COLLAPSIBLE SOIL SUSCEPTIBILITY MAP FOR NEW MEXICO (1:750,000) BASED ON MULTIPLE PROXIES

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1 Introduction

Collapsible, or hydrocompactive soils, occur in regions with rapid accumulation of clay-rich sediment or where high-porosity sandstones are poorly cemented with shrink-swell clays. However, because they are stable under in situ conditions, little surficial evidence exists of their presence and hazard to structures, roads and other property. In the continental United States, these soils are present either in recent and rapidly aggraded loess deposits associated with deglaciation, or with recent, rapidly aggraded alluvium and poorly sorted eolian deposits in semi-arid environments (Lutenegger and Saber, 1988). In both cases, it is difficult to assess susceptibility at a site without performing geotechnical testing (Beckwith and Hansen, 1989; Williams and Rollins, 1991; and Momeni et al., 2012). The hazard, however, is real. Subsidence from collapsible soils can range from inches to feet, can occur over the course of days or months, and has led to up to $10 million of damage in New Mexico as of 1992 (National Resource Council, 1991); this damage occurs episodically, with entire small towns and housing developments affected and multiple homes condemned.

In semi-arid New Mexico and similar arid regions, collapsible soils occur mostly, though not always, along the medial to distal alluvial fan apron of mountain chains, where poorly sorted, clay-rich sediments rapidly build up and where surfaces are not repeatedly flooded (Johnpeer et al., 1985; and Beckwith and Hansen, 1989). These types of deposits are thought to be relatively common across New Mexico. However, there has not been a modern effort incorporating multiple lines of evidence to generate a statewide hazards map, nor has there been a single compilation of known collapsible soil incidents.

In this study, we present a statewide map of collapsible soil incidents and maps of susceptibility with metrics of reliability based on multiple sources and types of data. This map is meant to inform New Mexico communities and decision makers about the relative susceptibility of collapsible soil subsidence across New Mexico. It is not meant as an engineering tool for determining if a site has collapsible soils—the only way to determine that is through careful and engineer-guided geotechnical sampling (Beckwith and Hansen, 1989; Williams and Rollins, 1991; Jorgensen, 1998; and Momeni et al., 2012). However, the maps presented do provide a coarse picture of where we expect collapsible soils. These maps begin with a map of known collapsible soils followed by maps of susceptibility and quality from multiple proxies for collapsible soils, and finish with an aggregate of collapsible soil susceptibility and quality weightings of that susceptibility estimate.

We define collapsible, or hydrocompactive, soils as clastic sedimentary deposits that are metastable under *in situ* conditions, but that become unstable (i.e., begin to subside) over short times (days to years) with excessive wetting with water while being externally loaded (Williams and Rollins, 1991; Osipov and Sokolov, 1995; Rogers, 1995; and Li et al., 2016). Additionally, the material must be porous enough and thick enough to cause damage on collapse. The process of collapse is the destabilization of clay minerals and other cements that bridge and stiffen the bonds between other, generally larger grains (Osipov and Sokolov, 1995; Rogers, 1995; and Li et al., 2016; Fig. 1). The primary feature of a collapsible soil is a high porosity with the microstructural load bearing elements having water-sensitive strengths (Beckwith and Hansen, 1989; and Rogers, 1995). For example, a quartz-rich sand with primary grain contacts that are quartz grain on quartz grain will not be susceptible to collapse. A muddy quartz-rich sand where the grains are bound by shrink-swell, water-sensitive clay minerals and that have large pores will be extremely susceptible to collapse: the structural binding agents of the sediment are sensitive to the presence of water, and there is porosity that can collapse.

Sediments with these characteristics—high porosity and water-sensitive microstructure—can be deposited under a wide range of conditions, ranging from eolian or wind-blown deposition, to alluvial deposition by sheetwash and streams, to coastal deposition of clays (Rogers, 1995). In general, the deposits aggrade quickly so individual beds are not compacted mechanically and hydraulically before burial.

Globally, the most common collapsible deposits are loess, which is wind-blown clayey, very fine sand- to silt-sized sediment (Reinecke and Singh, 1975). These deposits generally occur downwind of major rivers. Coarser-grained collapsible soils in wind-blown sediments may also occur downwind of obstructions, where the wind-suspended sediments can all fall out without the sorting that leads to discrete wind-blown sand and loess deposits, though these have not been well documented in the literature. However, rapidly aggraded loess and other clay-rich eolian deposits are commonly found in these regions (Reinecke and Singh, 1975).

In semi-arid and drier regions, rapid alluvial deposition from high suspended load flows can lead to collapsible deposits. Prerequisites require a heightened high plasticity or shrink-swell clay content (greater than 10%), with a well-mixed suspended load during deposition (Rogers, 1995; Momeni et al., 2012). While most collapsible alluvial deposits are made of sand- and silt-sized grains, muddy gravel deposits can also be collapsible; bridging between clasts by water-sensitive clays can support coarse clasts (Rollins et al., 1994). Additionally, clay-sized alluvial deposits can possibly also form a box-work structure after rapid deposition that then can collapse on wetting, similar to collapsible soils in marine mudstones (Rogers, 1995).

Lastly, collapsible sediments have been found in proximal marine mudstones (Rogers, 1995). The depositional environment that leads to the box-work structure—hypothesized in alluvial collapsible muds but documented in marine muds—is not clear (Rogers, 1995). Nonetheless, these deposits have been documented to experience significant vertical compaction on wetting (Rogers, 1995). In New Mexico, these types of deposits have not been observed.

A complicating factor in mapping collapsible soils are weakly-cemented muddy sandstones. Most collapsible soils are unconsolidated sediments; however, the process leading to collapse in both traditional collapsible soils and weakly cemented muddy sandstones are similar. A muddy sediment is metastable until wetting with some possible loading. Then, the minerals bridging between grains and holding open the pore space destabilize, leading to large degrees of vertical subsidence. This process can happen in either weakly clay cemented sandstone, calcic soil horizons, or in classical hydrocompactive soils (Shehata and Amin, 1997).

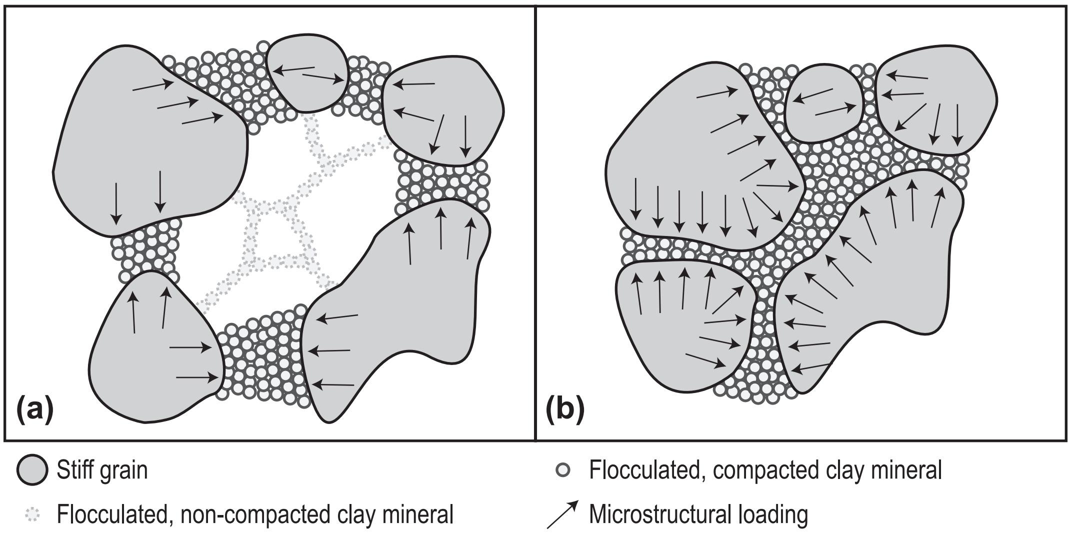


Figure 1. Schematic of hydrocompactive soil microstructure, adapted from Rogers (1995), showing the sediment (a) before and (b) after hydrocompaction.

Estimating susceptibility of the various different types of collapsible soils is challenging, especially on a statewide scale. We lack direct evidence from engineering metrics such as field and laboratory collapse testing, other than regions that have proven to be prone to collapsible soils. However, these regions are commonly not reported as they occur on private land and are often litigated.

Approaches to mapping collapsible soils generally incorporate several similar correlative factors that are estimated against a combination of mapping and engineering measurements of collapse potential. Collapsible soils are correlated with soil texture (particle size distribution); porosity; bulk density; deposit age; saturation history; climate zone; and vegetation cover or land use (Momeni et al., 2012). These factors are reported in multiple different maps and geospatial data, ranging from NRCS soil survey map data (STATSGO and SSURGO data; Soil Survey Staff, 1994 and 2014), to New Mexico Bureau of Geology and Mineral Resources (NMBGMR) statewide maps of landforms (Hawley et al., 2005), to the United States Geological Survey (USGS) National Land Cover Database (NLCD; Homer et al., 2015), to climate maps derived from various meteorological data, to various statewide groundwater level monitoring networks of the USGS and NMBGMR, to New Mexico Office of the State Engineer (NMOSE) well permit information. The challenge of the current study is how to (a) robustly and conservatively estimate collapse susceptibility without direct engineering calibration data; and (b) how to construct the map using a composite of data of different reliability, spatial resolution, and correlation to susceptibility.

In the following we outline our basic overlay (spatial weighted average) approach to estimating collapsible soils susceptibility, present the various mapped susceptibility results, and discuss the use and limitations of these maps. In particular, we discuss our general methodology and then step through how we weighted the susceptibility and quality for each proxy dataset used (Section 2). We present our map of known collapse features, the susceptibility associated with each dataset, and the total estimated susceptibility with quality information (Section 3). We finish with a discussion of the uses, with heuristics for use, and limitations of our mapped susceptibility (Section 4).

2 Method

The goal of this study is to consistently and conservatively map the susceptibility of collapsible soils across the state of New Mexico at a scale of between 1:250,000 and 1:500,000. Most collapsible soil susceptibility maps are produced at coarser scales (higher resolutions) than the current study. Because of the smaller area of interest in these studies, they incorporate detailed engineering sampling and measurements. In the current study, we are using pre-existing data with comparisons to the few known regions with collapsible soils.

Because of the lack of directly observable factors, such as frequent and well-located instances of collapsible soil subsidence and geotechnical measurements, we must use correlative proxies. Additionally, the spatial resolution of the map is too coarse to incorporate engineering sampling into our study. Rather, we must use correlative but qualitative mapped proxies. Unfortunately, consistent proxies are not always available across New Mexico, and, if they are, they do not always have the same level of confidence across the state. This requires us to develop a method that incorporates both the estimated susceptibility to collapse based on each set of available data, and our level of confidence in the underlying data set.

Before laying out our general approach, we emphasize that most of New Mexico, even regions with relatively thin soil cover or regions where much of a geomorphic surface has been extensively wetted, has a low, but significant, susceptibility to collapsible soils. Sites where construction is planned should be geotechnically examined for collapse potential. A low, finite susceptibility at the scale of the map (1:750,000) reflects the higher susceptibility below the scale of the map for inset surfaces and other site-specific conditions that can lead to damage due to hydrocompactive settling.

We used an expert-driven process that balanced the correlation between hydrocompaction susceptibility and proxy data, and the quality and reliability of the proxies. We had to use an expert-driven process because of the lack of extensive training data at the statewide scale. Additionally, each proxy has a different correlation and reliability, which were iteratively assigned, reflecting mixed independence of data, indirect vs. direct proxies (e.g., climate vs. grain-size data), and subscale site specific heterogeneity. We specifically use a spatial quality-weighted average.

Essentially, the method uses expert-generated susceptibility and quality-weighting factors for each input spatial dataset. The final susceptibility, S_{total}, at a given point is taken to be

$$S_{total} = \sum_i \frac{S_i Q_i}{Q_i} \qquad (1)$$

where S_i is the estimated susceptibility from a given layer i, Q_i is the weighting, or strength of correlation and reliability for layer i. Not all layers exist across the state, so we report the weighted susceptibility, the mean weighting and the number of layers used, along with all of the individual susceptibility and weighting of each layer.

Based on the correlative proxies outlined in Johnpeer et al. (1985), Beckwith and Hansen (1989), and Momeni et al. (2012), we generated or compiled maps of climate, landform age, source and sediment texture from a map of Quaternary landforms, soil texture and taxonomic classification from soils maps, vegetation and land-use maps, and maps of depth-to-water. Table 1 summarizes the information, source, spatial resolution, range of susceptibility and weighting for each input layer. We chose to have susceptibilities range from zero to four, and weights to range from zero to ten, both as integers. This is to recognize our lack of resolution of susceptibility and the broad range of correlation and reliability of the data.

Each proxy has a different resolution, varying from 10 m cell size to 4 km cell size, and often came in different projections and datums. In order to ensure a reliable statewide view, all proxies were projected to Web Mercator Auxiliary Sphere projection in the World Geographic System 1984 datum. After projection, each proxy was then resampled from their initial resolution to the same 500 m grid using majority area resampling—maximum value resampling was also examined but was found not to significantly shift the estimates.

