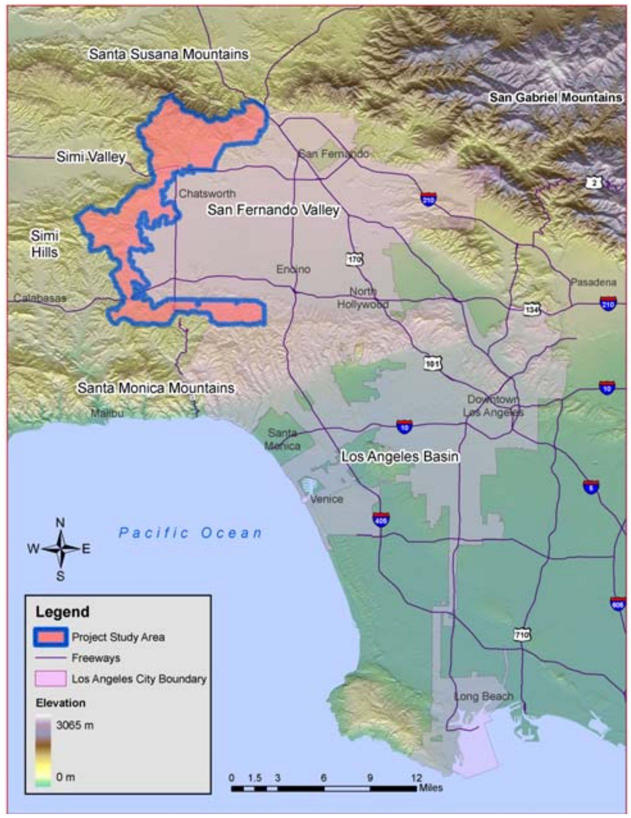
Upper Los Angeles River Area Recharge Suitability Analysis



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Executive Summary

This report describes the development of data sets and analyses conducted in order to perform a comprehensive Recharge Suitability Analysis (RSA) of a 150 square kilometer study area located at the western headwaters of the Los Angeles River, a significant source of groundwater to residents of Los Angeles, Glendale and Burbank. This study area primarily encompasses undeveloped portions of the Santa Susana Mountains, the Simi Hills, and the Santa Monica Mountains. This study was aimed at determining the most suitable areas to infiltrate water, before it becomes urban runoff with its associated pollutant loads. It is intended that the results of this research aid more sustainable watershed management of the San Fernando Basin (SFB) in order to relieve some of the pressure on distant water supply sources in the Sacramento-San Joaquin Delta, through a better understanding of the role of the natural environment within and immediately surrounding this study area.

The development of the input data sets required the preparation of a series of vector and raster GIS layers encompassing the RSA study area. This included, but is not limited to soil type and hydrologic group information, thirty years of precipitation data, and percent slope and catchment boundaries derived from a digital elevation model, which were then used to generate additional intermediate data layers such as an adjusted infiltration which takes slope, soil type and land cover imperviousness into account. This series of data was used as input into the two main parts of the RSA, a Direct Infiltration Analysis and the Flow Accumulation Analysis. The Direct Infiltration Analysis consisted of two steps, a Rainfall and Runoff Analysis, which allowed an initial examination of direct infiltration with respect to catchments. The Flow Accumulation Analysis utilized output from the Direct Infiltration Analysis as input, which proceeded in two steps, analyses of Flow Direction and Flow Accumulation. The accumulation results were also examined with respect to the average runoff which accumulates within each catchment, then combined with the results of the Direct Infiltration Analysis. The findings of the RSA include identification of groups of catchments which exhibit a high potential for recharge, based on the results of the Direct Infiltration and Flow Accumulation Analyses.

There are, however, four sets of shortcomings with the current analysis that would need to be addressed in order to use these analytical results as a basis for detailed groundwater management plan. First, higher resolution spatially distributed geospatial datasets are required to perform the evapotranspiration portion of the analysis, in order to derive catchment-based infiltration and runoff values that take evapotranspiration into account. Second, although data from bore logs and some surface water monitoring data were collected as part of this study, the data were not directly applicable to the various infiltration analyses discussed herein. Third, this study did not address current land use / land cover other than in terms of imperviousness and the resultant impact on infiltration and runoff. And fourth, return flow or recharge from artificial sources was not factored into the input flow, only precipitation.

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Introduction

Background

The San Fernando Basin (SFB) is an unconfined aquifer that underlies the San Fernando Valley, in Los Angeles, California (Figure 1). It is a significant source of groundwater used to partially supply the water needs of 600,000 residents of Los Angeles, Glendale and Burbank. As the largest of four groundwater basins connected to the Upper Los Angeles River Area (ULARA), the SFB consists of 112,000 acres with an estimated capacity of 3,200,000 acre-feet of storage space for groundwater (State Water Rights Board, 1962). Despite nearly normal or above normal rainfall in the preceding years, the 2003 ULARA Watermaster Report indicates that the groundwater levels in the SFB have been declining (ULARA Watermaster, 2005). Groundwater recharge has been reduced by urban development in the ULARA, because impervious surfaces prevent a major portion of rainfall from infiltrating into the soils. Concern over urban runoff quality and the potential impact of pollutants on groundwater quality has also increased.

At present, imported water from the Sacramento-San Joaquin Delta is used to recharge from delivered water in the SFB. There is a growing awareness that the amount of this imported resource may be reduced and likely unavailable due to environmental concerns and growing demand at the source. Because of these concerns, the California Water Resources Board has funded the Mountains Restoration Trust (MRT) to pursue this research project, seeking a greater understanding of the native water conditions in the Upper Los Angeles River catchment.

The project study area (Figure 2) designated within the headwaters of the Los Angeles River covers approximately 150 km^2, and encompasses portions of the Santa Susana Mountains, Simi Hills, and the Santa Monica Mountains. The boundaries of the study area at its highest elevation are designated by the boundary of the Los Angeles River Watershed, and at its lowest elevation by the outer limit of intensive urban development within the San Fernando Valley. The eastern edge of the study area is also bounded by other projects managed by various nonprofit and municipal agencies, such as The River Project, a watershed plan for the Tujunga Wash supported by the California State Water Resources Control Board. For a detailed description of abbreviated terminology used in this report. Please see the List of Terms at the end of the report.

Purpose

One of the primary goals of this project is to conduct a Recharge Suitability Analysis (RSA) within this portion of the ULARA. This was accomplished by determining the most suitable areas to recharge native waters, before it becomes urban runoff with its associated pollutant loads. The results of this research will ultimately assist in

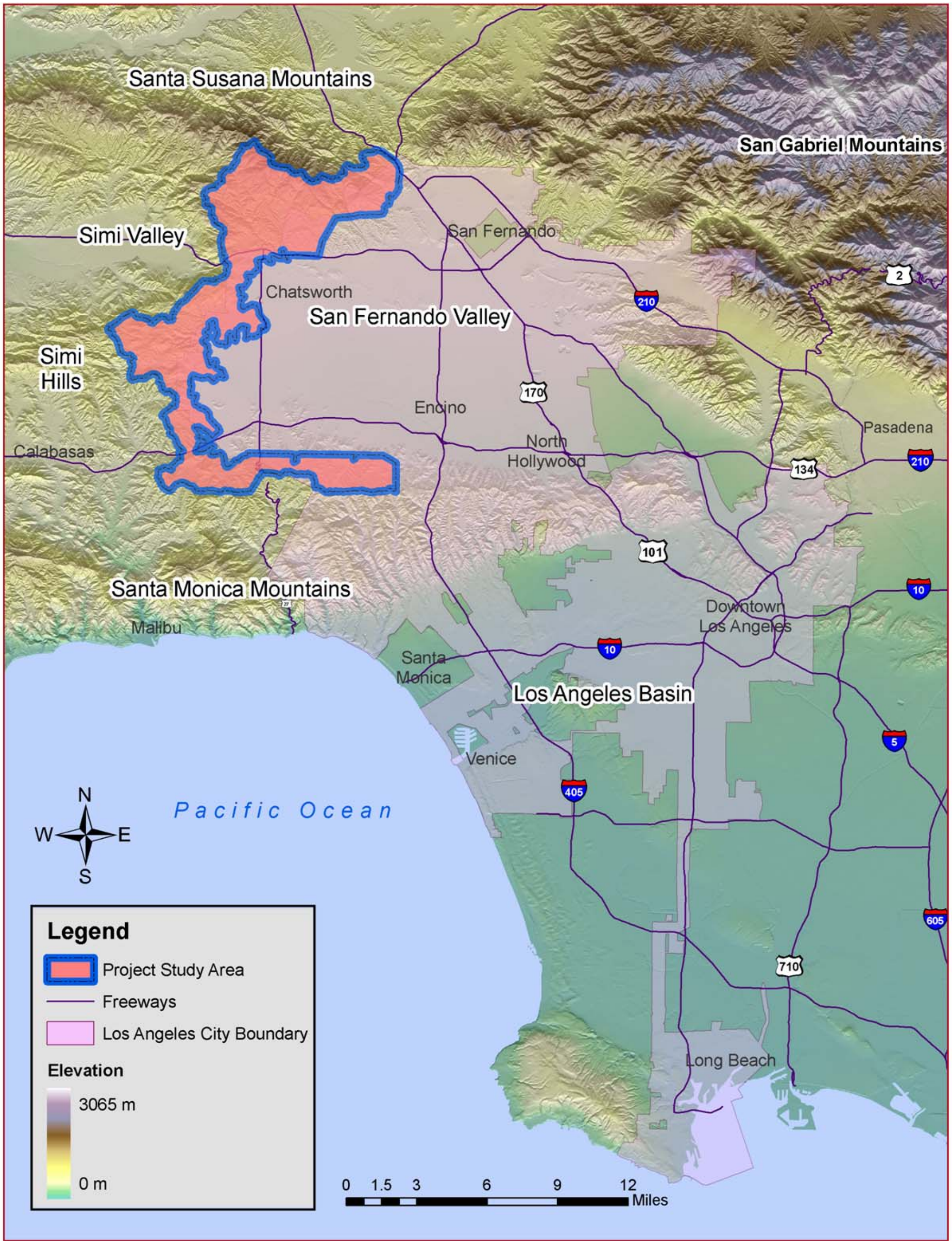

Figure 1. Location of RSA project study area with respect to San Fernando Valley, Los Angeles, California.

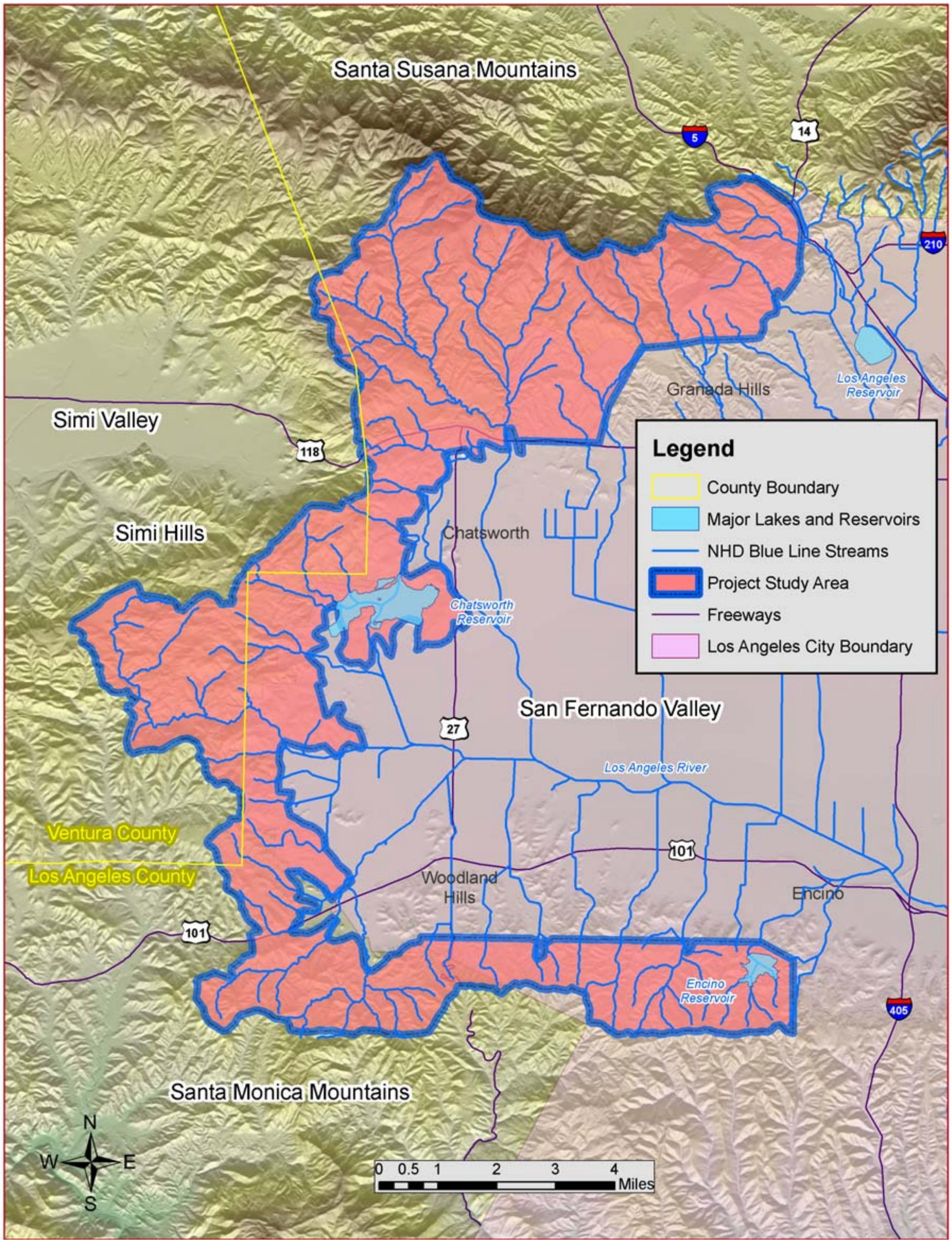

Figure 2. RSA project study area overlain on a 10 meter digital elevation model.

watershed management of the SFB through a better understanding of the role of the natural environment within and immediately surrounding this study area. Thus the various infiltration opportunities identified during this study provide potential methods for reducing the demand on the Sacramento-San Joaquin Delta (state aqueduct waters).

Data and Methodology

Overview

Four spatial datasets were utilized within this RSA, describing precipitation, land use/land cover (LULC), elevation, and soil characteristics. Each of these datasets is described below. The preparation of the datasets is the first step in the analysis, which then proceeds in two main parts, the Direct Infiltration Analysis and the Flow Accumulation Analysis.

The methodology was constructed around the question: how much rain falls per unit area, and then where does that water go once it reaches the surface? This simple question is challenging and was addressed using the methodology portrayed in Figure 3.

In overview, precipitation falls on the surface of the Earth in a predictable, but spatially variable pattern. Once that rain falls to the surface, the character of the surface impacts the behavior of the water. For instance, porous soils will absorb water, while concrete will cause water to flow downslope. The topographic characteristics of the ground surface are important, as both the slope and aspect (which way it faces) may alter the speed and path of water flow.

Once some water has infiltrated into soils and other water has moved downslope, an understanding of the route of that flowing water is important. A quantity of surface runoff that is not intercepted due to land cover or evapotranspiration will travel along a path that allows it to collect and infiltrate. And some, instead, will flow through the impervious storm water drainage system, leaving the study area relatively quickly en route to the ocean.

There remain numerous opportunities to intervene and change these outcomes. The findings herein suggest several catchments where, with modifications in land use practices, land cover or infrastructure, some water that currently flows from the study area might instead be retained and utilized to recharge the groundwater system.

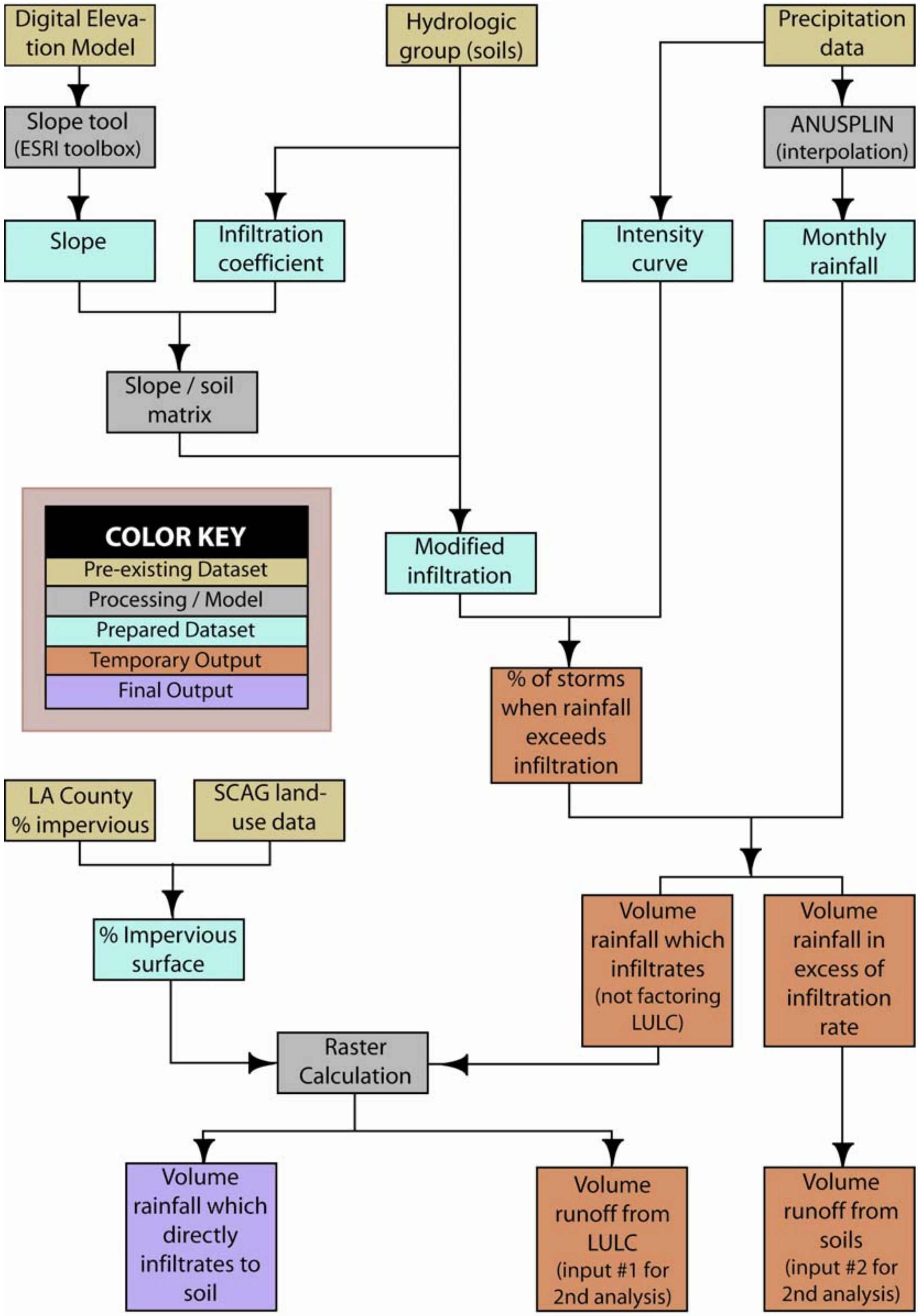

Figure 3. Schematic showing RSA methodology, including data preparation and the steps incorporated in the Direct Infiltration Analysis. The output of the Direct Infiltration Analysis was used as input data in the Flow Accumulation Analysis.

