Sonoma Valley Groundwater Recharge Potential Mapping Project

Technical Report

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Background

Groundwater resources in Sonoma Valley are increasingly the object of study with regard to use, development, and sustainability. Reports by the California Department of Water Resources (DWR), Sonoma County Water Agency (Agency), United States Geological Survey (USGS), and private consultants show a growing demand for limited local groundwater supplies and concomitant decline in availability. In 2006, the USGS estimated that groundwater pumping in Sonoma Valley had increased from around 6,200 acre-feet per year (AF/yr) in 1974 to 8,500 AF/yr in 2000, a 37 percent increase in groundwater extraction. On the basis of groundwater flow modeling, the USGS also estimated that from 1975 to 2000, 17,300 AF were lost from groundwater storage. Groundwater-level monitoring indicates evidence of groundwater level declines in localized areas in the valley, with associated threats to groundwater quality from seawater intrusion and geothermal upwelling (Agency, 2007).

In 2006, the Agency coordinated development of a voluntary, non-regulatory Sonoma Valley Groundwater Management Plan (Plan) with the participation and collaboration of a broad range of local stakeholders who served as a Basin Advisory Panel (BAP). The Plan, adopted by the Sonoma County Board of Supervisors, Valley of the Moon Water District, and City of Sonoma in 2007, identifies Basin Management Objectives (BMOs) and a range of actions to be taken to sustain groundwater resources. The BAP and a Technical Advisory Committee (TAC), which provides technical support to the BAP, have been carrying out the actions according to the Plan's schedule (Appendix F in Agency, 2007). One of the BMOs included in the Plan (BMO-3) includes the identification and protection of groundwater recharge areas and the enhancement of groundwater recharge where appropriate. The Plan recognizes that improved understanding and delineation of groundwater recharge are critically important for effectively managing groundwater resources and includes in its schedule the development, through identification and mapping, of high-potential groundwater recharge areas in Sonoma Valley.

On behalf of the BAP, the Agency applied for and obtained an AB303 Grant from DWR for $249,908 for installation of two multilevel groundwater monitoring wells and a groundwater recharge mapping project. While a Grant Agreement between the Agency and DWR was initially entered in 2009, funding was frozen on the grant due to state budgetary constraints. Following notification from DWR in November 2009 that partial funding of the grant was available, the Agency entered into an agreement with the Sonoma Ecology Center (SEC) in December 2009 to commence work on the groundwater recharge mapping project. This technical memorandum documents the methodology and results of the recharge mapping project pursuant to Task 2.5 of the Grant Agreement.

Project Objective and Purpose

The objective of this project is to develop a groundwater recharge potential map for the Sonoma Valley. The project is intended to provide improved information on the distribution of recharge potential in Sonoma Valley and assist in identifying areas that could be favorable locations for multiple-scale enhanced groundwater recharge projects. Additionally, data developed from the project will be coupled with other ongoing and planned recharge investigation techniques to inform and feed into the development of a fully coupled surface water/groundwater flow model for Sonoma Valley.

More information about this project and other groundwater resources in the Sonoma Valley is available in the Sonoma Valley Knowledge Base: http://knowledge.sonomacreek.net/category/topics/groundwater-resources.

Previous Sonoma Valley Groundwater Recharge Investigations

Previous investigations of groundwater recharge in Sonoma Valley have been conducted by multiple research groups (DWR, 1975 and 1982; USGS, 2006; Bauer, 2008; LLNL, 2010). DWR's studies were primarily based on slope and soil type, the USGS and Bauer study utilized numerical modeling approaches, and LLNL utilized tracer studies using stable isotopes.

DWR assessed areas of natural recharge in Sonoma County in studies published in 1975 and 1982. The 1975 study covered the entire county and was based on mapping of geologic units (DWR, 1975). The DWR (1982) map of recharge areas focused on Sonoma Valley and was based on data from a U.S. Department of Agriculture (USDA) Sonoma County soil survey (Miller, 1972). The DWR (1982) study used three recharge classifications (Recharge Areas, Potential Recharge Areas, and Slow Recharge Areas) based on soil type (infiltration rate) and topographic slope using the general methodology of Muir and Johnson (1979). Soil permeability and slope were considered the most important factors in determining the recharge potential.

The USGS 2006 study included the performance of a seepage run of Sonoma Creek and portions of some tributaries, which indicated that losing stream reaches (areas contributing to groundwater recharge) were limited to Kenwood Fan area of Sonoma Creek at the time of the streamflow measurements (May 2003). In developing a numerical groundwater flow model for the study, the USGS grouped the Sonoma Valley into three primary, and highly generalized, recharge zones for MODFLOW groundwater flow model.

Bauer (2008) developed a new recharge model based on a soil moisture budget model and extended the area of recharge included in the MODFLOW model to encompass the entire Sonoma Creek watershed. Mountain-front recharge in the Sonoma Creek watershed originating in the highland areas outside the model domain was added to the model and accounted for separately from aerial recharge within the model domain. Bauer's modeling approach included the development of a Soil Moisture Budget (SMB) computed on a monthly time-step and accounts for the following parameters: Precipitation, Interception, Soil Moisture Storage (SMS), Available Water Capacity (AWC), and Potential Evapotranspiration.

Project Approach

Groundwater recharge is recognized as one of the most difficult components of the hydrologic budget to quantify. The extent to which water recharges an aquifer depends on a number of factors. Some of these factors are land use, soil permeability, slope, precipitation patterns, type of surficial deposits, thickness of surficial deposits, vegetation, and connection of surficial deposits with underlying aquifers. A wide variety of techniques can be applied to investigate groundwater recharge. Scanlon et al. (2002a) classified these recharge estimation techniques into physical (lysimeter, zero flux plan, and Darcy's Law), tracer (chemical, heat, and isotope), and numerical modeling approaches and recommended using multiple adaptive techniques to provide the most reliable estimates.

The relative recharge potential mapping conducted for this study integrates the infiltration characteristics of soil types, geologic formations, slope, and vegetation. The term recharge potential is used because the actual recharge rate also depends on other factors such as the distribution of precipitation, the locations of streams and other surface water bodies, and the connection to deeper aquifers (which are not incorporated into this study). Potential constraints or limitations that are not directly incorporated into the analysis include the presence of shallow or perched groundwater, natural springs, and existing groundwater quality. As such, site-specific assessments should be conducted prior to planning medium to large-scale recharge enhancement projects.

Recharge Analysis Methodology

Tasks performed for the study have included: (1) assembling and compiling existing GIS data sources; (2) developing the approach to the mapping project; (3) contacting other researchers for additional data sources and assembling and conferring with a panel of geologists to rank geologic formations relative to recharge potential; (4) identifying and reviewing supplemental sources of data; (5) developing a land-use GIS layer; and (6) convening project meetings to overview status and results.

Sources Contacted. The following experts were contacted and contributed to discussion on groundwater recharge analysis and mapping. Of note are the individuals identified as members of the geology panel. This group participated in a multi-week process of analysis and dialogue leading to the synthesis of recent California Geologic Survey (CGS) geologic maps into a geologic map for the Sonoma Creek watershed.