2.1 Climate-based susceptibility

In semi-arid regions, climate and collapsible soil susceptibility are correlated, with wetter climates having lower susceptibility and drier climates having greater susceptibility (Johnpeer et al., 1985; Beckwith and Hansen, 1989; and Shehata and Amin, 1997). New Mexico climate ranges from arid desert to alpine tundra across the state, largely due to elevation relief but also because of latitudinal effects. This climate range necessitates more generalized climate considerations than previously used in most smaller-scale collapsible soil susceptibility maps in the southwest.

However, climate impacts on hydrocompactive soils is a complicated interaction of precipitation amount and timing, and temperature values and timing, requiring considerations beyond precipitation thresholds (Beckwith and Hansen, 1989). We were unable to find a climate map of sufficient resolution for our application, but Peel et al. (2007) developed Köppen-Geiger climate zone maps based on estimates of mean, maximum and minimum monthly temperatures, and monthly accumulated precipitation. The Köppen-Geiger climate maps were developed in the late 19th century and used to classify the vegetation, soil and climate of different regions of the world (Essenwanger, 2001). Since then, this classification has remained a reliable way to understand climate as it affects vegetation across a region (Peel et al., 2007). Köppen-Geiger climate classification appeared to provide an understandable approach that would correlate with collapsible soil susceptibility across all of New Mexico.

We used publically-available 4-km resolution grids of monthly gridded precipitation and temperature data from the PRISM Climate Group (PRISM Climate Group, 2004) as an input for the method of Peel et al. (2007) to construct Köppen-Geiger climate maps. In particular, we aggregated the monthly estimates to average monthly precipitation, average monthly mean temperature, average monthly minimum temperature, and average monthly maximum temperature from 1981 to 2016 (PRISM Climate Group, 2004). These maps were input into the schema of Table 1 in Peel et al. (2007) to find the Köppen-Geiger climate class at a 4-km resolution across the state (Fig. 2).

Table 1. Correlative data, source, resolution, range of susceptibility and range of quality.

Proxy	Resolution or Scale	Susceptibility	Quality	Source
Climate type	4 km	1 to 3	5	Peel et al. (2007) and PRISM
Landform emplacement	1:500,000	1 to 4	9	Hawley et al. (2005)
Landform dep. env.	1:500,000	1 to 4	8	Hawley et al. (2005)
Landform age	1:500,000	1 to 4	7	Hawley et al. (2005)
Landform composition	1:500,000	1 to 4	7	Hawley et al. (2005)
Landform texture	1:500,000	1 to 4	5	Hawley et al. (2005)
Soil texture	1:30,000 to 1:250,000	1 to 4	5 to 7	Soil Survey Staff (1994 and 2014)
Soil taxonomic order	1:30,000 (10 m)	n/a, 1 to 3	9	Soil Survey Staff (2014)
Soil taxonomic suborder	1:30,000 (10 m)	n/a, 1 to 3	8	Soil Survey Staff (2014)
Soil taxonomic great group	1:30,000 (10 m)	n/a, 1 to 3	7	Soil Survey Staff (2014)
Landuse	10 m	n/a, 0 to 3	6	Homer et al. (2015)
Depth-to-Water	1 km	n/a, 1 to 3	3 to 6	derived from NM Office of the State Engineer

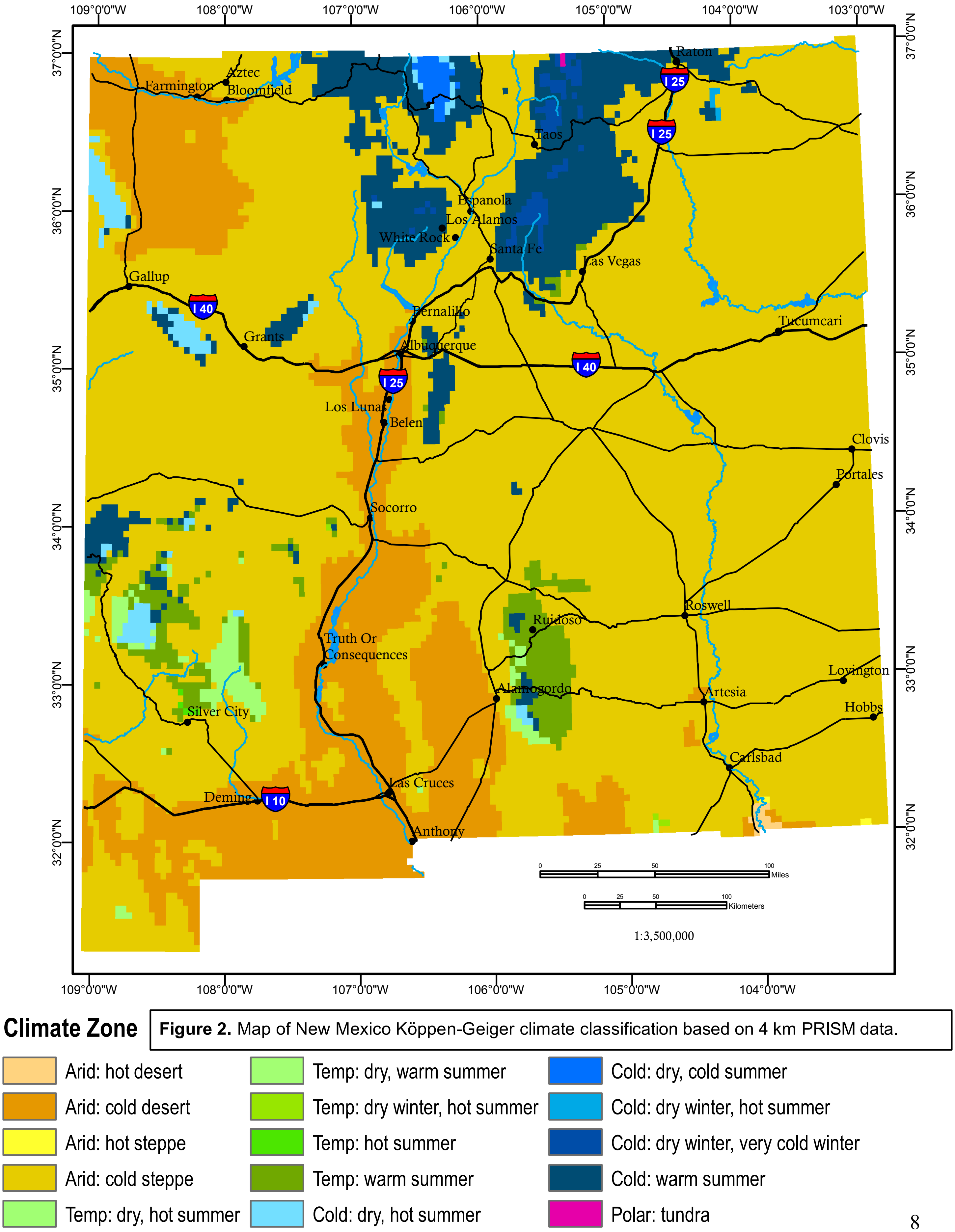


Figure 2. Map of New Mexico Köppen-Geiger climate classification based on 4 km PRISM data.

While the Köppen-Geiger classification disaggregates into three levels with a total of thirty climate zones, we chose to focus on the five first-order, precipitation and mean annual temperature related climate classifications (tropical, arid, temperate, cold and polar; Table 2). This recognizes both the weak correlation of climate with collapsible soil susceptibility and our coarse susceptibility classification.

2.2 Quaternary landform-based susceptibility

Hawley et al. (2005) compiled a 1:500,000 scale map of surficial geologic materials for the state of New Mexico from a variety of published maps, unpublished data, and expert knowledge (generalized in Fig. 3). The dataset emphasizes characterization of Pliocene and younger (approximately 5.3 million years old to the present) geologic features, and subdivides surface materials principally by method of emplacement, depositional environment and age of deposit, and secondarily by deposit or rock composition and sediment texture. Each of these factors was considered for its correlation to hydrocompaction susceptibility.

“Method of emplacement” refers to the process that deposited the rock or sediment, such as water deposition (alluvial) or wind deposition (eolian) (Table 3). As previously discussed, collapsible soils are most commonly associated with eolian and certain alluvial deposits; these emplacement methods are given the highest susceptibility ratings. Lower susceptibility factors are associated with lacustrine and mass-wasting deposits, and the lowest is assigned to bedrock-dominated map units. A related characteristic is depositional environment, which refers to a deposit’s landscape position, such as floodplain, alluvial fan, or hillslope (Table 3). The susceptibility associated with a depositional environment is here considered a function of the degree of post-deposition stabilization (principally periodic flooding, saturation and hydraulic settling) expected for that setting. For example, a depositional environment along a perennial river with a shallow water table and frequent flooding should be assigned a lower susceptibility than a depositional environment in an upland environment such as an alluvial fan or dune field.

Due to the importance of depositional processes on the formation of collapsible soils, the method of emplacement and depositional environment susceptibility factors were given high weights, and subsequently had a dominant influence on the final results. As a consequence, some factors needed to be adjusted iteratively to better reflect regions with known collapse features. In particular, we increased the susceptibility for the river alluvium unit (map unit AR in the original map) significantly. Our original assessment was that alluvium along perennial rivers is typically hydraulically stabilized by flooding and high water levels, and would have a relatively low susceptibility. However, this map unit was commonly associated with collapsible soils in the vicinity of Española; ratings were necessarily increased to reflect this. Ratings for several colluvial units were similarly increased, particularly those for map units C, CR, and CA. Despite being principally colluvial units, each of these map units is associated with large areas of weakly-cemented sedimentary rocks that are in places surrounded by sheetwash-dominated small alluvial fan deposits—features with known collapsible soil locales. The susceptibilities of these units were thus increased.

Table 2. Relationship between Köppen-Geiger climate classification and collapsible soil susceptibility. Quality factor is 5.

ID	Class	Subclasses	Susceptibility (0-4)
10	**Tropical**		0
11		Rainforest	
12		Monsoon	
13		Savanah	
20	**Arid**		3
21.1		hot desert	
21.2		cold desert	
22.1		hot steppe	
22.2		cold steppe	
30	**Temperate**		2
31.1		dry, hot summer	
31.2		dry, warm summer	
31.3		dry, cold summer	
32.1		dry winter, hot summer	
32.2		dry winter, warm summer	
32.3		dry winter, cold summer	
33.1		no dry season, hot summer	
33.2		no dry season, warm summer	
33.3		no dry season, cold summer	
40	**Cold**		2
41.1		dry, hot summer	
41.2		dry, warm summer	
41.3		dry, cold summer	
41.4		dry summer, very cold winter	
42.1		dry winter, hot summer	
42.2		dry winter, warm summer	
42.3		dry winter, cold summer	
42.4		dry winter, very cold winter	
43.1		no dry season, hot summer	
43.2		no dry season, warm summer	
43.3		no dry season, cold summer	
43.4		no dry season, very cold summer	
50	**Polar**		1
51		Tundra	
52		Frost	

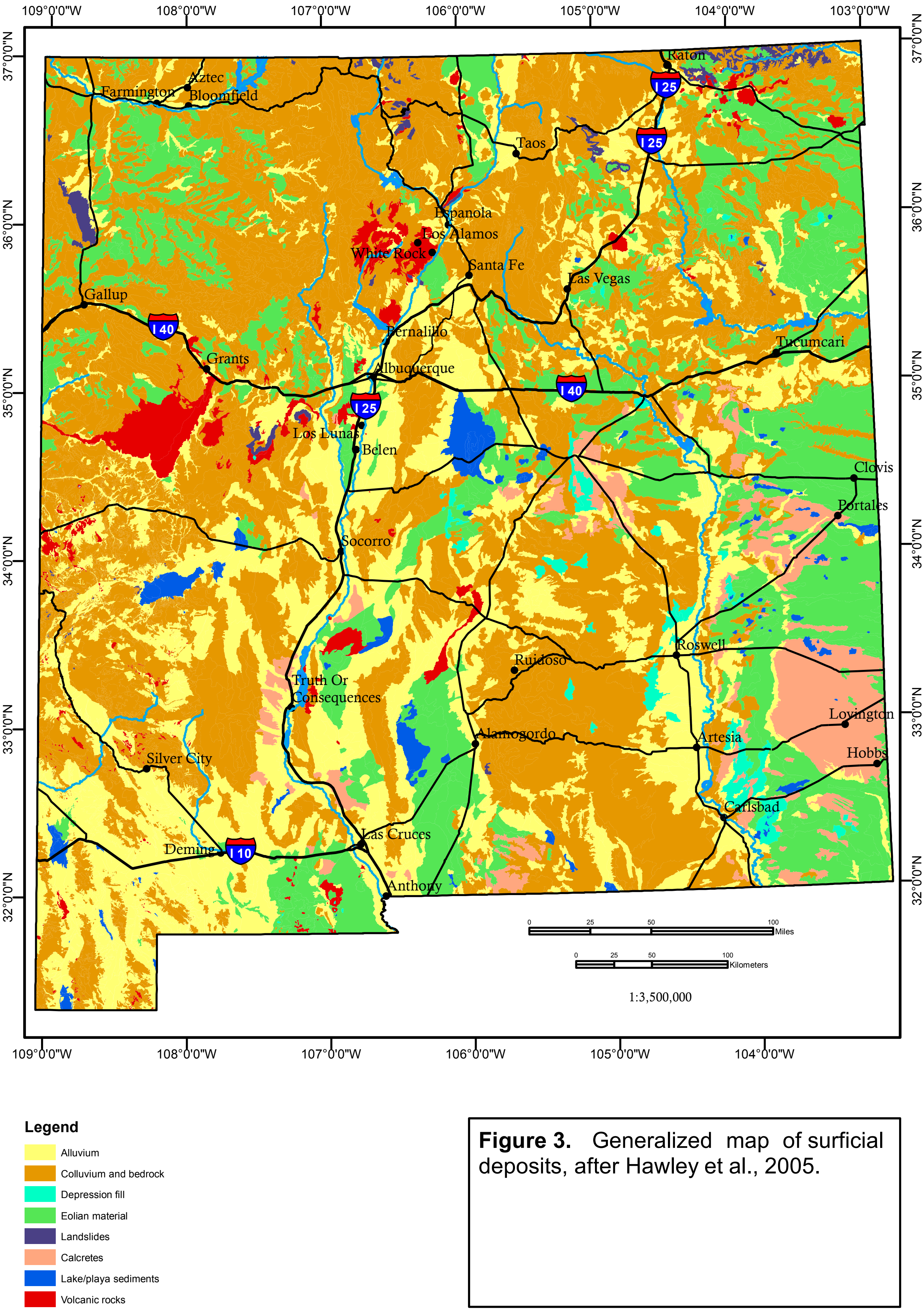


Figure 3. Generalized map of surficial deposits, after Hawley et al., 2005.