Precipitation

The primary input of water into the study area is precipitation. Given a Mediterranean climate, the majority of precipitation is received between October and April. The 30 year precipitation totals used for this project indicate that 88% of the rainfall volume falling on the study area occurred during those months.

Spatial Pattern

The National Climatic Data Center provides hourly rainfall measurements from many rain gauges in and around the study area (NOAA, 2007). Hourly rainfall intensity from the prior 30 years recorded at five stations within or near the study area were downloaded from the National Climatic Data Center in a tabular American Standard Code for Information Interchange (ASCII) format. The ASCII data was imported into Microsoft Excel spreadsheets and organized according to different temporal scales, including hourly intensity, rainy season and annual volumes. These data were used to generate estimates of monthly mean rainfall across the study area. In general, the analysis was governed by the extent of the data record.

An interpolation model was utilized to generate monthly mean rainfall surfaces using monthly rainfall totals recorded between December 1976 and December 2006. The ANUSPLIN FORTRAN program is specifically designed to fit surfaces to noisy climate data as functions of independent variables (Price et al., 2000 and Hutchinson, 2004). ANUSPLIN utilizes an interpolation approach using thin-plate smoothing splines that factors in topography as well as a scalable neighborhood window. The model finds the optimum neighborhood of data points when interpolating intervening data. Each output layer consists of a spatially-varying rainfall volume depicted as a continuous surface in the form of a grid. Table 1 depicts the mean, minimum and maximum values found within the output surface for each month. An example output surface is provided in Figure 4 for the wettest month (January). During January, the northern part of the study area receives substantially less rain than the remainder of the study area.

Table 1. Mean, minimum and maximum interpolated rainfall, by month.

Month	Mean (Inches)	Minimum (Inches)	Maximum (Inches)
January	4.43	3.04	5.82
February	4.43	3.13	5.72
March	3.77	2.69	4.84
April	1.09	0.78	1.40
May	0.45	0.35	0.55
June	0.05	< 0.01	0.09
July	0.03	0.02	0.04
August	0.18	0.14	0.21
September	0.29	0.22	0.36
October	0.73	0.50	0.96
November	1.47	0.93	2.00
December	2.45	1.86	3.03

Intensity Measurements

Thirty years of hourly rainfall data from four rain gauges within the study area were used to assess the frequency at which predefined thresholds of intensity were surpassed by the rainfall. Twelve intensity curves were generated, one for each month, as intensity in dry and wet months varies substantially in the RSA study area.

The thresholds were defined using the infiltration rates of the soils found within the study area, which will be described later in this document. For this project, a mean intensity curve was created (Figure 5) to calculate the annual frequency for which precipitation intensity exceeds the infiltration rates of the study area soils. When infiltration rate is surpassed, the remaining precipitation volume is considered runoff, moving downslope.

For example, in the study area, soils with silt loam or loam textures possess an estimated infiltration rate of 0.225 inches per hour, without considering the effect of slope (NRSC, 2007a). Given the rainfall intensity curve represented in Figure 5, only 4.84% of the rainfall surpassed an intensity of 0.225 inches per hour. Thus for each grid cell matching this scenario (silt loam or loam), the amount of infiltration for that cell was assigned a monthly precipitation volume less 4.84%, because this was assumed to contribute to runoff.

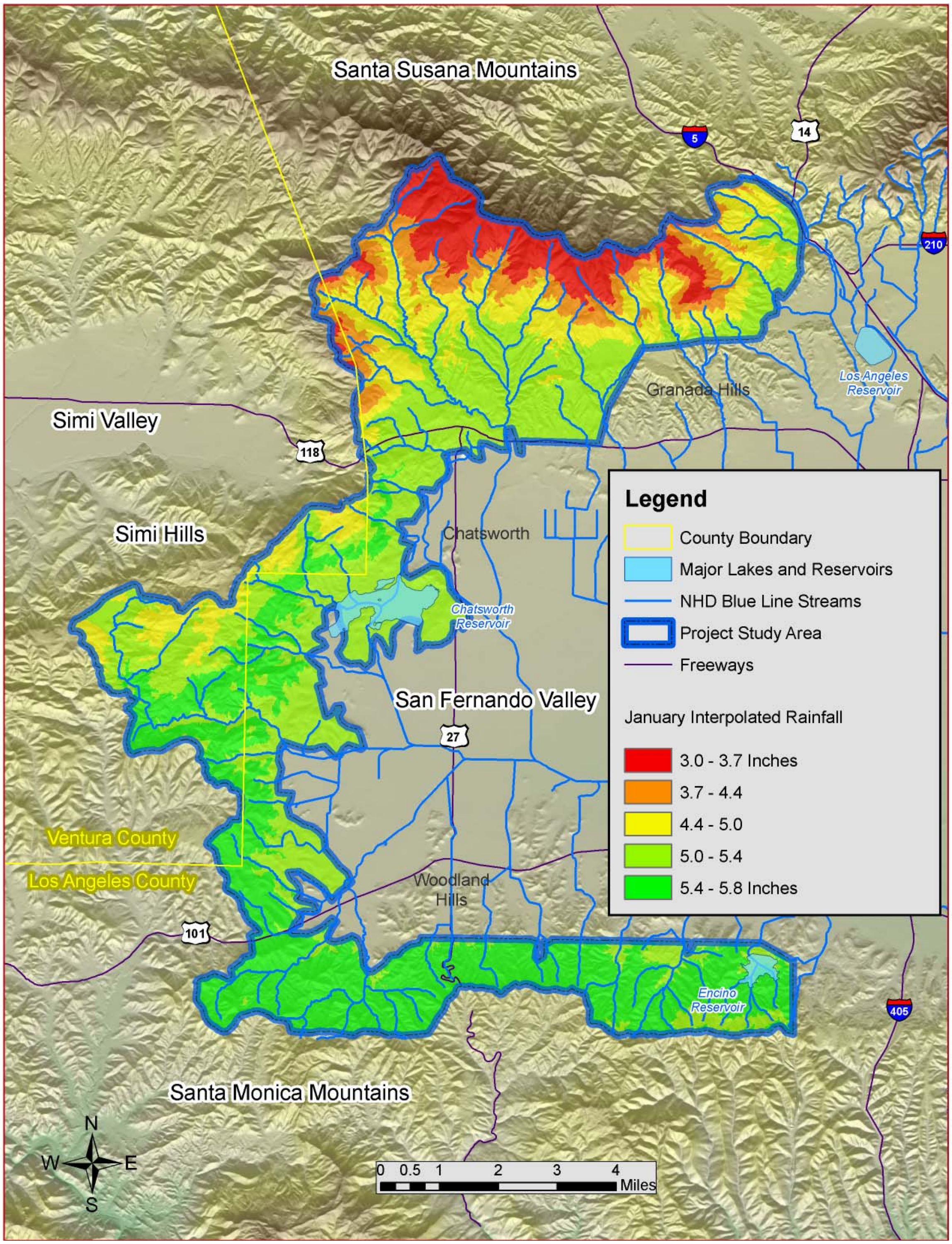

Figure 4. Results of the ANUSPLIN analysis, overlain on a 10 meter digital elevation model. This is spatially-variable rainfall volume layer for January, the wettest month, depicted as a continuous surface in the form of a raster grid.

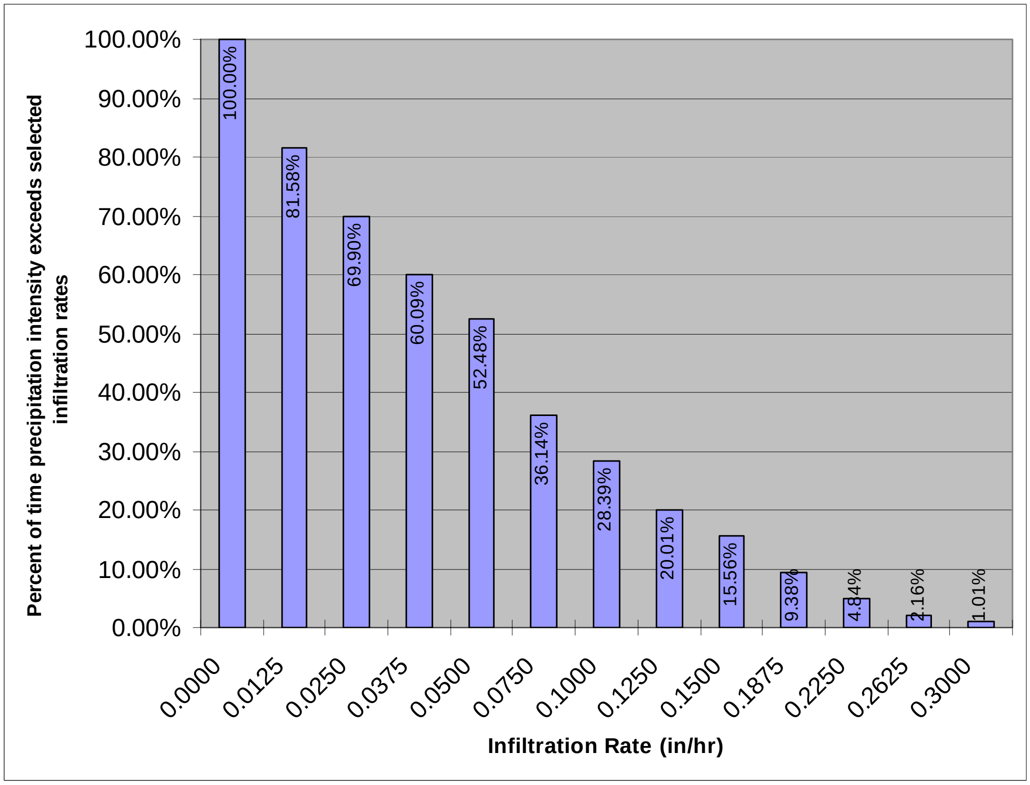

Figure 5. Annual rainfall intensity curve, illustrating the frequency that precipitation intensity exceeds the infiltration capacities of the surficial soils within the RSA study area.

Soil Characteristics

Natural Resources Conservation Service Soil Survey Geographic Data

The surficial soils data used in this study was obtained from the Natural Resources Conservation Service Soil Survey Geographic (SSURGO) Database (NRCS, 2007a and b). The digital SSURGO layer consists of a detailed soil map depicting the spatial distribution of known major soil units in the SFB, as of January 2007. To the best of our knowledge, SSURGO offers the most current and detailed soil information available for this area. The SSURGO dataset was developed by digitizing maps, collecting and compiling soil information into planimetric maps and then digitizing, or by obtaining recent remotely sensed imagery and other information to revise preexisting digitized maps (USDA, 1995). SSURGO soil data are freely available to the public, and can be downloaded in Microsoft Access format through the SSURGO Soil Data Mart (NRCS, 2007c). Initially, a comprehensive soil map was generated for a large region encompassing the RSA study area (Lam et al., 2007). For the purpose of this study the SSURGO soil data downloaded from the Soil Data Mart included soil survey areas which fall within the SFB, specifically survey areas CA674, CA675, CA676, and CA692. Though SSURGO data ranges in scale from 1:12,000 to 1:24,000, the RSA study area soil surveys were all produced at the coarsest resolution. SSURGO spatial data includes survey area and map unit polygon boundaries, and the tabular data consists of a set of ASCII delimited files which provides additional data such as soil horizon information which can be imported into the Microsoft Access SSURGO template database.

The United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) application Soil Data Viewer (v. 5.0, NRCS, 2007d) was utilized to view SSURGO data for southern California and generate thematic soil property maps of the RSA study area. The Soil Data Viewer typically allows a user to view one SSURGO soil survey area at a time. In order to visualize all of the soil data in one map view pre-processing of both the spatial and tabular soil survey data was required for our study area (USDA, 1995; NRCS, 2005). The four soil survey areas (CA674, CA675, CA676, and CA692) were first combined into one layer, and using the Soil Data Viewer and a SSURGO template database, the data were merged and clipped using the boundaries of the four United States Geological Survey (USGS) quadrangles encompassing the study area.

Hydrologic Groups

A SSURGO hydrologic group is defined as "a grouping of soils that have similar runoff potential under similar storm and cover conditions" (Table 2; NRCS, 2007d and e). Using the Soil Data Viewer, a new SSURGO soil map "unit name" thematic map was generated for the study area. Next, the dominant hydrologic group for each map unit was created using the viewer, based on the percentage composition of each map unit component (Figure 6). The study area is comprised of Soil Group D (56.7%), Soil Group C (25.5%), and Soil Group B (15.2%). Soil Group A is not present in the study area. Additionally, 2.6% of the study area is not classified within the SSURGO Hydrologic Groups since urban and water features are typically not classified in the SSURGO dataset.

Table 2. SSURGO hydrologic group infiltration rates.

SSURGO Hydrologic Group	Soil Textures	Infiltration Capacity	Percent of Study Area
A	Sand, loamy sand or sandy loam	> 0.30 inches/hour	0%
B	Silt loam or loam	0.15 – 0.30 inches/hour	15.2%
C	Sandy clay loam	0.05 – 0.15 inches/hour	25.5%
D	Clay loam, silty clay loam, sandy clay, silty clay, or clay	0.00 – 0.05 inches/hour	56.7%
Unclassified			2.6%

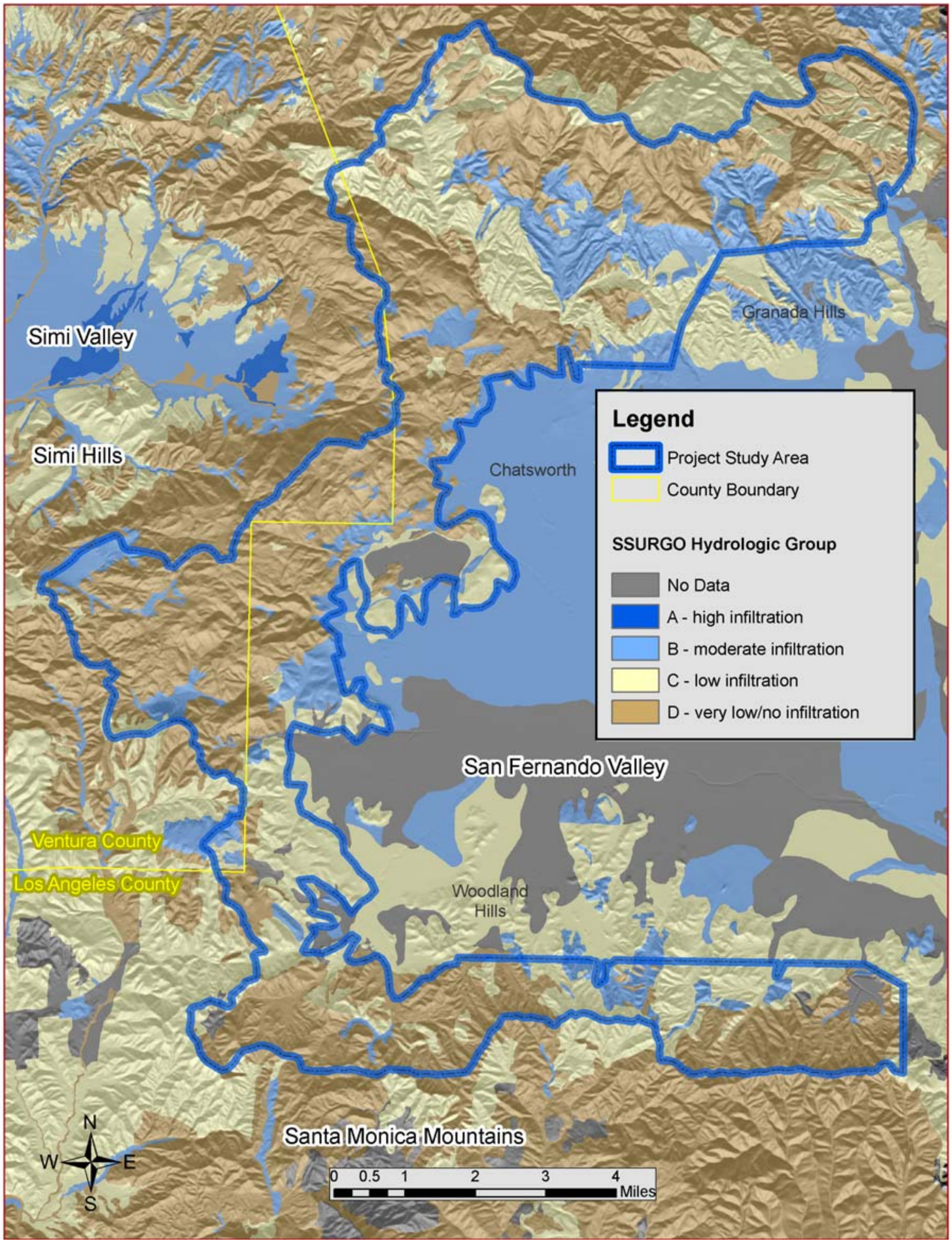

Figure 6. SSURGO hydrologic groups within RSA project study area, depicted according to infiltration capacity (as defined in the SSURGO data), overlain on a 10 meter digital elevation model.

DEM and Slope

The speed at which water travels when moving downslope impacts the potential for infiltration. The steeper the slope, the more quickly water moves over a given surface. Thus the faster water flows, the lower the infiltration potential. Thus a critical component of the RSA is the generation of a digital elevation model (DEM) and corresponding slope layer.

A 10 m resolution DEM was utilized to generate a slope layer for the RSA (Figure 7). The original DEM is a raster surface which was cleaned of spurious pits or sinks (areas of internal drainage, small imperfections in the dataset) prior to being used in this study. The percent slope layer shown in Figure 7 was generated from the elevation data using the slope function in ArcGIS 9.2.

Slope / Soil Infiltration Analysis

The speed at which water runs off a soil is impacted both by the soil infiltration characteristics and the slope of the soil surface. A high-slope soil has a lesser ability to infiltrate than does a similarly textured low-slope soil. To account for this within the analysis, thresholds were developed to express the variation of the SSURGO soil infiltration ratio with respect to both soil and slope. These thresholds were then used to generate raster surfaces expressing an adjusted infiltration capacity for each soil type in the RSA study area. The resultant infiltration rate raster layer was used to adjust the runoff volume, as discussed in the section entitled "Direct Infiltration Analysis" below (Braun et al., 2003; Charles et al., 2003).

For each hydrologic group there is a range of possible infiltration rates, provided with the SSURGO dataset (NRCS, 2007d and e). Each of the SSURGO infiltration capacity ranges shown in Table 2 was first divided into three distinct infiltration thresholds, minimum (min), maximum (max) and mean (Table 3). To refine this matrix further, middle-points were added between the minimum and mean (referred to as 'sub' in this report), and between the mean and maximum (referred to as 'prime' in this report) values, as shown in Table 3. The infiltration rates were then ranked from 0-12, which resulted in a total of thirteen possible ranks. The percentages of time the hourly rainfall intensity was less then or surpassed each of the thirteen infiltration thresholds is also provided in Table 3. For instance, given the 30 years of rainfall data analyzed, the rainfall intensity exceeded 0.05 inches/hr 52.5% of the time. Table 4 was then created to express the relationship between runoff speed and different combinations of soil type and slope. Lastly, the five possible outcomes in Table 4, Very Fast, Fast, Medium, Slow, Very Slow, were attributed with rank modifiers (-2, -1, 0, 1, 2) as shown in Table 5.