- Basin Advisory Panel and Technical Advisory Committee. Presentations were made to these groups. They contributed questions, comments, and inputs.
- Lorraine and Alan Flint, USGS. The Flints are currently working on a project to model potential climate change scenarios and groundwater recharge in Sonoma County. They explained their recharge modeling work and suggested factors to incorporate and GIS layers to assist in developing the map.
- Geology panel representatives from USGS (C. Farrar), CGS (W. Haydon), DWR (M. Nordberg), SCWA (M. Trotta), SEC (R. Lawton) and consulting firm Parker GroundWater (T. Parker). The geology panel analyzed the geologic formations of Sonoma Valley and classified them into a simplified set of thirteen classes with similar water infiltration characteristics.

Literature Reviewed. The following documents were reviewed as part of developing a methodology for groundwater recharge analysis and mapping. Each document contributed key insights, knowledge, leads to other information, and overall understanding of the topic.

- Muir and Johnson, 1979. USGS Open File Report 79-1065, Groundwater recharge potential classification and mapping for coastal and central Santa Cruz County. Defined and evaluated factors affecting recharge potential. Muir and Johnson specified good recharge areas as soils with >0.6 inch infiltration/hour and slopes of less than 15%. Geology was identified as a factor but not implemented. Vegetation was identified as a secondary factor but considered transitory and not implemented.
- DWR, 1982. Bulletin No. 118-4, Evaluation of Ground Water Resources: Sonoma County Vol. 4, Sonoma Valley. DWR utilized Muir & Johnson methodology to map GOOD and SECONDARY recharge areas in Sonoma County.
- Luhdorff & Scalmanini, April 1999. VOMWD Master Plan for Ground-Water Development and Management. And John Olaf Nelson Water Resources Management, 1999, VOMWD Strategic Water Supply Plan. Both reports utilized the DWR 1982 groundwater recharge maps in their analysis.
- C. Farrar et al., 2006. USGS Scientific Investigations Report 2006-5092, Geohydrological Characterization, Water-Chemistry and Ground-Water Flow Simulation Model of the

Sonoma Valley Area, Sonoma County, California. Farrar et al. defined recharge sources and processes for Sonoma Valley, focusing only on the valley floor.

- J. Mulder, January 2008. DWR Administrative Draft, Determining Potential Groundwater Recharge Zones Based on Soil Mapping and Slope. Mulder described modernized GIS methods for deriving a recharge potential map based on soil and slope and another independent map based on underlying geology. Described methods for upgrading scaling of contributing element values.
- Bauer, J., 2008. Masters Thesis: Update to Regional Groundwater Flow Simulation of Sonoma Valley including a New Model for Recharge and Three Future Scenarios. Bauer updated and expanded USGS 2006 flow model. Incorporated mountain front recharge into flow model and expanded area analyzed to include foothills.

Model Elements. Through the contacts made and literature reviewed, several simple, qualitative groundwater recharge models were found. The following table shows the element composition of these models along with the Sonoma Valley Watershed model.

Comparison of Groundwater Recharge Mapping Models

	Santa Cruz County (Muir & Johnson)	Butte County 1 (Mulder)	Butte County 2 (Mulder)	SVWS Model
Element	Weight	Weight	Weight	Weight
Vegetation	0.0%	0.0%	0%	10%
Soil	25.0%	37.5%	0%	25%
Slope	12.5%	62.5%	0%	15%
Geology	62.5%	0.0%	100%	50%
TOTAL	100.0%	100.0%	100%	100%

Analysis. The Santa Cruz County study (Muir & Johnson, 1979) defined a three element model: **soil**, **slope**, **geology**; however, the geology element was not integrated into the final result. Vegetation was identified as a secondary factor, but considered transitory and not implemented. The DWR study (1982) utilized the incomplete Muir & Johnson model in characterizing Sonoma Valley. The VOMWD documents (1999) rely on the DWR analysis (1982). The DWR analysis for Butte County (2008) modernizes derivation methods and describes more refined scaling for elements. However it generates separate maps for soil/slope and geology. Integration of all three elements into one map was not discussed.

In personal communications with Lorraine and Alan Flint of USGS, they suggested that **soil** is underweighted in these models.

In summary, although methods were improved and more refined element scaling described, no substantive improvements in model structure were found in these later studies over those in the Santa Cruz County study of 1979.

SVWS Model Composition. This project implements a model with four elements: **vegetation**, **soil**, **slope,** and **geology**. Element weightings vary modestly from the Santa Cruz County study and more significantly from the Butte County study. Geology remains the dominant factor, followed by soil and slope. Vegetation is new and is the fourth element used to derive the recharge potential layer. In rough consistency with the Santa Cruz County study (where it was classified as of secondary importance), vegetation is given the lowest weight of the four basic elements. Impervious surface ratings, an important attribute of landcover, were not addressed by the vegetation data used. Impervious surfaces are therefore implemented separately as a constraint for use in later analysis, where it can be overlaid on the recharge potential layer.

Data Updates. The sources of GIS data used and modification/derivation processes used are documented here.

- **Vegetation.** Data source: San Francisco Bay Open Space Council, Upland Habitat Goals Project Vegetation Map. Per expert opinion (geology panel members, et al.), SEC researcher D. DiPietro ranked vegetation polygons into three classes (poor, good, very good) based on the degree to which vegetation promotes or inhibits precipitation infiltration into the soil.
- **Soil.** Data source: NRCS SSURGO Soils Database. SEC researcher B. Sesser reclassified soil polygons into five classes and ranked them (Very Low, Low, Moderate, High, Very High) based on values in the average permeability (PERM_AVG) data element. Average permeability rates greater than 0.6 inches per hour (the Santa Cruz County study threshold) were ranked as high or very high.
- **Slope.** Data source: USGS 10-Meter Digital Elevation Model. SEC researcher B. Sesser used ArcMap functions to merge and clip quarter quadrangle DEM maps to the Sonoma Valley boundary and create a slope map. This was reclassified into ten classes based on slope percent and ranked with the highest score assigned to the lowest slope percentages and the lowest score assigned to the highest slope percentages.
- **Geology.** Data sources: CGS 2006 and USGS 1993. A geology panel was convened to determine how to reclassify Sonoma Valley geology according to recharge potential. See participants listed above in Sources Contacted section. CGS (2006) maps were used for all quads except for Petaluma Point (not available). USGS (1993) was used for that unavailable quad. Guided by geology panel discussion, SEC researchers B. Sesser and R. Lawton simplified the geologic features into thirteen classes based on similarities in permeability, porosity and fractures. These thirteen groups were then ranked into six classes (Poor, Poor to Fair, Fair, Fair to Good, Good, and Good to Very Good). Use of the latest CGS (2006) geology maps provided much greater detail on alluvial formations in valley floor and differences in volcanic formations in mountainous areas than was provided in previous CGS mapping.
- **Impervious Surfaces.** Data source: NLCD Impervious Surfaces dataset, 2001. Source data set was clipped to Sonoma Valley watershed boundary. Impervious surface data does not have a predefined classification scheme (for illustration, it has been shown with arbitrary classes defined). Rather it is available in its entire range of 0 to 100% impervious ratings for individual 30-meter grid cells. In future projects, thresholds or classes will need to be defined as appropriate for specific analyses.
- **Protected Lands.** Data Source: Sonoma County Agricultural Preservation and Open Space District, 2005. Composite spatial database of private-protected, public-protected, and public-unprotected lands in Sonoma County. Remaining land is assumed to be private. Sonoma County wide file was clipped to the Sonoma Valley Watershed boundary.
- **Vineyard.** Data source: U.C. Berkeley, A. Merenlender’s lab, September 2007. Vineyard polygons come from five different data sets that were generated for various projects by the following individuals and/or organizations: (1) E. Heaton, (2) K. Lohse, (3) A. Whipple, and (4) M. Deitch - all affiliated with U.C. Berkeley and A. Merenlender's IHRMP North Coast GIS lab at the U.C. Hopland field station; (5) T. Robinson of the Sonoma County Agricultural

Preservation and Open Space District. Sonoma County wide data set was clipped to the Sonoma Valley watershed boundary.