Table 3. Relationship between map unit component and collapsible soil susceptibility. Quality factors are 9 for mode of emplacement and 8 for depositional environment.

Unit Code	Unit Name	Mode of Emplacement	Default Age Class (See Table 4)	Depositional environment	Emplacement Susceptibility	Environment Susceptibility
A	Alluvium, undivided	Alluvial	o2 and y	Any	3	3
AR	River alluvium	Alluvial	o2 and y	Valley floor	3	3
AV	Valley-fill alluvium	Alluvial	o2 and y	Valley floor	3	3
AP	Alluvium on erosion surfaces--piedmont and escarpment footslopes	Alluvial	None	Piedmont	3	4
AF	Fan alluvium, undivided	Alluvial	o2 and y	Piedmont	4	4
AB	Bolson-floor alluvium, undivided	Alluvial	o2 and y	Bolson-floor	3	3
ABS	Bolson-floor alluvium, saline	Alluvial	o2 and y	Bolson-floor	4	4
AL	Alluvial-lacustrine complex	Alluvial, lacustrine	None	Bolson-margin	3	3
E	Eolian deposits, undivided	Eolian	y	Any	2	4
ES	Eolian deposits, gypsiferous	Eolian	y	Any	3	4
ED	Dune sand	Eolian	y	Any	2	4
EDS	Dune sands, gypsiferous	Eolian	y	Any	3	4
EM	Eolian deposits, older, loamy sand to sandy clay loam	Eolian	o	Any	4	4
L	Lacustrine deposits, undivided	Lacustrine	o2 and y	Bolson-floor	2	2
LE	Lacustrine and eolian deposits, undivided	Lacustrine, eolian	o2 and y	Bolson-floor	3	2
LS	Lacustrine deposits with salts	Lacustrine	o2 and y	Bolson-floor	3	3
P	Playa deposits	Playa	o2 and y	Bolson-floor	3	3
PS	Playa deposits with evaporites	Playa	o2 and y	Bolson-floor	4	3
C	Colluvium-undivided	Colluvial	None	Slopes	2	2
CA	Colluvium in combination with valley-fill alluvium	Colluvial, alluvial	None	Any	3	2

Table 3. (continued)

Unit Code	Unit Name	Mode of Emplacement	Default Age Class (See Table 4)	Depositional environment	Emplacement Susceptibility	Environment Susceptibility
CR	Colluvium with large areas of bedrock outcrop (usually >50%)	Colluvial	None	Any	3	2
CW	Colluvium with large areas of weakly-consolidated sedimentary-rock outcrops	Colluvial	None	Any	3	2
CB	Block-rubble colluvium	Colluvial	None	Slopes	1	1
CJ	Colluvium-landslide complexes	Colluvial	None	Slopes	1	1
JC	Colluvium-landslide complexes	Colluvial	None	Slopes	2	2
J	Landslides, undivided	Colluvial	None	Slopes	2	2
D	Depression fills, undivided	Alluvial, eolian, lacustrine	None	Dry depressions	2	2
DB	Fills of depressions on and adjacent to basalt flows	Eolian, lacustrine, colluvial	None	Dry depressions	3	2
DC	Fills of solution-subsidence depressions in gypsiferous carbonate terrain	Alluvial, colluvial	None	Dry depressions	3	3
DD	Fills of deflational depressions	Eolian, lacustrine	None	Dry depressions	3	2
DK	Karst-plain deposits	Alluvial, colluvial, eolian, lacustrine	None	Piedmont	2	3
DS	Fills of solution-subsidence depressions in saline-gypsum evaporite terrain	Alluvial, colluvial, eolian, lacustrine	o2 and y	Dry depressions	3	3
GF	Colluvium, high altitude	Colluvial	None	Slopes	1	1
GT	Glacial till	Glacial	None	Slopes	1	1
V	Volcanic rocks, undivided	Volcanic	t	Any	1	1
VA	Andesite	Volcanic	None	Any	1	1
VB	Basalt flows	Volcanic	None	Any	1	1

Table 3. (continued)

Unit Code	Unit Name	Mode of Emplacement	Default Age Class (See Table 4)	Depositional environment	Emplacement Susceptibility	Environment Susceptibility
VBS	Basaltic tuff rings	Volcanic	None	Any	1	1
VR	Rhyolitic and dacitic volcanics and sedimentary fills	Volcanic	None	Any	1	1
K	Calcretes, undivided	Alluvial, eolian	o	Uplands	1	3
KG	Gravelly calcrete	Alluvial	o	Uplands	1	3
KM	Calcrete	Alluvial, eolian	o	Uplands	2	3
KT	Caprock calcrete	Alluvial, eolian	t	Uplands	1	3
KTG	Gravelly caprock calcrete	Alluvial	t	Uplands	1	3
AKT	Shallow draws of the High Plains	Alluvial	None	Drainages	2	3
CAKT	Deep draws of the High Plains	Alluvial, colluvial	None	Drainages	2	3

Older deposits were assigned lower hydrocompaction susceptibilities for two reasons. First, older deposits will have had more exposure to stabilizing phenomena (e.g., flooding and saturation) simply due to their older age, leading to higher likelihoods of stabilization of initially collapsible soils. Second, New Mexico experienced significantly wetter climatic conditions during the episodic glacial periods of the Pleistocene epoch (approximately 2.6 million to 12,000 years ago), such that deposits that existed during the Pleistocene likely encountered enough flooding and saturation to stabilize the deposit. Hawley et al. (2005) utilized a set of age classes that characterized most surficial deposits across New Mexico. Their map units and assigned collapsible soil susceptibility factors are given in Table 4.

Hawley et al. (2005) made secondary classifications of map units based on composition or texture for much of, but not all of, the state. Where secondary classifications were mapped, multiple designations were often given to reflect the mix of compositions or textures present in that map unit. For the purpose of this product, each individual designation was assigned a susceptibility factor, and the maximum susceptibility factor for any given combination of designations was used for the composition and/or texture susceptibility factor.

In Hawley et al. (2005), composition refers to either the composition of bedrock (in the case of bedrock or colluvium) or the composition of clasts/grains composing a deposit. In either case, we only considered a few compositions to correlate significantly to hydrocompaction susceptibility (Table 5). Specifically, the weakly-cemented sedimentary rock compositions—particularly those cemented by clays—could be collapsible, and, also, their presence as clasts in a deposit suggest the deposit may be made of appropriate materials to form a collapsible soil.

Texture in Hawley et al. (2005) refers to the grain- and clast-sizes found as constituents of a given deposit. As noted in the Introduction, collapsible soils are typically associated with sandy, silty, and loamy deposits. These textures are given high susceptibility factors, while gravelly deposits and clays are given lower, but still non-zero, susceptibility ratings (Table 6).

2.3 SSURGO and STATSGO soil texture-based susceptibility

The National Resource Conservation Service (NRCS) has mapped the soils of the majority of New Mexico at a 1:30,000 scale (Soil Survey Staff, 2014). The mapped units and associated data are available in the SSURGO database. The remainder of the state has been mapped at 1:250,000 scale, with that data available in the STATSGO database (Soil Survey Staff, 1994; Fig. 4). These data include a broad suite of mostly agriculturally important information, mainly for only the top 2 m of the sediment. However, they report soil textures and the soil taxonomic classifications of mapped soils.

Table 4. Relationship between map unit age classes and collapsible soil susceptibility. Quality factor is 7.

Age Class	Age Class Name	Age	Age Susceptibility
h	Holocene	Holocene	4
o	Undivided "older Pleistocene"	Middle-Upper Pleistocene	2
o1	Early-phase "older Pleistocene"	Middle? Pleistocene	2
o2	Late-phase "older Pleistocene"	Upper? Pleistocene	2
o2 and y	Undivided y and o2	Upper Pleistocene	3
t	Pliocene and "lower Pleistocene"	Pliocene-Lower Pleistocene	1
u	Undivided	Unspecified	3
y	Holocene and "younger Pleistocene"	Late Wisconsin and Holocene	4

Table 5. Relationship between map unit subunit composition classes and collapsible soil susceptibility. Quality factor is 7.

Composition Class	Composition Class Name	Description	Composition Susceptibility
b	Mafic volcanics	Mafic volcanics: mainly basalt and basaltic andesite flow units, limited areas of vent units (cinders, scoria, tuff).	1
c	Carbonate rocks	Carbonate rocks: limestone and dolomite, in part cherty; may include minor amounts of sandstone, shale and mudstone; local gypsiferous rocks.	1
e	Evaporitic sedimentary rocks	Evaporitic sedimentary rocks: includes gypsum, anhydrite, and sodium-potassium chloride salt sequences.	2
f	Foliated metamorphic rocks	Foliated metamorphic rocks: mostly metasediments including phyllite, schist and slate, with lesser amounts of quartzite, gneiss, and greenstone.	1
g	Conglomerate	Conglomerate, with lesser amounts of conglomeratic sandstone and mudstone: gravel-size clasts usually make up 35% to 65% of rock.	2
i	Intermediate volcanics and volcaniclastic rocks	Intermediate volcanics and volcaniclastic rocks: mostly laharic breccias and tuffs, with lesser amounts of andesitic lava as well as mudstone, sandstone, and conglomerate.	1
k	Calcrete	Calcrete	1
m	Mudstone, shale, and siltstone	Mudstone, shale, and siltstone; may have minor amounts of sandstone and carbonate rocks.	3
n	Metamorphic rocks, undivided	Metamorphic rocks, undivided; includes minor areas of small plutons.	1
p	Plutonic and associated crystalline rocks	Plutonic and associated crystalline rocks: mostly silicic and intermediate types including granite, monzonite, syenite, diorite, granodiorite, dacite to andesite porphyries, pegmatites, gneisses, and schist.	1
q	Quartzite	Quartzite, with lesser amounts of silicic metasediments and metavolcanics.	1
r	Silicic volcanics	Silicic volcanics: includes rhyolite, dacite, and quartz latite; mostly welded tuff, with lesser amounts of poorly welded tuff, lava, and pumice.	1
s	Sandstone	Sandstone; may include minor amounts of conglomerate, mudstone, siltstone, shale, and carbonate rocks.	3
u	Metavolcanics and associated metasediments	Metavolcanics and associated metasediments: includes metarhyolite, amphibolite, schist, phyllite, greenstone, quartzite and metaconglomerate.	1
v	Volcanic rocks	Volcanic rocks (excluding all Quaternary and some Pliocene units): undivided assemblages of mafic, silicic, and intermediate composition.	2

Table 5. (continued)

Composition Class	Composition Class Name	Description	Composition Susceptibility
w	Sedimentary rocks, weakly consolidated	Weakly consolidated sedimentary rocks: includes sandstone, mudstone, and conglomeratic sandstone to mudstone with mixed clast lithologies.	4
x	Mixed clast assemblages	Mixed clast assemblages: designates units with subrounded to well-rounded gravel of mixed composition, usually resistant types including quartzite, quartz, chert, petrified wood, rhyolite, basalt, granite, gneiss, and metavolcanics.	1
y	Sedimentary rocks, undivided	Sedimentary rocks, undivided	2
z	Mixed igneous and metamorphic rocks, undivided	Mixed igneous and metamorphic rocks: undivided assemblages of plutonic, metamorphic, and volcanic clasts, including quartzite, rhyolite, basalt, granite, and gneiss.	1
a[1]	Mixed clast assemblage	Equivalent to code xx for this report	1
h[1]	Mixed clast assemblage	Equivalent to code xx for this report	1
t[1]	Mixed clast assemblage	Equivalent to code xx for this report	1
l[1]	Mixed clast assemblage	Equivalent to code xx for this report	1
j[1]	Mixed clast assemblage	Equivalent to code xx for this report	1
o[2]	Mixed clast assemblage	Equivalent to code xy for this report	2
xx	Mixed clast assemblage	Mixed clast assemblage with major component of volcanic/volcaniclastic rocks, clastic sedimentary rocks, and plutonic/metamorphic rocks.	1
xy	Mixed sedimentary rock assemblage	Mixed clast assemblage with major component of sandstone, limestone and mudstone.	2

[1] - Original composition code, equivalent to code xx (J.W. Hawley, pers. comm. November 2016)

[2] - Original composition code, equivalent to code xy (J.W. Hawley, pers. comm. November 2016)

Table 6. Relationship between map unit subunit textural classes and collapsible soil susceptibility. Quality factor is 5.

