Erosion Modeling for Land Management – Scaling from plots to forest catchments in the Tahoe Basin

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Abstract

Land management and its effects on water quality are of paramount concern in the sub-alpine Tahoe Basin where regulatory agencies are working to set Total Maximum Daily Loadings (TMDL) for tributary streams to the Lake. Runoff and erosion measurement in the field and modeling at the catchment scale is quite difficult, but often the only possibility of generating realistic data and results for subsequent analyses. A distributed hydrologic model with locally–derived sediment yield equations developed from rainfall simulation (RS) studies at the 1 m^2 scale across the Basin is employed to evaluate the scaling effects of using the RS data and the possible sediment and fines loading reductions possible from the forested uplands comprising some 80% of the Basin area. The scaling factor, SGF, was found to be independent of sub-basin areas between <1 ha to 100's ha, but was dependent on sub-basin dominant soil type (granitic or volcanic). The mean area-weighted SGF value for granitic-based sub-basins was ~22, while this value for the mixed volcanic soil type sub-basins was ~2.5. The greatest sediment and fines loading and possible reductions were largely associated with disturbed soils of volcanic origin on the California side of the Lake. Sediment and fines loading of east-side tributaries was quite small. While some load reduction may be possible from the forested soils, the potential reductions per unit land area are much greater with the more disturbed soils associated with unpaved roads, recreational and ski run areas. The modeling effort completed here as part of the TMDL assessment for the Tahoe Basin provided considerable insight into where the greatest erosion potential may occur, the relative levels of sediment and fines load reduction possible and general corroboration of the applicability of RS research efforts across the Basin.

Keywords: erosion, forest soils, modeling, runoff, scaling, watersheds

1.0 INTRODUCTION

Regulatory concerns related to water quality from mixed urban, rangeland and forested watersheds has resulted in formulation of catchment models that describe the effects of land-use practices and conditions on pollutant loading and downstream water quality. Nowhere is this more evident then in the Lake Tahoe Basin straddling California and Nevada in the Sierra Nevada. Water quality in the Tahoe Basin integrates an extremely broad set of environmental variables, many of which exist and operate beyond immediate stream and watercourse channels. Many of the fine sediment particles, known to contribute to Lake clarity loss, are derived from forest upland source areas. Regulatory agencies in the Basin are keen on developing and modeling methods and treatments that are expected to reduce sediment movement from those forest upland settings and provide land managers with opportunities to help improve Lake clarity and overall watershed health. This information is intended to be used with other approaches such as urban treatment, stream treatment, approaches to improve air quality and so on, to achieve an overall reduction in pollutant loading to Lake Tahoe, ultimately resulting in an overall improvement in water quality and Lake clarity. This effort is directed at modeling the land-water interface in which management practices affect possible sediment transport across the landscape and into streams eventually discharging to the Lake. Here, erosion processes are briefly described followed by a review of modeling and scaling associated with erosion at the plot and catchment area scales.

Description of the erosion process as detachment, transport and deposition most aptly applies to bare, or nearly bare soils of high erosion potential. In more fully developed, less-disturbed soils, erosion may also be described as aggregate breakdown and a filtering process prior to possible detachment and transport (Grismer, 2007). Originally, detachment of sediment from the soil surface was considered to result primarily from raindrop impact (e.g. Hudson, 1975), while the erosive power of overland flow has been more fully recognized and is an important element during snowmelt. Generally, erosion processes may be classified as sheet, rill, gully and in-stream erosion that may occur individually, or more likely at the catchment scale, simultaneously on the landscape. Sheet and rill erosion result from uniform detachment and removal of sediment particles by overland flow, or raindrop impact evenly distributed across a slope or within small defined channels, respectively (Hairsine and Rose, 1992a; Rose, 1993). In contrast, gully erosion refers to concentrated flow channels and rates of sediment transport are related to soil strength, flow velocities and depths (transport capacity). As overland flows are concentrated along a hillslope, the dominant erosion types are expected to follow a downslope sequence of splash–sheet–rill–gully (Loch and Silburn, 1996). In-stream erosion involves direct removal of stream bank sediments. Given the scale of most rainfall simulation or erosion plot studies, we focus here on sheet and rill erosion modeling. Most erosion models predict sediment detachment and transport rates based on one, or at most two erosion types raising the possibility that the processes considered by the model being used are not truly representative of the processes actually occurring in certain areas of the catchment.

Merritt et al. (2003) provides a comprehensive overview of erosion and sediment transport models that can be used as a guide for model selection in a particular application. Of the available model types, empirical models (e.g. USLE) are generally the simplest and are based primarily on the analysis of observations and characterization of response from these data (Wheater et al., 1993). Computational and data requirements for such models are usually less than that for conceptual and physically based models as Jakeman et al. (1999) noted “the feature of this class of models is their high level of spatial and temporal aggregation and their incorporation of a small number of causal variables.” Empirical model parameter values are developed from calibrations either locally, but more often transferred from calibrations at experimental sites. Conceptual models (e.g. HSPF) typically represent a basin as a series of internal storages that incorporate the underlying transfer mechanisms of sediment and runoff generation in their structure. While providing a general description of watershed processes, detailed information is required to represent specific processes (Sorooshian, 1991). This enables such models to provide an indication of the qualitative and quantitative effects of land use changes, without requiring large amounts of spatially and temporally distributed input data. Lumped conceptual models may be operated in a semi-distributed manner by disaggregating a basin into linked sub-basins that are modeled individually. Beck (1987) noted that conceptual models are intermediate between empirical and physical models, that while aggregated they still represent the processes governing system behavior. Physical models (e.g. WEPP) rely on solution of conservation of mass and momentum equations describing streamflow and sediment and associated nutrient generation from the hillslope or catchment (e.g. Bennett, 1974) and typically involve considerable parameterization. Theoretically, physical model parameters are independently measurable, however in practice, the large number of parameters involved and their spatial variability across a basin means that these parameters must often be calibrated against observed data (Beck et al., 1995; Wheater et al., 1993). Generally, the governing equations are derived at small scale and under very specific physical conditions, though regularly applied at much greater scales, and under different physical conditions. Beven (1989) argues that despite the fundamental process nature of physically-based model parameters, problems of over-parameterization are not circumvented unless additional parameter observations are available at an appropriate scale. Scaling up physical parameters to the small basin scale is questionable and the parameters may lose their physical significance (Lane et al., 1995; Seyfried and Wilcox, 1995). With calibration-based model parameterization, Beven (1991) notes that even "physically-based distributed models are no different from any conceptual model."

Jakeman et al. (1999) noted that environmental modeling is hampered by problems of natural complexity, spatial heterogeneity and the lack of available data. Complexity of natural systems stems from variations, or changes in transport media, dimensions, temporal and spatial scales, and thresholds of water, sediment and nutrient transport over, through and in the media. Natural systems, from plot to catchment scales, tend to exhibit considerable variation. Assumptions of homogeneity in topography and soil characteristics, for example, are typically employed in sediment and water quality models to reduce this variation.

Complicating further the forested basin modeling issues, contemporary empirical, conceptual, physical or lumped/distributed parameter modeling aimed at quantifying basin rates of soil detachment, transport and deposition have been developed from a number of plot-scale studies typically in agricultural or rangeland settings. Since these phenomena are complex and depend on many parameters, model calibration is difficult, especially because field data are usually insufficient and relate to small spatial and temporal contexts. While some study plots on the order of 100 m^2 in size with run/slope lengths of 10's of meters (e.g. Croke et al., 1999), most erosion parameter data is developed from plots on the order of one square meter. Most of the soil conditions studied are either bare, tilled or with limited cover crops, stubble or mulches. Modeling sediment transport in the forest environment has been limited and is complicated by the highly variable conditions across the landscape. In contrast to agricultural settings, both pristine and disturbed forestry environments exhibit large spatial variability in vegetation and soil hydraulic properties. In forests, runoff generating mechanisms range from overland flow to surface saturation excess flow in less disturbed and near-stream areas with highly variable spatial and temporal patterns of hydraulic conductivity, infiltration capacity and surface erodibility (Bonell and Gillmour, 1978; Johnson and Beschta, 1980; Incerti et al., 1987; Bonell, 1993; Huang et al., 1996). While there are significant disturbed surfaces in managed forests where soil losses can be high, there are also large areas where surface roughness, mulch and vegetative cover promote sediment deposition and reduce total sediment yield. As discussed below, Croke and Nethery (2006) underscored significant sediment redistribution across the landscape when comparing the performance of RUSLE, WEPP and TOPOG erosion models against results from their large-scale rainfall simulator.

While well-recognized, the up-scaling problem has been considered secondarily in only a few studies typically directed at erosion model performance evaluations. Monitoring studies (Evans, 1993; Boardman and Favis-Mortlock, 1993) have shown that mean soil loss rates from field-sized areas are much smaller than those from plot-sized areas. In contrast, Yu and Rosewell (2001) found that doubling the run length from 20 to

41 m in a wheat stubble plot study had no effect on measured erosion rates, but when tripled to a ~62 m length, erosion rates increased by roughly half again. However, corresponding WEPP-based estimates of erosion rates doubled and then quadrupled as plot length doubled and tripled, respectively. In studying scale effects on computed soil losses using USLE for a large basin subdivided into small areas through a regular (square) mesh, Julien and Frenette (1987) developed a scale-dependent correction factor that decreases with increasing grid cell size. Later, Julien and Gonzales del Tanago (1991) showed that this correction factor was primarily dependent on the average slope and not on the spatial patterns of the other USLE factors. Arnold et al. (1993) computed runoff and fine sediment erosion using the SWAT model (a model based on SCS curve numbers for runoff and MUSLE for soil loss estimates) for various subdivisions of an experimental watershed (Bingner et al., 1997) and found that, while runoff volume was more-or-less unaffected by sub-basin area, fine sediment yields were highly size-dependent. A sensitivity analysis of the WEPP to different resolutions and accuracy of three elevation data sets by Renschler and Harbor (2002) indicated that coarser resolutions overestimated basin sediment yields as compared to that from higher resolution data. Croke et al. (1999), using a large rainfall simulator covering a forest area having disturbed (road and snig) soils as well as older harvested forest soils, noted that "inconsistencies between small- and large-scale plot yields highlighted the difficulties of using plot-scale data that do not accommodate sediment deposition and storage in calculating hillslope contributions to a basin sediment budget." Their study emphasized the need to explicitly consider scale and process in determining sediment yields and that modeling such "heterogeneous landscapes must include explicit recognition of the

importance of sediment exhaustion, deposition and storage processes across a range of spatial scales."