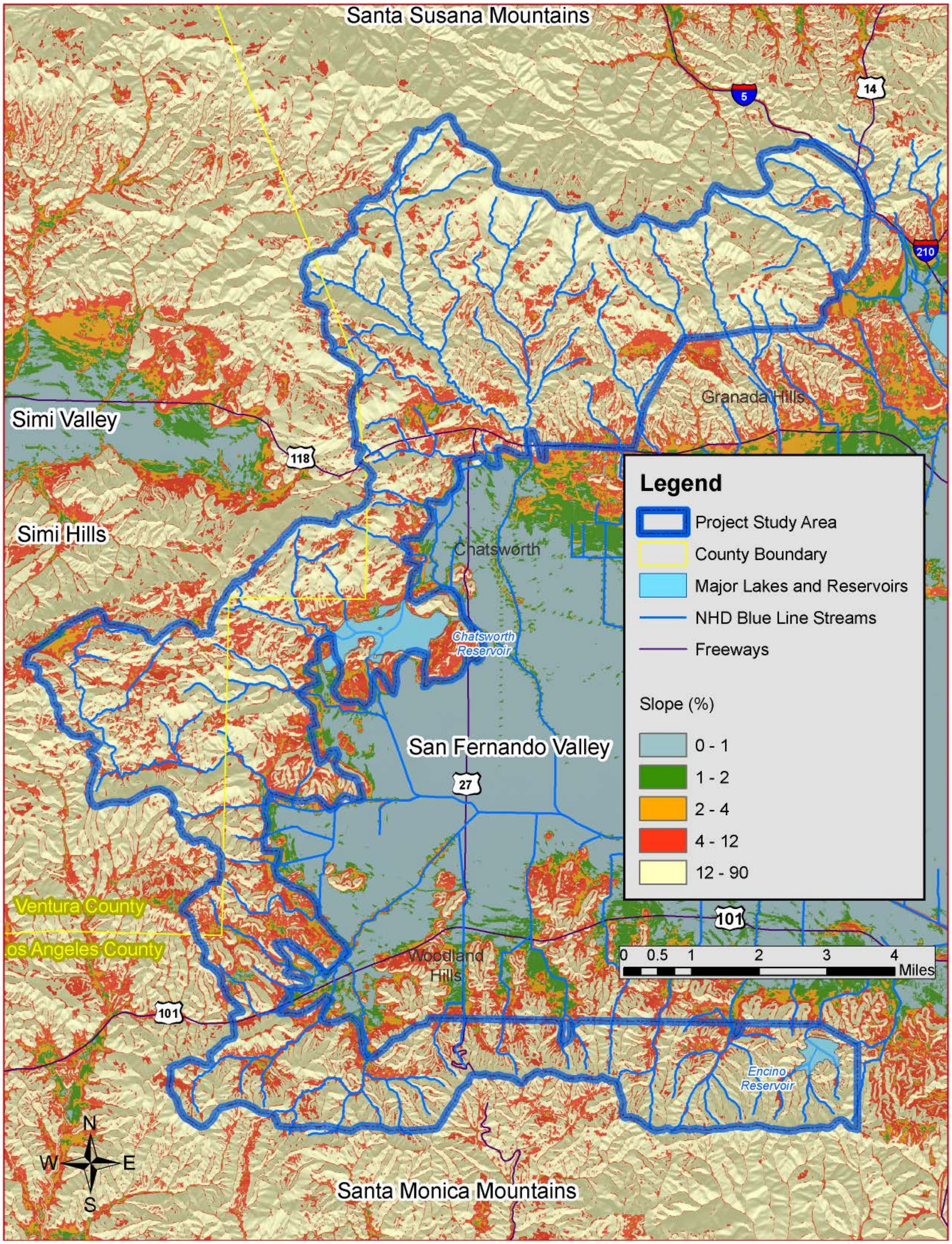

Figure 7. Percent slope raster layer generated for RSA study area from a 10 m digital elevation model. The slope layer is overlain on top of the 10 m digital elevation model.

Table 3. Infiltration threshold rankings.

Processing Rank	SSURGO Hydrologic Group	Infiltration Threshold (inches/hour)	Precipitation < Threshold	Precipitation > Threshold
0	D min	0	0.00%	100.00%
1	D sub	0.0125	18.42%	81.58%
2	*D mean*	*0.025*	*30.10%*	*69.90%*
3	D prime	0.0375	39.91%	60.09%
4	D max C min	0.05	47.52%	52.48%
5	C sub	0.075	63.86%	36.14%
6	*C mean*	*0.1*	*71.61%*	*28.39%*
7	C prime	0.125	79.99%	20.01%
8	C max B min	0.15	84.44%	15.56%
9	B sub	0.1875	90.62%	9.38%
10	*B mean*	*0.225*	*95.16%*	*4.48%*
11	B prime	0.2625	97.84%	2.16%
12	B max	0.3	98.99%	1.01%

Table 4. Runoff rate by hydrologic group and slope class.

SSURGO Hydrologic Group	A	B	C	D
Slope Class				
0 – 1 %	Very Slow	Very Slow	Slow	Slow
1 – 2 %	Very Slow	Slow	Slow	Medium
3 – 4 %	Slow	Slow	Medium	Rapid
5 – 12 %	Medium	Rapid	Rapid	Very Rapid
> 12 %	Rapid	Rapid	Very Rapid	Very Rapid

Table 5. Runoff rate rank adjustments.

Runoff Rate	Infiltration Processing Rank adjustment
Very Slow	+ 2 ranks
Slow	+ 1 rank
Medium	No change
Rapid	-1 rank
Very Rapid	-2 ranks

The combined impact of each soil type (and its associated infiltration range) and slope on each cell of the infiltration raster relied on the union of those two important characteristics within each cell. First, each cell in the infiltration raster was attributed with an initial rank expressing the mean infiltration (processing ranks 2, 6, 10) based on the SSURGO soil type located therein. Next, each cell was attributed with a runoff rate from Table 4 according to its slope class. Lastly, the infiltration rate for each cell was modified using the ranking modifiers in Table 5. The adjusted infiltration layer shown in Figure 8 provides a better understanding of the soil and slope conditions within the study area, illustrating direct infiltration potential versus runoff potential for each cell.

Land Use / Land Cover

Land use is a major component in understanding the flow of water on the surface. The amount of runoff from a particular type of land use is estimated using an imperviousness coefficient. For example, a commercial land use parcel is estimated to pass 91% of the precipitation that falls on it to runoff. This land use class includes parking lots, buildings, cars, and other impervious surfaces. The other 9% is considered precipitation that falls on the landscaping, lawn, or other pervious surfaces associated with these land uses.

SCAG Land Use Dataset

The Southern California Association of Governments (SCAG) maintains a land-use dataset to support large scale planning (SCAG, 2007). Land-use is categorized with a modified Anderson classification system (Anderson, 1976), using a one acre minimum mapping unit for critical land uses (government facilities) and a 2.5 acre minimum mapping unit for non-critical land uses (Figure 9).

The data are stored in vector polygon format. Figure 9 displays SCAG data divided into nine major classes consisting of Residential, Commercial, Industrial, Transportation/Utilities, Mixed Commercial/Industrial, Open Space and Recreation, Agriculture, Vacant/Undifferentiated, and Water. These major classes were condensed from a total of 104 detailed subcategories, for instance the class Transportation/Utilities includes the subcategories airports, electrical power facilities, and solid waste disposal facilities. Table 6 provides the percent of each major land use class within the RSA study area. For the purposes of this project the original SCAG dataset of 104 subcategories was processed into a raster with 10 m cells, each cell taking on the characteristics of the dominant component within the cell. For instance, a cell that has 75% residential, 15% commercial, and 10% open space contained within it was designated a residential cell.

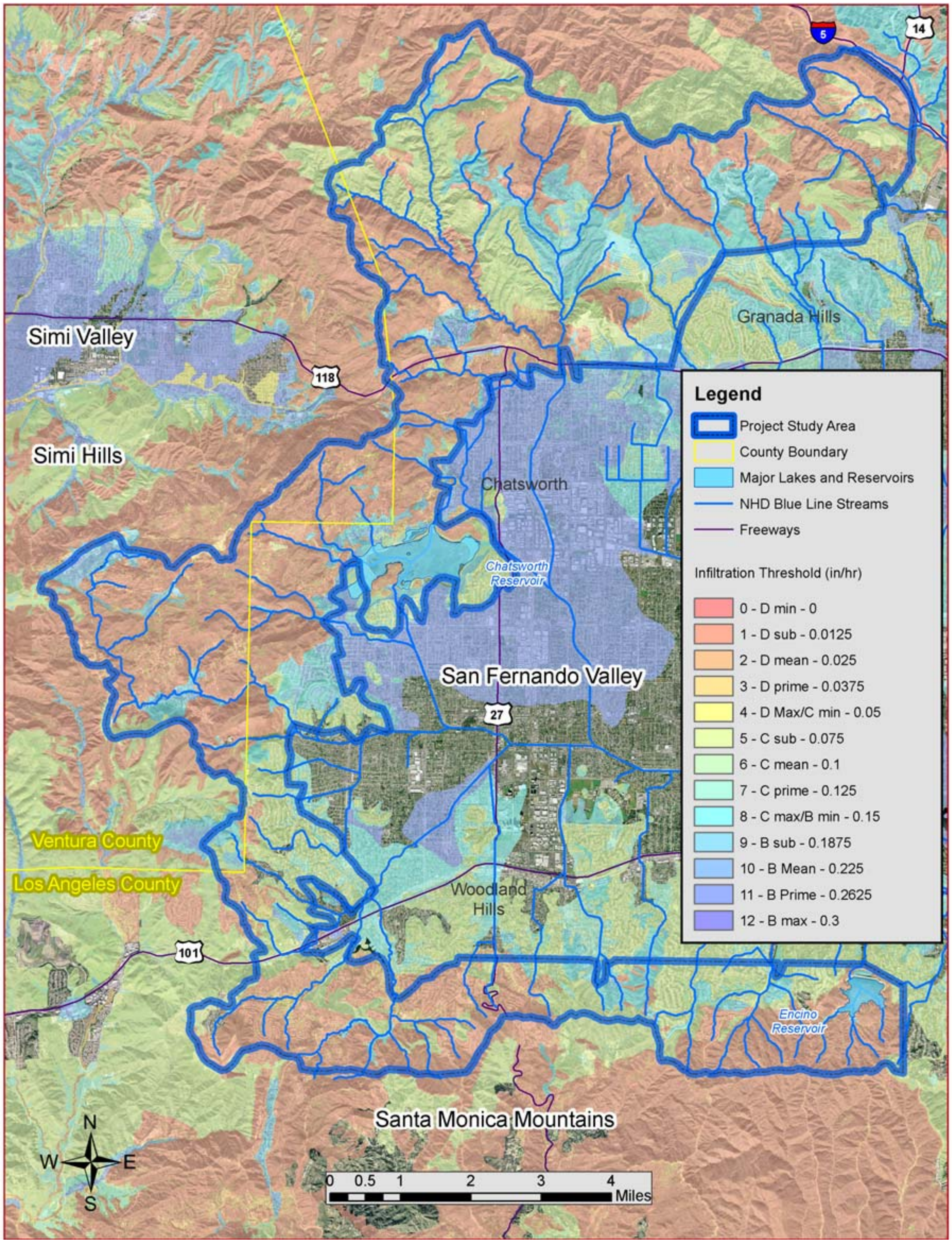

Figure 8. Raster layer showing adjusted infiltration rates according to Tables 3, 4 and 5, which takes into account both soil type and slope, overlain on 2005 aerial imagery.

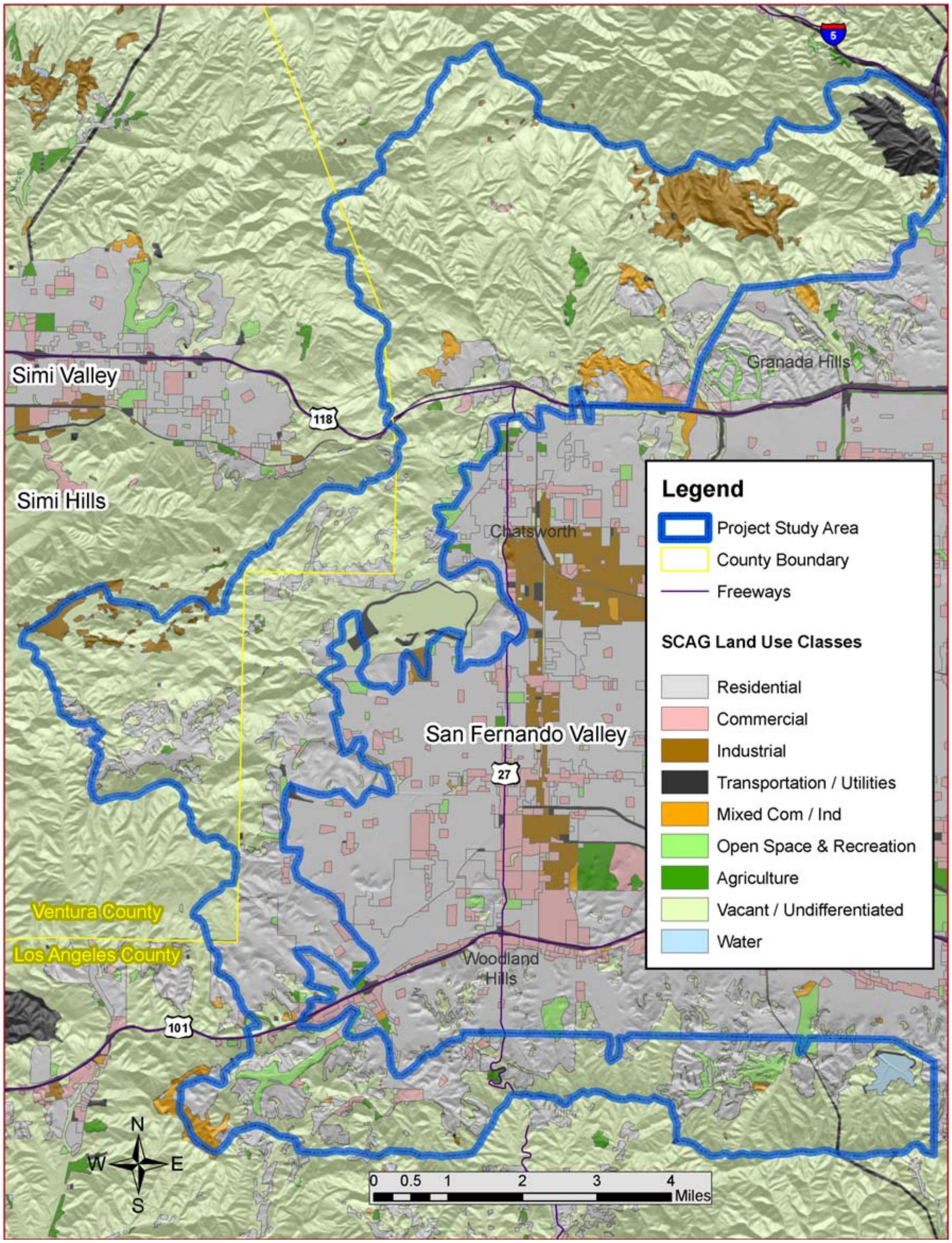

Figure 9. 2005 update of 2001 SCAG land use categories, overlain on top of the 10 m digital elevation model. The 104 SCAG land use subcategories were collapsed into nine major classes for display purposes only.

Table 6. Percentage of each major land use category within the study area.

SCAG Land Use Classes	Area (acres)	% Land Use
Residential	7989	21.3
Commercial	362	1.0
Industrial	1189	3.2
Transportation / Utilities	775	2.1
Mixed Commercial / Industrial	568	1.5
Open Space and Recreation	561	1.5
Agriculture	184	0.5
Vacant / Undifferentiated	25672	68.6
Water	151	0.4

Percent Imperviousness

The Los Angeles Department of Public Works (LADPW) has generated a land use imperviousness dataset (Yang et al., 2002; LADPW, 2007). This information correlates with the SCAG land use classifications, and provides an imperviousness coefficient for each type of land use. These data were joined to the SCAG spatial dataset, providing access to the imperviousness coefficient within the GIS calculations (Figure 10) discussed in the section entitled "Direct Infiltration Analysis" below.

Catchments

The catchment delineation was generated using the National Hydrography Dataset (NHD; USGS, 2007) and the Nature Conservancy Toolset (FitzHugh, 2005). This toolset delineates reach catchments (the area draining overland into each reach) for each stream reach and lake in the hydrographic dataset. During the delineation process, raster analyses were performed to generate flow direction, flow accumulation, stream definition, stream segmentation, and watershed delineation, producing an enhanced NHD data layer (Sheng et al., 2007 and Sheng, 2007). The enhanced NHD hydrographic coverage along with USGS 10 m DEMs were used in the catchment boundary delineation process to develop a vector representation of catchments for each stream reach and body of water. A total of 333 catchments or segments thereof (some catchments straddle the study area boundary) were delineated within the RSA study area, as shown in Figure 11.

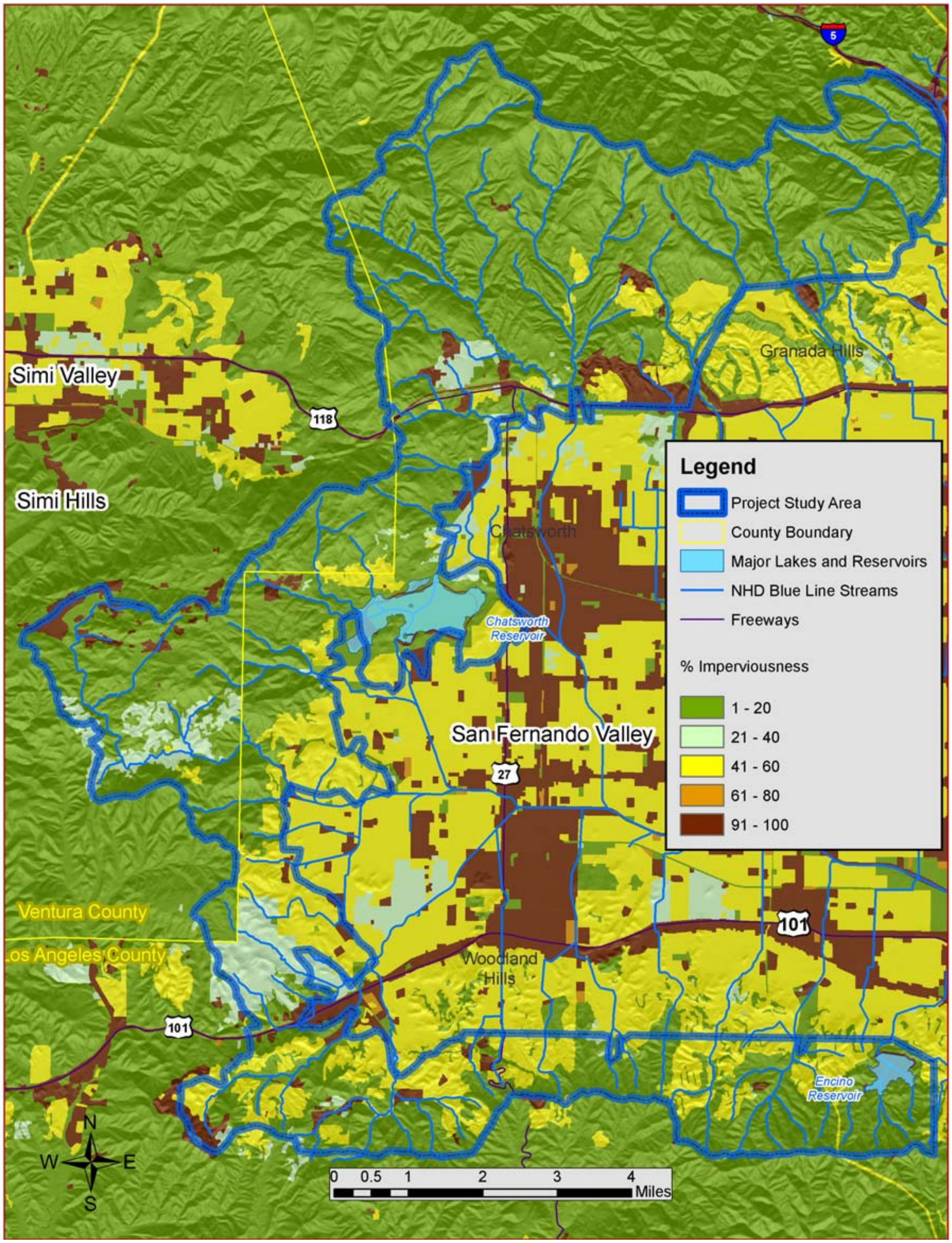

Figure 10. Land use imperviousness dataset created using SCAG land use map and LADPW imperviousness coefficients, overlain on top of the 10 m digital elevation model.