- **Shallow Groundwater.** Data source: Sonoma County Water Agency, October 2010. Polygons were created that delineate shallow groundwater areas as indicated by shallow wells (less than 15 feet to groundwater).

Recharge Potential Analysis

Derivation. The Recharge Potential map layer is derived by combining the ranked versions of the four model elements: vegetation, soil, slope, and geology. In ArcMap, SEC researcher B. Sesser used the map algebra function of the spatial analyst to compute a recharge potential value for each grid cell by summing the scores of the four ranked elements. The resulting layer has raw scores ranging from 21 to 94 (100 maximum possible). The raw scores were then classified into seven intervals based on the Jenks Natural Breaks Optimization methodology. The Jenks methodology was chosen because it identifies natural classes in the source data by seeking to reduce the variance within classes and maximize the variance between classes.

Analysis. The updated geology layer reveals areas of high recharge potential that were previously obscured, especially relatively high-porosity air-fall tuff formations in the mountain belts and alluvial deposits on the valley floor due to better identification of individual units. Significant areas of high recharge potential are found in these areas:

- The main channel of Sonoma Creek from its emergence from the Mayacamas Mountains at Kenwood to the beginning of tidal influence near the Highway 12 crossing.
- Much of the Yulupa Creek and Annadel Creek watersheds north of Bennett Valley Road.
- The lower reaches of Calabazas, Stuart, and Butler Creeks and their floodplains below 450 feet elevation.
- A lengthy band running northwest to southeast on the east slope of Sonoma Mountain that crosses the headwaters of Snag, Graham, Asbury, Mill, Winkle, and Dowdall Creeks.
- The lower reaches of Carriger/Fowler, Felder, Rodgers, Fryer, Nathanson, and Arroyo Seco Creeks.
- The main channel of Hyde Creek for nearly its entire length.
- The bulk of main stream channels of Pharris and Tolay Creeks.
- Numerous small, unnamed streams throughout Sonoma Valley have areas of modest size but high recharge potential.
- The entire valley floor from Verano Avenue south to the beginning of tidal influence near Highways 12 and 121 (moderately high recharge potential).

Constraints and Opportunities Analysis

Land Ownership Analysis. The following table shows the distribution of recharge potential within land ownership categories in the Sonoma Valley.

- The land ownership category with the largest acreage of high recharge potential is privately owned. Future initiatives seeking candidates for recharge projects will therefore benefit from a component to address the interests of private land owners, identifying their concerns and presenting appealing options.

- Land ownership categories with lesser obstacles to overcome are Conservation Lands and Public. There may be some attractive, quick-win project candidates in these latter categories; however, their total acreage is modest.

Distribution of Recharge Potential within Land Ownership Categories

Recharge Potential	Public and Private Conservation Lands		Private		Public (City, County, State, Federal)		TOTAL	
	Acres	Percent	Acres	Percent	Acres	Percent	Acres	Percent
poor	9,113	27.3%	18,018	53.9%	6,303	18.9%	33,435	100%
fair	7,363	21.4%	26,211	76.3%	774	2.3%	34,348	100%
good	1,884	10.7%	15,238	86.5%	494	2.8%	17,616	100%
very good	1,876	9.1%	18,222	88.4%	508	2.5%	20,606	100%
TOTAL	20,238	19.1%	77,690	73.3%	8,078	7.6%	106,006	100%

Land Use Analysis. Land use analysis is shown here in two steps. Because a detailed vineyard acreage map is available, it is shown separately following the overall analysis. The following table shows the distribution of recharge potential within major land use categories.

- Nearly fifty percent of the watershed is in natural vegetation. The vast majority of natural vegetation acreage has poor or fair recharge potential. There will be limited opportunities to identify enhanced recharge project candidates here.
- More than one-fourth of the watershed is in agriculture. Agricultural acreage is about evenly divided into the four recharge potential categories. This is a key land use category to focus efforts to identify enhanced recharge project candidates.
- About ten percent of watershed is in the Residential land use category. The majority of residential acreage has good or very good recharge potential. This suggests there is an opportunity for public awareness campaigns to promote good practices here.
- Less than five percent of the watershed is in the Urban/Developed land use category. Although the majority of this acreage has good or very good recharge potential, the small total amount may mean there are few opportunities for projects here.

Distribution of Recharge Potential within Land Use Categories

	Poor		Fair		Good		Very Good		TOTAL ACRES
Land Use Category	Acres	Percent	Acres	Percent	Acres	Percent	Acres	Percent	
Intensive Agriculture	3,064	16.8%	4,861	26.6%	4,275	23.4%	6,064	33.2%	18,264
Working Landscapes	3,316	29.0%	2,432	21.3%	2,902	25.4%	2,784	24.3%	11,434
Residential	752	7.0%	2,690	25.1%	3,004	28.0%	4,266	39.8%	10,712
Urban/Developed	707	15.1%	641	13.7%	1,564	33.4%	1,765	37.7%	4,677
Natural Vegetation	13,979	28.6%	23,544	48.2%	5,761	11.8%	5,588	11.4%	48,872
Wetlands	10,093	99.7%	13	0.1%	6	0.1%	7	0.1%	10,118
Water	1,530	79.2%	170	8.8%	103	5.3%	128	6.6%	1,932
TOTAL	33,441	31.5%	34351	32.4%	17615	16.6%	20602	19.4%	106,009

The following table shows the distribution of recharge potential in vineyards in Sonoma Valley. Nearly two thirds of vineyard acreage is rated as good or very good for recharge potential. This suggests vineyard acreage would be a good opportunity area for identifying candidates for enhanced recharge projects.

Distribution of Recharge Potential within Vineyard									
	Poor		Fair		Good		Very Good		Total
	Acres	Percent	Acres	Percent	Acres	Percent	Acres	Percent	Acres
Vineyard	1,077	7.3%	4,307	29.0%	3,892	26.2%	5,583	37.6%	14,859

Impervious Surfaces Analysis. Impervious surfaces are an important attribute of a watershed's landcover. Most impervious surface in our watershed is concentrated in the valley floor on relatively flat land. Consequently beneath these areas the other contributing elements often have high recharge potential rankings. Although these areas are partially or entirely blocked to infiltration by impervious surfaces they may still merit interest for future projects. The following table shows the distribution of recharge potential within arbitrary classes of impervious surface rating.

