1.350×10^5	9.993×10^7	9.980×10^7	0.135
12	2.7	0	27	7.096×10^3	1.421×10^5	9.993×10^7	9.979×10^7	0.142
13	2.4	0	24	6.307×10^3	1.484×10^5	9.993×10^7	9.978×10^7	0.148
14	2.25	0	22.5	5.913×10^3	1.543×10^5	9.993×10^7	9.978×10^7	0.154
15	2.12	0	21.2	5.571×10^3	1.599×10^5	9.993×10^7	9.977×10^7	0.160
16	2	0	20	5.256×10^3	1.651×10^5	9.993×10^7	9.976×10^7	0.165
17	1.88	0	18.8	4.941×10^3	1.700×10^5	9.993×10^7	9.976×10^7	0.170
18	1.75	0	17.5	4.599×10^3	1.746×10^5	9.993×10^7	9.976×10^7	0.175
19	1.88	0	18.8	4.941×10^3	1.796×10^5	9.993×10^7	9.975×10^7	0.180
20	1.78	0	17.8	4.678×10^3	1.843×10^5	9.993×10^7	9.974×10^7	0.184
21	1.68	0	16.8	4.415×10^3	1.887×10^5	9.993×10^7	9.974×10^7	0.189
22	1.59	0	15.9	4.178×10^3	1.929×10^5	9.993×10^7	9.974×10^7	0.193
23	1.5	0	15	3.942×10^3	1.968×10^5	9.993×10^7	9.973×10^7	0.197
24	1.42	0	14.2	3.732×10^3	2.005×10^5	9.993×10^7	9.973×10^7	0.201
25	1.34	0	13.4	3.522×10^3	2.041×10^5	9.993×10^7	9.972×10^7	0.204
26	1.26	0	12.6	3.311×10^3	2.074×10^5	9.993×10^7	9.972×10^7	0.208
27	1.19	0	11.9	3.127×10^3	2.105×10^5	9.993×10^7	9.972×10^7	0.211
28	1.12	0	11.2	2.943×10^3	2.134×10^5	9.993×10^7	9.972×10^7	0.214
29	1.05	0	10.5	2.759×10^3	2.162×10^5	9.993×10^7	9.971×10^7	0.216
30	1	0	10	2.628×10^3	2.188×10^5	9.993×10^7	9.971×10^7	0.219
Eq.	—	—	C4 = C2•E†	C5 = C4•A‡	C6 = $\sum$(C5)	C7 = $\sum$(C3)	C8 = C7−C6	C9 = (C6/C7)•100

*Estimated from Hill, B.E. "Field Volcanism." Scientific Notebook 088. pp. 348–361. San Antonio, Texas: CNWRA. (2001)
†E = 10 m^3/km^2-yr [915 ft^3/mi^2-yr] (erosion) for this model run
‡A = 262.8 km^2 [101.5 mi^2] (area) for 1-cm [0.4-in] isopach (see text)

APPENDIX G

Table G. Application of Observed Rate of Erosion at Parícutin (Mexico) to Potential Remobilized Tephra and Sediment Dilution at Fortymile Wash (Nevada)					
Year (C1)	**Relative Sediment Yield (C2)**	**Cumulative Eroded (Contaminated) Tephra (m^3) (C3)**	**Cumulative Eroded (Noncontam.) Sediment (m^3) (C4)**	**Cumulative Total Sediment (m^3) (C5)**	**Dilution (Contam./ Total Sed.) (%) (C6)**
1	6.75	1.774×10^4	5.525×10^3	2.326×10^4	76.25
2	7	3.614×10^4	1.105×10^4	4.718×10^4	76.58
3	5.67	5.104×10^4	1.658×10^4	6.761×10^4	75.48
4	4.94	6.402×10^4	2.210×10^4	8.612×10^4	74.34
5	4.5	7.584×10^4	2.762×10^4	1.035×10^5	73.30
6	4.25	8.701×10^4	3.315×10^4	1.202×10^5	72.41
7	4	9.752×10^4	3.868×10^4	1.362×10^5	71.60
8	3.88	1.077×10^5	4.420×10^4	1.519×10^5	70.91
9	3.75	1.176×10^5	4.972×10^4	1.673×10^5	70.28
10	3.56	1.269×10^5	5.525×10^4	1.822×10^5	69.67
11	3.06	1.350×10^5	6.078×10^4	1.957×10^5	68.95
12	2.7	1.421×10^5	6.630×10^4	2.084×10^5	68.18
13	2.4	1.484×10^5	7.182×10^4	2.202×10^5	67.38
14	2.25	1.543×10^5	7.735×10^4	2.316×10^5	66.61
15	2.12	1.599×10^5	8.288×10^4	2.427×10^5	65.86
16	2	1.651×10^5	8.840×10^4	2.535×10^5	65.13
17	1.88	1.700×10^5	9.392×10^4	2.640×10^5	64.42
18	1.75	1.746×10^5	9.945×10^4	2.741×10^5	63.72
19	1.88	1.796×10^5	1.050×10^5	2.846×10^5	63.11
20	1.78	1.843×10^5	1.105×10^5	2.948×10^5	62.51
21	1.68	1.887×10^5	1.160×10^5	3.047×10^5	61.92
22	1.59	1.929×10^5	1.216×10^5	3.144×10^5	61.34
23	1.5	1.968×10^5	1.271×10^5	3.239×10^5	60.77
24	1.42	2.005×10^5	1.326×10^5	3.331×10^5	60.20
25	1.34	2.041×10^5	1.381×10^5	3.421×10^5	59.64

Table G. Application of Observed Rate of Erosion at Parícutin (Mexico) to Potential Remobilized Tephra and Sediment Dilution at Fortymile Wash (Nevada) (Continued)					
Year (C1)	**Relative Sediment Yield (C2)**	**Cumulative Eroded (Contaminated) Tephra (m^3) (C3)**	**Cumulative Eroded (Noncontam.) Sediment (m^3) (C4)**	**Cumulative Total Sediment (m^3) (C5)**	**Dilution (Contam./ Total Sed.) (%) (C6)**
26	1.26	2.074×10^5	1.436×10^5	3.510×10^5	59.08
27	1.19	2.105×10^5	1.492×10^5	3.597×10^5	58.52
28	1.12	2.134×10^5	1.547×10^5	3.681×10^5	57.98
29	1.05	2.162×10^5	1.602×10^5	3.764×10^5	57.44
30	1	2.188×10^5	1.658×10^5	3.846×10^5	56.90
Eq.	—	—	C4 = E†•A‡•C1	C5 = C3+C4	C6 = (C3/C5)•100

†E = 10 m^3/km^2-yr [915 ft^3/mi^2-yr] (erosion) for this model run (i.e., normal or relative sediment yield = 1)
‡A = 552.5 km^2 [213.2 mi^2] or area within watershed not covered by contaminated tephra fall