Texture Class	Texture Name	Description	Texture Susceptibility
s	Sand	Sand. A particle-size term designating 0.06 to 2 mm clasts.	4
i	Silt	Silt. A particle-size term designating 0.004 to 0.06 mm clasts.	3
c	Clay	Clay. A particle-size term designating <0.004 mm clasts.	2
m	Loam	Loam. A term denoting sand-silt-clay mixtures with <35% clay, <50% silt, and varying amounts of sand.	4
g	Gravel	Gravel. A particle-size term designateing >2mm clasts comprising. Also a material class for unconsolidated sedimentary deposits with more than 50-65% >2mm clasts.	1
1	Pebbly	Pebbly: gravel is dominantly 2 to 64 mm across.	1
2	Cobbly	Cobbly: gravel is dominantly 64 to 256 mm across.	1
3	Bouldery	Bouldery: gravel is dominantly >256 mm across.	1

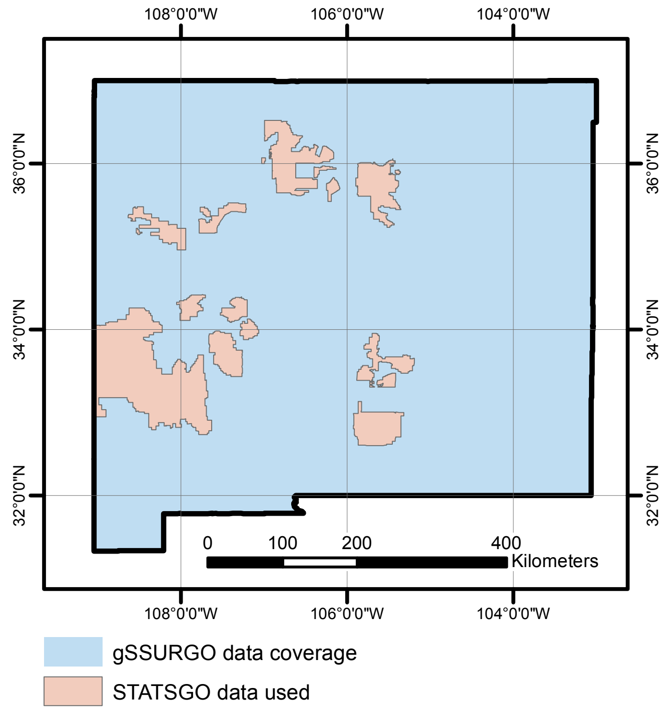


Figure 4. Map of gSSURGO coverage and areas where STATSGO data was used.

Our method for translating SSURGO and STATSGO textures to susceptibilities is described in this section. As discussed above, hydrocompaction susceptibility is a function of sediment texture, and we infer that the textures described for the deeper sections of each SSURGO soil map unit probably reflect the nature of the underlying, unaltered sediment (Fig. 5). SSURGO and STATSGO soil map units range from simple units with a single soil series, to complex units with more than one series. Each series is associated with a type soil profile (pedon), but type profiles for each series are defined from region to region, and there is significant variability in pedons used even from one quadrangle to the next.

Soil textures are presented in SSURGO and STATSGO through texture designations that indicate specific ranges in grain size distribution for the constituent particles <2 mm in diameter (Fig. 6). As outlined in the introduction, some grain size distributions are more conducive to forming collapsible soils than others; these texture ranges are given higher susceptibility factor ratings than the surrounding ranges (Fig. 6). Soil texture designations are given for each soil horizon in the type pedon for each soil series, and individual map units may contain one or more soil series. A complicating factor in using SSURGO and STATSGO texture data, therefore, is in parsing the mix of soil textures to produce a meaningful contribution to the collapsible soil susceptibility map. Initially, textures were translated to susceptibility factors using the maximum susceptibility rating occurring across all horizons in the type pedons found in each map unit. However, we found that the majority of map units contain at least one horizon with the maximum susceptibility factor (four)—this purely conservative approach therefore contributed little in differentiating regions of varying susceptibility and was abandoned. To find a susceptibility factor for each soil map unit, two constraints were used (Fig. 7):

1) Only textures within the bottom third of each pedon were considered. The justification for this constraint is that shallow horizons are affected by near-surface soil-altering (pedogenic) processes that often cause a net fining of the soil texture in these horizons. As a result, the shallower horizons reflect weathering and alteration of the parent material, and are consequently usually closer to the loam field (a high susceptibility field) than the unaltered underlying parent sediment. Given the large range in soil and type pedon depths (commonly varying between 0 and 1.5 m, with up to 3 m depths in some datasets), a firm cut-off depth did not appear applicable for the entire state. Thus a fractional cut-off was used. The maximum susceptibility factor across all soil textures in the basal third of each type pedon was assigned as the susceptibility factor for that soil series (Fig. 7b), which may be one of several for a map unit.

2) The susceptibility factor for each map unit was then determined by considering both the individual susceptibility factors associated with each component soil series and the proportion of each series in the map unit. For each map unit, SSURGO and STATSGO give the expected areal extent of each component as a percentage of the map unit covered by that component. From this, the frequency distribution for the maximum soil texture susceptibility factors for the basal one third of each soil series pedon can be determined. For each map unit, the 90th percentile soil texture susceptibility factor was assigned as the susceptibility factor for the map unit (Fig. 7b). This level was selected in order to 1)

prevent minority map unit components (areal coverage <5% of the map unit) from controlling the susceptibility factor for the map unit as a whole, and 2) provide a susceptibility factor that is both conservative and useful in differentiating areas of varying collapsible soil susceptibility.

The SSURGO digital dataset often does not include texture information for "minor constituents" of each map unit. Our review of the data found that in some cases up to 45% of the map unit may be "minor constituents," but generally these components are <20%. Given time constraints, we chose to disregard the minor constituents for map units with at least 80% defined major components (e.g., Fig. 7b). For the few map units with >20% minor constituents, we sought additional information in the original NRCS soil map manuscripts, available from the NRCS website. Where the minor constituents and their abundances were well enough defined to provide additional information, we added these components to our own database for the purposes of determining a susceptibility factor for that map unit.

Quality factor varies with the resolution of the dataset. For results derived from the higher-resolution SSURGO dataset, quality factor used was 7; for results from the STATSGO dataset, the factor used was 5.

2.4 SSURGO soil taxonomy-based susceptibility

Soil profiles are a reflection of the local climate, ecology, local topography, parent material and time for development (Schaetzl and Thompson, 2005), with each soil taxonomic classification reflecting a different interaction of these factors (Soil Survey Staff, 1999). However, these factors are the same as those that correlate with collapsible soil susceptibility, leading us to use the readily available maps of soil taxonomic classification as a proxy for collapsible soil classification (Schaetzl and Thompson, 2005; and Momeni et al., 2012).

The soil taxonomy is a hierarchical scheme, going from twelve global soil orders to individual indicator horizons (Soil Survey Staff, 1999). In this work, because of the coarse susceptibility scale and the low resolution (1:750,000) of the final map, we have chosen to construct taxonomically based susceptibility maps from the soil taxonomic order, suborder and great group levels, the three coarsest levels of the taxonomy. These taxonomic levels reflect the first order controls of climate, ecology, local topography, parent material and age. As part of soil mapping, the soil taxonomic classification is generally determined for each map unit's characteristic soil profiles (Soil Survey Staff, 1994 and 2014). Because of the relatively fine scale of soil mapping (less than 1:30:000) relative to the variations in soil forming factors, multiple characteristic soil profiles are common within map units (a composite soil map unit), but the taxonomic classification for each of these profiles is reported as components of a map unit (Soil Survey Staff, 1994, 1999 and 2014). In the soil taxonomic unit, the order is indicated by the final syllable of the last word in the name (Soil Survey Staff, 1999).

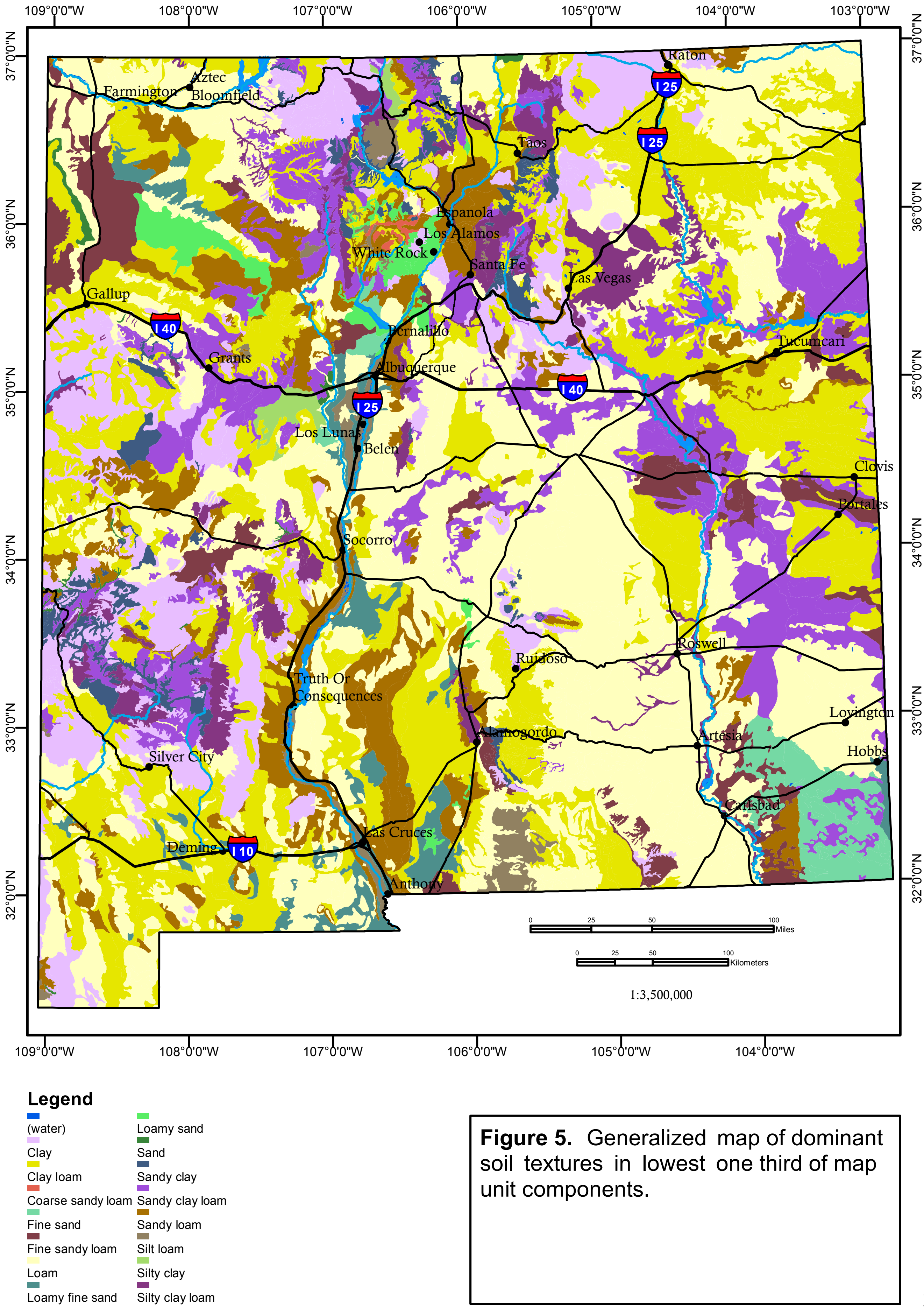


Figure 5. Generalized map of dominant soil textures in lowest one third of map unit components.

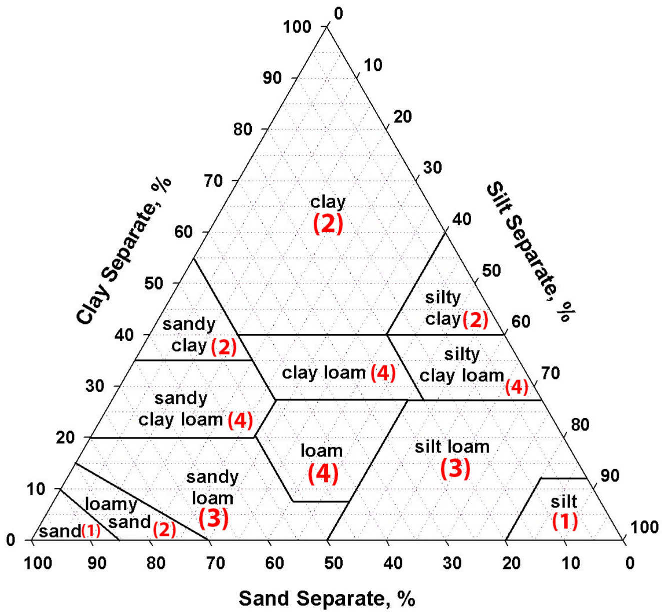


Figure 6. The NRCS soil texture triangle, with the assigned susceptibility ratings given for each texture in parentheses in red.