- At the watershed level, over 90 percent of acreage is in categories with impervious surface ratings of 50 percent or less. Seventy-one percent of very good recharge potential lies in areas with impervious surfaces ratings of less than 2 percent. These areas are typically wildland and agriculture.
- Areas with 25 percent or less impervious surfaces often represent low to medium density single-family residence areas.

The above categories are the most obvious project opportunity areas.

- Less than 5 percent of high recharge potential acreage lies in categories of greater than 50 percent impervious surface rating. These are typically roads and urban center settings.

These data suggest there is relatively little direct recharge opportunity lost to roads and the cores of urban areas. However, these areas may be considered for projects that can utilize channelized runoff as an infiltration water source. Also, they may also be helpful in identifying localized areas of concern for high stormwater runoff levels.

Distribution of Recharge Potential within Impervious Surfaces Categories										
Recharge Potential	0-1% Impervious		2-25% Impervious		26-50% Impervious		51-75% Impervious		76-100% Impervious		Total
	Acres	Percent	Acres	Percent	Acres	Percent	Acres	Percent	Acres	Percent	Acres
poor	32,668	97.7%	390	1.2%	216	0.6%	141	0.4%	8	0.0%	33,423
fair	32,519	94.7%	1,426	4.2%	295	0.9%	91	0.3%	6	0.0%	34,338
good	13,497	76.7%	1,716	9.7%	1,272	7.2%	1,002	5.7%	118	0.7%	17,605
very good	14,794	71.8%	3,167	15.4%	1,746	8.5%	809	3.9%	90	0.4%	20,606
TOTAL	93,478	88.2%	6,698	6.3%	3,529	3.3%	2,043	1.9%	223	0.2%	105,972

Use of this Information for Identifying Potential Projects

The objective of this project was to develop a groundwater recharge potential map for the Sonoma Valley and assist in identifying areas that could be favorable locations for multiple-scale enhanced groundwater recharge projects. In the constraints and enhancements analysis, above, some specific candidate areas are listed that could merit further investigation. Potential constraints or limitations that are not directly incorporated into the analysis include the presence of shallow or perched groundwater, natural springs, and existing groundwater quality. As such, site-specific assessments should be conducted prior to planning medium- to large-scale recharge enhancement projects.

Some potential projects that could be evaluated using information from this study include:

- Medium- to large-scale rainfall/stormwater infiltration on environmental corridors, agricultural lands, large private properties, and homeowner associations.
- Small-scale rainfall/stormwater infiltration on rural and urban residential properties.
- Groundwater recharge area conservation (e.g., Open Space District or Land Trust acquisitions).
- Recharging deeper aquifers through surface spreading (when the surficial potential recharge map is used in conjunction with available subsurface data).

The potential benefits of such projects include flood mitigation, increasing baseflows to local streams and wetlands, surface water quality improvements, and addressing groundwater level declines.

This information can assist in highlighting special interest areas when additional GIS data is incorporated with it:

- Soil thickness. Incorporating soil thickness data can reveal candidate areas for “enhanced recharge projects.” Such projects are good candidates in areas where relatively thin soil, especially with poor recharge potential, is present over geologic formations with high recharge potential.
- Depth to groundwater. Incorporating depth to groundwater data can assist in locating areas that have low incremental storage capacity. Areas with lower incremental water storage capacity are likely to be poor candidates for medium- to large-scale recharge projects. However, depending upon site-specific conditions, a small-scale enhanced recharge project may be successful in such an area (e.g., promotion of stormwater infiltration through contoured swales at a residential property).

We anticipate that GIS tools will be useful for evaluating opportunities using expert knowledge and simply zooming in to look, for example, at the potential for addition of retention ponds next to large parking lots (to utilize channelized runoff) due to the presence of an open field. This kind of analysis will be best done manually.

As previously described, groundwater recharge is recognized as one of the most difficult components of the hydrologic budget to quantify and the most successful studies of recharge integrate multiple adaptive techniques and methods (Scanlon et al., 2002). Accordingly, this study represents one method that will be coupled with other ongoing and planned recharge investigation techniques, including seepage runs along Sonoma Creek and its tributaries, the voluntary groundwater-level monitoring program, water quality sampling, stable isotope studies, and the development of a fully coupled surface water/groundwater flow model for Sonoma Valley.