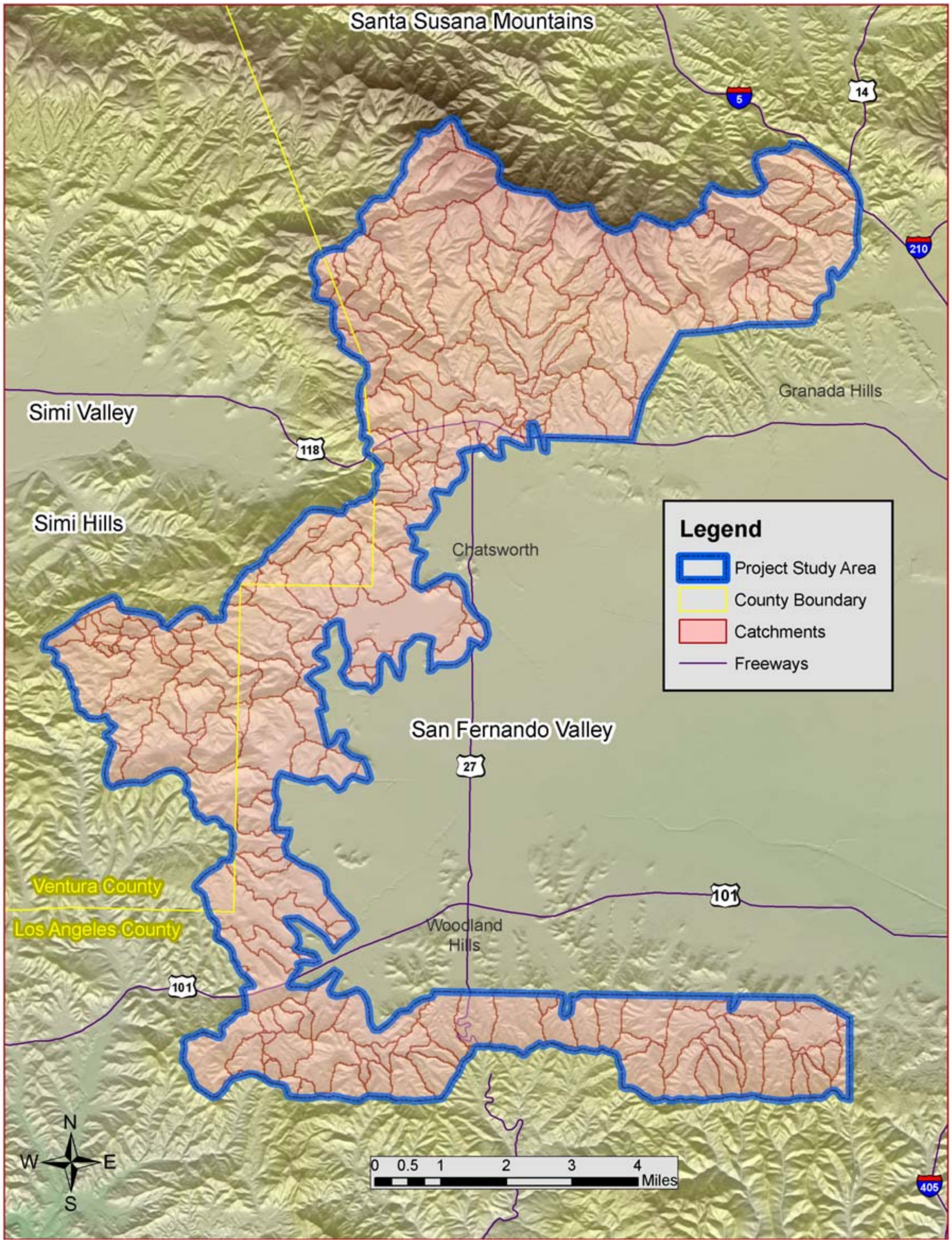

Figure 11. Catchments delineated with Nature Conservancy Toolset, overlain on top of the 10 m digital elevation model.

Results

Direct Infiltration Analysis

With the derived data described above, the final steps in the RSA (Figure 3) were performed. In most steps this entailed a raster calculation, where raster layers (whose cells overlay one another), were processed using the ArcGIS 9.2 Map Algebra tools, such that the values of the same cell in multiple layers were combined in a given calculation. In the simplest example, if one layer had a cell with a value of "3", and another layer had a value of "4", and the calculation required that the two rasters be multiplied, the resulting raster would have that cell labeled with a value of "12". This same calculation would be repeated for each and every cell and their associated values in the study area.

Rainfall and Runoff Analysis

Based on a review of 30 years of rainfall that fell within the RSA study area and the immediate surroundings, the rainy season is considered to be October to April. To begin the Direct Infiltration analysis, the rainy season total precipitation raster (Figure 12) was combined with the intensity curve (Figure 5) and the adjusted infiltration layer (Figure 8) to assess what happens to the water falling on each cell. This process consisted of two steps, where first the rainfall raster was modified by the intensity to produce a new raster layer expressing the volume of precipitation available to infiltrate into each cell. This first output layer proceeded forward in the infiltration process such that the volume of precipitation that equaled the infiltration capacity of each cell was subtracted from the precipitation total, providing a first approximation of the runoff volume per cell.

The runoff volume was modified by adjusting the derived infiltration quantity layer (Figure 8) with the LULC impervious surface layer (Figure 10). In this step, the infiltration volume is multiplied by the imperviousness percentage, and then the result is subtracted from the infiltration volume. The output of this step is provided in Figure 13, which represents the total volume of water that has the potential to infiltrate in-situ during the rainy season, per cell, taking into account loss of infiltration related to impervious land use or cover. Additionally, another output layer was generated that expresses the volume of water that has the potential to run off due to impervious surfaces. This runoff output was then added to the first runoff volume created above to generate the total potential runoff volume per cell (Figure 14). This layer was later used in the flow accumulation modeling (see section "Flow Accumulation Analysis").

About one third of the study area potentially contributed between four and six inches of infiltration volume each average rainy season. Nearly 60 percent of the study area contributes between two and eight inches of rain during this season. Figure 13 indicates

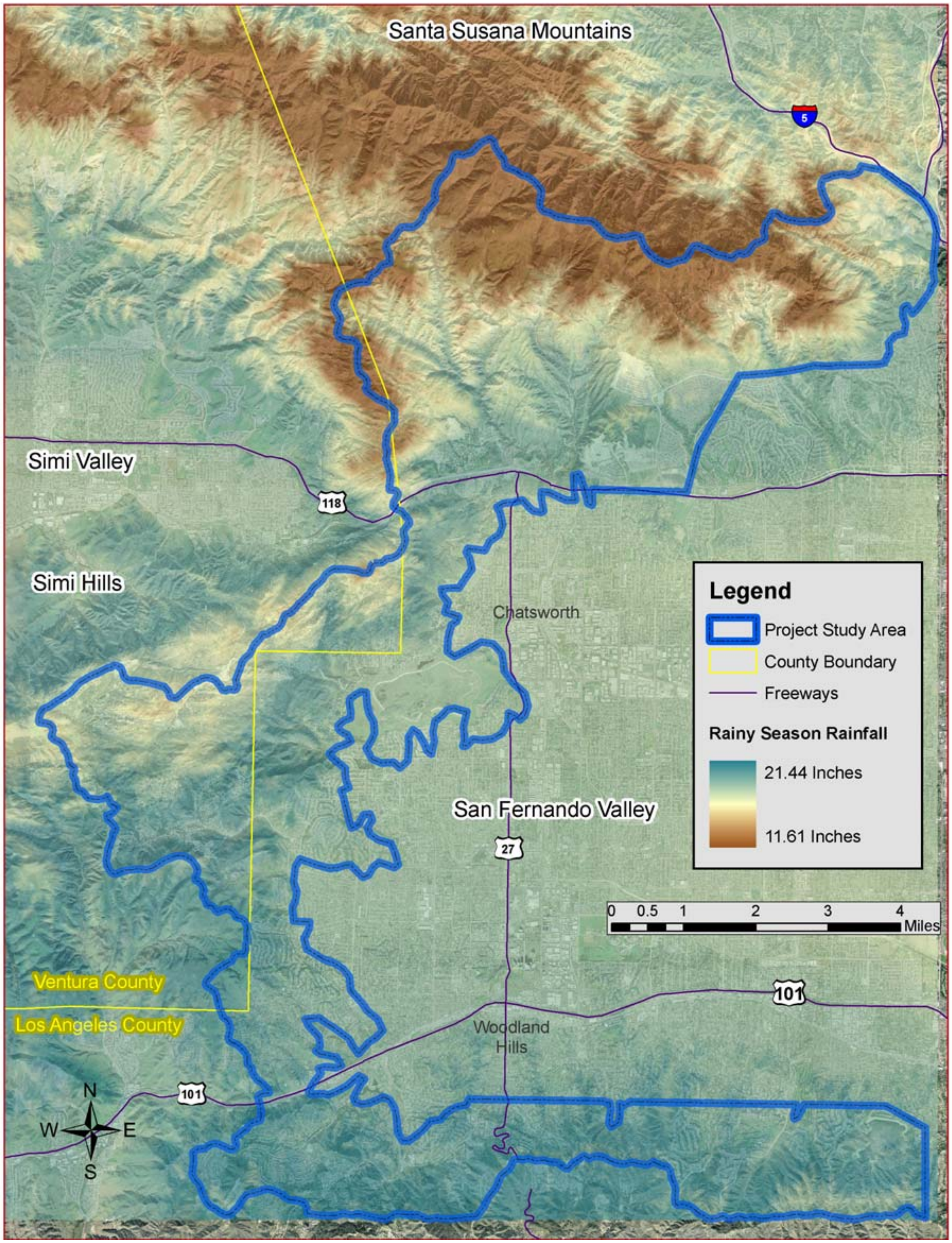

Figure 12. Raster surface showing the total rainfall (inches) falling on the study area during the rainy season, overlain on 2005 aerial imagery.

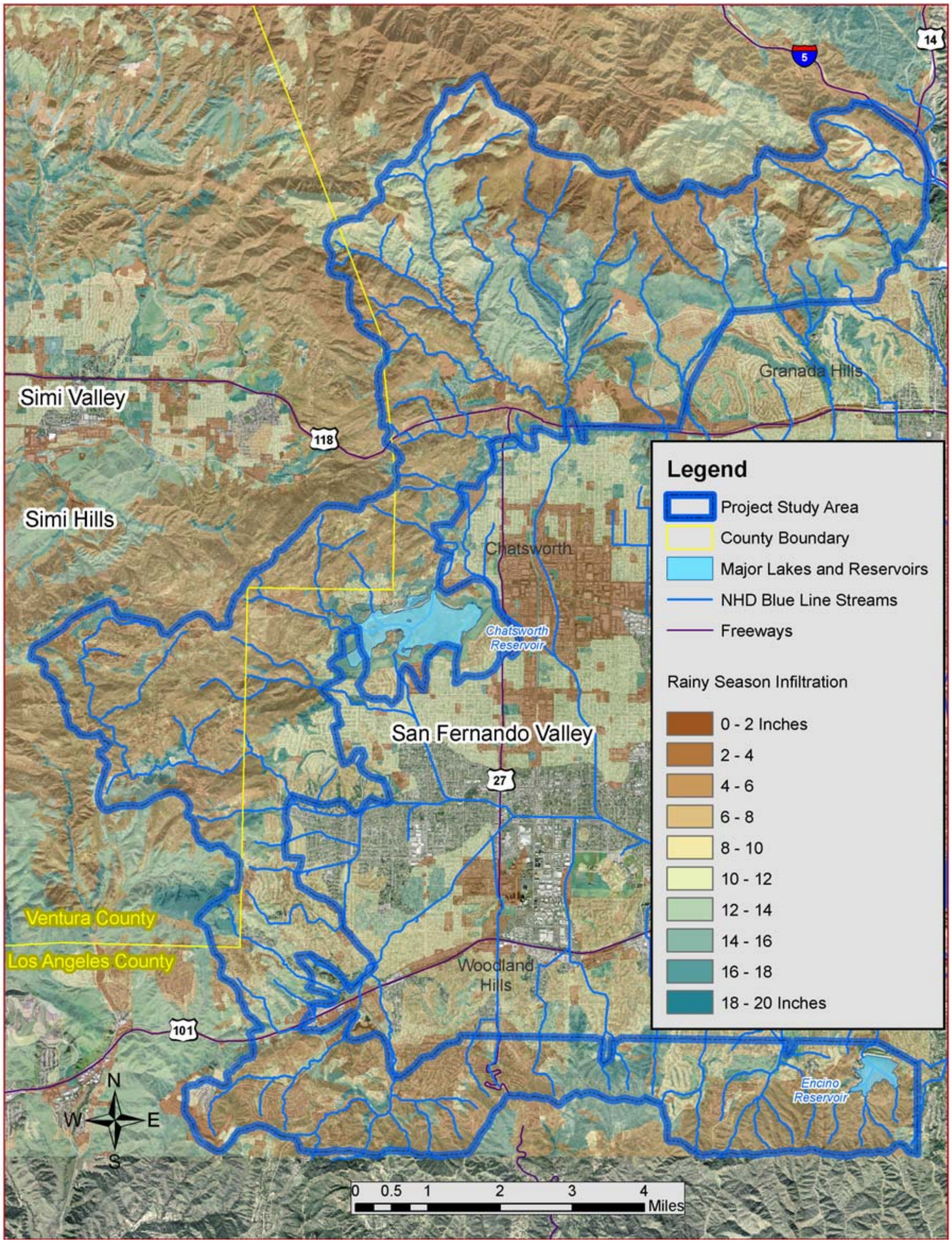

Figure 13. Raster surface showing total infiltration across study area during the rainy season, overlain on 2005 aerial imagery.

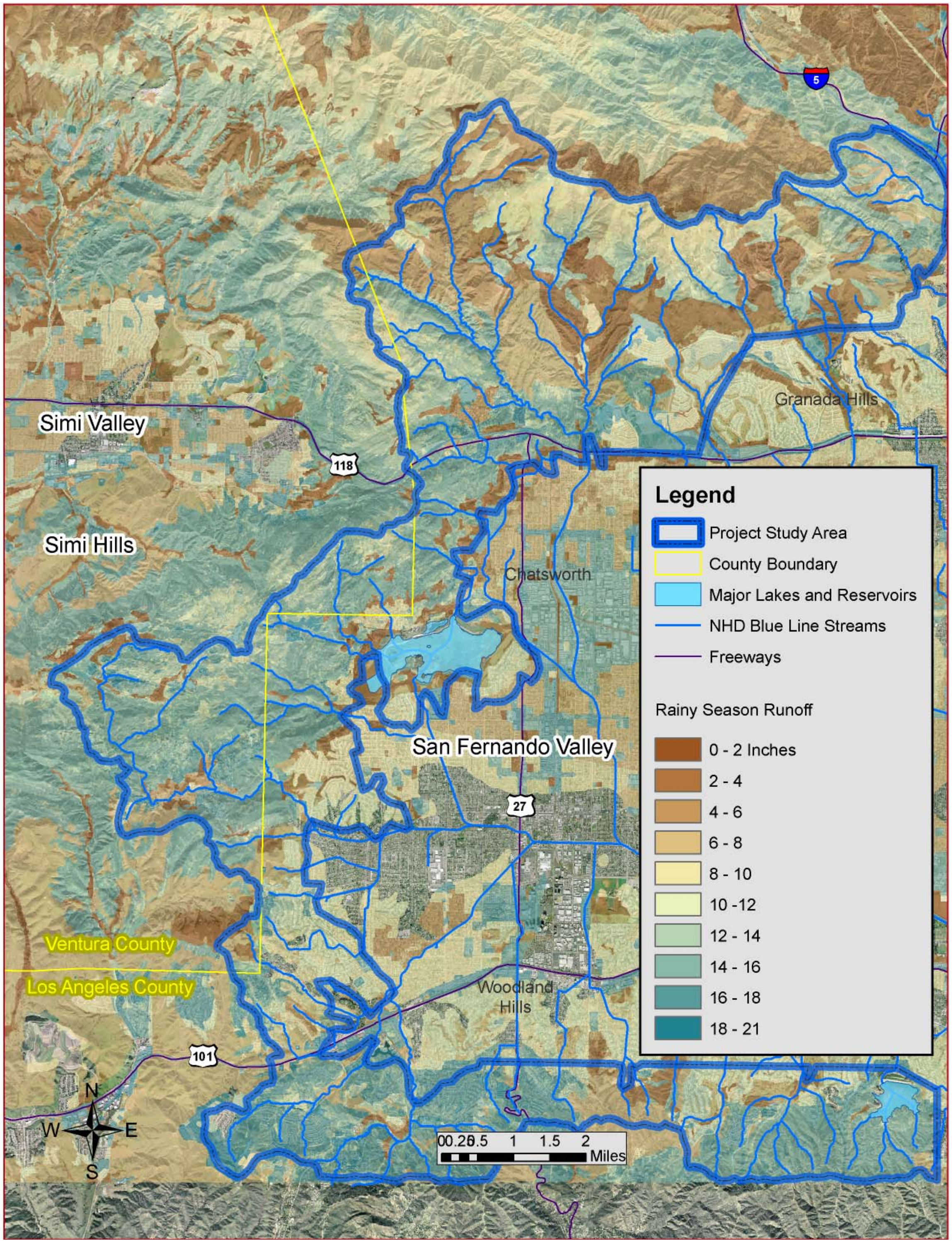

Figure 14. Raster layer showing total runoff (inches) across study area during the rainy season, overlain on 2005 aerial imagery.

that the largest areas of higher potential infiltration exist primarily in the north, though smaller patches also occur in central and southern parts of the study area.

Direct Infiltration By Catchment

Direct infiltration is the primary method for the study area soils to receive water. The wettest month (January) is used to illustrate the variation of potential infiltration across the study area (Figure 15). During the seven months of the year (October to April) with more than half an inch of rain on average, the result is similar, though the total potential infiltration volumes vary from month to month. In most cases (cells), during the drier months (May to September) the monthly infiltration potential was less than half an inch. One of the primary goals of this study is to identify particular catchments or groups of catchments with the greatest potential for direct infiltration and runoff, and runoff accumulation. In order to illustrate where direct infiltration and runoff are most likely to occur on a catchment basis, the original catchments shown in Figure 11 were grouped according to tributary reach, as shown in Figure 16. The original 333 catchments in the study area were thus collapsed into a smaller set of 46 combined catchments, each containing one outlet. Any catchment not containing an outlet reach was not included in a combined catchment (Tributary Number "0", Figure 16).