It appears possible to address some of this scaling problem through separate consideration of runoff and erosion rates from different land-uses or smaller homogeneous area within a sub-basin, summing flows and sediment yields and then routing through progressively larger catchment areas from each sub-basin appropriately. In an effort to account for sediment deposition and upscale application of USLE-based erosion assessments, the Sediment Delivery Ratio (SDR) concept was developed. SDR is considered a function of slope (Kling, in Hadley et al., 1985; Kothyari et al., 1994 & 1996) or, using morphologic criteria, a travel time probability density function evaluated as a function of slope and slope length (Ferro and Minacapilli, 1995). Assuming uniform flow, constant intensity rainfall and the SDR concept where travel times were taken as proportional to the ratio between the path length to the closest stream and a representative velocity (Santoro et al., 2002), Amore et al. (2004) found no real scale dependence of RUSLE and WEPP in predicting runoff and erosion from Sicilian sub-basins between 0.5 and 20 km^2 despite comparisons between results from sub-basins having very different areal distributions of soil and land uses, size and average steepness. As found in earlier studies (Nearing, 1998 & 2000; Nearing et al., 1999), relative prediction error increased as erosion rates decreased due in part to naturally greater coefficients of variation of erosion at lower erosion rates. Their results suggested that a finer resolution of area characteristics was "not necessarily needed for a better estimate for eroded soil." On the other hand, Croke and Nethery (2006), while noting that the process-based models better simulated large plot runoff and erosion, questioned whether any erosion model is yet ready for deployment across a watershed in decision making.

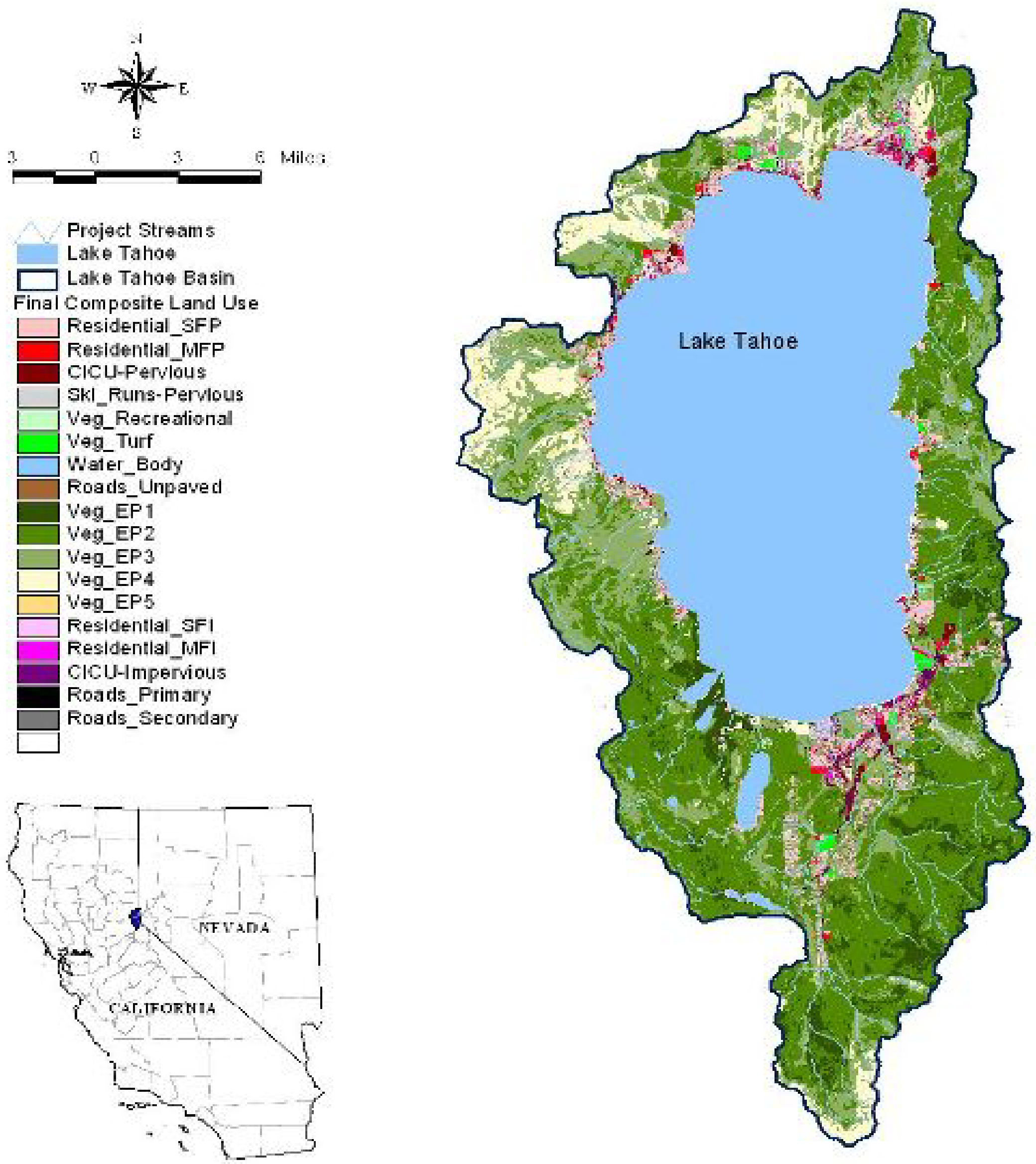
The research objectives considered here attempt to address two of the limitations described above associated with erosion modeling at the basin scale. The first objective is to determine the scaling effects of using process level data developed from rainfall simulations on one square meter plots to describe sub-basin scale sediment and fines (silt & clay) transport rates from different land-uses where sub-basins scales range from 1 to 1000 ha. This objective involves consideration of realistic erosion rates from relatively undisturbed forest soils as yet not otherwise quantified in addition to bare soil conditions associated with unpaved fire roads. The second objective is to determine the possible sediment loading reductions possible with restoration of disturbed soils within the sub-basins and the Lake Tahoe Basin as a whole as a guide for land managers and policy makers in the Basin. This objective also involves application of plot-scale data developed from comparisons of soil restoration treatments described by Grismer and Hogan (2004, 2005a & 2005b). Overall, the objectives here are an effort to gain a better understanding as outlined by Merritt et al. (2003) below.

> *In order to address the growing requirements of catchment managers for tools that can effectively and efficiently capture spatial aspects of soil erosion and sediment transport, on-going work on such tools needed. The development of a distributed model of relatively low complexity and plausible physical basis is required. Whilst considerable work is required to improve erosion and sediment transport models, this needs to undertaken in conjunction with efforts to improve data quality and monitoring… Model performance and accuracy remain a major difficulty in model development particularly with spatially distributed models. Ongoing accuracy and sensitivity assessment of models is needed to prioritize modifications to model structures, identify more efficient parameterisations, and target data acquisition necessary for testing.*

2.0 TAHOE BASIN SETTING

Considered a national treasure, and designated by the USEPA as an Outstanding National Resource Water, the beauty of Lake Tahoe and its surrounding watershed has captured the eyes and imaginations of the public and scientists for many decades. Situated centrally in the Sierra Nevada, the Tahoe Basin straddles the California - Nevada state border, and covers approximately 840 km^2 with lake elevation at about 1895 m. The Basin is characterized by steep mountain slopes, evergreen and mixed forests, and urban development at various locations around the perimeter of the Lake. Popular recreational activities include skiing, hiking, and camping, as well as other outdoor activities (see Figure 1).

Figure 1. The Lake Tahoe Basin and associated land-use categories.

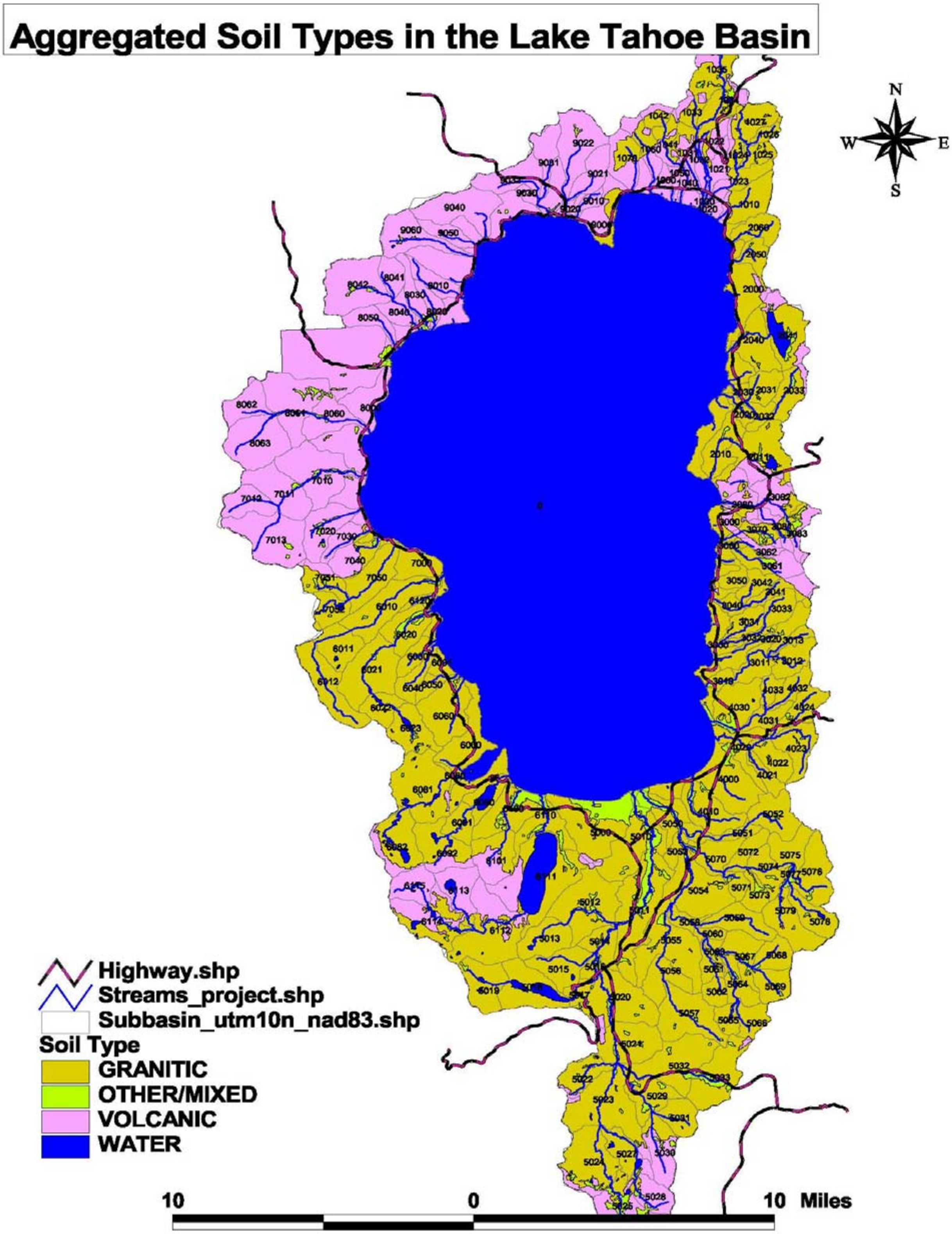


Here, we consider the sediment and nutrient loading from forested upland soils, ranging in functional condition from drastically disturbed (e.g. unpaved roads) to relatively undisturbed (or not recently disturbed, e.g. vegetated, forests). These soils have the potential to be mobilized at the present time and/or may be mobilized in the future as part of forest management activities. The majority of the sediment and nutrient loading is expected to occur from disturbed soils that have been impacted by road development, recreation and past logging activities. These soils have been degraded in part or whole through loss of structure, infiltration capacity and aggregate stability (a measure of erodibility). Simon et al. (2003) and Grismer and Hogan (2004) found that sediment sources from upland soils are dependent on three primary factors: 1) soil origin or parent material, 2) level of disturbance and associated soil physical condition, and 3) slope. Finer-textured soils associated with those of volcanic (andesitic) origin are generally more readily degraded and eroded as compared to those of granitic or metamorphic geologic origin. Finer-grained volcanic soils are more readily mobilized by runoff events (rainfall or snowmelt), but may as a result of the finer grains have greater potential aggregate strength as compared to the larger grained granitic soils that are more difficult to mobilize in most runoff events, but may lack structure resulting in possible soil slumping. Fine sediment movement results from soil aggregate breakdown associated with lack of soil cover and high levels of soil disturbance. In contrast, improved soil tilth (the physical and biological functional condition of the soil) increases soil infiltration rates or capacity, thereby reducing runoff rates in non-saturated soil conditions. Steeper slopes result in greater runoff rates, hence mobilization power to transport sediments downslope. Elevation and east-west location in each sub-basin also plays a role in estimation of runoff and erosion (e.g. higher elevations on the west shore of the Lake are associated with higher precipitation or snow depths, resulting in greater potential runoff).