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Appendix A. Model Elements

Figure A1. Element 1—Vegetation

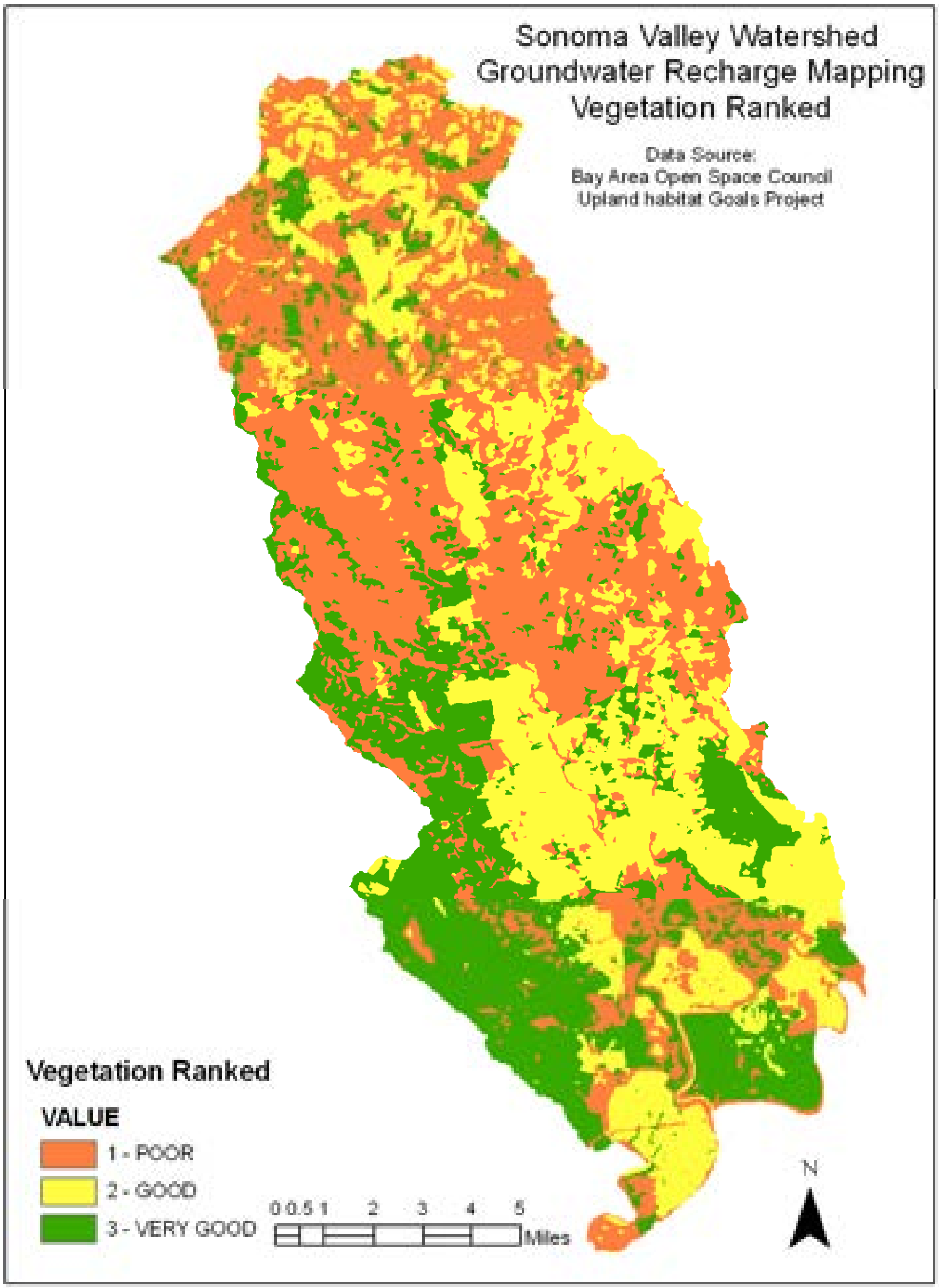