The rainy season precipitation and direct infiltration results associated with each of the 46 combined catchments are provided in Table 7. According to these results, out of a total of 64,796 acre feet of recorded rainfall falling in the RSA study area during the rainy season, potentially 25,742 acre feet, or roughly 40%, directly infiltrates into the soils. On average, each of the 46 combined catchments has the potential to directly infiltrate approximately 550 acre feet of precipitation during the rainy season. In six of these combined catchments, greater than 60% of the rainy season precipitation has the potential to be directly infiltrated (Table 7, percentages highlighted in orange). Another six combined catchments infiltrate 50-60% of the precipitation (Table 7, percentages highlighted in blue). Of the 46 combined catchments and their associated tributaries, the top 10 contributing the most to direct infiltration include yet another set of catchments, which are highlighted in green in Table 7. These 10 dominate over the other 36 catchments in terms of direct infiltration volume due to their large drainage areas. Table 8 provides a summary of these top 10 combined catchments, described in terms of relative size and amount of infiltration (Figure 17). The most promising combined catchments are not only the largest (associated with the longest tributary reaches), but are also those which possess the highest potential for direct infiltration.

The rainy season runoff results attributed to each of the 46 combined catchments is provided in Table 9. Out of the total 64,796 acre feet of precipitation, potentially 36,796 acre feet, approximately 57%, is considered runoff. The average potential runoff within the 46 combined catchments is about 783 acre feet. The results in Table 9 show that in 14 combined catchments more than 60% of the precipitation is likely to leave as runoff

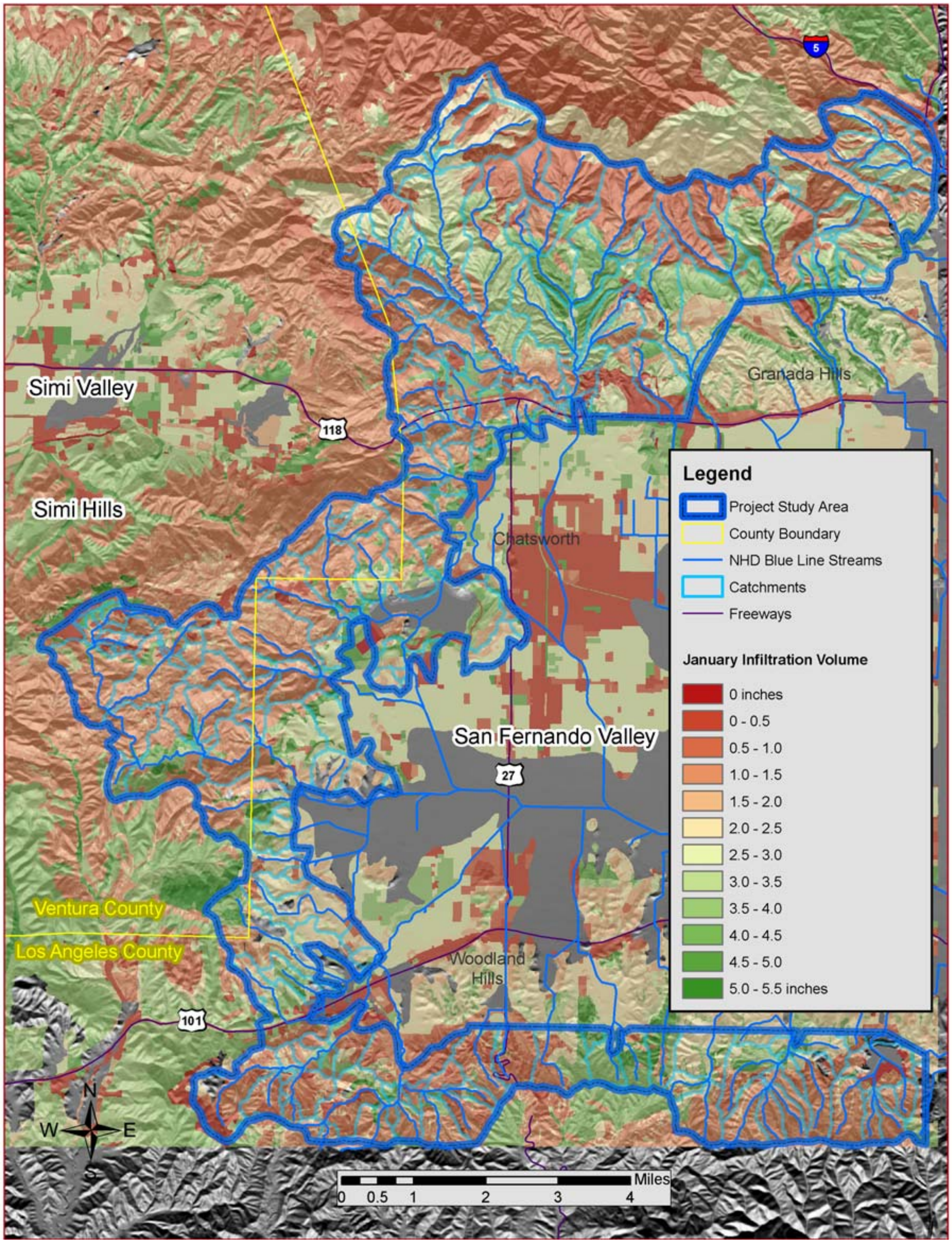

Figure 15. The infiltration volume (inches) for the month of January within RSA study area, overlain on the 10 m digital elevation model.

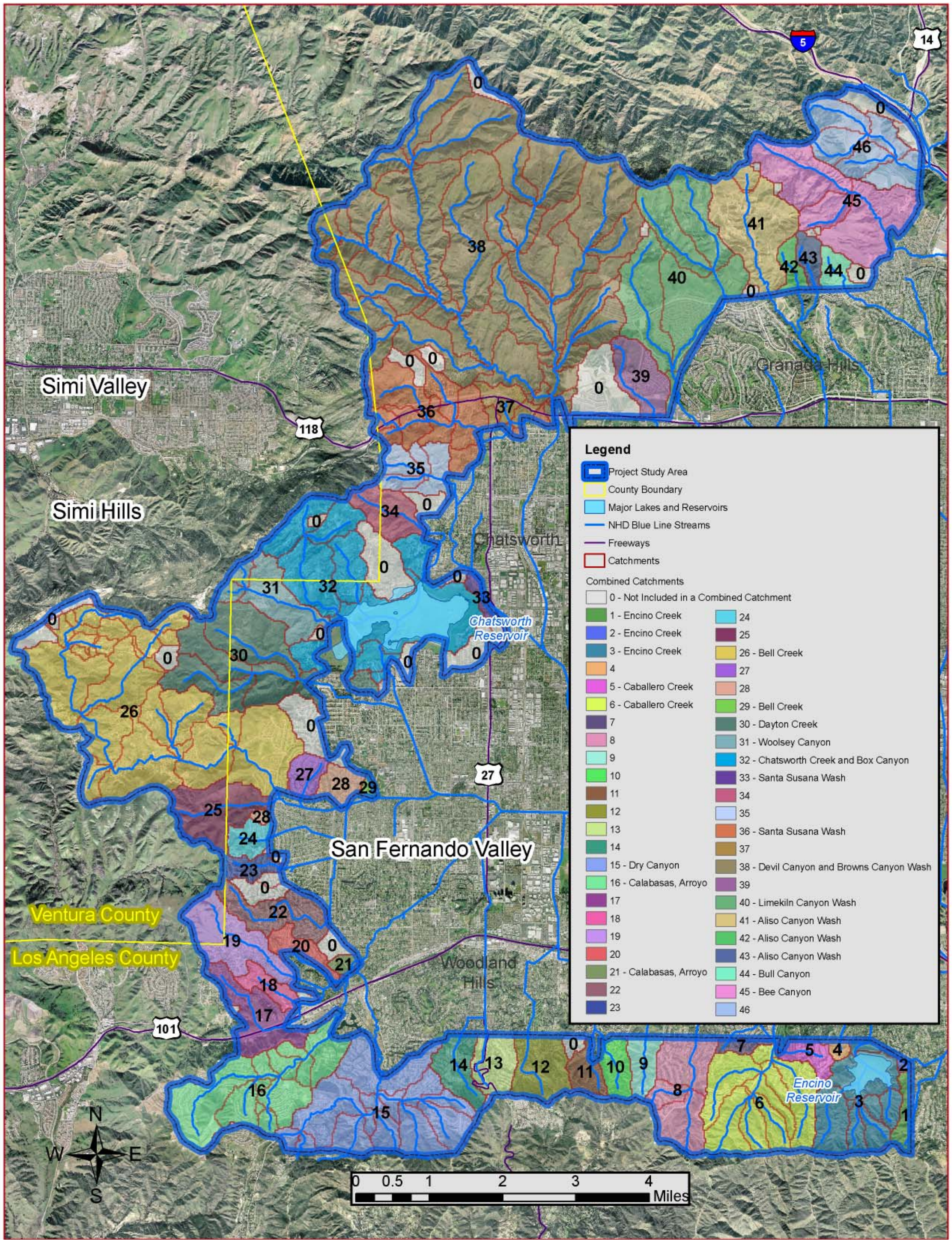

Figure 16. Combined catchments, each encompassing one tributary entering or exiting the study area. Based on original catchments shown in Figure 11 overlain on 2005 aerial imagery.

Table 7. Results of direct infiltration analysis. Tributary Numbers correspond to Figure 16. Percentages in orange and blue indicate > 60% and 50-60% direct infiltration, respectively.

Tributary Number	Tributary Name	Combined Catchment Area (acre)	Rainy Season Total Precipitation (acre feet)	Rainy Season Direct Infiltration (acre feet)	Direct Infiltration as % of Precipitation
0	Not included in a Combined Catchment	2,537	4,456.22	1,751.33	
1	Encino Creek	123	230.49	79.44	34
2	Encino Creek	21	39.12	17.33	44
3	Encino Reservoir	941	1,780.04	372.58	21
4		50	94.55	43.04	46
5	Caballero Creek	162	302.28	148.99	49
6	Caballero Creek	1,284	2,433.59	827.79	34
7		80	148.41	63.95	43
8		678	1,292.69	574.39	44
9		193	371.02	245.43	66
10		195	372.74	236.66	64
11		161	311.34	215.42	69
12		389	742.29	307.45	41
13		283	539.93	136.96	25
14		288	551.16	127.21	23
15	Dry Canyon	1,757	3,384.45	931.66	28
16	Calabasas, Arroyo	1,348	2,598.04	643.34	25
17		463	877.22	385.87	44
18		152	284.55	150.59	53
19		578	1,093.72	521.84	48
20		168	308.43	121.82	40
21	Calabasas, Arroyo	55	99.86	42.17	42
22		435	805.98	308.08	38
23		143	271.59	126.01	46
24		163	303.06	181.02	60
25		520	981.32	334.91	34
26	Bell Creek	3,655	6,628.30	2,308.85	35
27		158	286.01	112.33	39
28		196	352.87	127.46	36
29	Bell Creek	29	52.25	29.94	57
30	Dayton Creek	1,373	2,484.88	738.74	30
31	Woolsey Canyon	526	934.53	255.56	27
32	Chatsworth Creek, Box Canyon	2,293	4,051.16	1,363.87	34
33	Santa Susana Pass Wash	72	126.05	61.81	49
34		316	556.48	169.15	30
35		389	706.22	236.46	33
36	Santa Susana Pass Wash	1,076	1,910.29	684.45	36
37		232	424.60	130.89	31
38	Devil Canyon, Browns Canyon Wash	8,332	12,689.40	6,417.43	51
39		365	666.93	279.11	42
40	Limekiln Canyon Wash	1,943	2,993.15	1,561.28	52
41	Aliso Canyon Wash	842	1,225.78	628.23	51
42	Aliso Canyon Wash	124	191.36	102.96	54
43	Aliso Canyon Wash	130	192.70	127.41	66
44	Bull Canyon	142	244.29	156.39	64
45	Bee Canyon	1,253	2,011.26	815.09	41
46		830	1,392.95	540.22	39
Total		37,447	**64,795.50**	**25,742.90**	

Table 8. Direct infiltration results in terms of size of combined catchments and amount of infiltration.

Tributary Number	Tributary Name	Rainy Season Direct Infiltration (acre feet)	Relative Size and Infiltration of Combined Catchments
38	Devil Canyon and Browns Canyon Wash	6,417	very large, moderately high infiltration
26	Bell Creek	2,309	large, low infiltration
40	Limekiln Canyon Wash	1,561	small, moderately high infiltration
32	Chatsworth Creek and Box Canyon	1,364	large, low infiltration
15	Dry Canyon	932	small, low infiltration
6	Caballero Creek	828	small, low infiltration
45	Bee Canyon	815	small, low infiltration
30	Dayton Creek	739	small, low infiltration
36	Santa Susana Pass Wash	685	small, low infiltration
16	Calabasas, Arroyo	643	small, low infiltration

(Table 9, percentages highlighted in orange), and in 14 others 50-60% of the precipitations potentially leaves as runoff (percentages highlighted in blue). The 10 combined catchments with the highest potential runoff relative to the other 36 are highlighted in green in Table 9. Table 10 provides the catchment groupings in terms of relative size and amount of potential runoff. The combined catchments experiencing the greatest amount of runoff are the same as those identified in Tables 7 and 8 which also exhibit the highest potential for direct infiltration (Figure 17). In both cases, the Devil Canyon / Browns Canyon Wash and Bell Creek tributaries encompass the largest areas and greatest potential for both direct infiltration and runoff.

The Devil Canyon and Browns Canyon Wash network of streams is located in the central Santa Susana Mountains (Figure 18). Brown's Canyon is now parkland and contains more wilderness than any other Los Angeles River tributary outside of the Angeles National Forest. This area is still relatively undeveloped, has porous soils, and gentle slopes. This focus area accumulates surface runoff from several tributaries, including Browns Canyon Wash, Mormon Canyon, Blind Canyon, Devil Canyon, Ybarra Canyon and Falls Creek. This combined catchment includes only catchments that average more than four inches of infiltration in the month of January. Of note in Figure 18 is a development just north of where the legend is displayed, which is more recent than any of the datasets utilized in this analysis. That development has changed the slope angle and LULC condition of a portion of this area. Another development is currently being considered just north of the confluence of Brown's Canyon and Mormon Canyon, which could also greatly impact the conditions shown.

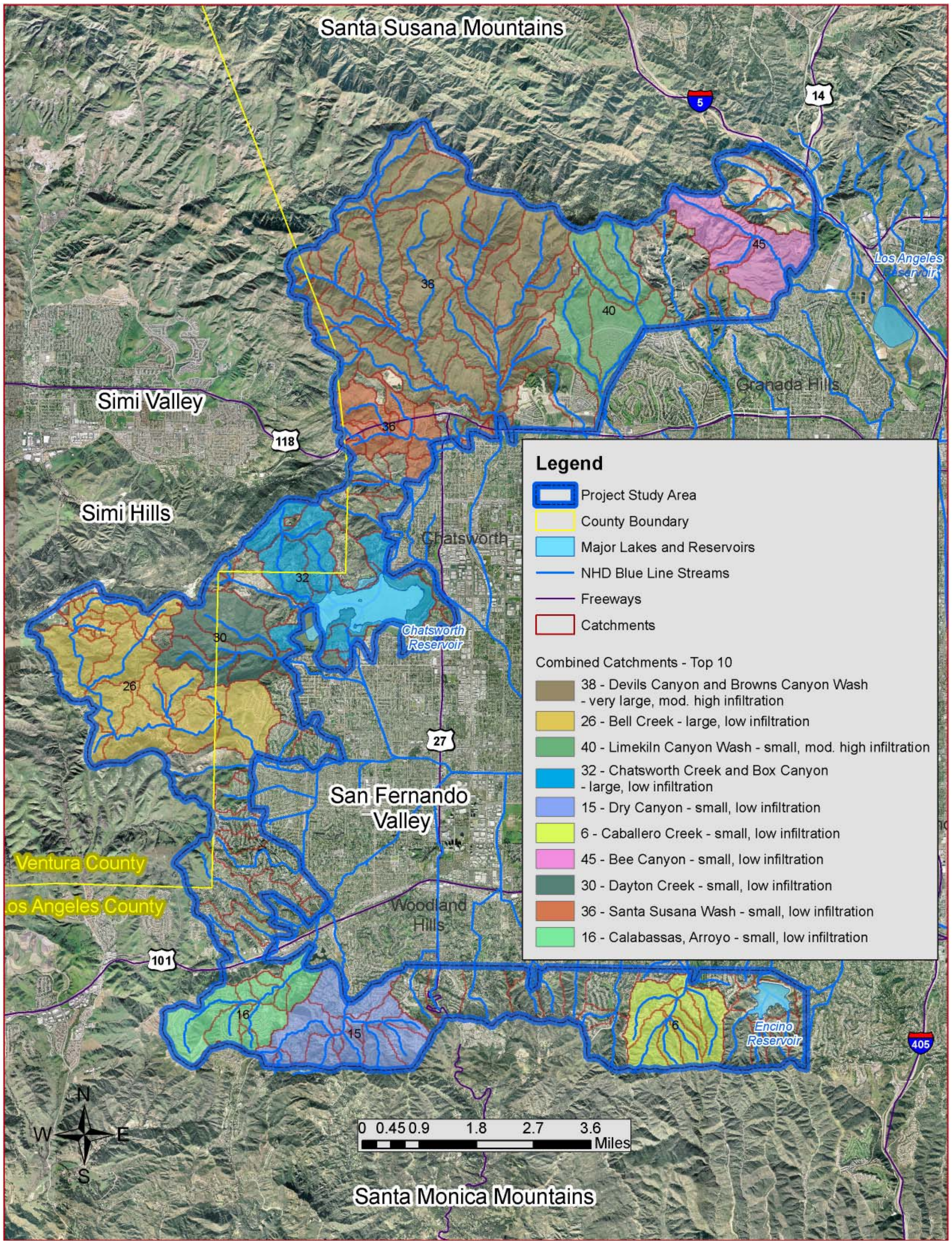

Figure 17. Combined catchments and associated tributaries with the highest potential for direct infiltration, according to analyses of rainy season precipitation and SSURGO hydrologic group classifications (Tables 4 and 8). Overlain on 2005 aerial imagery.

Table 9. Results of runoff analysis. Tributary Numbers correspond to Figure 16. Percentages in orange and blue indicate > 60% and 50-60% runoff, respectively.

Tributary Number	Tributary Name	Combined Catchment Area (acre)	Rainy Season Total Precipitation (acre feet)	Rainy Season Runoff (acre feet)	Rainy Season Runoff as % of Precipitation
0	Not included in a Combined Catchment	2,537	4,456.22	2,598.23	
1	Encino Creek	123	230.49	136.69	59
2	Encino Creek	21	39.12	21.09	54
3	Encino Reservoir	941	1,780.04	1,127.35	63
4		50	94.55	49.75	53
5	Caballero Creek	162	302.28	148.46	49
6	Caballero Creek	1,284	2,433.59	1,533.72	63
7		80	148.41	79.81	54
8		678	1,292.69	699.53	54
9		193	371.02	124.64	34
10		195	372.74	132.74	36
11		161	311.34	94.92	30
12		389	742.29	425.45	57
13		283	539.93	396.47	73
14		288	551.16	417.20	76
15	Dry Canyon	1,757	3,384.45	2,409.93	71
16	Calabasas, Arroyo	1,348	2,598.04	1,808.81	70
17		463	877.22	456.47	52
18		152	284.55	114.33	40
19		578	1,093.72	408.63	37
20		168	308.43	154.54	50
21	Calabasas, Arroyo	55	99.86	54.91	55
22		435	805.98	448.40	56
23		143	271.59	140.61	52
24		163	303.06	119.20	39
25		520	981.32	583.29	59
26	Bell Creek	3,655	6,628.30	4,276.62	65
27		158	286.01	103.16	36
28		196	352.87	148.82	42
29	Bell Creek	29	52.25	20.94	40
30	Dayton Creek	1,373	2,484.88	1,740.31	70
31	Woolsey Canyon	526	934.53	675.34	72
32	Chatsworth Creek and Box Canyon	2,293	4,051.16	1,871.58	46
33	Santa Susana Pass Wash	72	126.05	60.98	48
34		316	556.48	387.11	70
35		389	706.22	469.31	66
36	Santa Susana Pass Wash	1,076	1,910.29	1,211.91	63
37		232	424.60	289.56	68
38	Devil Canyon and Browns Canyon Wash	8,332	12,689.40	6,248.49	49
39		365	666.93	373.47	56
40	Limekiln Canyon Wash	1,943	2,993.15	1,404.19	47
41	Aliso Canyon Wash	842	1,225.78	594.36	48
42	Aliso Canyon Wash	124	191.36	88.29	46
43	Aliso Canyon Wash	130	192.70	65.17	34
44	Bull Canyon	142	244.29	86.55	35
45	Bee Canyon	1,253	2,011.26	1,147.67	57
46		830	1,392.95	847.26	61
Total		37,447	**64,795.50**	**36,796.20**	

Table 10. Runoff results in terms of size of combined catchments and amount of runoff.