Nutrient loading in runoff is a function of several factors associated with relative functionality of the soil, the soil type, elevation, aspect and, of course, amount and type of disturbance. In general, Tahoe Basin soils have low levels of nutrients compared to many other watersheds and those low nutrient levels have resulted in the original famed Lake clarity. In undisturbed forest soils, most nutrients are bound in the soil particulate, organic and plant matter above and below the ground surface. Finer-textured soils are more readily able to adsorb or bind nutrients and make them available for plant use. Further, in forested settings, high carbon soil organic matter tends to result in a slow nutrient cycling (or turnover) rate. However, because the nutrients can be particulate bound, when the particulates are mobilized following disturbance, more nutrients are transported to streams. Fire-based disturbances "liberate" a fraction of the nutrients in organic and plant matter that are then readily mobilized during subsequent runoff events. As the soil "recovers" or "heals" by rebuilding long-chain organic carbon compounds, these nutrients are gradually re-adsorbed and bound in the soil organic matter and plant tissues. Generally, disturbances that result in loss of soil hydrologic function (i.e. infiltration capacity) also result in greater nutrient losses.

When all other factors are equal, the greatest sediment and nutrient loading in forested upland areas of the Tahoe Basin is expected from bare, disturbed volcanic soils followed by bare, disturbed mixed (metamorphic/granitic/volcanic) and then granitic soils (See Figure 2). Larger particle sizes and very limited nutrient levels found in granitic soils reduces their relative overall contribution to stream and Lake sediment and nutrient loading with the exception of very disturbed granitic soil areas lacking cover and soil structure (aggregate stability). Fine sediment loadings are particularly associated with bare or nearly bare soils found in unpaved roads, some ski runs, recreation areas and utility-line (CICU) corridors in the forested uplands. Across the Basin, nutrient losses are expected to be greatest from the finer-textured volcanic soils and recently burned areas. While very limited data of nutrient loading in runoff from either soil exists, an attempt has been made to quantify sediment and fines loading from the different soil types through recent data collection and associated research completed by Grismer and Hogan (2004, 2005a & 2005b) and Grismer et al. (2007). This research has shown that the production of fine sediment (i.e. silts and clays) in runoff can be directly related to the overall erodibility of a soil in a sub-basin. Thus, quantification of sediment yield enables direct determination of the fractions of the total sediment load that are silt and clay sized particles.

Figure 2. Sub-watersheds and soil types across the Tahoe Basin.



3.0 MODELING APPROACH & METHODOLOGY

As suggested by Merritt et al. (2003), for the purposes of land management decisions based on load (sediment and nutrient) allocations in the Tahoe Basin, a semi-distributed conceptual model (LSPC, Loading Simulation Program in C++) developed by the US EPA was employed (Tetra-Tech, 2005). LSPC system components include an integrated system for GIS watershed data analysis, a watershed customizable interface for GIS-driven input configuration, a database for data storage and management, and a watershed model that can be rapidly configured and run. This watershed modeling system includes streamlined Hydrologic Simulation Program, Fortran (HSPF) algorithms for simulating hydrology, sediment, and general water quality on land as well as a simplified stream transport model. By automatically linking upstream contributions to downstream segments, LSPC overcomes difficulties experienced with large-scale watershed simulation while allowing users to freely model sub-areas within a topdown framework. Importantly from a land-allocation of sediment and nutrient loading perspective, LSPC enables users to link in-stream water quality directly to point and non-point source loads. Through use of the Microsoft Access database to manage model data and weather text files that drive the simulations, comprehensive output files by sub-basin for all land-uses, reaches, and simulated modules can be expressed on hourly or daily intervals. The Tahoe Basin LSPC model divides the 840 km^2 Basin into 184 sub-basins.

As the HSPF functions at the core of the LSPC model, we briefly review and outline use of HSPF following Merritt et al. (2003) and then consider its application in the Tahoe Basin. A basin-scale conceptual model, HSPF was developed from the 1960s Stanford Watershed Model (Crawford and Linsley, 1966) for the simulation of watershed hydrology and water quality using hydrologically pervious, or impervious homogeneous land-use segments (Walton and Hunter, 1996). In the Tahoe Basin application, delineation of sub-basins was based primarily on topography, but also took into consideration spatial variation in sources, hydrology, jurisdictional boundaries, and the location of water quality monitoring and streamflow gaging stations. The spatial division of the watersheds allowed for a more refined representation of pollutant sources and a more realistic description of hydrologic factors. The great variation in topography and land uses in the basin required that the sub-basins be small enough to minimize these averaging effects and to capture the spatial variability. The overall Basin was divided into 184 sub-basins representing 63 direct tributary inputs to the Lake with an average size of 460 ha. Areas between stream mouths that directly drain into the lake ("intervening zones") were modeled separately. Twenty land-use categories (see Figure 1, Table 1) were identified in each sub-basin. Water quantities (infiltration, interflow and runoff rates, soil moisture storage and deep percolation rates) and quality (erosion and sediment transport) are calculated for each land-use in each sub-basin. Water, sediment and chemical fluxes are then added to the stream and routed to the basin outlet. The inputs to the model include snowmelt, rainfall, evaporation, air and water temperatures, solar radiation, sediment grain-size distributions, point-source discharges, and water quality data (Cheung and Fisher, 1995) for each sub-basin. The outputs from the simulation are a temporal history of runoff, flowrates, sediment load and nutrient concentrations along with a time series of water quantity and quality at each desired outlet in the catchment. HSPF is one of the few conceptual models of watershed hydrology and water quality that explicitly integrates the simulation of land and soil contaminant runoff processes with in-stream hydraulic and sediment–chemical interactions. Modeling with HSPF relies heavily on calibration for parameterization (Walton and Hunter, 1996).

Table 1. Tahoe Basin land-use categories as used in LSPC model.

Land Use Description	**Impervious/Pervious**	**Category Name**
Water Body	Impervious	Water_Body
Single Family Residential	Pervious	Residential_SFP
	Impervious	Residential_SFI
Multi Family Residential	Pervious	Residential_MFP
	Impervious	Residential_MFI
Commercial/Institutional/ Communications/Utilities	Pervious	CICU-Pervious
	Impervious	CICU-Impervious
Transportation	Impervious	Roads_Primary
	Impervious	Roads_Secondary
	Pervious	Roads_Unpaved
Vegetated Cover/Forests	Pervious	Ski_Areas-Pervious
	Pervious	Veg_Unimpacted 1-5*
	Pervious	Veg_Recreational
	Pervious	Veg_Burned
	Pervious	Veg_Harvest
	Pervious	Veg_Turf

* This subcategory was further refined into five new subcategories based on erosion potential.

Extensive LSPC/HSPF model calibration to long-term stream monitoring data from USGS and LTIMP sites was conducted in the Tahoe Basin (Tetra-Tech, 2005) that incorporated results of studies by Simon et al. (2003). Model calibration followed a sequential, hierarchical process that began with hydrology followed by calibration of water quality related parameters. As inaccuracies in the hydrology simulation propagate into the water quality simulation, the accuracy of the hydrologic simulation has a significant impact on the accuracy of the water quality simulation. The model was calibrated using both historical stream monitoring data and locally observed stormwater runoff monitoring data. Data from 12 USGS streamflow gages and 10 LTIMP water quality gages around the perimeter of Lake Tahoe were used for model calibration (see Figure 3). Calibration included a time series comparison of daily, monthly, seasonal, and annual values, and individual storm events. Composite comparisons (e.g., average monthly streamflow values over the period of record) were also made.

Land managers and regulators in the Basin were interested in determining possible land management practices that result in possible reductions in sediment loading from the different forest land-use categories of each sub-basin and the Basin as a whole. This perspective suggested that an appropriate time-scale for assessment should be free of temporal variations that may be associated with individual storm events as well as month-to-month seasonal variations in stream loadings associated with spring snowmelt variability. Thus, average annualized flows and loading results from the calibrated LSPC model for each land-use category of each sub-basin were employed in the analyses here examining "scale" and management effects on sediment yields. Here, the focus was only on the pervious "Vegetated" and "Unpaved roads" land-use categories as they comprise the upland sediment source areas outside of the urban land-uses as described below.

- <u>Veg_Unimpacted</u>: Forested areas that have been minimally impacted in the recent past. This layer was further divided into five erosion potential categories (EP1-EP5) by Simon (2003). The five erosion potential land-uses are synthesized categories that include the effects of geology, soil type (erodibility), land-use or cover, average land slope and elevation (precipitation level). EP1 represents the lowest relative erosion potential while EP5 represents the highest relative erosion potential.

- <u>Veg_Recreational</u>: Lands that are primarily vegetated and are characterized by relatively low-intensity uses and small amounts of impervious coverage. These include the unpaved portions of campgrounds, visitor centers, and day use areas.

- <u>Veg_Ski Runs-pervious</u>: Lands within otherwise vegetated areas for which some trees have been cleared to create a run.

- <u>Veg_Burned</u>: Areas that have been subject to controlled burns and/or wildfires in the recent past.

- Veg_Harvested: Lands that have been thinned in the recent past for the purpose of forest health and defensible space (areas cleared to reduce the spread of wildfire).

- Roads_Unpaved: Unpaved USFS and California and Nevada State Park roads and recreational trails (buffered to 2- feet width, based on Basin-wide average trail width).