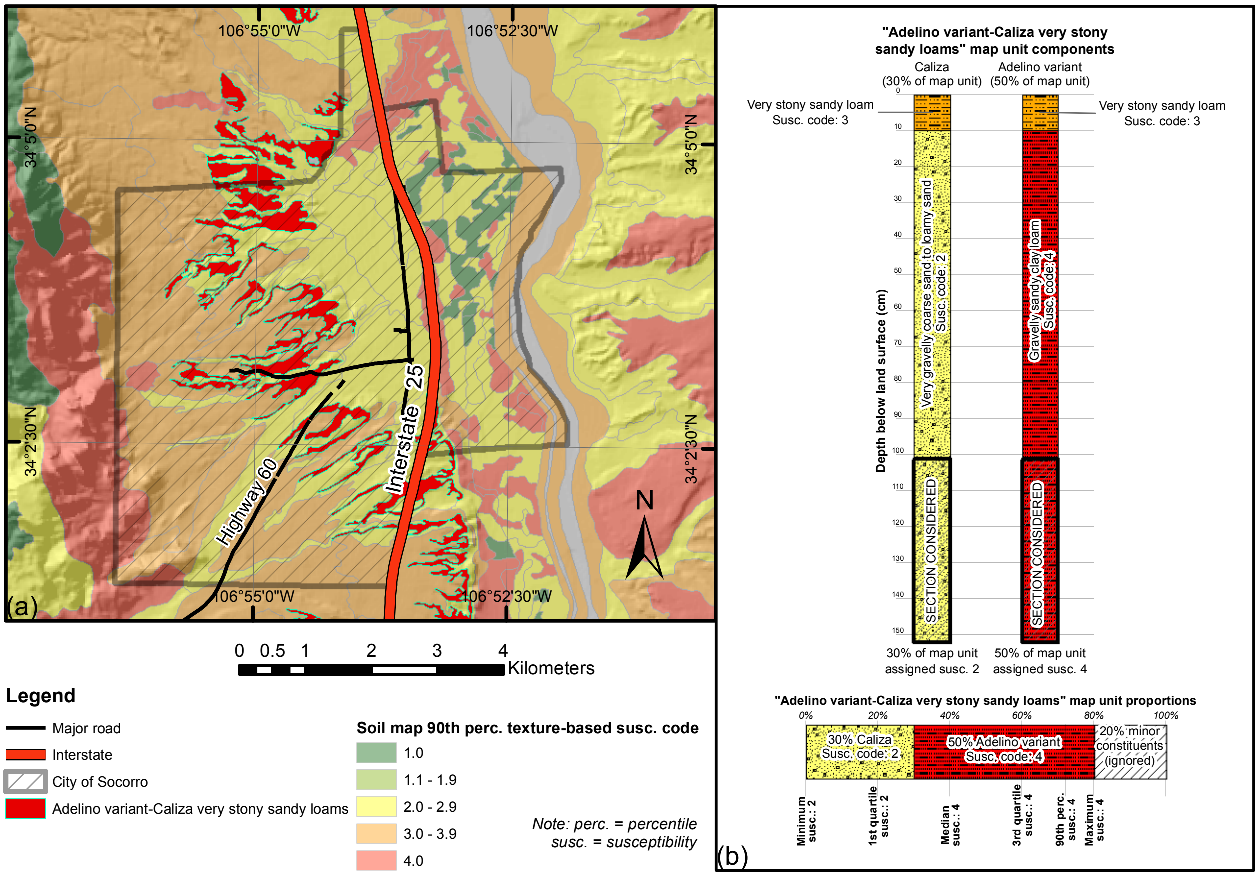


Figure 7. Illustration of the method used to assign a single texture-based collapsible soil susceptibility factor to each soil map unit. (a) Soil map texture-based 90th percentile collapsible soil susceptibility factors circa the city of Socorro. (b) Examination of the components constituting one of the Socorro-area map units, depicting the depth range considered for assigning a texture-based susceptibility to each component and how component abundance is used to determine map unit susceptibility ratings.

Soil order is the coarsest taxonomic level (Soil Survey Staff, 1999). The classification of a soil profile into a soil order is based on the presence or absence of diagnostic features, such as accumulation of salts and clays, translocation of clay horizons, leached horizons associated with transport of metals, alumina or silica, and metal, alumina or silica accumulations (Soil Survey Staff, 1999). Of particular importance to our study are Aridisols, associated with dry environments; Inceptisols and Entisols, associated with lack of pedogenesis; Andisols, associated with volcanic-sourced soils; and Vertisols, associated with thick layers of shrink-swell clays similar to clay-only collapsible soil features. Table 7 summarizes the susceptibilities we have assessed for soil taxonomic order.

Below soil order is the taxonomic sub-order (Soil Survey Staff, 1999). Each order has five to six sub-orders. The sub-orders reflect differences in degree of leaching/accumulation of metals and clays, duration of wetness, climate, horizon development or lack thereof, and other features broadly differentiated by soil development style and desirability for plant growth (Soil Survey Staff, 1999; and Schaetzl and Thompson, 2005). The suborder is identified as a prefix modifying the order indicator (the last one or two syllables) (Soil Survey Staff, 1999). For example, a carbonate soil in New Mexico would be classified as a Calcid, or an Aridisol (low moisture conditions) with a strong calic horizon (Soil Survey Staff, 1999). Soil taxonomic sub-order yields information on climate and moisture condition, accumulation or leaching of salts and metals, translocation of clays and age, but at a more refined level than the soil taxonomic order. Table 8 summarizes the susceptibility factors associated with each sub-order modifier from Soil Survey Staff (1999).

Finally, each characteristic soil profile is assigned a great group below the sub-order taxonomic level. The great group indicator has one or two physical elements with a diagnostic property. This may be moisture regime, an indicator horizon such as calcic, halic or argillic horizons, or some other diagnostic property. Once again, these profile characteristics are associated with parent material, age and formation environment, which correlate with the susceptibility of collapsible soils. Our choices for the susceptibilities associated with great groups are summarized in Table 9.

We used the gridded soil survey geographic (gSSURGO) database to estimate taxonomic-based susceptibilities across New Mexico (Soil Survey Staff, 2014). In gSSURGO, each map unit key is associated with a set of profile keys, each of which is assigned an order, sub-order and great group taxonomic class. Using Tables 7-9 and the gSSURGO database, we constructed three grids of susceptibility based on the soil taxonomic order, sub-order and great group. As mentioned above, a single soil map unit may include multiple characteristic horizons of different soil taxonomic units. Given the resolution and application of our final product, we chose to use the greatest susceptibility at the order, sub-order and great group levels for composite soil map units.

Table 7. Relationship between soil taxonomic order and collapsible soil susceptibility. Quality factor is 9.

Soil Order	Susceptibility (0-4)
Alfisol	1
Andisol	3
Aridisol	3
Entisol	3
Gelisol	1
Histosol	1
Inceptisol	2
Mollisol	2
Oxisol	1
Spodosol	1
Ultisol	1
Vertisol	2

Table 8. Relationship between soil taxonomic sub-order and collapsible soil susceptibility. Quality factor is 8.

Sub-order		Susceptibility (0-4)
Name element	Connotation	
Alb	albic horizon	1
Anthr	modified by humans	1
Aqu	aquic conditions	1
Ar	mixed (plowed) horizon	1
Arg	argillic horizon	2
Calc	calcic horizon	2
Camb	cambic horizon	1
Cry	cold	1
Dur	duripan	1
Fibr	least decomposed stage	1
Fluv	flood plain	3
Fol	mass of leaves	1
Gyps	gypsic horizon	3
Hem	intermediate stage of decomposition	1
Hist	presence of organic materials	1
Hum	presence of organic matter	1
Orth	'the common ones'	n/a
Per	perudic moisture regime	2
Psamm	sandy texture	2
Rend	high carbonate content	2
Sal	presence of salic horizon	3
Sapr	most decomposed stage	1
Torr	torric moisture regime	3
Turb	presence of cryoturbation	1
Ud	udic moisture regime	1
Ust	ustic moisture regime	2
Vitr	presence of glass	2
Xer	xeric moisture regime	2

Table 9. Relationship between taxonomic great group and collapsible soil susceptibility. Quality factor is 7.

Great Group		Susceptibility (0-4)
Name element	Connotation	
Acr	extreme weathering	1
Al	high aluminum, low iron	n/a
Alb	presence of albic horizon	1
Anhy	very dry	3
Anthr	antropic epipedon	1
Aqu	aquic conditions	1
Argi	argillic horizon	2
Calci	calcic horizon	2
Calc	calcic horizon	2
Camb	cambic horizon	2
Cry	cold	1
Dur	duripan	1
Dys	low base saturation	n/a
Dystr	low base saturation	n/a
Endo	implying a groundwater table	1
Epi	perched groundwater table	1
Eutr	high base saturation	n/a
Ferr	presence of iron	n/a
Fibr	least decomposed stage, organic horizon	1
Fluv	flood plain	3
Fol	mass of leaves	1
Fragi	fragipan	1
Fragloss	see formative elements fragi and gloss	1
Fulv	dark brown color, presence of organic carbon	1
Glac	ice lenses or wedges	1
Gyps	gypsic horizon	3
Gloss	presence of glossic horizon	1
Hal	halite present	3
Hapl	minimum horizon development	3
Hem	intermediate stage of decomposition	1
Hist	presence of organic materials	1
Hum	presence of organic matter	1
Hydr	presence of water	1
Kand	1:1 layer silicate clays	1
Kan	1:1 layer silicate clays	1
Luv	illuvial	n/a
Melan	black, presence of organic carbon	1
Moll	mollic epipedon	3
Natr	presence of natric horizon	1
Pale	excessive development	1
Petr	cemented (old) horizon	2
Plac	presence of thin pan	1

Table 9. (continued)

Great Group		Susceptibility (0-4)
Name element	**Connotation**	
Plagg	plaggen epipedon	1
Plinth	presence of plinthite	1
Psamm	sandy texture	2
Quartz	high quartz content	n/a
Rhod	dark red color	1
Sal	salic horizon	3
Sapr	most decomposed stage	1
Somb	sombric horizon	1
Sphagn	presence of sphagnum	n/a
Sulf	presence of sulfides or their oxidation products	n/a
Torr	torric moisture regimes	3
Ud	udic moisture regime	1
Umbr	umbric epipedon	3
Ust	ustic moisture regime	2
Verm	wormy or mixed by animals	1
Vitr	presence of glass	2
Xer	xeric moisture regime	3

2.5 Vegetation and land-use-based susceptibility

Vegetation and land-use are correlated with collapsible soil potential, as they reflect the aridity, youth, and depth-to-water and history of saturation of a deposit. However, once again, these factors are not direct proxies for collapsible soils; engineering measures would be needed to determine the true susceptibility. To form a uniform base for our map of vegetation and land-use, we use the most recent (2011) USGS National Land Cover Database (NLCD; Fig. 8; Homer et al., 2015). This classification uses the same codes to cover the entirety of North America. While not all classes appear in New Mexico, we have made a susceptibility correlation for each class (Table 10).

Regions where land-use does not have a meaningful correlation with hydrocompaction susceptibility, such as developed areas, are excluded from the analysis, while regions that in New Mexico correlate with desert and prairie ecosystems (i.e., drylands) are given a higher susceptibility. Land-use that correlates with higher elevation and wetter environments are given a low susceptibility. Cultivated regions are given a moderate susceptibility, despite the fact that most cultivated regions along the river valleys have been wetted repeatedly. This accounts for rarer situations, such as where a recently emplaced field is on a young distal alluvial fan lobe, on weakly clay-cemented sandstone, or on loess or other eolian deposit, that present higher susceptibilities of collapsible soils than in longer-term, flood irrigated fields.

2.6 Depth-to-water-based susceptibility

In general, if a deposit has been repeatedly saturated then the pore space has probably collapsed. This implies that regions with shallow groundwater, which are generally close to streams, have a lower susceptibility than those with deeper groundwater tables. In New Mexico, depth-to-water (DTW) below ground surface (BGS) is measured at each NMOSE permitted water well by the driller at the time of completion. This data is freely available from the NMOSE. However, the location of wells is relatively uncertain compared to the resolution of the 1:30,000 soils maps and NLCD maps, the density of measurements is highly variable across the state, and DTW can vary dramatically over relatively short (100s m) distances depending on topography, date of drilling and pumping history.

With these limitations in mind, we have constructed variable susceptibility and variable quality metrics related to DTW based on both the DTW and the density of measurements. First, we find the median DTW (ft below ground surface; Fig. 9), the range of DTW in each cell, and number of wells within each square kilometer across the entire state (Fig. 10). Then, we use

$$s_{dtw} = \begin{cases} 1, if\ d \le 15\ ft\ bgs; \\ 2, if\ 15\ ft\ bgs < d \le 40\ ft\ bgs;\ and \\ 3, if\ d > 40\ ft\ bgs \end{cases} \quad (2)$$

where s_{dtw} is the susceptibility based on the median DTW and d is the median DTW. These thresholds were chosen based on observations of normal annual to decadal variations of groundwater levels in basin-fill aquifers across the state observed by Rinehart while conducting a statewide groundwater change analysis (Rinehart et al., 2015, 2016 and 2017). Regions with deeper groundwater are more likely to have never flooded and been saturated through the entire thickness. The quality factor for each 1-km cell is from

$$Q_{dtw} = \begin{cases} 3 \;+\; (3 \;-\; n) if\ m \geq 5; \\ \quad else\ 3\ if\ m\ < 5 \end{cases} \tag{3}$$

where Q_{dtw} is the DTW-based quality, n is the number of susceptibility classes from Eq. 2 crossed by the range of DTW in each cell, and m is the number of wells in each cell. This form was arrived at iteratively to capture both reliability from the number of wells, but to also capture loss of certainty due to aquifer or topographic changes within a cell.