Tributary Number	Tributary Name	Rainy Season Runoff (acre feet)	Relative Size and Runoff from Combined Catchments
38	Devil Canyon and Browns Canyon Wash	6,248.49	very large, very high runoff
26	Bell Creek	4,276.62	large, moderately high runoff
15	Dry Canyon	2,409.93	small, low runoff
32	Chatsworth Creek and Box Canyon	1,871.58	large, low runoff
16	Calabasas, Arroyo	1,808.81	small, low runoff
30	Dayton Creek	1,740.31	small, low runoff
6	Caballero Creek	1,533.72	small, low runoff
40	Limekiln Canyon Wash	1,404.19	small, low runoff
36	Santa Susana Pass Wash	1,211.91	small, low runoff
45	Bee Canyon	1,147.67	small, low runoff

and Dayton Creek drain into this area, which encompasses Bell Canyon Park and most The second noteworthy combined catchment is Bell Creek located to the southeast of Brown's Canyon, bordered by Las Virgenes Canyon Park to the south (Figure 19). Bell of Roscoe-Valley Circle Park in the eastern part of this focus area. The Bell Creek area, however, is considerably developed, has a lower capacity for direct infiltration than the Brown's Canyon focus area, and at present is subject to significant pollution problems.

Chatsworth Reservoir is a regionally significant habitat and recreational resource located between the Devil Canyon / Browns Canyon Wash (Figure 18) and Bell Creek (Figure 19) combined catchments. This facility is currently not utilized to hold water due to a long-standing trepidation about its ability to withstand an earthquake. The reservoir is also said to have a bottom clay layer as part of its construction (Blevins, personal communication, 2007). The reservoir lies within the Chatsworth Reservoir Creek and Box Canyon combined catchment (Figure 17), a large catchment area that ranks within the top 10 combined catchments in terms of total rainy season precipitation and potential for infiltration and runoff (Tables 7, 8 and 9).

Flow Accumulation Analysis

To finalize a representation of the surface water flow within the RSA study area, the hydrologic analysis functions in ArcGIS 9.2 Spatial Analyst were utilized to assist in modeling the movement of water across the study area surface. The surface flow modeling included overland flow direction and surface flow accumulation calculations using the spatial datasets discussed above as input. The purpose of creating a flow direction layer is to know where the water is going as well as where it came from. The newly

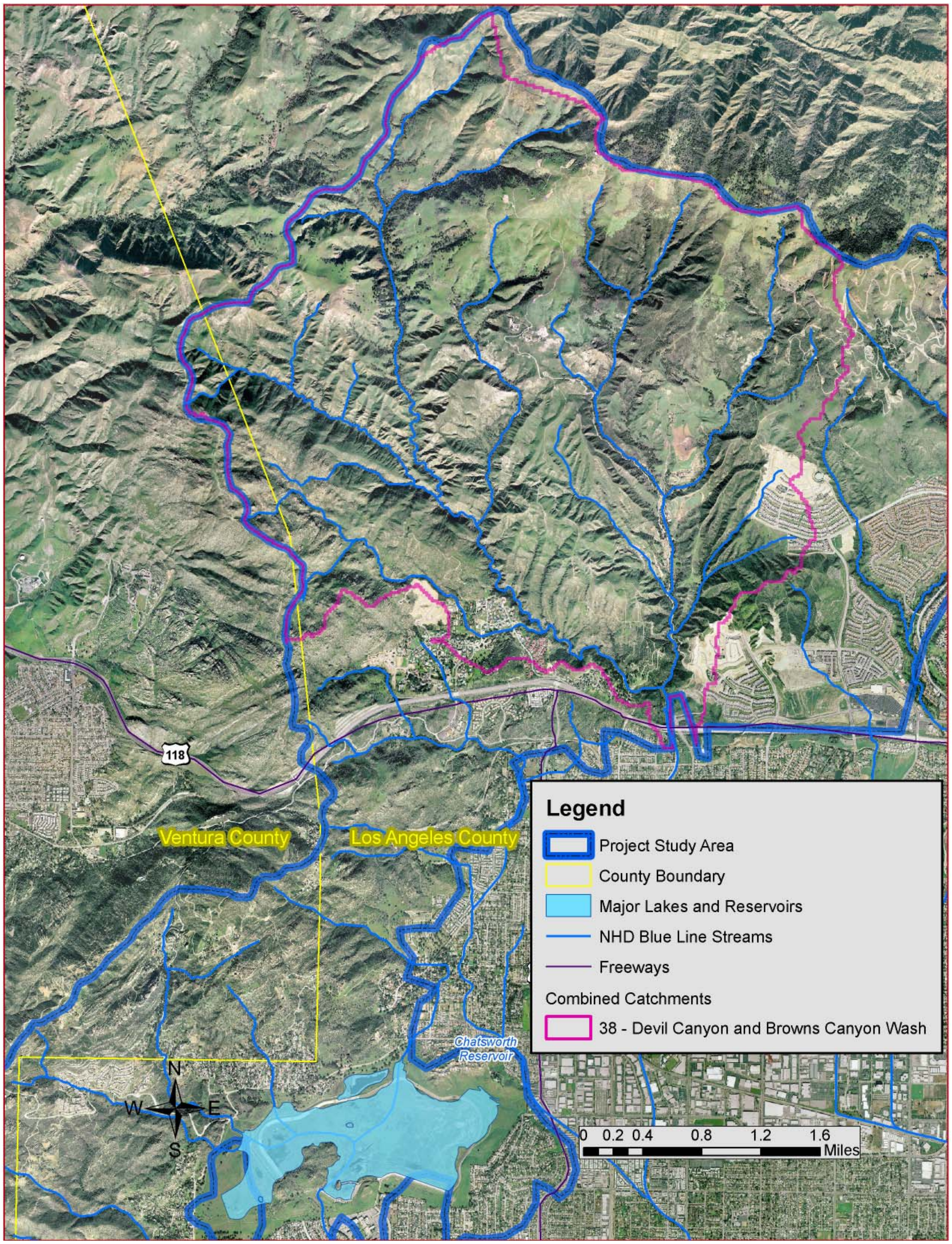

Figure 18. Detailed view of Brown's Canyon focus area, overlain on 2005 aerial imagery.

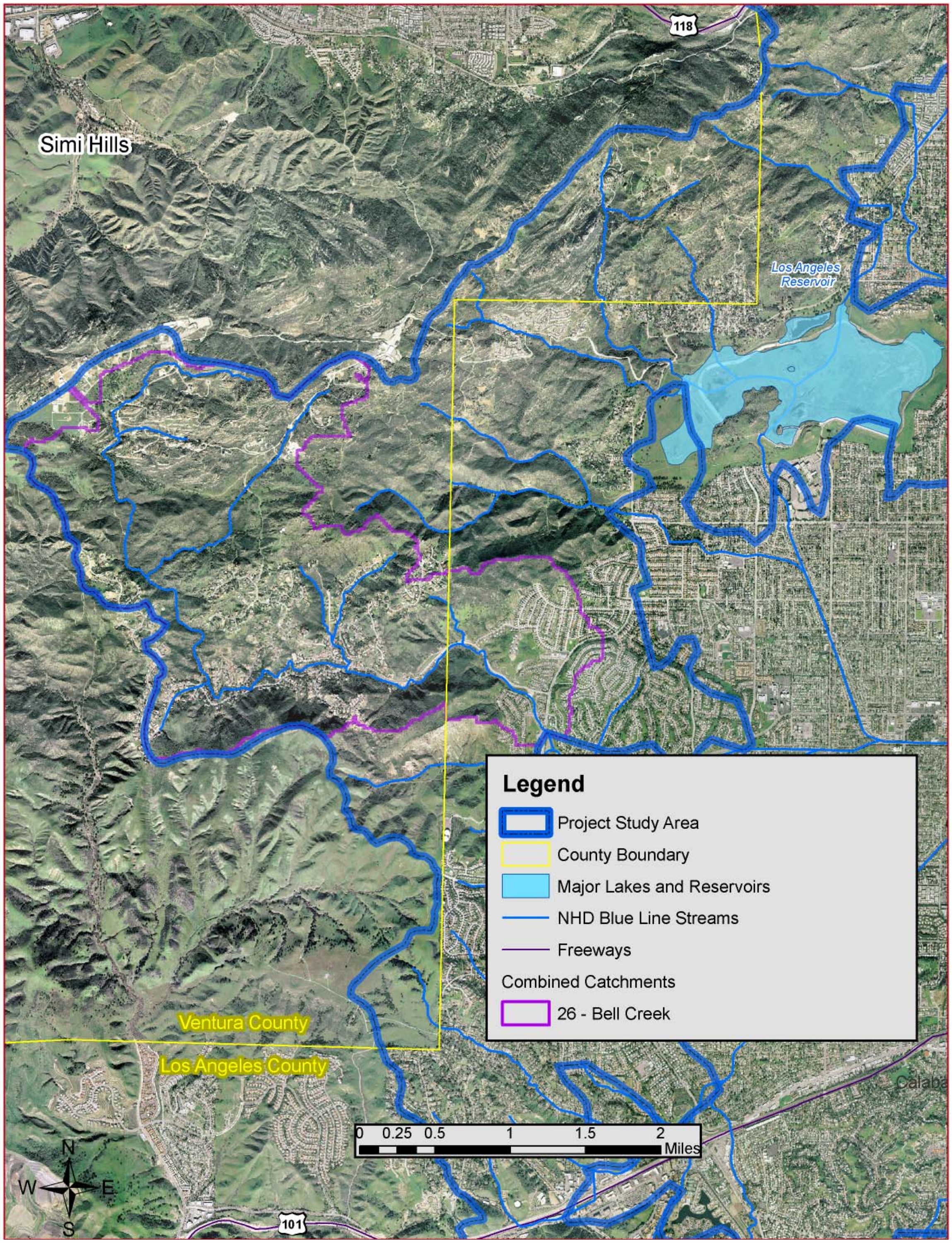

Figure 19. Detailed view of Bell Canyon and Bell Creek focus area, overlain on 2005 aerial imagery.

generated flow direction layer is then used as input into the flow accumulation analysis. These calculations are discussed in detail below.

Flow Direction

The first step in modeling the flow accumulation involves determining the flow direction of surface water over the RSA study area. To perform the flow direction calculation, the 10 m DEM must be equivalent in area (identical spatial coverage) to the runoff layer. The runoff layer (Figure 14) was used as a mask to extract a subset of the DEM which exactly matched the study area runoff layer. Using the subset of the 10 m DEM as input, the ArcGIS 9.2 Flow Direction tool was then used to create a raster layer of flow direction from each cell to it's steepest downslope neighbor. The direction of flow is determined by finding the direction of steepest descent (maximum drop) from each cell (Jenson and Domingue, 1988). Each pixel (cell) is assigned a flow path to one of its adjacent or diagonal neighbors, in the direction of the steepest downward slope.

Flow Accumulation

The second step in the flow accumulation modeling consisted of utilizing the ArcGIS 9.2 flow accumulation function to create a raster of accumulated flow to each cell. This is accomplished by summing the runoff from all the cells that flow into each downslope cell in the output raster. Thus the flow accumulation value of each cell represents a compounded estimate of the quantity of runoff that ends up on each cell from upstream. The input data include the newly generated flow direction layer and the mean rainy season runoff layer (Figure 14). The latter is converted to acre feet then used as a weight raster in the flow accumulation analysis, to determine where most of the water that did not infiltrate (i.e. runoff) ends up.

The result of the flow accumulation calculation for each combined catchment is provided in Figure 20. The green and blue shades indicate higher rainfall runoff volumes. This process assumes that there was no evapotranspiration, or further interception (due to either land use or cover or the runoff encountering further imperviousness) or loss to groundwater (due to direct infiltration or man-made diversions). Cells with a high flow accumulation represent areas of concentrated flow, such as streams. Cells with a value of zero represent topographic highs when the precipitation fell to the ground surface. It is important to bear in mind that the Direct Infiltration analysis that produced the input weight runoff layer already took into account interception, soil type, and loss to groundwater in terms of direct infiltration when the precipitation fee to the ground surface.

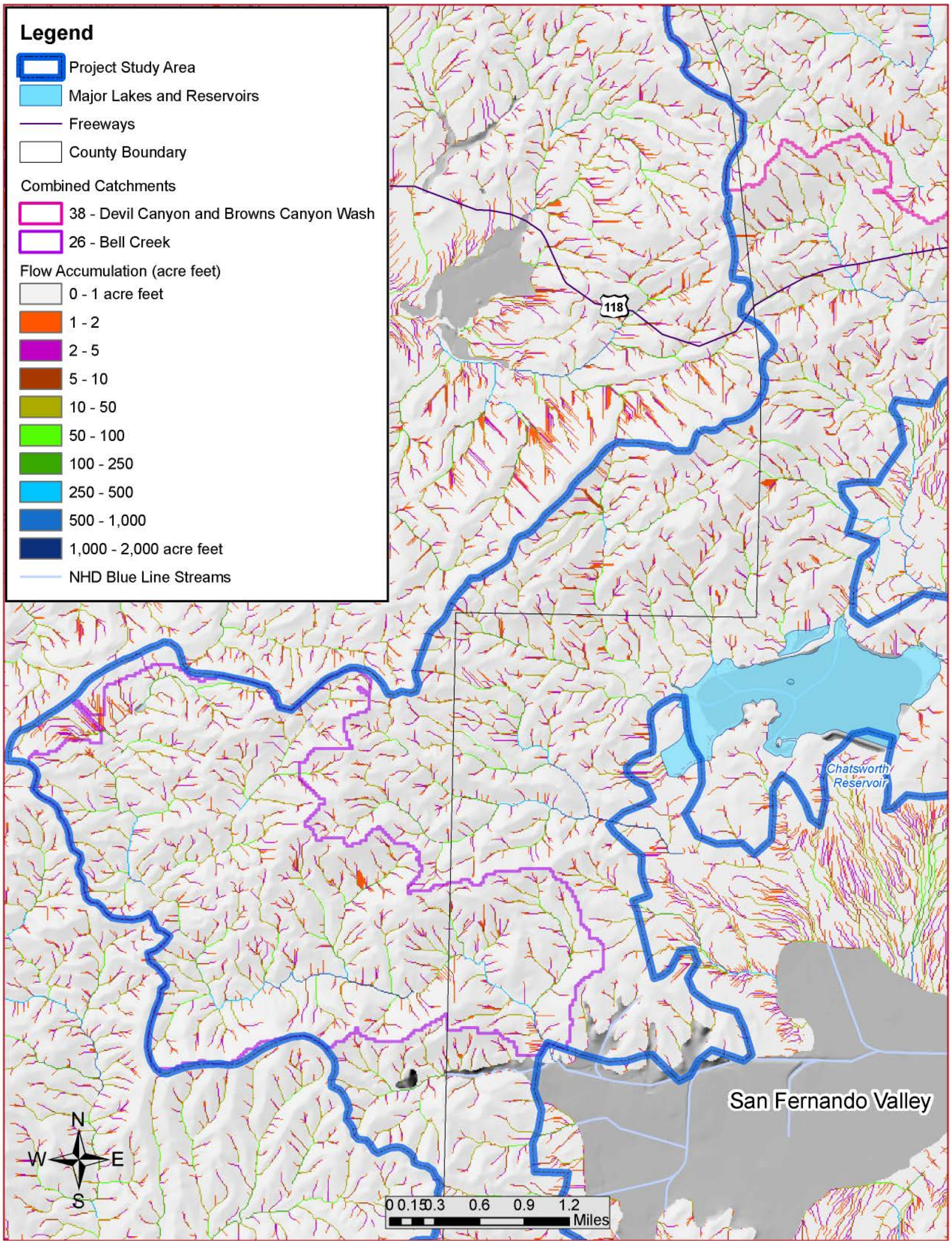

Figure 20. The runoff accumulation within the study area during the rainy season, representing the amount of the rain that fell on each cell and was converted to runoff plus the runoff from upslope cells. Close up view of the Bell Creek Tributary and Chatsworth Reservoir area overlain on a 10 meter digital elevation model.

Flow Accumulation By Catchment

In order to ascertain which catchments within the study area posses the greatest potential for runoff accumulation, the rainy season flow accumulation analysis results associated with each of the 46 combined catchments are provided in Table 11. The top 10 combined catchments with the greatest estimated mean accumulated runoff are highlighted in blue. The average amount of runoff flow accumulation during the rainy season can range between of 0.38 to 5.24 feet in the combined catchments. Table 12 provides a summary of the top 10 combined catchments in terms of relative size and total accumulated runoff. The most promising combined catchments are those which possess the highest potential for direct infiltration, surface runoff, and lastly concentrated runoff. Though the Caballero and Dayton Creek tributaries exhibit the greatest mean flow accumulation, the Devil Canyon / Browns Canyon Wash and Bell Creek outlets still rank in the top 10 in terms of total accumulated flow, as do Chatsworth Creek and Box Canyon combined catchments.

Evapotranspiration

Interception and evapotranspiration are known to reduce the volume of water available for infiltration and runoff. These volumes can be expected to vary spatially and temporally. Spatially, it is anticipated that evapotranspiration will be different with respect to south-versus north-facing slopes. Temporally, evaporation will be greatest on hot, windy, dry days, and will be greatly reduced when air is cool, calm, and humid.

In order to roughly approximate evapotranspiration in the RSA study area, reference and pan evapotranspiration values were obtained from the Ventura County Watershed Protection District (VCWPD), Los Angeles County Department of Public Works (LADPW), and the California Irrigation Management Information System (CIMIS). Data was obtained from 33 measurement stations located near the RSA study area. The 11 CIMIS stations provided daily reference evapotranspiration data, while the 22 LADPW and VCWPD stations recorded monthly pan evapotranspiration. Reference evapotranspiration is considered evapotranspiration from standardized grass (ETo) and/or alfalfa (ETr) surfaces. These values are calculated using the modified Penman (also known as the CIMIS Penman) and the Penman-Monteith equations. Most CIMIS weather stations are located on actively growing grass. Pan evaporation is a measurement that combines or integrates the effects of several climate elements: temperature, humidity, solar radiation, and wind, and can be used to estimate reference evapotranspiration (Allen et al., 1998).

Evapotranspiration values from the 33 stations for each month were averaged and interpolated using the ArcGIS 9.2 Spatial Analyst kriging tool, producing raster surfaces depicting the estimated number of inches of evapotranspiration per month. Significant temporal variation in evapotranspiration across the study area could not be identified using these values. To illustrate, the average rainy season (October to April)

Table 11. Results of flow accumulation analysis. Tributary Numbers correspond to Figure 16.