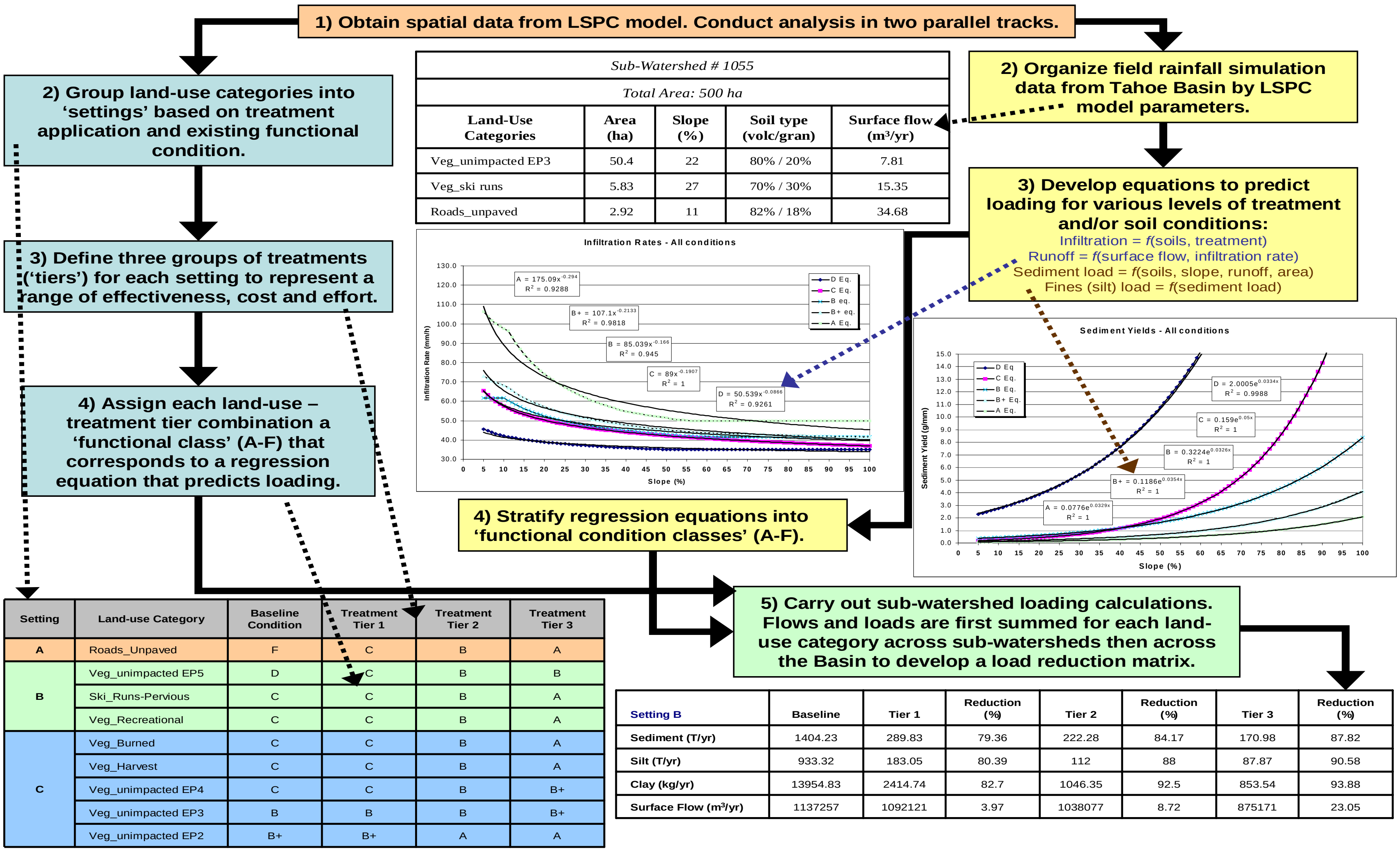
The flowchart in Figure 3 summarizes the modeling approach used to determine both the "scale" factors for each sub-basin and the load reductions possible with soil rehabilitation. Sediment yield equations developed from the erosion data obtained by from rainfall simulations (RS) across the Basin (Grismer & Hogan, 2004, 2005a, 2005b; Grismer & Ellis, 2006; Grismer et al., 2007; and Hatchett et al., 2006) are summarized in terms of soil type, soil functional class (Table 2) and baseline land-use in Table 3. These equations relate soil type, slope and land use/treatments to sediment yields and particle-size distributions in runoff on an approximately one square meter scale. The Class D regression equation resulted from RS experiments on thin, sparsely covered, highly disturbed soils associated with trails and roadcuts. Similarly, the Class C regression equation was developed from simulations on grass-covered hillslopes (primarily ski runs and road cuts) around the Basin and seemingly represents the minimum level of treatment following land disturbance. Practices such as hydroseeding with little or no follow-up treatment, non-native grass re-establishment and temporary straw covers are typically associated with this level of functional condition. The Class B regression equation includes a number of RS tested erosion control treatments that involve some effort at rehabilitating the soil that establishes a functional surface cover of grasses, forbs and mulch (such as pine needles or tub-ground wood chips). More intensive erosion control/restoration efforts aimed at restoring soil function are described by the Class A regression equation. These efforts include such practices as incorporation of coarse, organic amendments into the soil profile, soil loosening and restoration of functional surface cover including vegetation and mulch. RS tests on Class A soils often resulted in little, if any runoff and erosion.

The RS scale of measurement was not expected to capture the hillslope length associated with the sub-basin analyses conducted here, and is generally considered to result in overestimation of runoff rates and sediment loads as noted in the literature review above. Sub-basin "scale" factors were determined from optimization such that the model baseline sediment loading for each sub-basin was the same as that from the calibrated LSPC model for the upland source areas. In most sub-basins, sediment loading from each land-use category was also the same with the exception of the un-paved roads. Two different scales of soils information were considered in the analyses; (a) soil-type fractions at the sub-basin scale (e.g. 80% granitic/ 20% volcanic) applied to sediment yields from all land-uses, and (b) soil-type fractions at the land-use scale within each sub-basin. As will be discussed later, the finer spatial resolution of soil type had little effect on the "scale" factor values for all but a few sub-basins.

Table 2. Descriptions for soil functional condition classes.

Functional Class	Description
A	Fully functional forest soils – limited erodibility, high infiltration rates and sustainable soil nutrient conditions
B+	Approaching functional soil conditions as per class A; may not be sustainable, or are limited by available soils & slope.
B	Functional surface soil protection and initiation towards hydrologic functionality; long-term condition uncertain.
C	Temporary vegetative (e.g. straw) cover condition providing little erosion control, though has the appearance of cover.
D	No protective surface cover and limited infiltration capacity due in part to dispersed soil aggregates
F	Compacted bare soil conditions of highly erodible nature.

Figure 3. Schematic illustration of modeling approach to determine SGFs and treatment effects on sediment loads in each sub-basin.



Sub-Watershed # 1055				
Total Area: 500 ha				
Land-Use Categories	**Area (ha)**	**Slope (%)**	**Soil type (volc/gran)**	**Surface flow (m^3/yr)**
Veg_unimpacted EP3	50.4	22	80% / 20%	7.81
Veg_ski runs	5.83	27	70% / 30%	15.35
Roads_unpaved	2.92	11	82% / 18%	34.68

Setting	Land-use Category	Baseline Condition	Treatment Tier 1	Treatment Tier 2	Treatment Tier 3
A	Roads_Unpaved	F	C	B	A
B	Veg_unimpacted EP5	D	C	B	B
	Ski_Runs-Pervious	C	C	B	A
	Veg_Recreational	C	C	B	A
C	Veg_Burned	C	C	B	A
	Veg_Harvest	C	C	B	A
	Veg_unimpacted EP4	C	C	B	B+
	Veg_unimpacted EP3	B	B	B	B+
	Veg_unimpacted EP2	B+	B+	A	A

Setting B	Baseline	Tier 1	Reduction (%)	Tier 2	Reduction (%)	Tier 3	Reduction (%)
Sediment (T/yr)	1404.23	289.83	79.36	222.28	84.17	170.98	87.82
Silt (T/yr)	933.32	183.05	80.39	112	88	87.87	90.58
Clay (kg/yr)	13954.83	2414.74	82.7	1046.35	92.5	853.54	93.88
Surface Flow (m^3/yr)	1137257	1092121	3.97	1038077	8.72	875171	23.05

Table 3. Regression equations relating soil type and condition to sediment yields (SY in gm/mm runoff) as a function of slope (**S,** %).

Class	**Baseline Land-uses**	**Ganitics/metamorphics**	**Volcanics**
A	Rehabilitated Veg-soils	SY=0.05*exp(0.034**S**)	SY=0.105*exp(0.0323**S**)
B	Rehabilitated Veg-soils	SY=0.061*exp(0.041**S**)	SY=0.18*exp(0.0324**S**)
C	Veg-Recreation, Skiruns, Burned, Harvested	SY=0.279*exp(0.0326**S**)	SY=0.76*exp(0.033**S**)
D	CICU-pervious	SY=0.366*exp(0.0326**S**)	SY=2.006*exp(0.0334**S**)
F	Unpaved-roads	SY=1.75*exp(0.033**S**)	SY=5.0*exp(0.033**S**)
Veg-Unimpacted		**Soil type incorporated into land-use**	
A	EP1	SY=0.0776*exp(0.0329**S**)	
B+	EP2	SY=0.1186*exp(0.0354**S**)	
B	EP3	SY=0.3224*exp(0.0326**S**)	
C	EP4	SY=0.76*exp(0.033**S**)	
D	EP5	SY=2.001*exp(0.0334**S**)	

Grismer and others also developed data sets relating SY to particle-size distribution parameters such as the less-than-30% particle-size (D_{30}), silt and clay fractions (%) of the sediment in the runoff. D_{30} is a widely-used particle-size parameter in engineering analyses of soil hydraulic conductivity and stability. For example, Figure illustrates the dependence of the D_{10} and D_{30} particle-sizes on SY for runoff from volcanic soils. The regressions for inverse particle-size as a function of SY are generally quite good and highly significant (>99%). Note that they are independent of treatment; that is a function of soil type only. Similarly, the silt fraction (%) of the runoff sediment is directly correlated to the D_{30} particle-size as shown in Figure . Again, the regressions for inverse silt or clay fraction as a function of D_{30} are generally quite good and highly significant (>99%). However, note that here they are independent of both treatment and soil type and are function of particle-size distribution only. This observation simplifies estimation of silt and clay fractions in runoff from any of the soil types found in the Basin.

Figure 4. Dependence of D_{10} and D_{30} particle-sizes on SY for runoff from volcanic soils.