Figure A2. Element 2—Soil

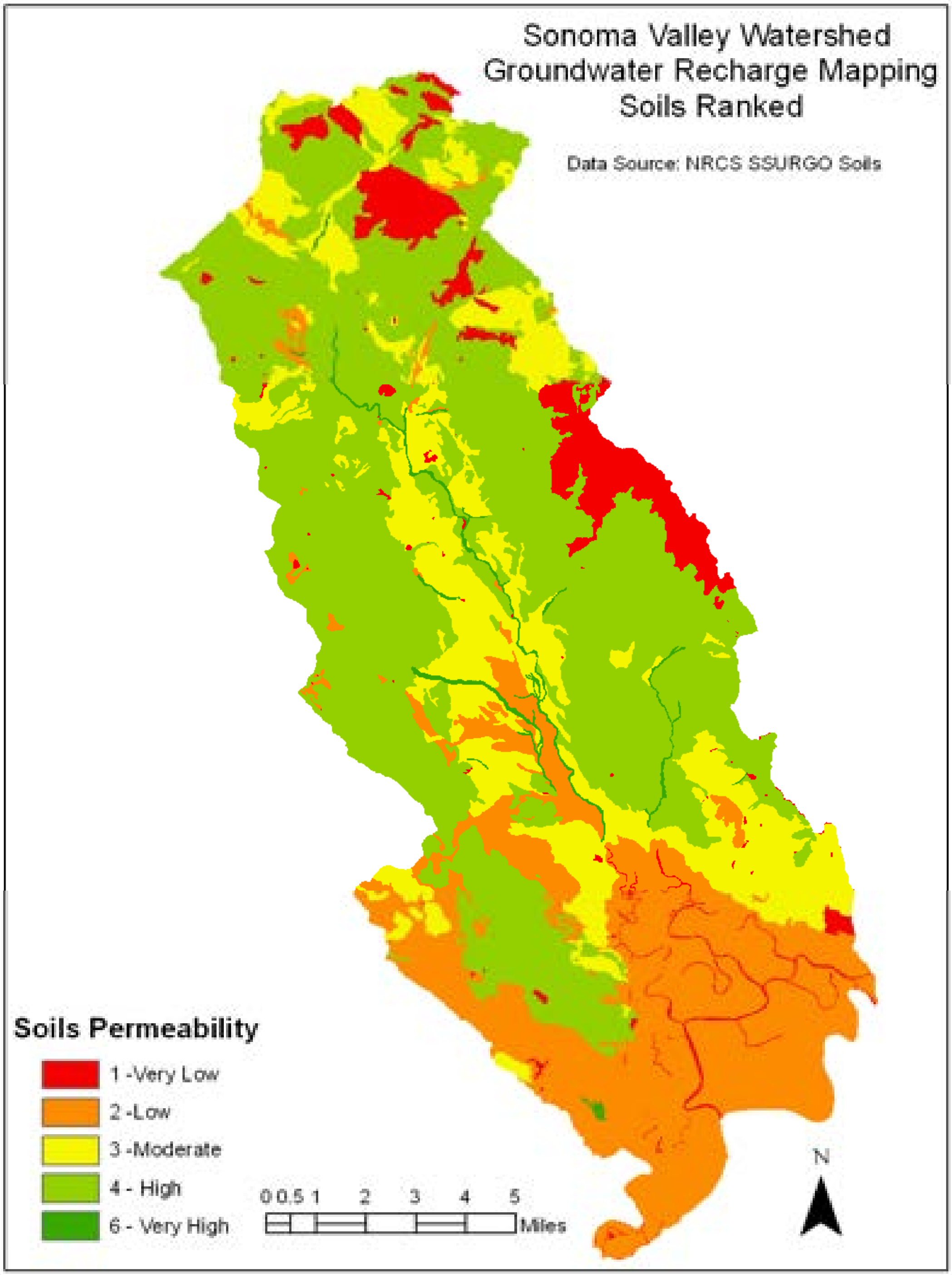


Figure A3. Element 3—Slope