Tributary Number	Tributary Name	Combined Catchment Area (acres)	Mean Flow Accumulation within Combined Catchments (acre feet)
0	Not included in a Combined Catchment	2,537	0.99
1	Encino Creek	123	0.59
2	Encino Creek	21	0.49
3	Encino Reservoir	941	2.01
4		50	0.58
5	Caballero Creek	162	1.39
6	Caballero Creek	1,284	5.24
7		80	2.91
8		678	2.07
9		193	1.43
10		195	1.24
11		161	1.58
12		389	1.57
13		283	2.15
14		288	3.04
15	Dry Canyon	1,757	3.25
16	Calabasas, Arroyo	1,348	3.58
17		463	1.94
18		152	0.74
19		578	0.69
20		168	0.55
21	Calabasas, Arroyo	55	0.83
22		435	1.12
23		143	2.09
24		163	1.01
25		520	1.62
26	Bell Creek	3,655	3.91
27		158	0.38
28		196	0.55
29	Bell Creek	29	0.50
30	Dayton Creek	1,373	4.50
31	Woolsey Canyon	526	1.99
32	Chatsworth Creek and Box Canyon	2,293	1.72
33	Santa Susana Pass Wash	72	0.70
34		316	3.22
35		389	1.92
36	Santa Susana Pass Wash	1,076	3.94
37		232	1.39
38	Devil Canyon and Browns Canyon Wash	8,332	2.85
39		365	1.19
40	Limekiln Canyon Wash	1,943	2.16
41	Aliso Canyon Wash	842	1.33
42	Aliso Canyon Wash	124	1.13
43	Aliso Canyon Wash	130	0.98
44	Bull Canyon	142	0.59
45	Bee Canyon	1,253	1.85
46		830	3.28

Table 12. Flow accumulation analysis results in terms of size of combined catchments and total potential accumulated flow.

Tributary Number	Tributary Name	Combined Catchment Area (acre)	Relative Accumulated Flow in Combined Catchments
38	Devil Canyon and Browns Canyon Wash	8,332	very high flow accumulation
26	Bell Creek	3,655	moderately high flow accumulation
6	Caballero Creek	1,284	high flow accumulation
30	Dayton Creek	1,373	high flow accumulation
15	Dry Canyon	1,757	low flow accumulation
16	Calabasas, Arroyo	1,348	low flow accumulation
36	Santa Susana Pass Wash	1,076	low flow accumulation
40	Limekiln Canyon Wash	1,943	low flow accumulation
32	Chatsworth Creek and Box Canyon	2,293	low flow accumulation
46		830	low flow accumulation

evapotranspiration is provided in Figure 21. Though spatial variation in evapotranspiration was anticipated, none can be identified. The results erroneously indicate there is no significant spatial variation with respect to evapotranspiration across the RSA study area. Since the closest data input location is approximately 1.7 km south-west of the RSA study area and it heavily influences the interpolated surface, it is recommended that additional input data be collected and used to further refine the evapotranspiration analysis before integrating evapotranspiration results into the rainfall, runoff and infiltration analyses.

An additional analysis was performed to simulate the effects of vegetation, referred to as root-zone water capacity, on the fate of precipitation (Thornwaithe and Mather, 1957; Braun et al., 2003). The amount of water held in the soil's root zone can be used as a proxy to estimate evapotranspiration, and any water below the root zone is assumed to become recharge. The root-zone water capacity (RWC) is multiplied by the estimated maximum root depth and the available water capacity (AWC), with this approach as follows:

$$\text{RWC (in)} = \text{Root Depth (feet)} \times \text{AWC (inches/feet)} \qquad \text{Eq. 1}$$

The optimal method involves obtaining root depths for all vegetation types occurring in the study area, taking variation in soil texture into account. The CALVEG dataset summarizes the vegetation of the RSA study area (CDFFP, 2003). Mature root depths for each type of vegetation were approximated based on published values for Mediterranean climates (Hellmers et al., 1955; Kummerow et al., 1977; De Baets et al., 2007; Rome, 1977; Padilla and Pugnaire, 2007; Gordon and Rice, 1992; USDA, 2008). Detailed information on the root depths of each vegetation type for every soil texture occurring in the study area is not readily available, so a simple matrix was compiled listing maximum

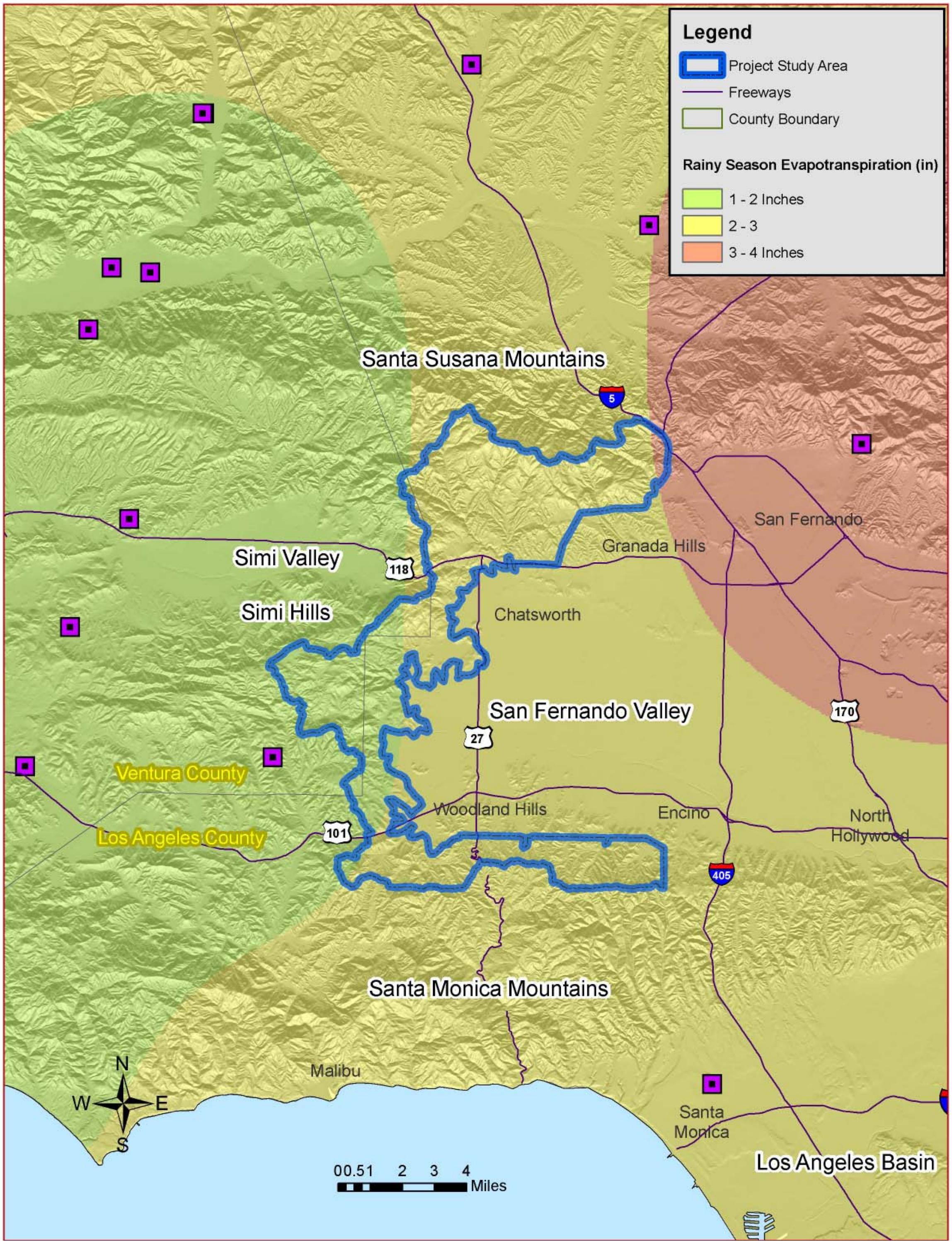

Figure 21. Evapotranspiration data obtained from 33 stations surrounding the RSA study area. Only the stations closest to the study area are shown. Overlain on 10 m digital elevation model.

root depths for the different types of vegetation. The next step of the analysis involved using the SSURGO Soil Data Viewer (NRCS, 2007d) to generate the AWC map of the RSA study area. Equation 1 was then used to calculate the RWC using ArcGIS 9.2. This rough approximation reveals that the RWC may range from 0 to up to 182 inches in the RSA study area, as illustrated in Figure 22, and gives a rough guide to the spatial variability of evapotranspiration across the study area.

These results have several important implications. The first is to note that the higher estimates are fictitious, since the evapotranspiration cannot exceed the precipitation from one growing season to the next unless springs and other features bring additional water back to the surface where plants can access it. The second point worth noting is the spatial variability, which shows the significance and variability of the loss of water across the study area. The third and probably most important point worth noting for the task at hand is that the evapotranspiration from the vegetation cover will substantially reduce the surface runoff and groundwater recharge in most years. Some additional site-specific data would need to be collected and analyzed to explore these relationships further. If more comprehensive information was available regarding the spatio-temporal variability of precipitation and infiltration as well as the variability of vegetation root depth with respect to soil type, more detailed AWC root depth maps could be compiled and used to generate the RWC layer. The comprehensive RWC map could then be used to estimate recharge potential by subtracting RWC (i.e. Figure 22) from the potential infiltration capacity (Figure 13) as follows:

$$\text{Recharge Potential} = \text{Total Rainy Season Infiltration} - \text{RWC} \qquad \text{Eq. 2}$$

This raster calculation would remove the volume of water that may transpire from the estimated total volume of water that has the potential to infiltrate in-situ during the rainy season. The result would provide a volume estimation of recharge potential and thus the opportunity to identify and compare areas of lower versus higher recharge potential at a local (i.e. site-specific) scale.

Slope and Siting Suitable Recharge Areas

The results of the infiltration and runoff estimations indicate that the most promising combined catchments are those that are the largest (associated with the longest tributary reaches) and possess the highest potential for direct infiltration (Tables 7 - 12). In order to further refine these findings, it is important to determine the best existing locations for collecting runoff and enhancing natural infiltration opportunities. The following close examination of the spatial variability of slope within the RSA study area augments the catchment-based infiltration, rainfall and runoff results by drilling down to the level of individual stream segments.

Slope is a critical factor in siting infiltration basins. As previously mentioned in the Slope/Soil Infiltration Analysis discussion, the speed at which water runs off a soil is

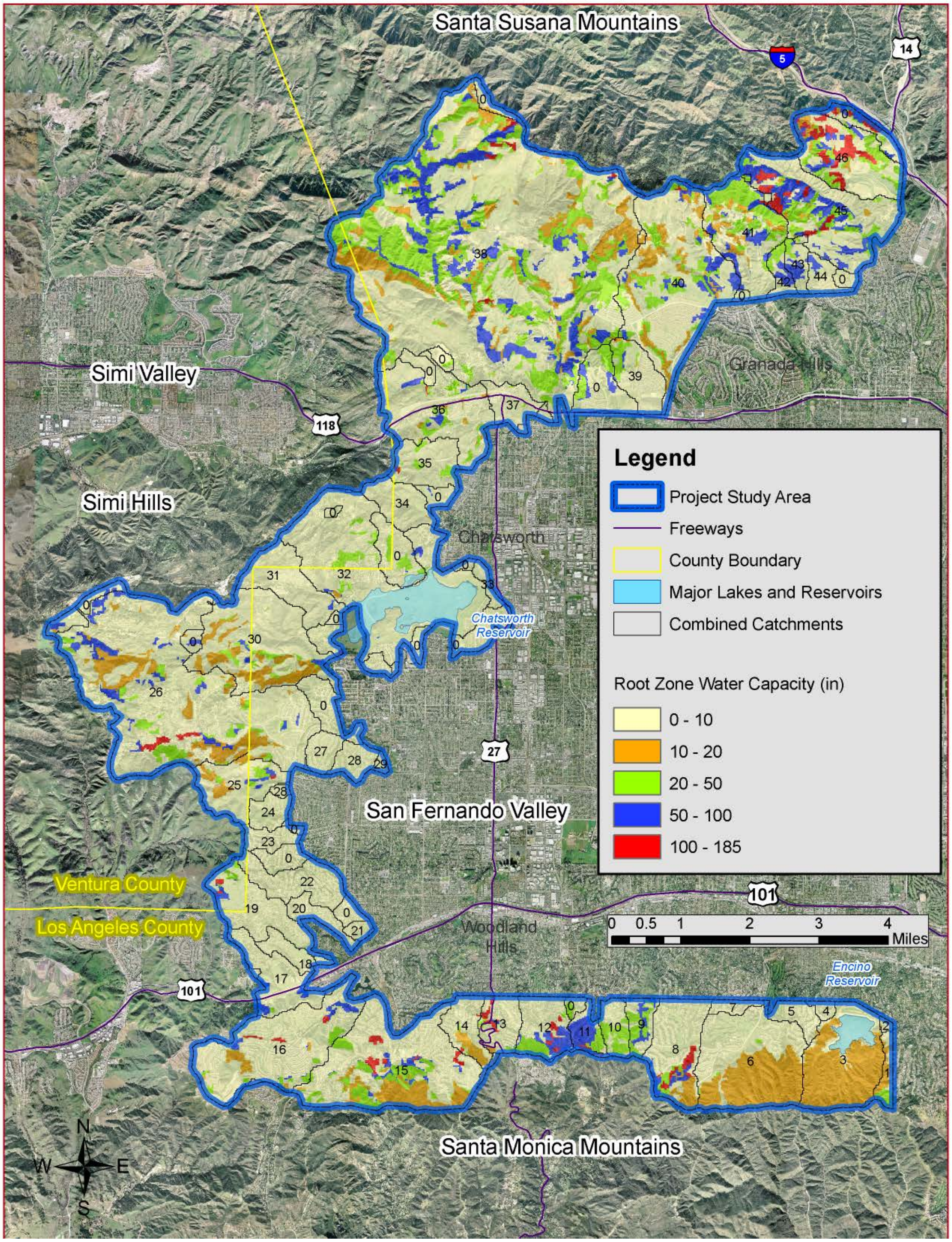

Figure 22. Estimated root-zone water capacity (RWC) for the RSA study area.

directly related to the slope of the land it flows over, which strongly influences infiltration or percolation, runoff, runoff accumulation, and erosion (i.e. de Vries and Simmer, 2002). In terms of slope, the goal in determining the best locations for utilizing existing land for recharge is to identify catchments where water can most easily spread out over a large area in a thin layer that flows downhill slowly and infiltrates into the surficial soils with limited runoff and erosion. Slope is the primary criterion for the design of Best Management Practice (BMP) recharge impoundments (LADPW, 2002; CASQA, 2003). The current literature varies in terms of recommended slope for siting infiltration areas. For instance, siting criteria provided in the California Stormwater BMP Handbook (CASQA, 2003) and by Burkett and Wong (2005) advises an upper limit of 15% slope, while the Los Angeles County Urban Storm Water Mitigation Plan (LADPW, 2002) specifies a slope of 5% or less. As an example in practice, the findings of one recharge suitability study conducted in a semi-arid region indicated that spreading grounds should have a slope of less than 3%, based on experience with numerous flood spreading stations (Ghayoumian et al., 2005). These values coincide with those utilized to generate the slope classes in the Direct Infiltration Analysis (Table 4) that were applied to the RSA study area (Figure 7). Utilizing the slope classes defined in Table 4, optimal recharge areas previously identified within the combined catchments can be further refined by focusing on the slope of the stream segments themselves as well as the surrounding land surface.

Table 13 provides a summary of the total area within each of the combined catchments according to slope class. The top five combined catchments determined to be very suitable to suitable in terms of slope class are indicated in green, with the totals for 0-2% and 2-4% highlighted in red. In order to better delineate where the most suitable areas are located, Table 14 summarizes the number and lengths of stream segments according to slope class occurring in each combined catchment (Figure 23). The top 5 combined catchments with the greatest total length of stream segments in slope classes 0-2% and 2-4% in are shown in green in Table 14. In order to determine where 0-4% slope of the land surface occurs within 500 ft of stream segments in the same slope class range, a 500 ft buffer drawn around each stream segment was used to extract the land surface (area) from the overall slope dataset (Figure 7). Table 15 provides a summary of the total land surface area with respect to combined catchment with less than or equal to 4% slope within 500 ft of a stream segment in slope class 0-2% or 0-4%. The top 10 with respect to 0-4% slope land surface area are highlighted in green. Figure 23 provides an example close-up view of a portion of the study area, illustrating exactly where the stream segments in each slope class occur within the combined catchments, and the localized areas where the slope of the land surface adjacent to stream segments in slope classes 0-4% occur (red). A few gaps occur in tributaries (segments depicted by slope class) shown in Figure 23 in cases where there is limited slope information for a given stream segment.

Table 13. Total area in acres within each combined catchment containing a given slope class.

Tributary Number	Tributary Name	Slope Class 0 - 2%	Slope Class 2 - 4 %	Slope Class 4 - 12%	Slope Class > 12%
0	Not included in a Combined Catchment	146.89	233.17	855.14	1,280.03
1	Encino Creek	0.02	0.15	4.25	117.62
2	Encino Creek	0.07	0.32	3.06	17.24
3	Encino Reservoir	**98.03**	**17.22**	126.22	698.07
4		0.17	0.32	8.55	40.61
5	Caballero Creek	2.15	8.40	55.48	95.76
6	Caballero Creek	10.84	34.28	215.56	1,023.12
7		1.80	3.01	31.20	43.45
8		2.62	10.67	137.75	527.20
9		0.42	1.51	24.90	166.01
10		1.56	5.01	37.84	149.95
11		3.11	8.89	36.36	112.16
12		2.40	9.56	118.31	258.04
13		6.87	13.76	75.36	186.63
14		2.67	11.61	78.05	195.33
15	Dry Canyon	24.60	67.28	388.73	1,275.26
16	Calabasas, Arroyo	23.02	68.84	345.63	910.49
17		27.27	35.30	140.52	259.47
18		15.09	13.49	48.49	75.04
19		21.66	68.07	235.64	252.41
20		18.11	28.95	75.19	46.24
21	Calabasas, Arroyo	9.34	14.30	22.30	8.79
22		20.38	57.03	184.29	171.67
23		3.06	16.57	40.11	83.51
24		1.28	7.58	30.31	122.71
25		8.89	13.61	80.67	417.83
26	Bell Creek	**48.81**	**139.38**	881.32	2,586.93
27		7.51	11.86	72.54	66.15
28		12.77	16.65	67.26	98.18
29	Bell Creek	2.91	3.53	7.56	14.52
30	Dayton Creek	16.67	41.20	320.16	993.76
31	Woolsey Canyon	3.19	10.99	131.18	381.42
32	Chatsworth Creek and Box Canyon	**554.24**	**175.74**	598.28	962.16
33	Santa Susana Pass Wash	20.08	5.11	16.70	27.52
34		1.24	5.46	52.69	255.67
35		10.00	15.26	92.35	271.38
36	Santa Susana Pass Wash	**65.95**	**70.91**	271.26	668.21
37		13.54	23.71	106.04	88.55
38	Devil Canyon and Browns Canyon Wash	**41.69**	**142.07**	1,296.13	6,852.55
39		7.43	16.82	134.57	205.70
40	Limekiln Canyon Wash	10.84	60.91	370.77	1,497.31
41	Aliso Canyon Wash	1.26	4.47	53.80	782.45
42	Aliso Canyon Wash	0.02	0.32	8.94	114.44
43	Aliso Canyon Wash	0.12	0.40	12.35	117.65
44	Bull Canyon	0.30	0.84	15.36	125.25
45	Bee Canyon	2.15	10.23	115.23	1,124.22
46		2.27	7.63	79.51	739.59
Total		**1,275.34**	**1,512.41**	**8,103.87**	**26,508.24**

Table 14. Total length (km) and total number of stream segments for a given slope class per combined catchment.