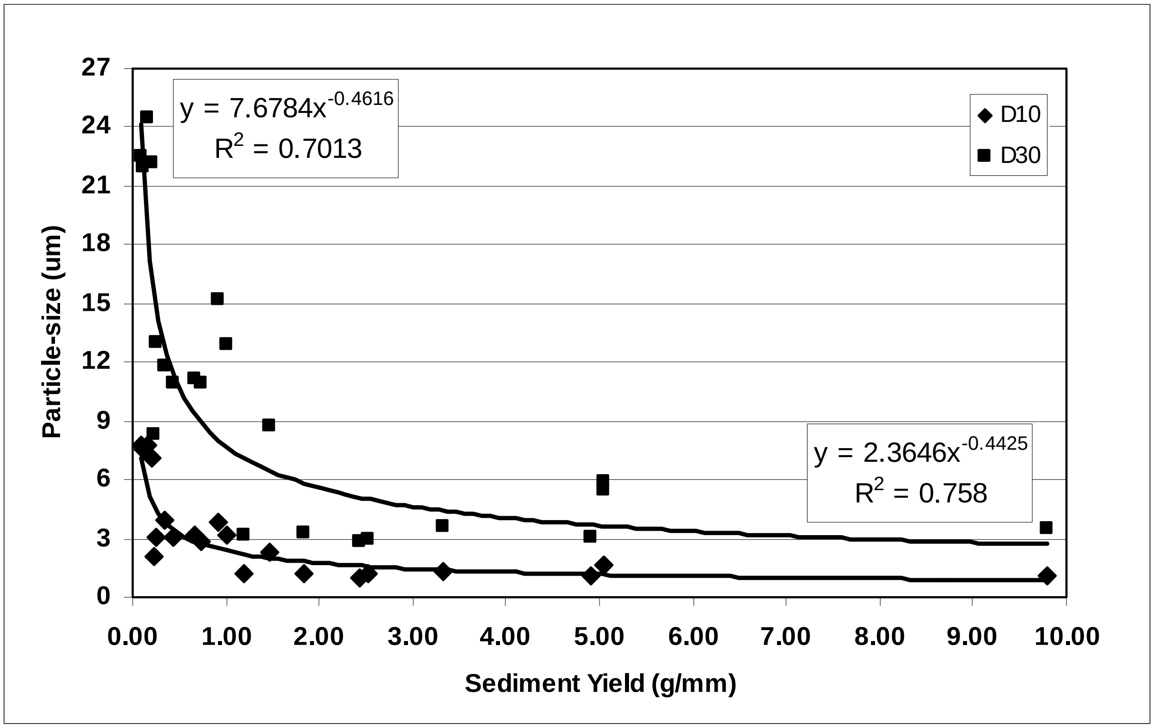
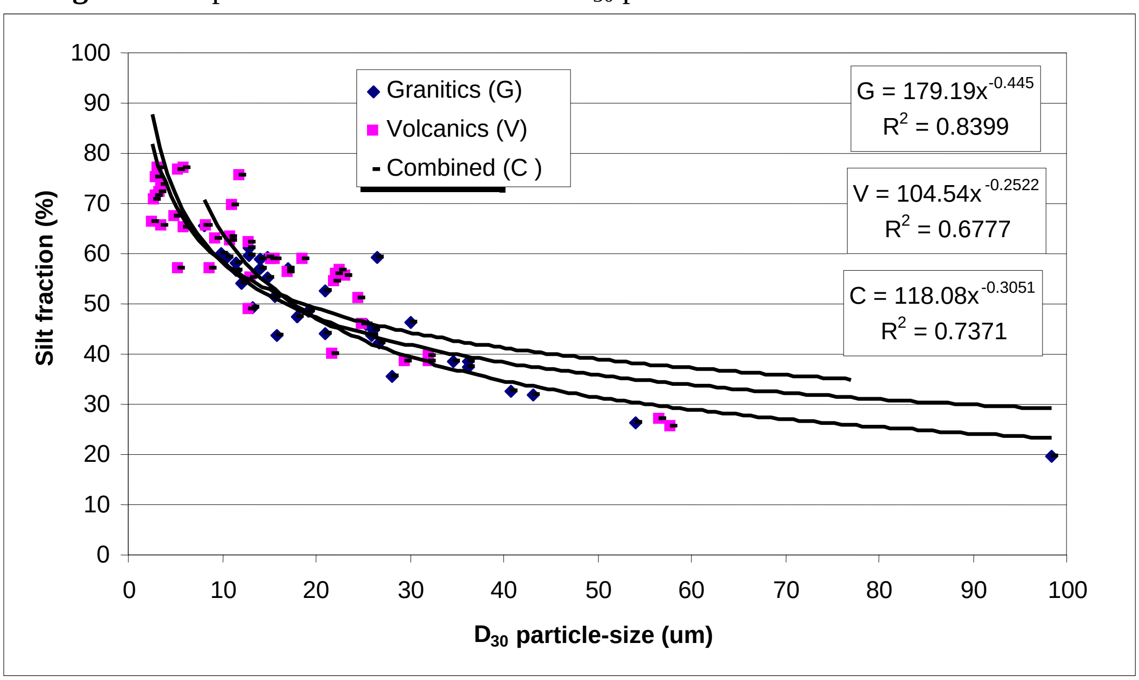


Figure 5. Dependence of silt fraction on D_{30} particle-size for runoff from all soils.



4.0 RESULTS & DISCUSSION

Analysis of the scaling, or soils-geology factor (SGF) variation across the Basin is considered first followed by a summary discussion of the possible sediment load reductions associated with soil rehabilitation efforts. Table A.1 (see Appdx) summarizes the sub-basin areas, soil type and SGFs for all 184 watersheds as organized by sub-basin number (see Fig. 2). In an effort to assess the sensitivity of SGF values on soil-type area resolution, the initial modeling efforts employed soil type resolution at the sub-basin scale rather than the land-use scale; that is, the granitic soil fraction for the sub-basin as a whole was applied to each land-use category within the sub-basin. Increasing the soil type resolution to the land-use category scale, in some cases at a spatial scale of less than one hectare, resulted in only minor, insignificant changes to the SGFs across the Basin. Figure 6 illustrates the frequency distribution of % changes in the SGF values when increasing spatial resolution with respect to the soil-type information. No change in SGF values occurred in 113 sub-basins and changes of less than +/- 1.0 % occurred in 177 of the sub-basins. There was net positive skew of %changes towards slightly positive values with an overall mean %change of 0.08% and standard deviation of 1.38%. With the exception of a 17.2% change in SGF for one small sub-basin, the remaining changes were practically insignificant. Nonetheless, the following discussion considers the SGF values from the finer-scale resolution of soil type information.

Similar to Amore and others as discussed above, no dependence of SGF on sub-basin forest area was found and only slight, but not significant dependence of SGF on volcanic soil fraction was found. A few outliers, or exceedingly large SGFs>4 were found for very small areas less than a few hectares. Rather, SGF values tended to group around the same values for adjacent sub-basins with similar granitic soil fractions. Not surprisingly, the very small sediment loadings associated with the granitic sub-basins on the east side of the Lake resulted in greater variability in SGFs as compared to those sub-basins on generally the north and west sides of the Lake having some volcanic fraction.

Closer inspection of the scatter of SGF values revealed that they tended to decrease at volcanic soil fractions of greater than about 5%. Weighting the SGF values by forest areas of sub-basins with >96% granitic (n=102) and <96% granitic (n=82) soil fractions resulted in SGF frequency distributions that followed similar patterns, but with weighted SGFs that differed by an order of magnitude. Though the numbers of sub-basins in each group differ by 20%, the total land areas modeled in each group are similar and differ by only ~2%. These frequency distributions are shown in Figure 7 and their basic statistics are provided in Table 4. The median/mean ratios and the coefficients of variation between the two distributions are nearly the same, while the area-weighted SGFs differ by nine times. From a modeling perspective and use of the RS plot-scale information, the one m^2 runoff and erosion rates are approximately 22 and 2.5 times greater, respectively for the very low, and more erodible soils. These values are within the range of other scaling adjustments such as the SDRs described above.

Table 4. Summary of weighted SGF frequency distribution statistics.

Statistic	**Granitics >96%**	**Granitics <96%**
No. of sub-basins	102	82
Modeled area (ha)	36 237	36 984
Mean	0.00044	0.00499
Median	0.00029	0.00357
Median/Mean	0.65	0.71
Std. Deviation	0.00044	0.00497
Coeff. Variation (%)	98.23	99.64
Weighted mean SGF	0.045	0.404

Figure 6. Frequency distribution of % changes in SGFs for all sub-basins when improving soil-type spatial resolution in the modeling.