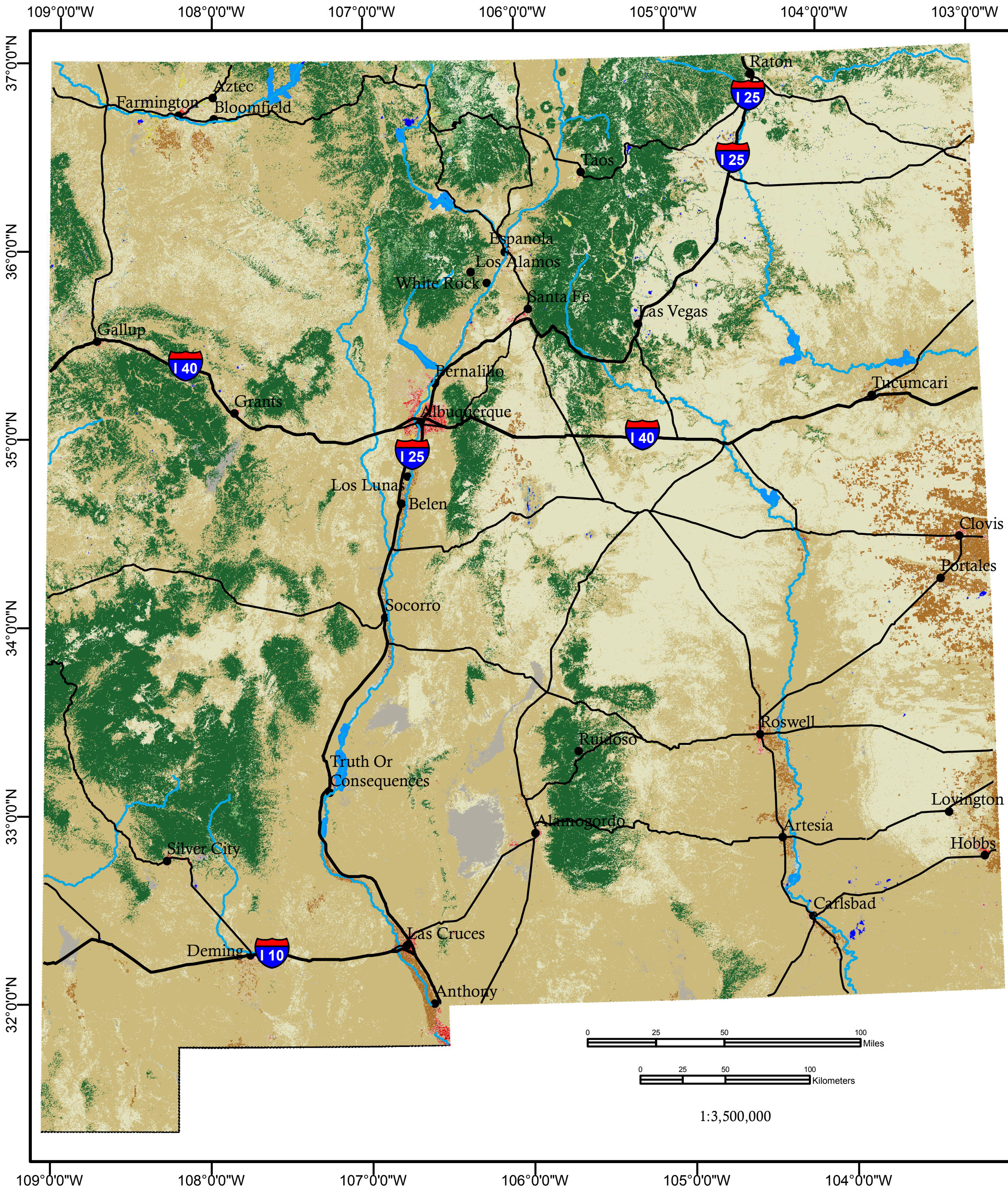


Figure 8. Map of NLCD land-use classifications.

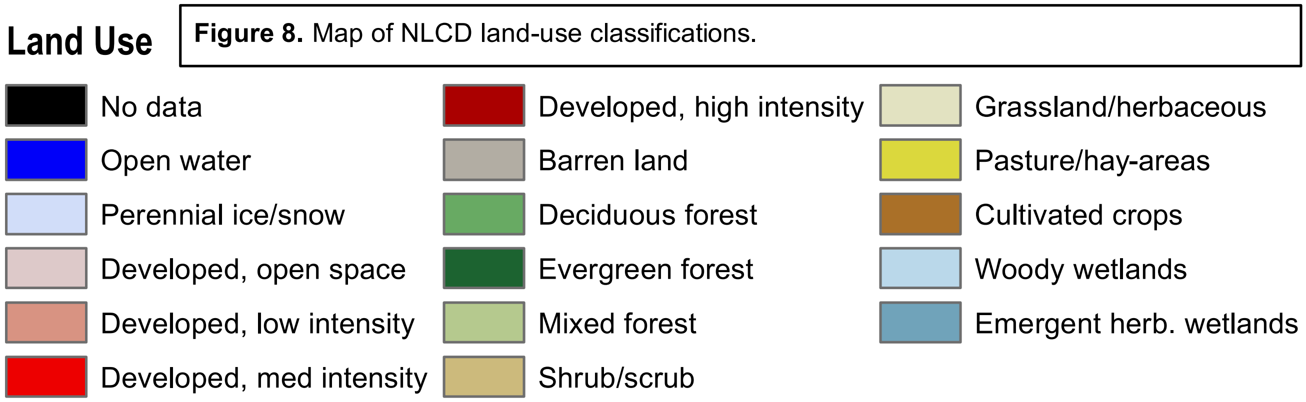
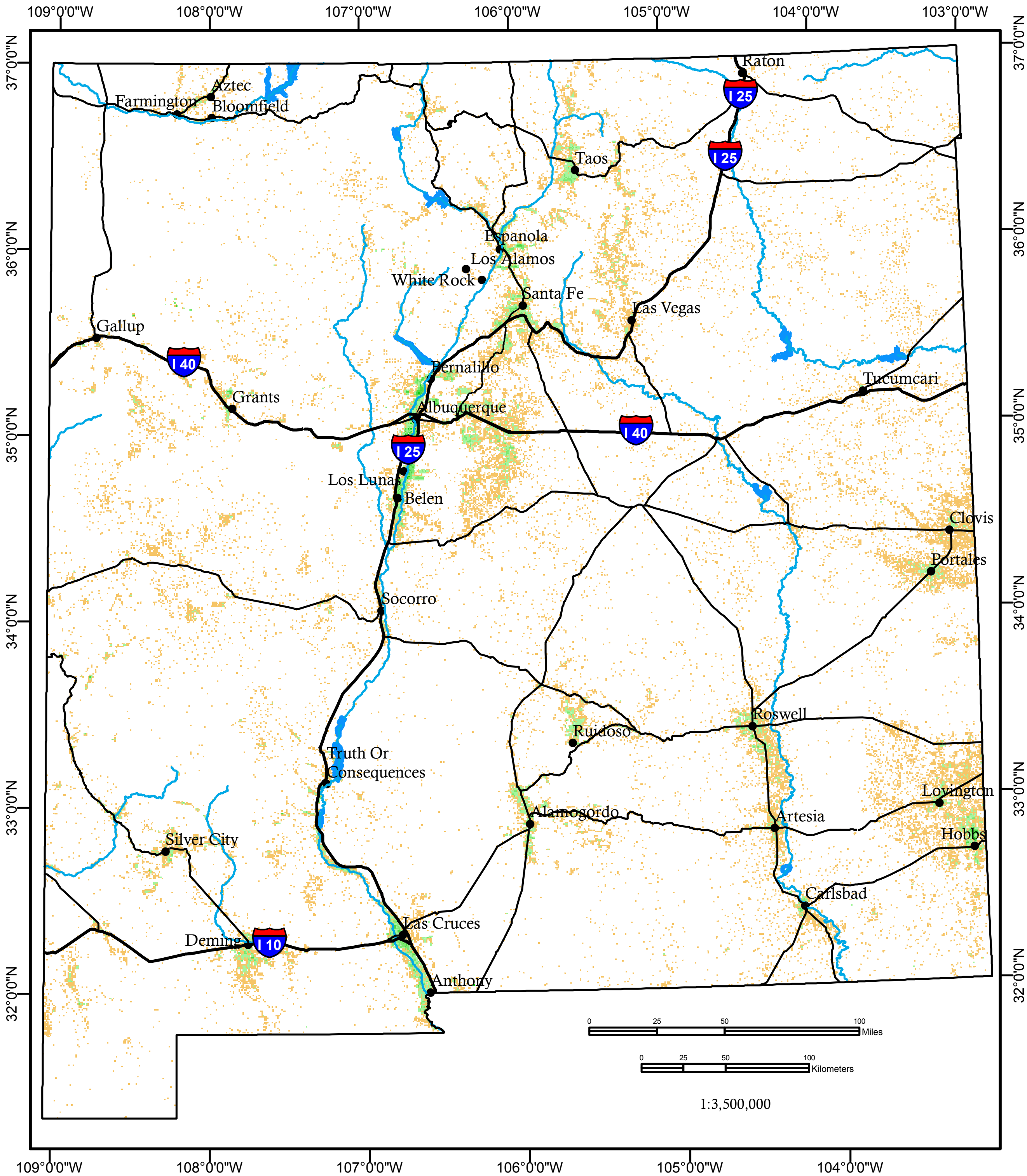


Table 10. Relationship between NLCD classification and collapsible soil susceptibility. Quality is 6.

Land-use Unit		Susceptibility (0-4)	Quality
Description	Code		
No data	0	-1	-1
Open water	11	0	6
Perennial ice/snow	12	0	6
Developed, open space	21	-1	-1
Developed, low intensity	22	-1	-1
Developed, medium intensity	23	-1	-1
Developed, high intensity	24	-1	-1
Barren land	31	3	6
Deciduous forest	41	1	6
Evergreen forest	42	1	6
Mixed forest	43	1	6
Dwarf scrub	51	1	6
Shrub/scrub	52	3	6
Grassland/herbaceous	71	3	6
Sedge/herbaceous	72	1	6
Lichens	73	1	6
Moss	74	1	6
Pasture/hay-areas	81	2	6
Cultivated crops	82	2	6
Woody wetlands	90	0	6
Emergent herbaceous wetlands	95	1	6



Number of Wells

	1 - 5
	6 - 20
	21 - 50
	51 - 100
	101 - 200

Figure 9. Map of the number of wells per square km.

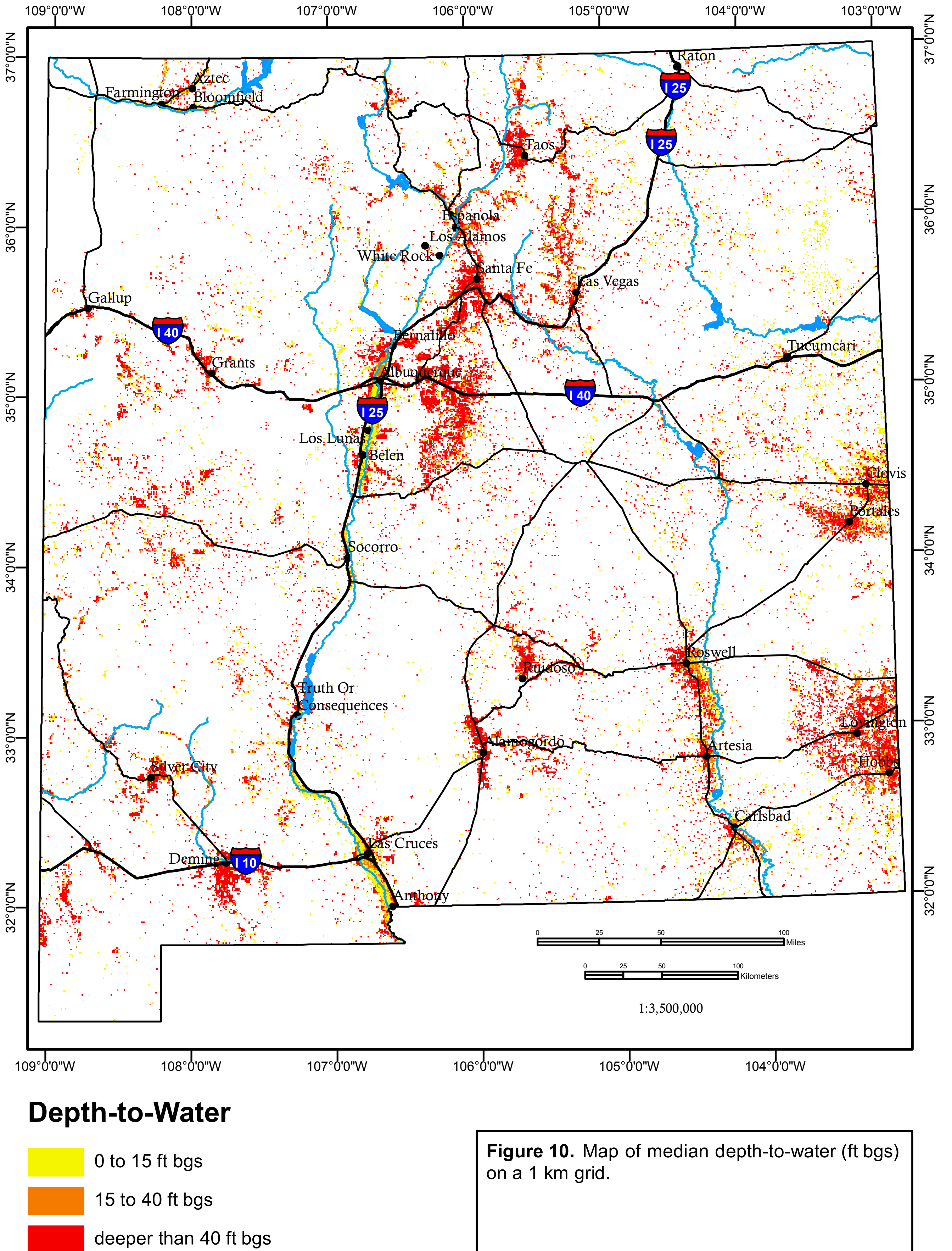


Figure 10. Map of median depth-to-water (ft bgs) on a 1 km grid.