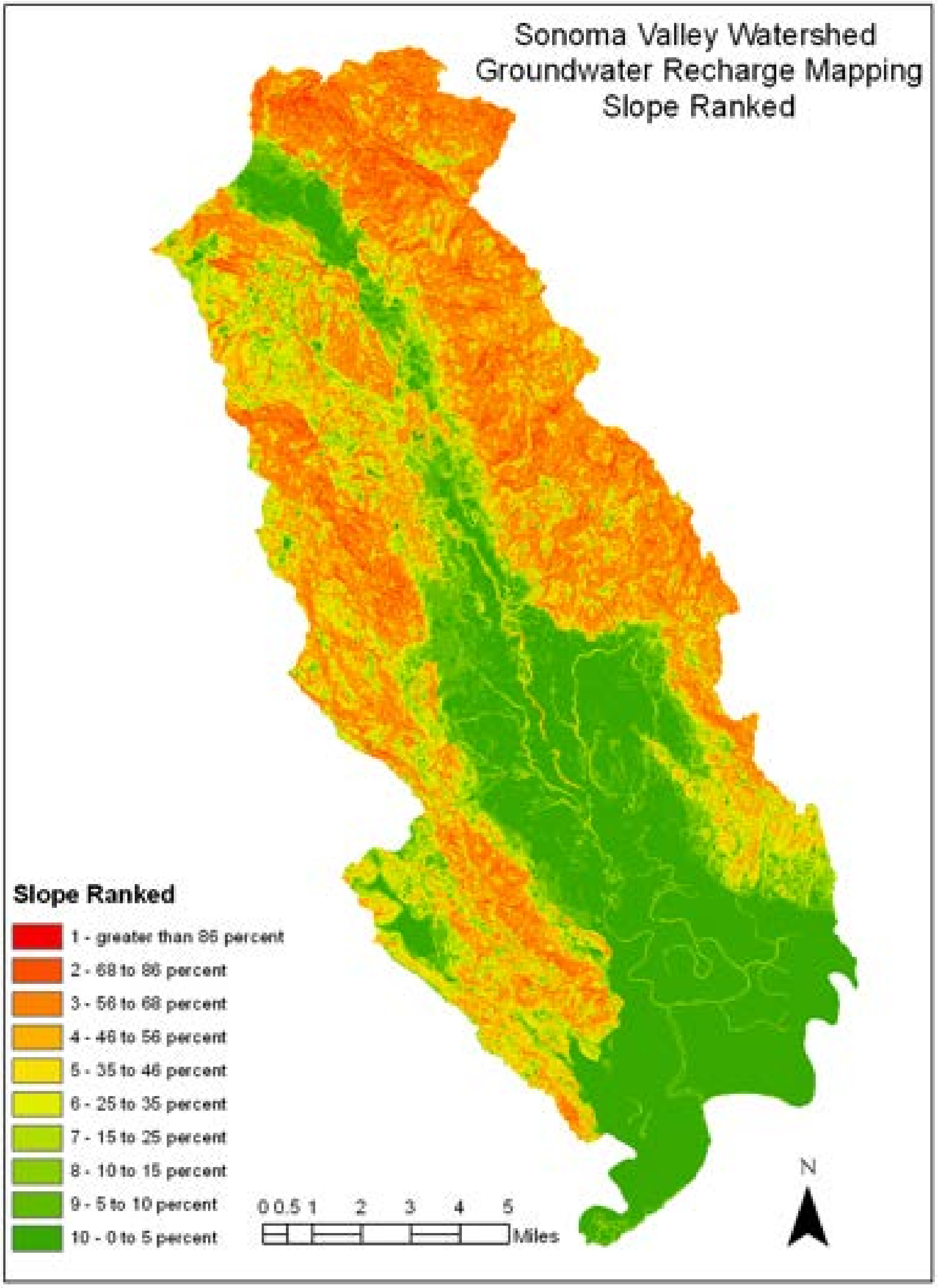


Figure A4. Element 4—Geology

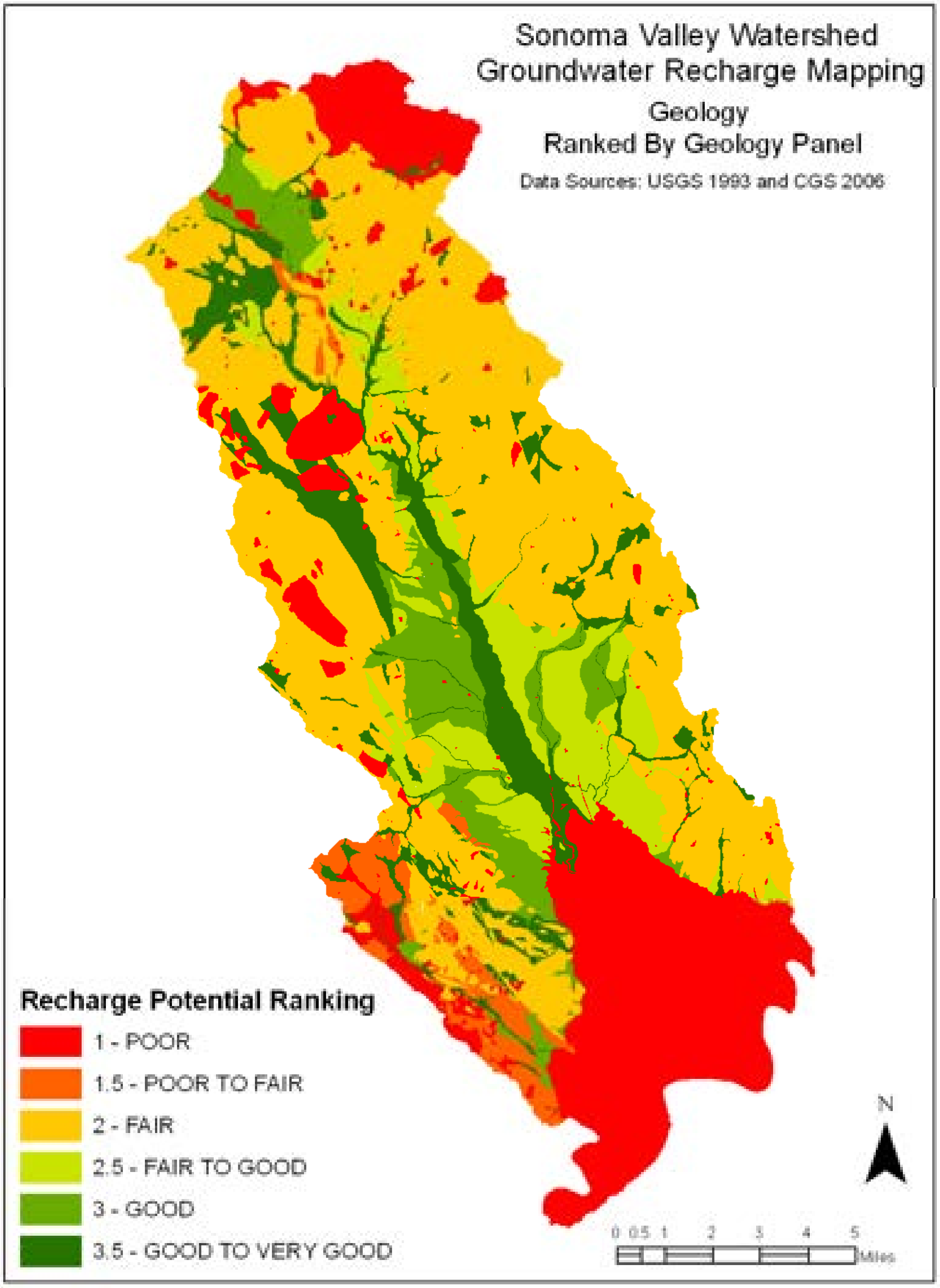
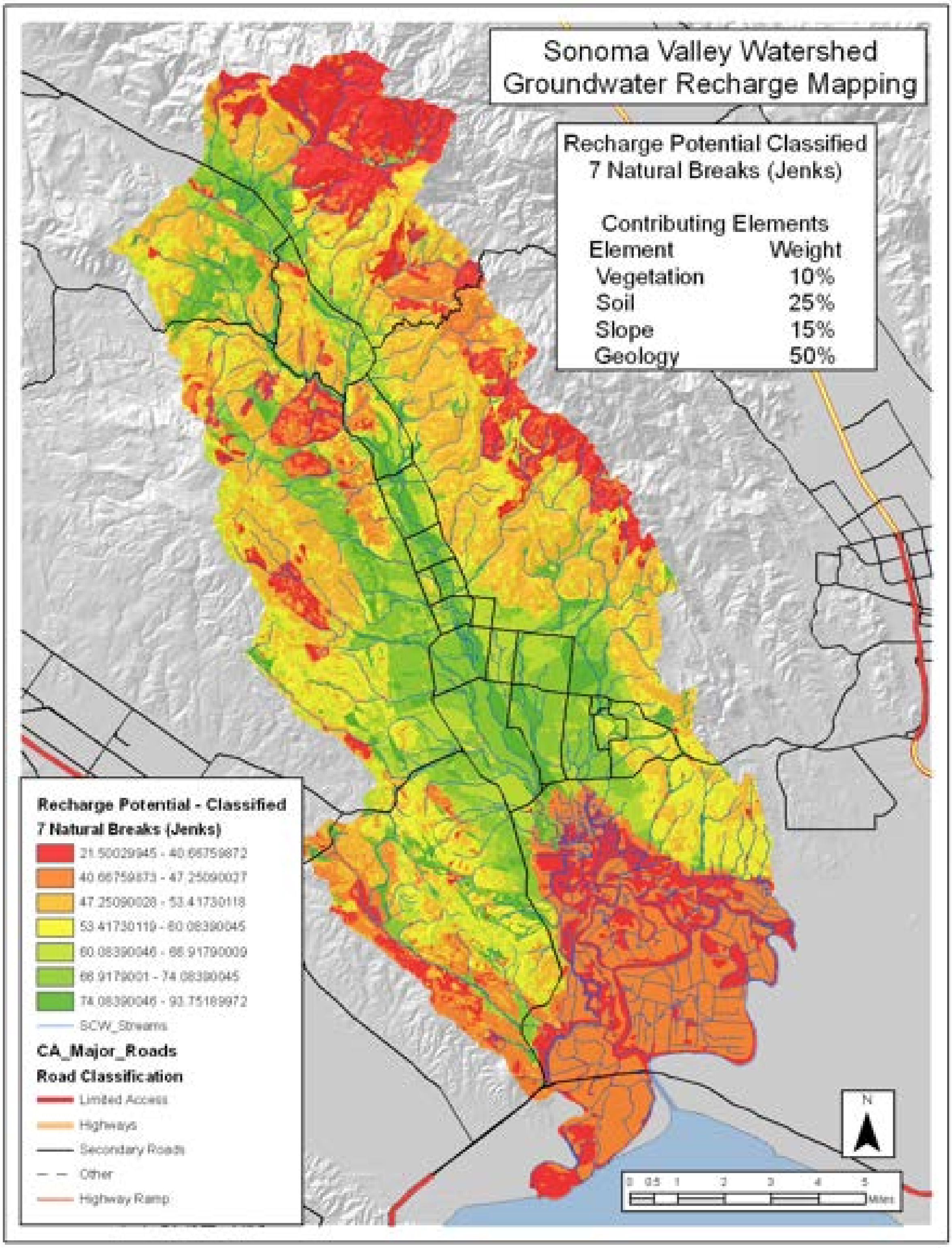