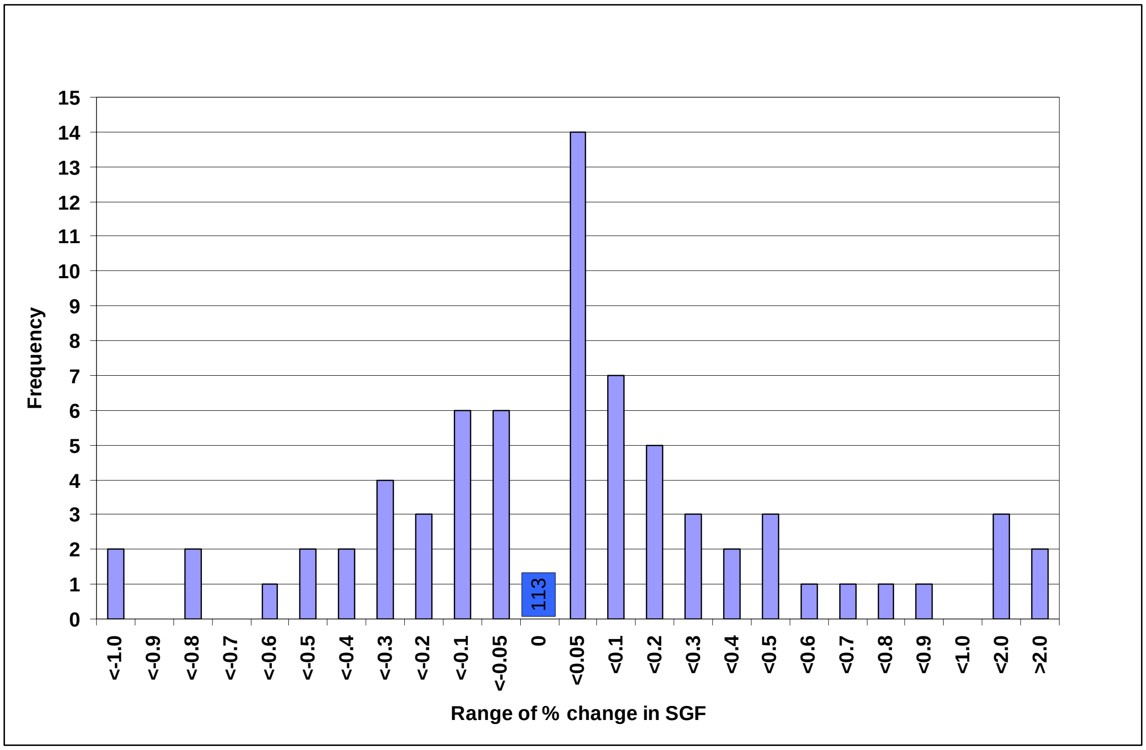
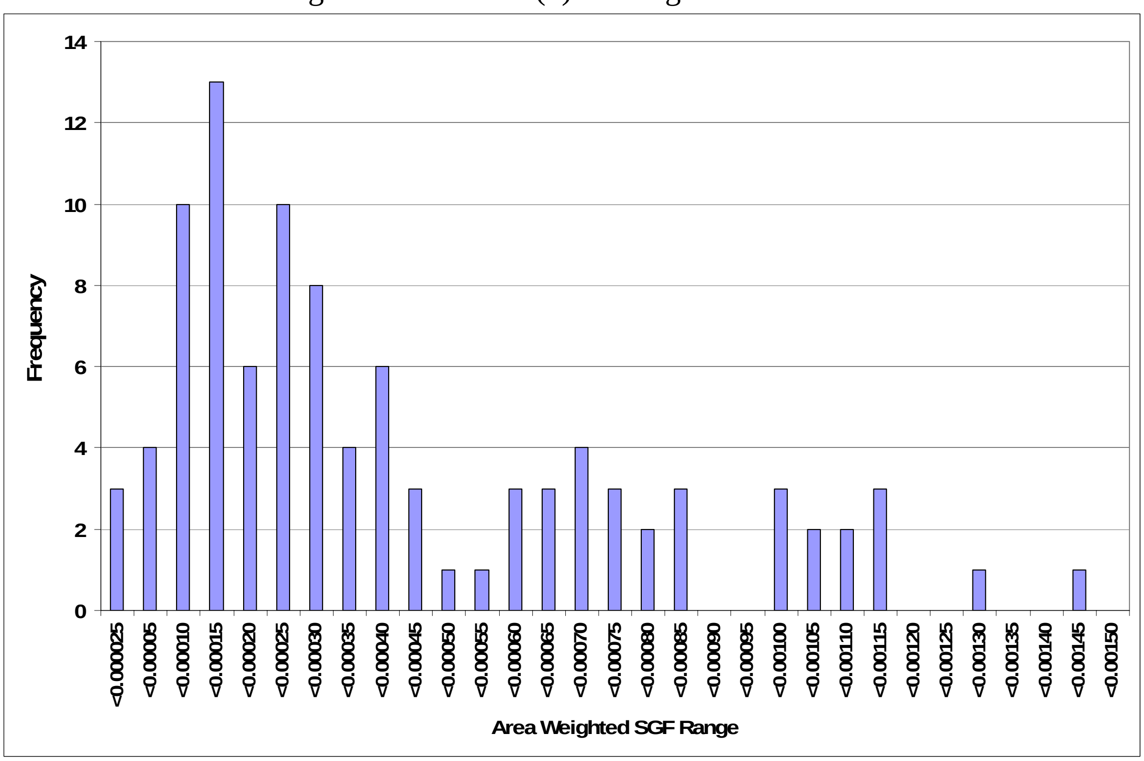
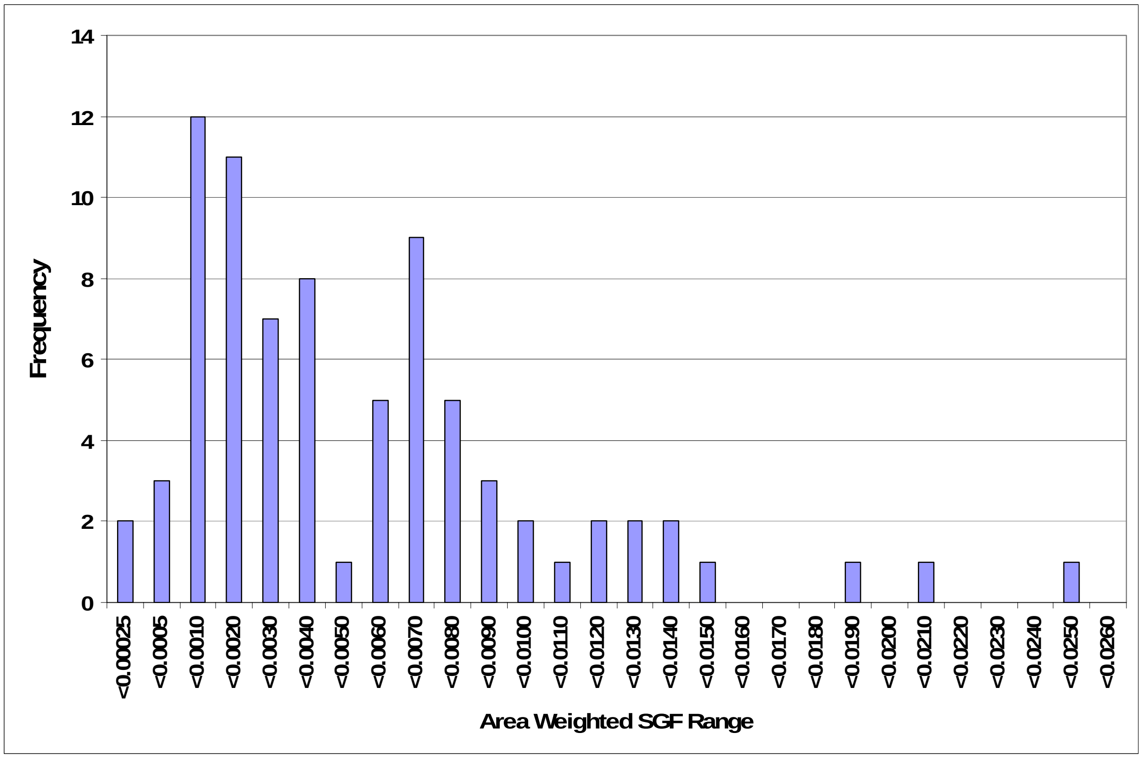


Figure 7. Area-weighted frequency distributions for SGFs in sub-basins with (a) >96% granitic soils and (b) <96% granitic soils.



(a)



(b)

Table summarizes the load reduction estimates for the primarily granitic soil based 122 sub-basins of the Lake's east side, largely located in Nevada (sub-basins 1000 – 5079), **Error! Reference source not found.** summarizes that for the 62 remaining mixed volcanic soil-type sub-basins of the Lake's west side, primarily located in California, and finally **Error! Reference source not found.** provides the overall load reduction matrix for the Tahoe Basin as a whole. The largest sub-basins that cross state lines of significance are those of the Trout and Truckee River systems on the Lake's south shore (sub-watersheds 5XXX) that have been included in the east side summary table (

Table).

Modeling results summarized in Tables 5 - 7 indicate that substantial sediment and fines load reductions of greater than 80% are possible at the first treatment tier; exceeding 90% reductions at the third treatment tier. While such reductions seem quite large, they stem from a combination of progressively greater soil cover, runoff diversions and retention for roads, and increased infiltration rates in disturbed soils. The soil restoration methods investigated by Grismer and others and upon which the runoff and erosion equations employed here are based have not been in common use in the Basin until the past few years. They represent the current state of knowledge related to soil restoration with respect to erosion control. For example, traditional straw and simple temporary or hydro-seeding type covers result in some erosion control but not at the levels found here with soil-based restoration efforts, which including soil tilling and incorporation of coarse organic materials. Not surprisingly, the greatest load reductions possible on both per area and total bases are those associated with unpaved roads followed by highly erodible, steep, high elevation soils. Predicted reductions in sediment and fines loading from unpaved roads are quite dramatic, approaching 99%. This is a result of the extremely high baseline loading from unpaved roads associated with bare soils and poor infiltration capacity. Such a nearly complete loading reduction is not likely unless the road is completely removed/obliterated and the soil functionality restored. It is important to underscore here that computation of these large reductions are based on the extensive rainfall simulation studies conducted across the Basin during the past four years. In many cases in these studies, some disturbed soil restoration treatments result in little, or no runoff such that there are sediment yield values of zero. These zero runoff plots were not included in the development of the erosion equations used here, resulting in an equation bias towards those plots yielding runoff. In addition, results from the small plot scale employed in the rainfall simulation studies are expected to dramatically over-estimate actual runoff and erosion rates at the sub-watershed scale as a result of variations in topography and soil conditions across the landscape. In the FUSCG modeling here, this was indeed the case, particularly for the east side granitic sub-watersheds in which the SGFs were approximately 0.05. On the other hand, this factor for the west side volcanic sub-watersheds were roughly 0.4. In either case, the sediment and fines load reductions suggested here are indeed possible and have been demonstrated in field studies; their implementation and effects at the sub-watershed scale remain to be seen.

Sediment and fines loadings from the east shore granitic sub-watersheds are a small fraction of that from the remaining sub-watersheds on the west and north shores of California, despite covering half again the total Basin area. For example, the combined sediment and silt loads from Settings A & B in 122 east shore sub-watersheds of 63 (sediment) and 44 (silt) tonnes/year are less than 4.8% of that generated from the remaining 62 sub-watersheds and less than 3.6% of the overall Basin loads. Soil treatments that result in improved infiltration rates can dramatically affect surface runoff rates, especially from very disturbed or highly erodible soils (e.g. unpaved roads, EP5) and is reflected in decreased surface flows of 20-50% at the full soil restoration level (Tier 3). It is expected that this translation of surface to subsurface flows will result in greater and more sustained stream base flows and some deeper groundwater recharge, but will have little effect on the overall sub-watershed annual total discharge. However, higher base flows and decreased peak flows in the sub-watershed stream channels should allow for more efficient stabilization of the channels as part of stream restoration efforts. This aspect is very important towards assessing the overall benefits of upland soils restoration.

Table 5. Load reduction summary for Settings A and B in sub-basins 1000 – 5079, roughly approximating the east side of Lake Tahoe.

Setting	Baseline	Tier 1	Tier 2	Tier 3
A & B – Disturbed Soils (370.2 ha)				
Sediment (T/yr)	63.05	9.49	9.21	6.10
Silt (T/yr)	44.00	7.03	4.62	3.33
Clay (kg/yr)	840.6	130.8	51.05	42.23
Surface Flow (m^3/yr)	135 290	127 441	127 072	89 104
C – Forested uplands (38 414.6 ha)				
Sediment (T/yr)	1911	1911	1232	473.7
Silt (T/yr)	1078	1078	603.2	201.6
Clay (kg/yr)	13 283	13 283	5896	1561
Surface Flow (m^3/yr)	12 140 727	12 140 727	12 110 435	9 786 518

Table 6. Load reduction summary for Settings A and B in sub-basins 6000 – 9060, roughly approximating the west side of Lake Tahoe.

Setting	Baseline	Tier 1	Tier 2	Tier 3
A & B – Disturbed Soils (539.9 ha)				
Sediment (T/yr)	1727	324.5	222.8	169.8
Silt (T/yr)	1172	200.8	111.8	86.6
Clay (kg/yr)	18 034	2559	1030	825.8
Surface Flow (m^3/yr)	1 144 047	1 068 223	1 010 271	860 577
C – Forested uplands (29 210.8 ha)				
Sediment (T/yr)	7630	7630	4724	1771
Silt (T/yr)	4248	4248	2336	767.0
Clay (kg/yr)	47 731	47 731	21 493	5648
Surface Flow (m^3/yr)	31 064 382	31 064 382	30 892 097	26 448 939

Table 7. Lake Tahoe Basin-wide load reduction summary for Settings A, B and C.