3 Results

3.1 Locations of known collapsible features

One the major results of this study is a map of the known locations where hydrocompaction has occurred, shown in Figure 11. The primary challenge with mapping collapsible soils is that, without expensive geotechnical testing, the only way to know if the hazard exists there is to load the soil and then wet it—in other words, to build a structure and focus the runoff, and see if the soil collapses. Often, hydrocompactive subsidence has occurred in private developments, on tribal land, or along roads, but it is not required to be reported. The mapped locations (Fig. 11) are where we know that hydrocompaction has occurred from loading and runoff either from structures, generally houses, or from roads. In general, the known locations are located in the alluvial apron or fan of mountains along the margins of major valleys. These locations are where classic semi-arid collapsible soils occur: in the poorly sorted but rapidly deposited, mud-rich sediments of alluvial fans.

Other areas of possible (rumored) collapse features are along some of the roads in and around the Navajo Agricultural Products Industry (NAPI) irrigated fields immediately south of Farmington. This region has both weakly clay-cemented sandstone and loess, both commonly associated with collapsible sediments. However, these features have not been confirmed and are therefore not mapped.

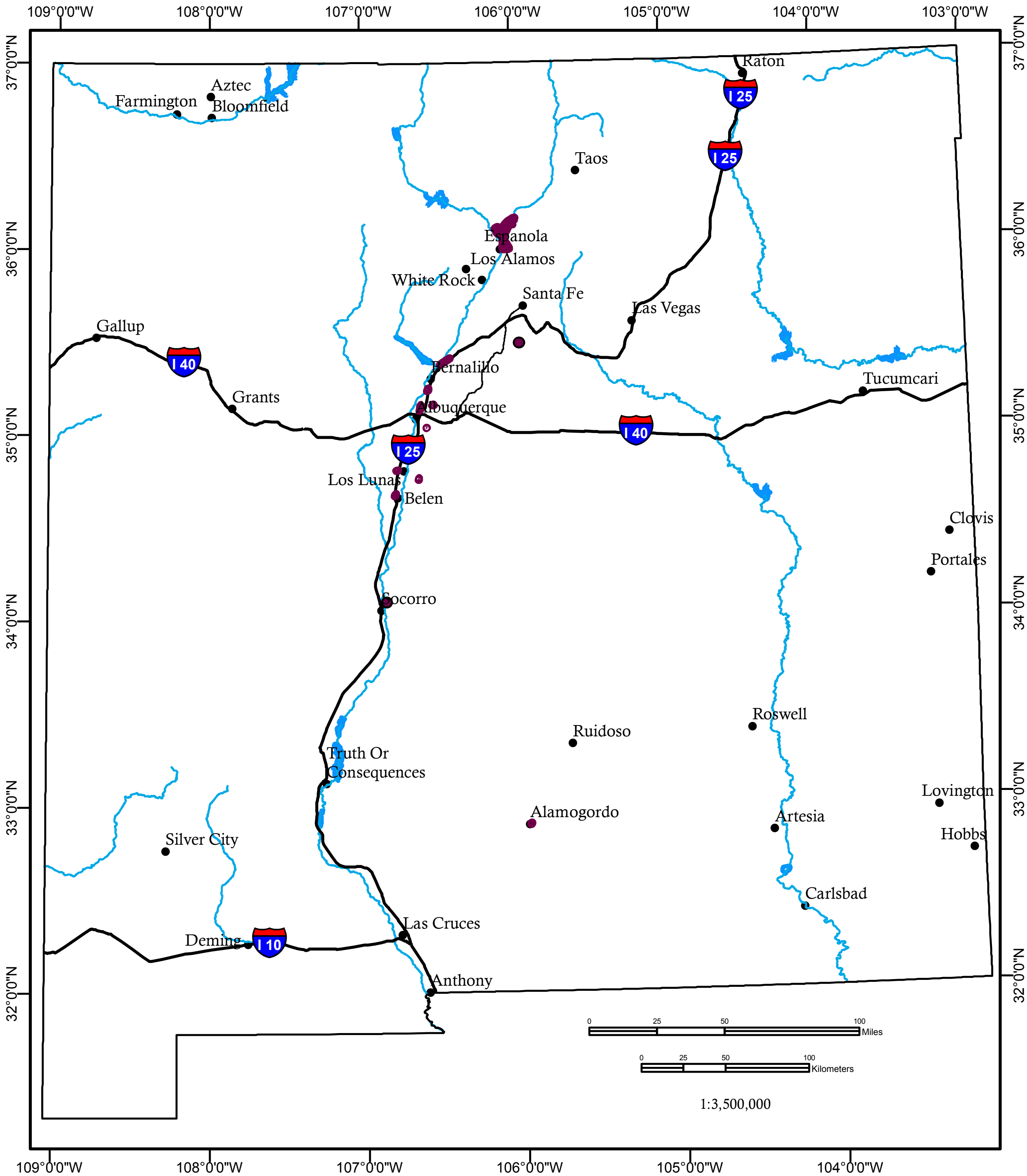
3.2 Climate-based susceptibility and quality

Figure 12 shows a map of estimated Köppen-Geiger climate classification-based susceptibilities. Most of the state is arid with an estimated susceptibility of 3. Except for 32 km^2 of alpine tundra in the Sangre de Cristo Mountains with a susceptibility of 1, the remainder of the state has either temperate or cold climate classifications with estimated susceptibilities of 2.

The broad swath of high susceptibility estimated from climate justifies the relatively low quality factor assigned to climate. Essentially, this susceptibility factor plays a role in biasing the final susceptibility, compensating for uncertainty in other proxies.

3.3 Quaternary landform-based susceptibility

Figures 13 through 17 show the landform map-based hydrocompaction susceptibility maps. In general, the mode-of-emplacement and depositional environment maps (Figs. 13-14) show common high-susceptibility factors reflecting the abundance of environments conducive to hydrocompactive sediments throughout New Mexico. Alluvial fan and eolian settings, in particular, show high susceptibilities in both maps. Low susceptibilities are principally associated with bedrock and mass-wasting-dominated slopes. The age-based susceptibility map (Fig. 15) shows far fewer areas of high susceptibility. Alluvial fan settings, which typically accumulate deposits over a range of time, show relatively high susceptibility factors.



Known Locations
Highways
Major Rivers
Reservoirs
Cities

Figure 11. Map of known hydrocompaction collapse features in New Mexico.

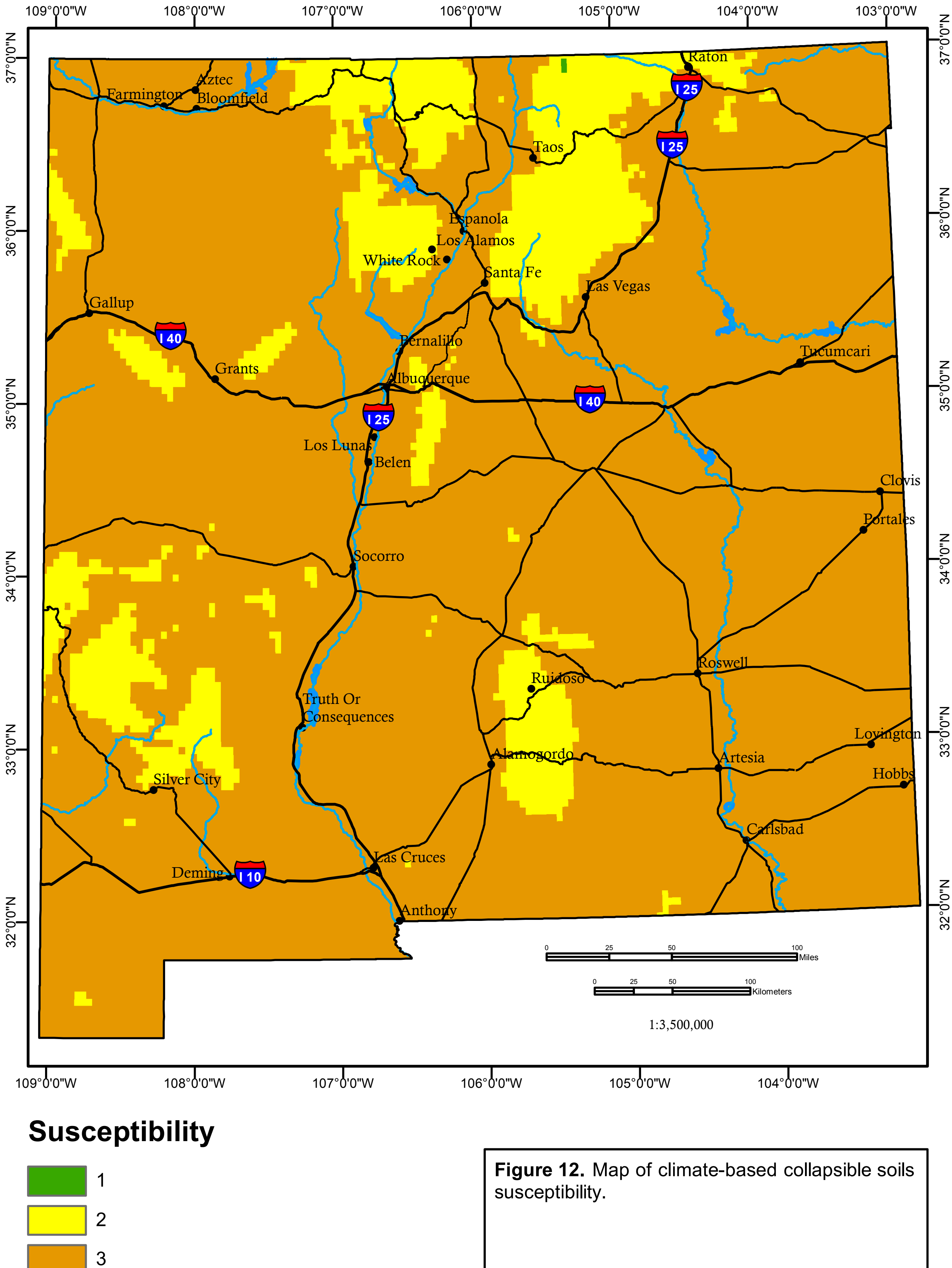


Figure 12. Map of climate-based collapsible soils susceptibility.