Tributary	Tributary Name	0-2% Slope Class # Segments	0-2% Slope Class Length (km)	2-4% Slope Class # Segments	2-4% Slope Class Length (km)	> 4% Slope Class # Segments	> 4% Slope Class Length (km)
1	Encino Creek					1	2.36
2	Encino Creek			1	0.94		
3	Encino Reservoir			1	3.68	5	4.52
4				1	4.84		
5	Caballero Creek					1	1.15
6	Caballero Creek	3	2.80	3	0.62	6	9.72
7				1	1.63		
8		1	5.73			2	2.65
9				1	6.62		
10						1	1.54
11						1	1.43
12				1	4.24		
13						1	1.67
14						1	2.40
15	Dry Canyon	2	4.14	4	3.20	7	7.85
16	Calabasas, Arroyo	5	3.47	2	3.34	2	1.33
17		1	2.85				
18		1	1.10				
19				1	3.44		
20		3	1.89				
21	Calabasas, Arroyo	1	0.64				
22				1	4.89		
23						1	1.47
24				1	2.48		
25						1	2.36
26	Bell Creek	2	3.61	4	3.61	13	11.44
27				1	1.13		
28		1	1.09				
29	Bell Creek	1	1.29				
30	Dayton Creek	1	2.60			4	5.99
31	Woolsey Canyon					3	3.48
32	Chatsworth Creek and Box Canyon	2	1.79			4	5.79
33	Santa Susana Pass Wash	1	2.46				
34						1	2.20
35		1	1.11			2	1.89
36	Santa Susana Pass Wash	1	1.53	2	1.63	5	4.78
37		1	0.94	1	0.42	1	0.46
38	Devil Canyon and Browns Canyon	5	9.89	5	3.35	29	44.47
39						1	2.87
40	Limekiln Canyon Wash	1	5.86			4	11.23
41	Aliso Canyon					2	4.14
42	Aliso Canyon					1	1.66
43	Aliso Canyon					1	1.95
44	Bull Canyon					1	3.23
45	Bee Canyon			1	3.31	2	3.81
46				1	0.89	4	5.33
Total		**34**	**55**	**33**	**54**	**108**	**155**

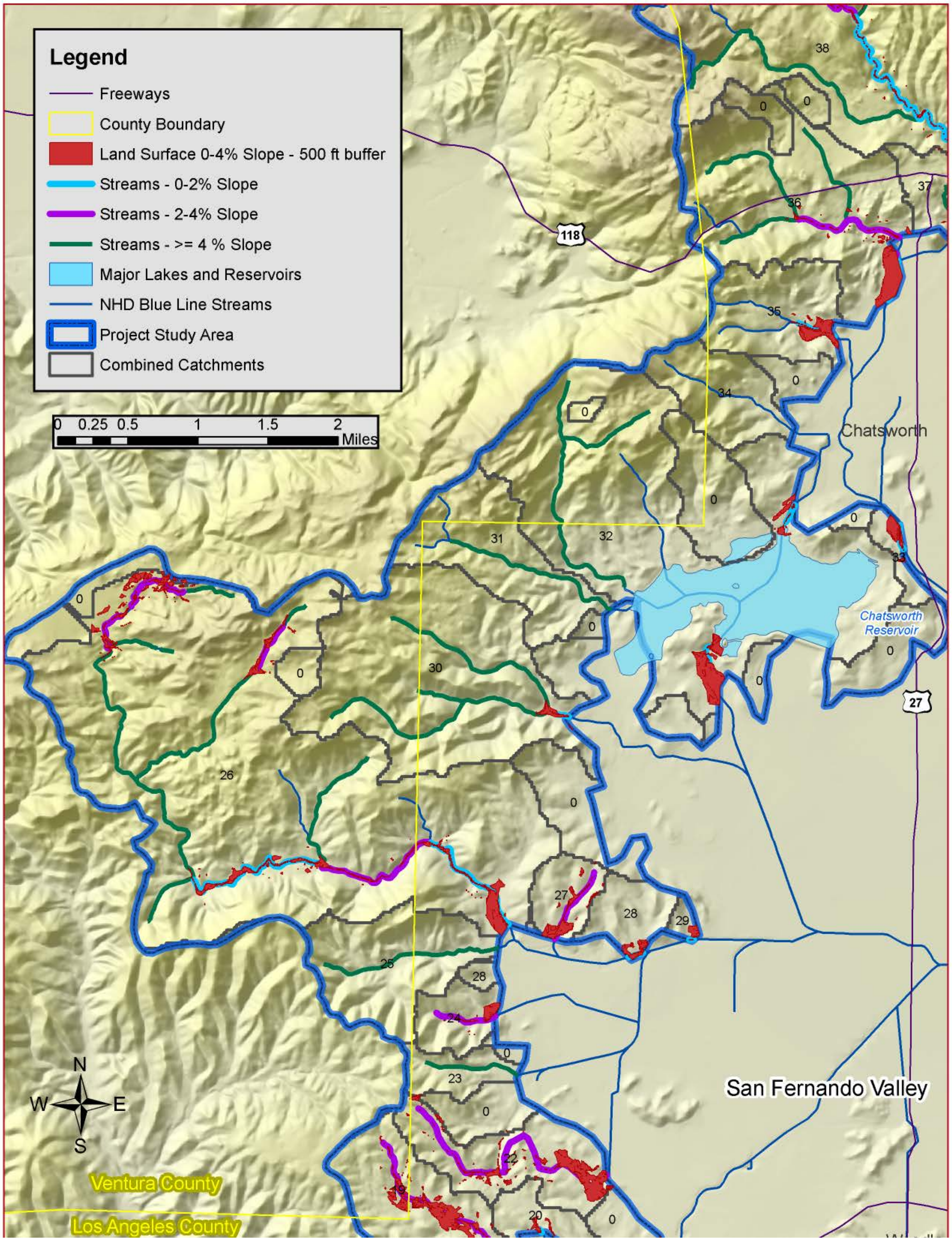

Figure 23. NHD Blue Line Streams delineated according to % slope and % slope of the land surface within 500 ft of 0-4% slope stream segments. Close up view of the Bell Creek Tributary and Chatsworth Reservoir area overlain on a 10 meter digital elevation model.

Table 15. Total land area (acres) in each combined catchment with less than or equal to 4% slope, within 500 ft of a stream segment in slope class 0-2% or 0-4%.

Tributary	Tributary Name	Total area (acres) within 500 ft of stream segment	
		0-2% slope class	0-4% slope class
0		0.9	8.5
2	Encino Creek		0.2
3	Encino Reservoir		5.9
4			0.1
5	Caballero Creek	1.3	4.0
6	Caballero Creek	2.5	13.5
7		0.1	0.9
8		1.0	5.5
9			1.0
12			5.1
13			0.1
15	Dry Canyon	13.1	38.7
16	Calabassas, Arroyo	11.5	64.5
17		19.6	39.7
18		2.9	6.9
19			52.2
20			9.7
21	Calabassas, Arroyo		9.7
22			42.4
23			0.2
24			6.6
26	Bell Creek	17.5	70.9
27			12.1
28		2.7	5.9
29	Bell Creek	1.0	3.0
30	Dayton Creek	1.8	5.0
32	Chatsworth Creek and Box Canyon	18.9	38.9
33	Santa Susana Pass Wash	7.1	9.3
35		7.7	17.1
36	Santa Susana Pass Wash	31.1	44.1
37		1.7	5.8
38	Devils Canyon and Browns Canyon Wash	3.6	17.3
39			0.1
40	Limekiln Canyon Wash	0.3	1.0
45	Bee Canyon		4.6
46			1.2

Thus the results of this slope analysis indicate that numerous combined catchments are promising for siting recharge impoundments, first in terms of the total length of 0-2% and 2-4% slope stream segments, and second in regards to land surface area containing these lowest slope classes. The three combined catchments - Devil Canyon and Brown's Canyon Wash (38), Bell Creek (26), and Chatsworth Creek and Box Canyon (32) - highlighted in the Direct Infiltration, Runoff and Accumulation Analyses, feature prominently in the results summarized in Table 15 as well.

Conclusions

This Recharge Suitability Analysis project was carried out within a study area designated within the headwaters of the Los Angeles River and encompassing portions of the Santa Susana Mountains, the Simi Hills, and the Santa Monica Mountains (Figure 2). The RSA basically consisted of two larger components, referred to as the Direct Infiltration Analysis and the Flow Accumulation Analysis.

To begin the Direct Infiltration Analysis, monthly mean rainfall surfaces were generated using monthly rainfall totals recorded between December 1976 and December 2006, using the ANUSPLIN interpolation routine (Figure 4). It turns out that roughly 88% of the rainfall volume falling on the study area is received between October and April. Thirty years of hourly rainfall data was used to assess the frequency at which predefined thresholds of intensity were surpassed by the rainfall (Figure 5), which were then related to the infiltration capacities of the soil types found within the study area (Figure 6). Other input data layers were generated, including percent slope (Figure 7), catchment boundaries (Figure 11), and evapotranspiration (Figures 21 and 22). A raster layer was created which expressed the adjusted infiltration rates within the study area, taking into account both slope and soil type (Figure 8). These layers as well as the LADPW percent imperviousness layer (Figure 10), which incorporates SCAG land use information, were then integrated into a Rainfall and Runoff Analysis, all part of the Direct Infiltration Analysis.

In order to illustrate where the most direct infiltration and runoff are occurring on a catchment basis, previously defined catchments (Figure 11) were grouped according to tributary reach (Figure 16). Estimates of total direct infiltration and runoff per combined catchment (in acre feet) were produced, in order to identify which groupings of catchments possess the highest potential for both direct infiltration and runoff (Figure 17). Out of a total of 64,796 acre feet of recorded rainfall falling in the RSA study area during the rainy season, 25,742 acre feet, or roughly 40% can be expected to infiltrate the surface, and 36,796 acre feet (57%) was predicted to leave the study areas as runoff (the exact proportion depends on local storage and/or evapotranspiration). Subsequently, a 10 m DEM was utilized as input into the flow direction analysis which finds the path of steepest decent from each cell in a raster, the first step of the Flow Accumulation Analysis. Flow accumulation provides a picture of the locations where the majority of the rainfall runoff is expected to accumulate, and an estimate of the volume. Some 0.38 to 5.24 acre feet of accumulated runoff may collect in a given combined catchment in an average year.

The average rainy season runoff and flow direction analysis results where then utilized in a final runoff accumulation analysis performed to determine the number of upslope cells flowing to a given location (Figure 20). In order to narrow down the best locations to focus on as potential recharge areas, an additional analysis of percent slope of stream segments as well as the land surface was performed since slope is an important recharge impoundment siting criteria. The latter analysis revealed relatively flat (0-4% slope) land surface areas within 500 feet of stream segments with the lowest slope (0-4%) within each combined catchment (Figure 23). Such areas could be further investigated for siting recharge impoundments, as opportunities where water can most easily spread out over a large area adjacent to stream segments with gentles slopes as well as infiltrate into the surficial soils. Summary tables of these results were compiled to allow a comparison or suitability ranking of the top combined catchments in terms of their relative potential for recharge (Tables 8, 10, 12 and 15).

According to the results of the various analyses including Rainfall and Runoff, Slope / Soil Infiltration Analysis, and Direct Infiltration and Flow Accumulation Analyses, the most suitable areas for recharge are the combined catchments which possess the highest potential for direct infiltration, runoff, and flow accumulation, and the lowest stream gradients with flat or nearly flat adjacent land area (Figure 23). The results show that some of these are also among the largest areas in extent, associated with the longest tributary reaches. The combined catchments considered the best candidates include Devil Canyon and Brown's Canyon Wash (Figure 18) and Bell Creek (Figure 19). Other combined catchments with significant potential for infiltration and/or runoff and the highest suitability in terms of land area and stream slope class may also warrant further investigation, include Chatsworth Creek and Box Canyon (32) which contains the Chatsworth Reservoir and Santa Susana Pass Wash (36) (Figures 20 and 23).

Last but not least, we need to note that there are four noteworthy limitations and shortcomings with the current analysis that would need to be addressed in order to use these analytical results as the basis for a site-specific groundwater management planning. First, the geospatial datasets utilized in the evapotranspiration portion of the analysis would need to be expanded in terms of spatial and temporal coverage, to be more effectively integrated into the infiltration and flow accumulation calculations. Second, additional data from bore logs or groundwater monitoring wells, and/or subsurface field investigations would need to be conducted to greater depths (i.e. > 100 feet) to effectively analyze the current groundwater flow conditions with a significant degree of confidence. Third, this study did not address current land use / land cover other than in terms of imperviousness and the resultant impact on infiltration and runoff. The water quality implications of current and future land uses would need to be characterized as well. Lastly, such a plan would need to consider return flow or recharge from artificial sources in addition to the precipitation considered in the current study.

Thus further investigations are recommended in the following areas:

- Consideration of the influence of evapotranspiration on infiltration and flow accumulation, based on more detailed input data collected from within the RSA study area,

- Consideration of water quality as a critical factor in the characterization of suitable locations for groundwater recharge from natural and/or artificial sources,
- Consideration of recharge from artificial sources into streams and aquifers, and
- Consideration of the effect, if any, of temporal variation of infiltration, runoff, and infiltration of run-on, across the study area.

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List of Terms

Abbreviation	Term	Description
ANUSPLIN	ANUSPLIN Software Package	Australian National University. Price et al., 2000, Hutchinson, 2004.
ArcGIS 9.2	Desktop Geographic Information Software, Version 9.2	A group of geographic information system software product lines produced by Environmental Systems Research Institute (ESRI; http://www.esri.com/).
ASCII	American Standard Code for Information Interchange	ASCII is a code used in computers, communications equipment, etc. for representing English characters as numbers, with each letter assigned a number from 0 to 127 (http://www.webopedia.com/TERM/A/ASCII.html).
AWC	Available Water Capacity	The amount of water that an increment of soil depth, inclusive of fragments, can store that is available to plants. (http://soildatamart.nrcs.usda.gov/documents/SSURGOMetadataTableColumnDescriptions.pdf)
BMP	Best Management Practice	Any method for controlling, removing, preventing, or reducing pollution.
CASQA	California Stormwater Quality Association	CASQA assists the State Water Resources Control Board (SWRCB) and municipalities throughout the state of California in implementing the National Pollutant Discharge Elimination System (NPDES) stormwater mandates of the Federal Clean Water Act (http://www.casqa.org/about/what.php).
CDFFP	California Department of Forestry and Fire Protection	Vegetation data consistent across all ownerships for assessing current conditions, monitoring changes over time, and determining management options. Polygons were derived from LANDSAT TM imagery. Each polygon is assigned a Wildlife Habitat Relationship (WHR) and CALVEG species, crown closure class, tree size class, and other attributes. http://gis.ca.gov/catalog/BrowseRecord.epl?id=1773
CIMIS	California Irrigation Management Information System	A program in the Office of Water Use Efficiency (OWUE), California Department of Water Resources (DWR) that manages a network of automated weather stations in the state of California (http://wwwcimis.water.ca.gov/cimis/welcome.jsp).
CSUN	California State University Northridge	18111 Nordhoff Street, Northridge, CA 91330 (www.csun.edu).
DEM	Digital Elevation Model	Gray scale images of the elevation of an area, wherein the pixel values are actually elevation is above mean sea level, coordinated to world space (longitude and latitude) (http://www.pcmag.com/).
ETo	Evapotranspiration (ET) from standardized grass	Evapotranspiration from a standardized grass surface (http://www.cimis.water.ca.gov/cimis/infoEtoOverview.jsp)
ETr	Evapotranspiration (ET) from standardized alfalfa	Evapotranspiration of a well-watered, actively growing, alfalfa surface (http://www.cimis.water.ca.gov/cimis/infoEtoOverview.jsp).
FAO	Food and Agriculture Organization	United Nations agency whose objective is to improve nutrition and eliminate hunger by increasing agricultural productivity (http://www.fao.org/).
LADPW	Los Angeles County Department of Public Works	Responsible for the construction and operation of Los Angeles County's roads, building safety, sewerage, and flood control works (http://dpw.lacounty.gov/PRG/DeptOverview/index.cfm).
LULC	Land use/Land Cover	Land use generally refers to modification of the natural environment or wilderness where land use refers to the “natural” vegetation cover (http://en.wikipedia.org/wiki/Land_use).

Abbreviation	Term	Description
Map Algerbra	An informal computer language for manipulating representations of continuous variables defined over a common domain.	Map algebra uses boolean logic to create new features and attribute relations by overlaying the features from two input map layers. Features from each input layer are combined to create new output features (http://en.mimi.hu/gis/map_algebra.html).
MRT	Mountains Restoration Trust	A California Public Benefit Nonprofit Organization committed to preserving, protecting and enhancing the natural resources of the Santa Monica Mountains in the County of Los Angeles, California(http://mountainstrust.org/).
NHD	National Hydrography Dataset	Comprehensive set of digital spatial data produced by the USGS that contains information about surface water features such as lakes, ponds, streams, rivers, springs and wells (http://nhd.usgs.gov/).
NOAA	National Climatic Data Center	An organization within the Department of Commerce and the National Environmental Satellite, Data and Information Service (NESDIS), managing the Nation's resource of global climate and weather related data and information in order to assess and monitor climate variation and change (http://www.ncdc.noaa.gov/).
NRCS	Natural Resources Conservation Service	A Federal agency that works to conserve and sustain natural resources (lwww.nrcs.usda.gov).
RSA	Recharge Suitability Analysis	A land suitability analysis aimed at identifying and delineating potential groundwater recharge areas.
RWC	Root-zone Water Capacity	The amount of water held in the soil's root zone. Used as a proxy to estimate evapotranspiration, where any water below the root zone is assumed to become recharge.
SCAG	Southern California Association of Governments	Develops long-range regional plans, strategies and information that provide for efficient movement of people, goods and information; enhance economic growth and international trade; and improve the environment and quality of life (http://www.scag.ca.gov/mission.htm).
SFB	San Fernando Groundwater Basin	This basin was adjudicated in 1979, and includes the water-bearding sediments beneath the San Fernando Valley, the Tujunga Valley, Browns Canyon, and the alluvial areas surrounding the Verdugo Mountains near La Crescent and Eagle Rock (http://www.dpla2.water.ca.gov/).
SSURGO	Soil Survey Geographic Database	Natural Resources Conservation Service Soil Survey Geographic Database (http://www.ncgc.nrcs.usda.gov/ products/ datasets/ssurgo/).
ULARA	Upper Los Angeles River Area	Basins located within the Los Angeles River Watershed in Los Angeles County, including San Fernando, Sylmar, Verdugo and Eagle Rock Basins (http://mwdh2o.com/ mwdh2o/pages/yourwater/supply/groundwater/PDFs/ SanFernandoValleyBasins/UpperLARiverAreaBasins.pdf)
USDA	United States Department of Agriculture	Federal organization that provides leadership on food, agriculture, natural resources, rural development and related issues based on public policy, the best available science, and efficient management (http://www.usda.gov/).
USGS	United States Geological Survey	Federal agency that provides reliable scientific information to describe and understand the Earth, minimize loss of life and property from natural disasters, manage water, biological, energy, and mineral resources, and enhance and protect our quality of life.(http://www.usgs.gov/).
VCWPD	Ventura County Watershed Protection District	The goal of the District is to protect life, property, watercourses, watersheds, and public infrastructure from the dangers and damages associated with flood and storm waters, through watershed planning, collaboration with stakeholders, and administration of adopted regulations, policies, and resolutions (http://www.vcwatershed.org/).