Setting	Baseline	Tier 1	Tier 2	Tier 3
A & B – A & B – Disturbed Soils (910.1 ha)				
Sediment (T/yr)	1790	334.0	232.0	175.9
Silt (T/yr)	1216	207.8	116.4	89.96
Clay (kg/yr)	18875	2690	1081	868.0

Surface Flow (m^3/yr)	1 279 337	1 195 665	1 137 343	949 680
C – Forested uplands (67 625.4 ha)				
Sediment (T/yr)	9541	9541	5955	2245
Silt (T/yr)	5325	5325	2939	968.6
Clay (kg/yr)	61 014	61 014	27 390	7209
Surface Flow (m^3/yr)	43 205 109	43 205 109	43002532	36235457

From a practical perspective, estimates of loading per unit land area and setting may be valuable in efficiently allocating of resources for possible treatment across the Basin. Table summarizes the loading rates per acre for each setting-treatment tier combination across the Basin. Loading rates are greatest from the land-uses comprising Setting B, as it includes both steeply sloping ski runs and the difficult-to-remediate EP5 category. It should be noted that in this modeling of sediment loading, sediment and fines loading from EP5 were consistently greater than those estimated from the LSPC model by an average of almost 52% across the Basin. This discrepancy between model results was the greatest of any of the land-use categories. Similarly, this modeling of loading from unpaved roads was consistently less than that predicted by the LSPC model by an average of ~29%. As such, the average loading per hectare is greater from Setting B as compared to those from Settings A or C due to much smaller slopes and differences between modeling results.

Table 8. Basin-wide sediment and fines loading per hectare for each setting-treatment tier combination.

Setting – Loading	**Baseline**	**Tier 1**	**Tier 2**	**Tier 3**
Setting A – 129.2 ha				
Sediment (kg/ha/yr)	517	59.1	12.98	6.58
Silt (kg/ha/yr)	378	33.1	5.90	2.78
Clay (kg/ha/yr)	6.58	0.37	0.05	0.02
Setting B – 780.8 ha				
Sediment (kg/ha/yr)	311	64.2	49.2	37.9
Silt (kg/ha/yr)	207	40.5	24.8	19.5

Clay (kg/ha/yr)	3.09	0.54	0.23	0.19
Setting C – 67 625 ha				
Sediment (kg/ha/yr)	24.4	24.4	15.2	5.74
Silt (kg/ha/yr)	13.6	13.6	7.51	2.48
Clay (kg/ha/yr)	0.16	0.16	0.07	0.02

In formulating management strategies directed at reducing loading to the Lake, restoration efforts that achieve the greatest reduction in loads per unit land area may be the most appealing with limited capital available. Table 9**Error! Reference source not found.** summarizes sediment and fines loading reductions per hectare associated with taking the baseline (existing or LSPC land-use conditions) and improving the soils to Tier 1 and Tier 3 treatment levels. Reductions in nutrient loading were not considered as the relative confidence in the treatment effects on these loadings is quite low. It is evident that the incremental improvement in loading reductions associated with full soil restoration (Tier 3) as compared to surface-cover type treatments (Tier 1) is relatively small for Settings A & B. However, the goals of full soil restoration include long-term sustainability whereas surface treatments typically require ongoing, repeated treatments. Similarly, tremendous sediment loading reductions per acre appear possible in the CA sub-watersheds as compared to the NV sub-watersheds.

Table 9. Comparison of annual sediment loading reduction per ha in taking baseline soil conditions in Settings A & B to the minimum (Tier 1) and maximum (Tier 3) treatment levels for the east side and west side sub-basins and the Tahoe Basin as a whole.

Sub-Basin Grouping	**East side (1000-5079)**		**West side (6000-9060)**		**Basin**	
Loading Parameters	**Baseline to Tier 1**	**Baseline to Tier 3**	**Baseline to Tier 1**	**Baseline to Tier 3**	**Baseline to Tier 1**	**Baseline to Tier 3**
Sediment (kg/ha/yr)	25.0	26.6	449	499	277	307
Silt (kg/ha/yr)	17.3	19.0	311	348	192	214
Clay (kg/ha/yr)	0.33	0.37	4.95	5.53	3.08	3.42

The forested setting (C) is the largest land-use category in the Tahoe Basin. In many cases, the forested soils are in a state of reasonably high hydrologic function as compared to those of the other two settings, which have far greater soil disturbance. Forest management practices associated with logging and fuels reduction in the Tahoe Basin have relatively low impacts on watershed soils. Ground-based, mechanized logging has been limited in USFS and CTC lands to relatively low gradient (slope) areas, which have deep soils with high infiltration capacities. The USFS relies primarily on cut-to-length (CTL) harvesting systems and hand crews for logging/thinning in the vast majority of the Tahoe Basin. The CTL system has relatively low ground pressure, minimal landing footprints and operates over a slash mat, which further buffers the soil for disturbance. Conventional logging ("skidding") is limited to only the most accessible, low-slope, resilient areas, as the impacts of this system can be far greater than CTL systems. Unfortunately, there is very little quantified information available on the effects of different harvesting systems and fuels reduction treatments on soil function, particularly in the Tahoe Basin. While some equipment may compact soils and reduce infiltration capacities, modern wide track crawlers and rubber-tire equipment appear to have minimal effects on soil function. For example, well-supervised mastication treatments that employ the excavator-type equipment may result in some soil improvements associated with addition of mulch layers to the soil surface, despite limited track compaction of some soil during the operation (Hatchett et al. 2006).

5.0 CONCLUSIONS

The modeling effort completed here as part of the TMDL assessment for the Tahoe Basin provided considerable insight into where the greatest erosion potential may occur, the relative levels of sediment and nutrient load reduction possible and general corroboration of the LSPC modeling effort conducted at the sub-basin scale. Results of rainfall simulations across the Basin were useful in developing soil, slope and treatment dependent loading equations that appeared easily “scaled” up to the sub-basin scale. While there was no spatial area dependence of the “scaling” factor, SGF, across the range of less than one to several hundreds of hectares, a soil type dependence was apparent. Rainfall simulation runoff and erosion rates at the one square meter scale were about 22 times greater on average than that from the granitic sub-basins with very small erosion rates, while only about 2.5 times greater on average that that from the volcanic/granitic mixed soil sub-basins. The greatest load reductions are largely associated with disturbed soils of volcanic origin on the California side of the Lake. While some load reduction is possible from the forested soils, the potential reductions per unit land area are much greater with the more disturbed soils associated with unpaved roads, recreational and ski run areas. Further modeling analyses are required at a finer resolution with greater hydrologic routing detail to determine possible load reductions at particular locations, however, this analysis gives a rough “first-cut” assessment of what levels of load reduction may be possible across the Basin. Refined scale modeling efforts will require quantitative data about erosion processes linked to various land management practices that does not currently exist. On the other hand, large-scale application of some restoration efforts may result in development of scale-appropriate technologies that reduce the treatment costs per unit area from those estimated here. Finally, fire effects on soils, runoff and erosion in the Basin is a topic that requires additional research and analyses beyond those considered here, though the analysis framework developed here could be applied to a fire analysis as well. Overall, the combination of local-scale measurements and distributed modeling appears to have worked well in developing information for regulatory agencies for determination of possible stream loadings to be expected in the Basin from various land management strategies.

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Table A.1. Summary of sub-basin soil types, areas and SGF values for Tahoe Basin.

Sub-basin No.	Tributary	Volc. Fraction	Gran. Fraction	Area (ha)	Forest Area (ha)	SGF
Basin	**Lake Tahoe**	0.174	0.826	82904.6	73221.7	NA
1000	IVZ 1000	0.881	0.119	519.8	147.1	3.674
1010	Mill Creek	0.121	0.879	520.3	388.4	0.591
1020	Incline Creek	0.997	0.003	7.4	0.3	7.500
1021	Incline Creek	0.973	0.027	232.7	138.4	2.454
1022	Incline Creek	0.607	0.393	298.5	220.5	1.851
1023	Incline Creek	0.371	0.629	352.3	224.6	2.051
1024	Incline Creek	0.214	0.786	136.3	133.6	0.916
1025	Incline Creek	0.000	1.000	208.2	208.2	0.192
1026	Incline Creek	0.000	1.000	115.9	115.9	0.194
1027	Incline Creek	0.076	0.924	434.9	434.9	0.474
1030	Third Creek	0.985	0.015	16.4	0.6	7.380
1031	Third Creek	0.785	0.215	227.2	103.7	2.543
1032	Third Creek	0.639	0.361	215.4	87.6	1.507
1033	Third Creek	0.324	0.676	210.2	209.8	0.105
1034	Third Creek	0.161	0.839	366.0	351.8	0.646
1035	Third Creek	0.250	0.750	570.5	570.0	0.508
1040	Wood Creek	0.977	0.023	76.3	16.5	6.138
1041	Wood Creek	0.413	0.587	267.0	244.1	0.788
1042	Wood Creek	0.392	0.608	181.0	181.0	0.119
1050	Burnt Cedar Creek	0.944	0.056	76.1	21.4	2.458
1060	Second Creek	0.630	0.370	364.2	329.4	0.679
1070	First Creek	0.600	0.400	463.8	446.0	0.989
2000	IVZ 2000	0.045	0.955	1191.3	1119.8	0.106
2010	Slaughter House	0.000	1.000	466.9	446.4	0.014
2011	Slaughter House	0.231	0.769	829.3	787.0	0.088
2020	Bliss Creek	0.000	1.000	145.4	143.5	0.245
2030	Secret Harbor Creek	0.000	1.000	72.2	70.9	0.180
2031	Secret Harbor Creek	0.000	1.000	299.6	299.6	0.133
2032	Secret Harbor Creek	0.000	1.000	160.9	160.8	0.258
2033	Secret Harbor Creek	0.109	0.891	402.2	402.2	0.121
2040	Marlette Creek	0.000	1.000	539.4	533.1	0.112
2041	Marlette Creek	0.252	0.748	767.8	621.0	0.161
2050	Bonpland	0.003	0.997	234.7	234.6	0.116
2060	Tunnel Creek	0.000	1.000	337.6	337.5	0.164
3000	IVZ 3000	0.218	0.782	1160.0	753.6	0.051
3010	Mcfaul Creek	0.000	1.000	122.6	19.0	0.011
3011	Mcfaul Creek	0.000	1.000	319.0	309.3	0.010
3012	Mcfaul Creek	0.000	1.000	358.5	358.5	0.011
3013	Mcfaul Creek	0.000	1.000	159.2	206.7	0.010
3020	Zephyr Creek	0.000	1.000	445.2	436.3	0.017
3030	North Zephyr Creek	0.000	1.000	20.5	13.7	0.015
3031	North Zephyr Creek	0.000	1.000	275.4	275.4	0.010
3032	North Zephyr Creek	0.000	1.000	127.3	126.6	0.011
3033	North Zephyr Creek	0.000	1.000	273.5	273.5	0.010
3040	Lincoln Creek	0.000	1.000	128.4	124.3	0.010
3041	Lincoln Creek	0.377	0.623	315.2	315.2	0.075
3042	Lincoln Creek	0.008	0.992	241.7	241.7	0.010
3050	Cave Rock	0.000	1.000	186.8	176.9	0.007