Figure A5. Recharge Potential Classified into Seven Natural Breaks Intervals (Jenks Methodology)



Appendix B. Constraints and Opportunities

Figure B1. Impervious Surfaces, Unclassified

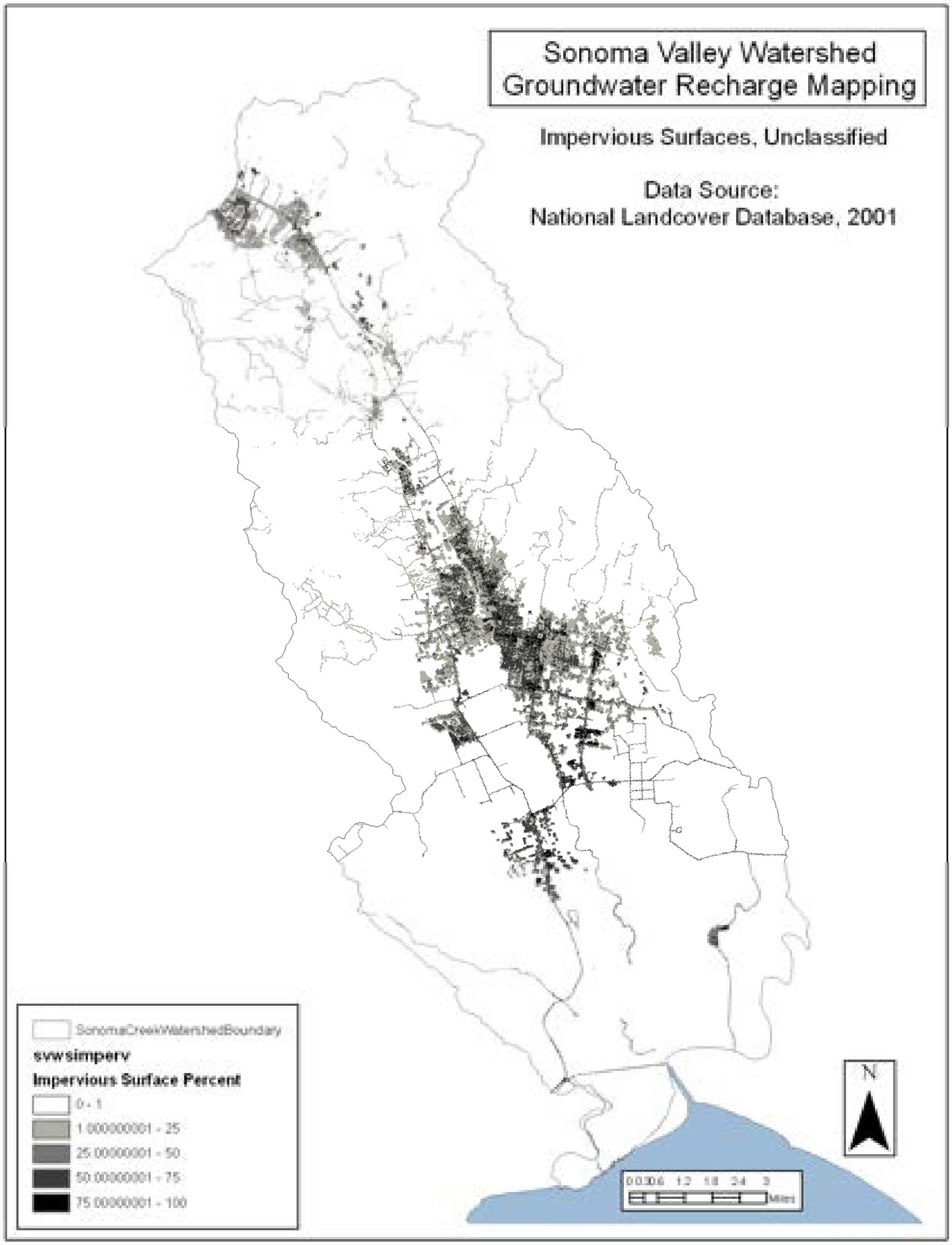


Figure B2. Protected Lands

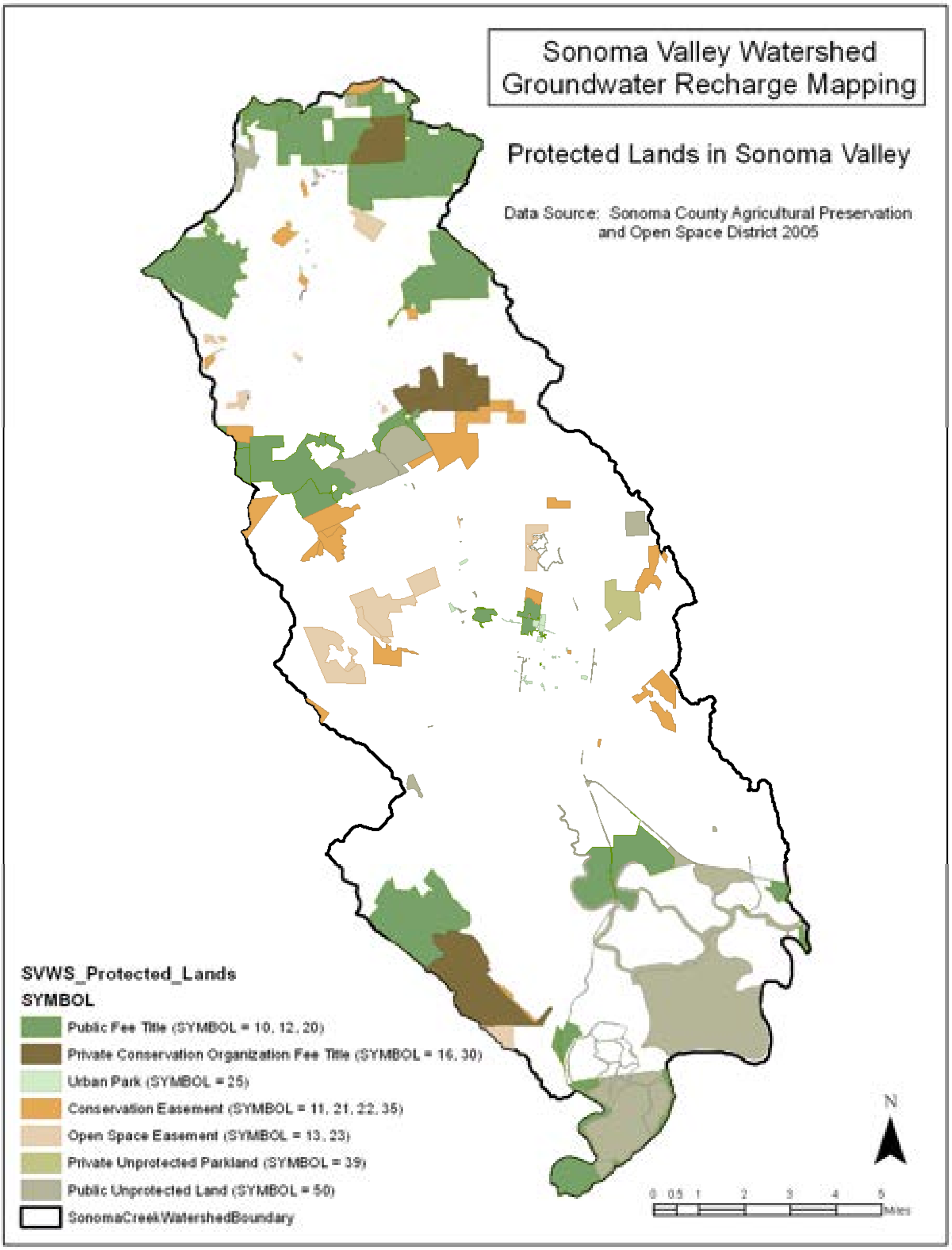


Figure B3. Vineyard

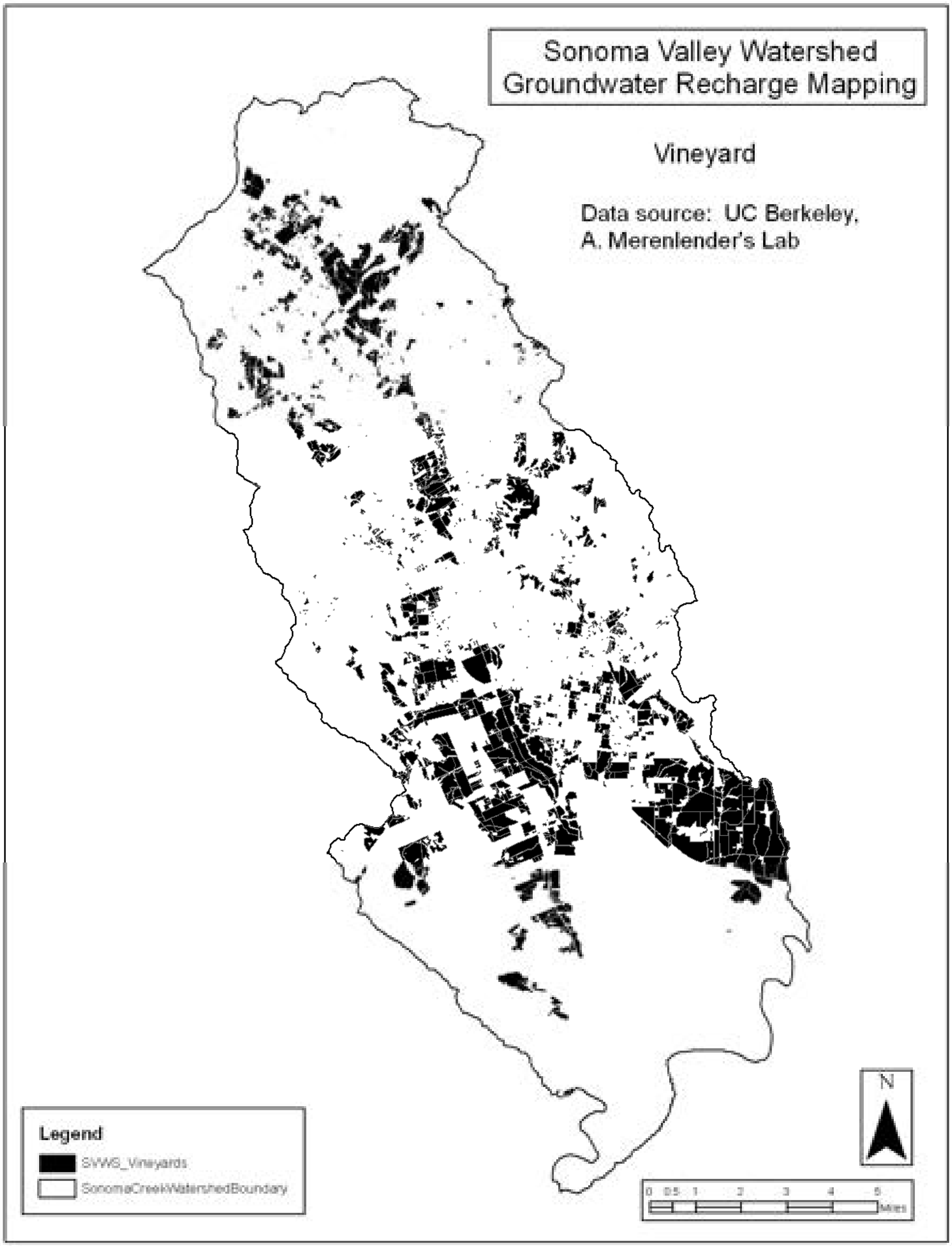


Figure B4. Shallow Groundwater