3060	Logan House Creek	0.000	1.000	19.9	14.0	0.007
3061	Logan House Creek	0.488	0.512	407.2	407.2	0.085
3062	Logan House Creek	0.734	0.266	146.5	146.5	0.054
3070	N. Logan House Creek	0.241	0.759	290.5	290.1	0.079
3080	Glenbrook Creek	0.657	0.343	237.9	195.4	0.115
3081	Glenbrook Creek	0.718	0.282	175.3	175.0	0.143
3082	Glenbrook Creek	0.762	0.238	407.4	402.5	0.135
3083	Glenbrook Creek	0.531	0.469	272.0	272.0	0.150
4000	IVZ 4000	0.000	1.000	978.4	529.8	0.038
4010	Bijou Creek	0.000	1.000	590.8	371.6	0.035
4020	Edgewood Creek	0.000	1.000	403.8	192.5	0.060
4021	Edgewood Creek	0.000	1.000	199.3	199.3	0.051
4022	Edgewood Creek	0.000	1.000	342.9	321.7	0.034
4023	Edgewood Creek	0.000	1.000	462.0	398.6	0.073
4024	Edgewood Creek	0.000	1.000	369.3	255.0	0.064
4030	Burke Creek	0.000	1.000	584.5	409.4	0.018
4031	Burke Creek	0.000	1.000	227.1	173.6	0.022
4032	Burke Creek	0.000	1.000	260.1	243.5	0.022
4033	Burke Creek	0.000	1.000	164.6	163.3	0.020
5000	IVZ 5000	0.021	0.979	1098.5	738.9	0.069
5010	Upper Truckee River	0.013	0.987	878.7	481.2	0.054
5011	Upper Truckee River	0.000	1.000	1253.2	830.1	0.042
5012	Upper Truckee River	0.009	0.991	1017.8	870.2	0.046
5013	Upper Truckee River	0.000	1.000	504.3	485.0	0.027
5014	Upper Truckee River	0.000	1.000	328.6	191.8	0.045
5015	Upper Truckee River	0.000	1.000	516.6	463.6	0.026
5016	Upper Truckee River	0.000	1.000	113.1	91.7	0.049
5017	Upper Truckee River	0.000	1.000	171.7	154.7	0.026
5018	Upper Truckee River	0.000	1.000	723.5	556.3	0.028
5019	Upper Truckee River	0.000	1.000	568.0	550.5	0.036
5020	Upper Truckee River	0.044	0.956	936.4	828.3	0.028
5021	Upper Truckee River	0.046	0.954	734.9	640.2	0.021
5022	Upper Truckee River	0.067	0.933	398.8	395.2	0.071
5023	Upper Truckee River	0.057	0.943	1113.3	1106.6	0.076
5024	Upper Truckee River	0.111	0.889	903.6	903.5	0.097
5025	Upper Truckee River	0.617	0.383	644.7	644.7	0.510
5026	Upper Truckee River	0.912	0.088	370.9	370.9	0.503
5027	Upper Truckee River	0.180	0.820	412.1	412.1	0.079
5028	Upper Truckee River	0.795	0.205	391.3	391.3	0.351
5029	Upper Truckee River	0.000	1.000	497.5	492.0	0.033
5030	Upper Truckee River	0.683	0.317	533.0	533.0	0.499
5031	Upper Truckee River	0.000	1.000	351.5	350.9	0.029
5032	Upper Truckee River	0.000	1.000	896.6	891.6	0.034
5033	Upper Truckee River	0.020	0.980	792.4	783.7	0.046
5050	Trout Creek	0.000	1.000	421.3	186.0	0.070
5051	Trout Creek	0.000	1.000	283.4	243.8	0.026
5052	Trout Creek	0.000	1.000	515.6	515.0	0.041
5053	Trout Creek	0.000	1.000	151.9	64.0	0.040
5054	Trout Creek	0.000	1.000	893.1	811.3	0.029
5055	Trout Creek	0.000	1.000	967.3	890.1	0.029
5056	Trout Creek	0.000	1.000	417.5	416.3	0.022
5057	Trout Creek	0.000	1.000	829.9	829.9	0.030
5058	Trout Creek	0.000	1.000	160.4	160.4	0.034

5059	Trout Creek	0.000	1.000	476.5	476.5	0.019
5060	Trout Creek	0.000	1.000	116.6	116.6	0.021
5061	Trout Creek	0.000	1.000	183.3	183.3	0.025
5062	Trout Creek	0.000	1.000	192.8	192.6	0.022
5063	Trout Creek	0.000	1.000	95.3	95.3	0.024
5064	Trout Creek	0.000	1.000	324.5	323.4	0.027
5065	Trout Creek	0.000	1.000	197.3	196.9	0.026
5066	Trout Creek	0.014	0.986	284.0	283.6	0.030
5067	Trout Creek	0.000	1.000	398.7	398.7	0.020
5068	Trout Creek	0.000	1.000	322.1	322.1	0.015
5069	Trout Creek	0.000	1.000	351.4	351.4	0.020
5070	Trout Creek	0.000	1.000	401.4	315.0	0.029
5071	Trout Creek	0.000	1.000	167.3	167.3	0.021
5072	Trout Creek	0.000	1.000	253.5	253.5	0.023
5073	Trout Creek	0.000	1.000	229.9	229.9	0.018
5074	Trout Creek	0.000	1.000	344.3	344.3	0.073
5075	Trout Creek	0.000	1.000	390.2	390.2	0.028
5076	Trout Creek	0.000	1.000	613.4	613.4	0.022
5077	Trout Creek	0.000	1.000	26.9	26.9	0.290
5078	Trout Creek	0.000	1.000	395.5	386.9	0.021
5079	Trout Creek	0.007	0.993	577.3	576.2	0.020
6000	IVZ 6000	0.001	0.999	701.7	672.8	0.043
6001	IVZ 6001	0.000	1.000	271.0	155.5	0.054
6010	General Creek	0.000	1.000	837.2	831.8	0.056
6011	General Creek	0.000	1.000	470.2	470.2	0.046
6012	General Creek	0.000	1.000	723.5	723.6	0.054
6020	Meeks	0.000	1.000	494.6	473.5	0.053
6021	Meeks	0.000	1.000	880.2	880.2	0.043
6022	Meeks	0.000	1.000	307.3	304.9	0.035
6023	Meeks	0.000	1.000	514.9	487.7	0.037
6030	Sierra Creek	0.000	1.000	236.3	220.6	0.043
6040	Lonely Gulch Creek	0.000	1.000	286.1	265.2	0.044
6050	Paradise Flat	0.000	1.000	165.6	156.2	0.038
6060	Rubicon Creek	0.000	1.000	759.6	718.5	0.036
6080	Eagle Creek	0.010	0.990	57.3	56.5	0.022
6081	Eagle Creek	0.018	0.982	1018.3	993.4	0.037
6082	Eagle Creek	0.216	0.784	730.6	700.3	0.046
6090	Cascade Creek	0.000	1.000	256.3	161.2	0.025
6091	Cascade Creek	0.000	1.000	285.0	284.6	0.015
6092	Cascade Creek	0.250	0.750	643.3	622.4	0.018
6100	Tallac Creek	0.000	1.000	370.5	366.7	0.062
6101	Tallac Creek	0.455	0.545	534.8	531.7	0.080
6110	Taylor Creek	0.000	1.000	472.0	460.2	0.207
6111	Taylor Creek	0.313	0.687	1546.2	868.9	0.060
6112	Taylor Creek	0.328	0.672	1171.6	1139.6	0.075
6113	Taylor Creek	0.901	0.099	494.4	461.8	0.109
6114	Taylor Creek	0.478	0.522	815.6	770.9	0.021
6115	Taylor Creek	0.994	0.006	400.6	386.2	0.013
6120	Unnamed Ck	0.000	1.000	72.1	64.2	0.062
7000	IVZ 7000	0.396	0.604	722.3	443.9	0.228
7010	Blackwood Creek	0.942	0.058	940.6	926.7	0.277
7011	Blackwood Creek	0.977	0.023	645.1	641.1	0.340
7012	Blackwood Creek	1.000	0.000	406.4	406.4	0.209

7013	Blackwood Creek	0.983	0.017	976.1	970.3	0.260
7020	Madden Creek	0.927	0.073	544.1	538.6	0.343
7030	Homewood Creek	0.890	0.110	268.1	262.0	0.535
7040	Quail Lake Creek	0.644	0.356	393.9	378.9	0.344
7050	Mkinney Creek	0.000	1.000	593.9	518.3	0.058
7051	Mkinney Creek	0.237	0.763	365.7	363.2	0.127
7052	Mkinney Creek	0.000	1.000	312.2	293.8	0.049
8000	IVZ 8000	0.952	0.048	1267.0	708.0	0.569
8010	Dollar Creek	1.000	0.000	290.4	99.0	1.048
8020	Lake Forest Crk #1	0.927	0.073	186.1	94.0	1.404
8030	Lake Forest Crk #2	0.930	0.070	269.4	219.6	1.108
8040	Burton Creek	0.950	0.050	258.5	251.8	1.291
8041	Burton Creek	1.000	0.000	248.7	248.7	0.630
8042	Burton Creek	0.964	0.036	924.7	924.4	0.966
8050	Tahoe State Park	0.999	0.001	284.6	284.8	1.111
8060	Ward Creek	0.948	0.052	475.9	435.1	0.313
8061	Ward Creek	0.925	0.075	877.1	863.8	0.311
8062	Ward Creek	0.995	0.005	392.6	384.1	0.101
8063	Ward Creek	0.995	0.005	847.8	847.8	0.270
9000	IVZ 9000	0.868	0.132	1556.6	970.2	0.707
9010	Kings Beach	1.000	0.000	119.5	91.7	0.855
9020	Griff Creek	0.900	0.100	48.9	19.3	1.405
9021	Griff Creek	1.000	0.000	374.3	371.9	0.689
9022	Griff Creek	0.985	0.015	762.2	739.9	0.685
9030	Tahoe Vista	0.929	0.071	355.5	199.4	1.183
9031	Tahoe Vista	0.998	0.002	356.3	344.0	0.985
9032	Tahoe Vista	0.995	0.005	528.2	489.7	0.978
9040	Carnelian Canyon	0.989	0.011	820.6	769.7	0.984
9050	Carnelian Bay Creek	1.000	0.000	240.6	238.9	1.102
9060	Watson	0.969	0.031	620.1	612.3	0.787