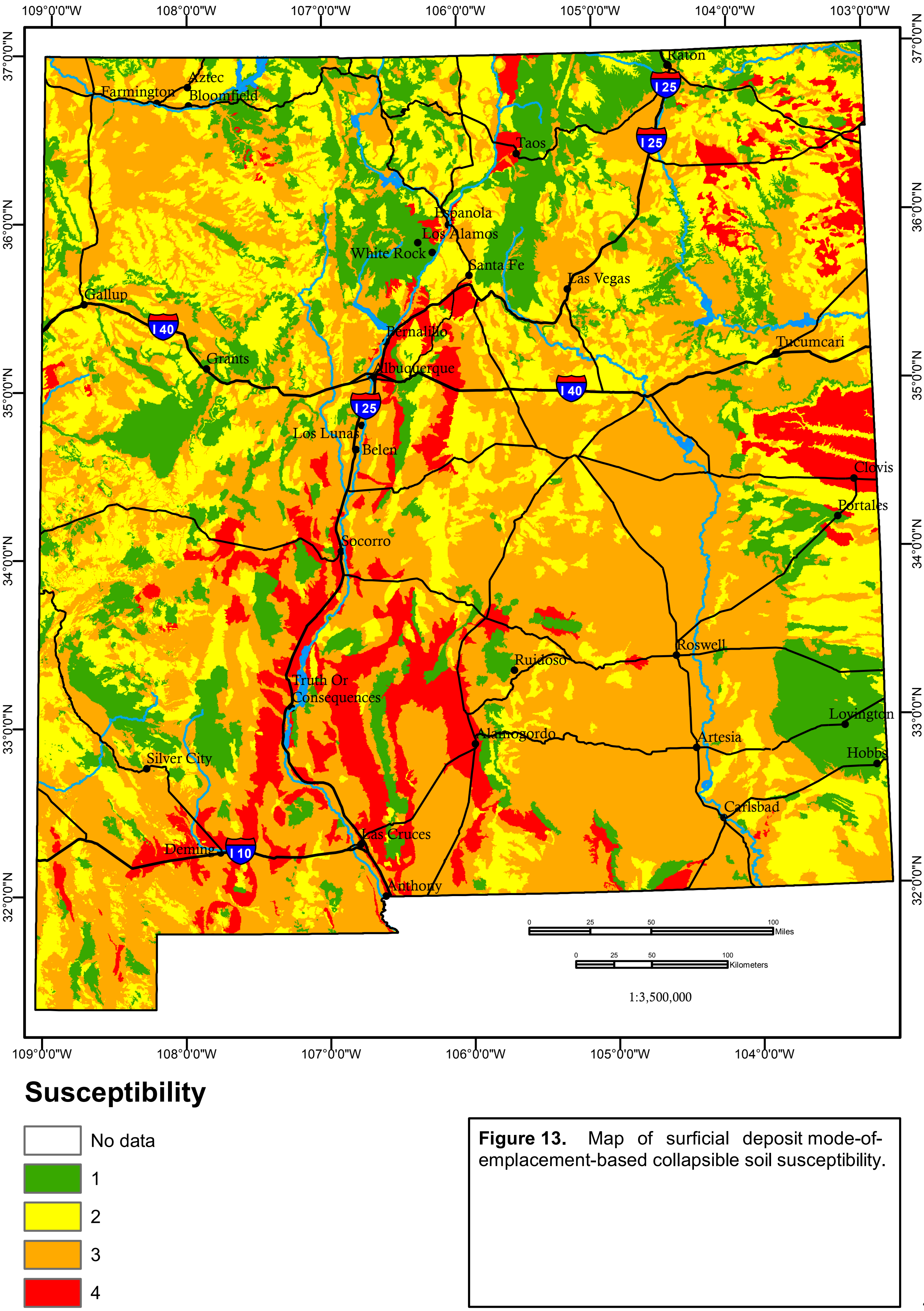
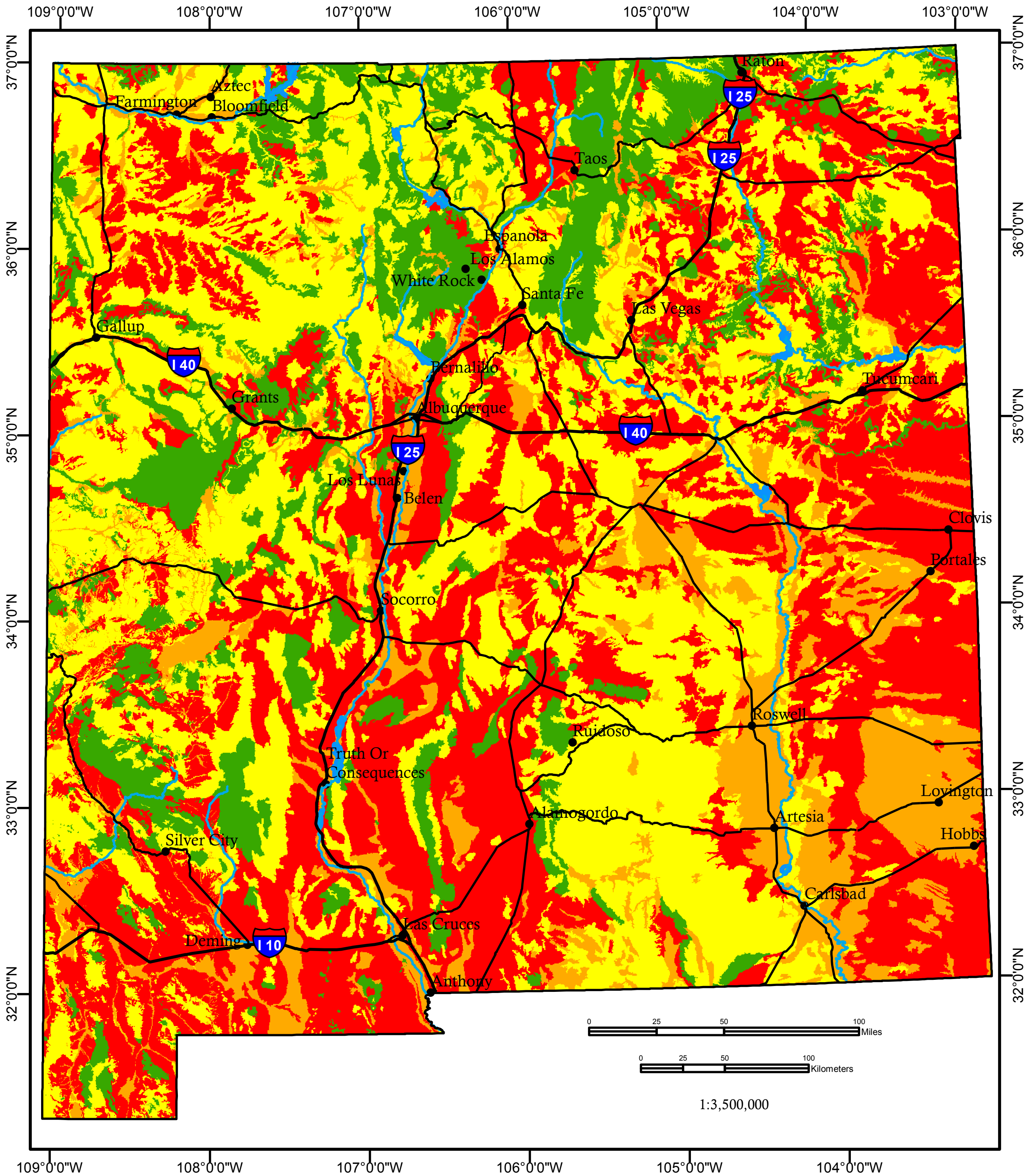


Figure 13. Map of surficial deposit mode-of-emplacement-based collapsible soil susceptibility.



Susceptibility

- No data
- 1
- 2
- 3
- 4

Figure 14. Map of surficial deposit depositional environment-based collapsible soil susceptibility.

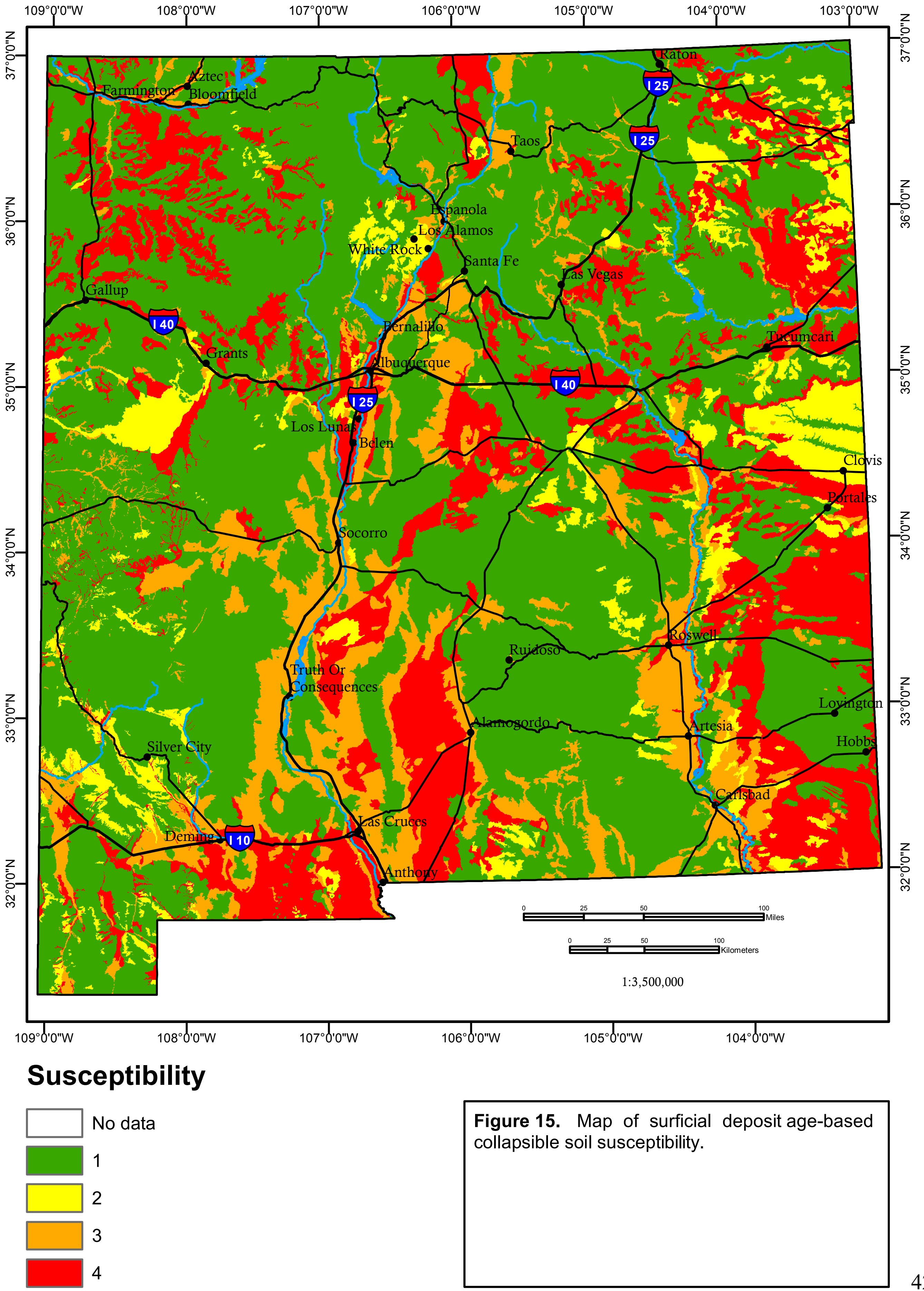


Figure 15. Map of surficial deposit age-based collapsible soil susceptibility.

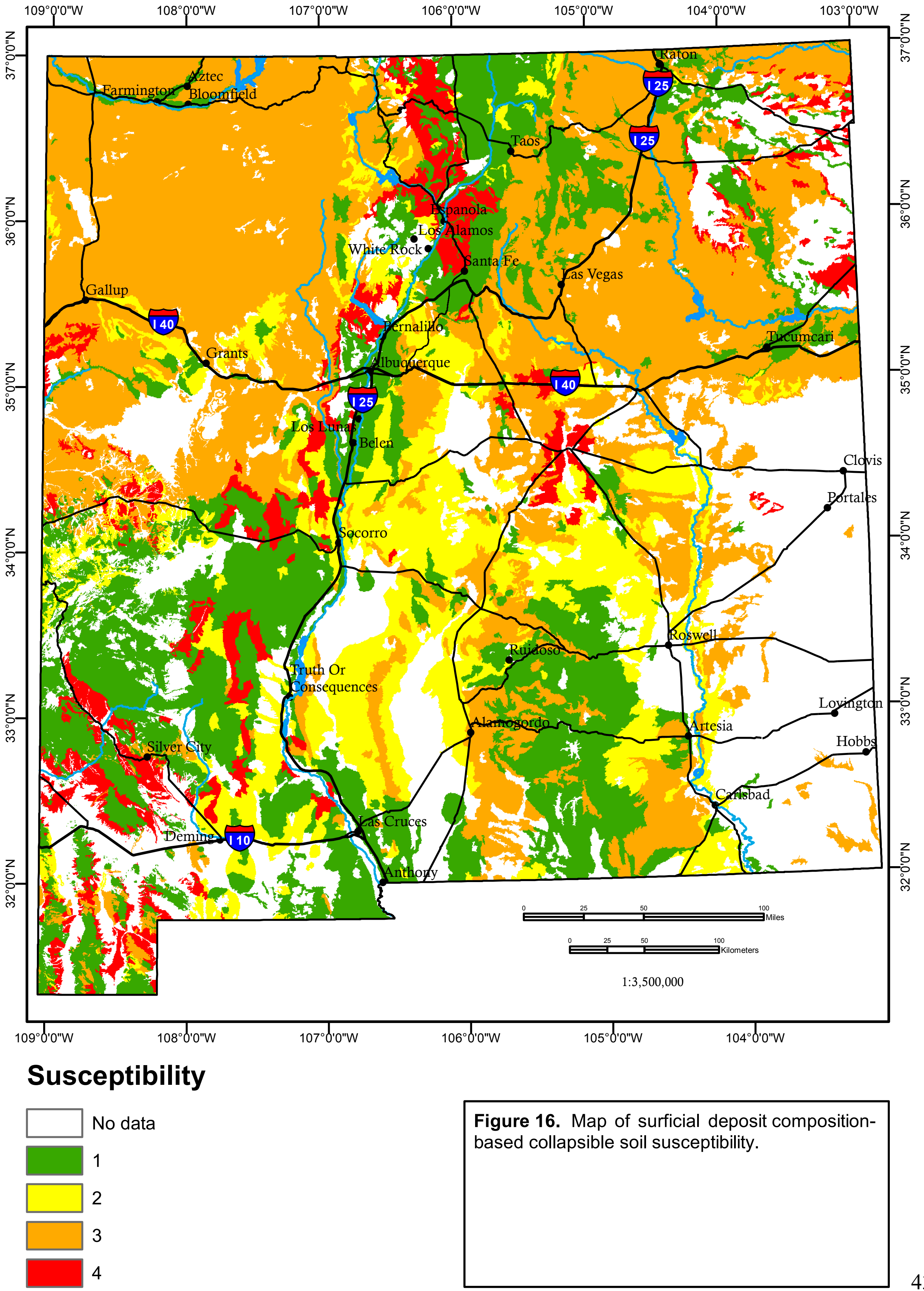


Figure 16. Map of surficial deposit composition-based collapsible soil susceptibility.

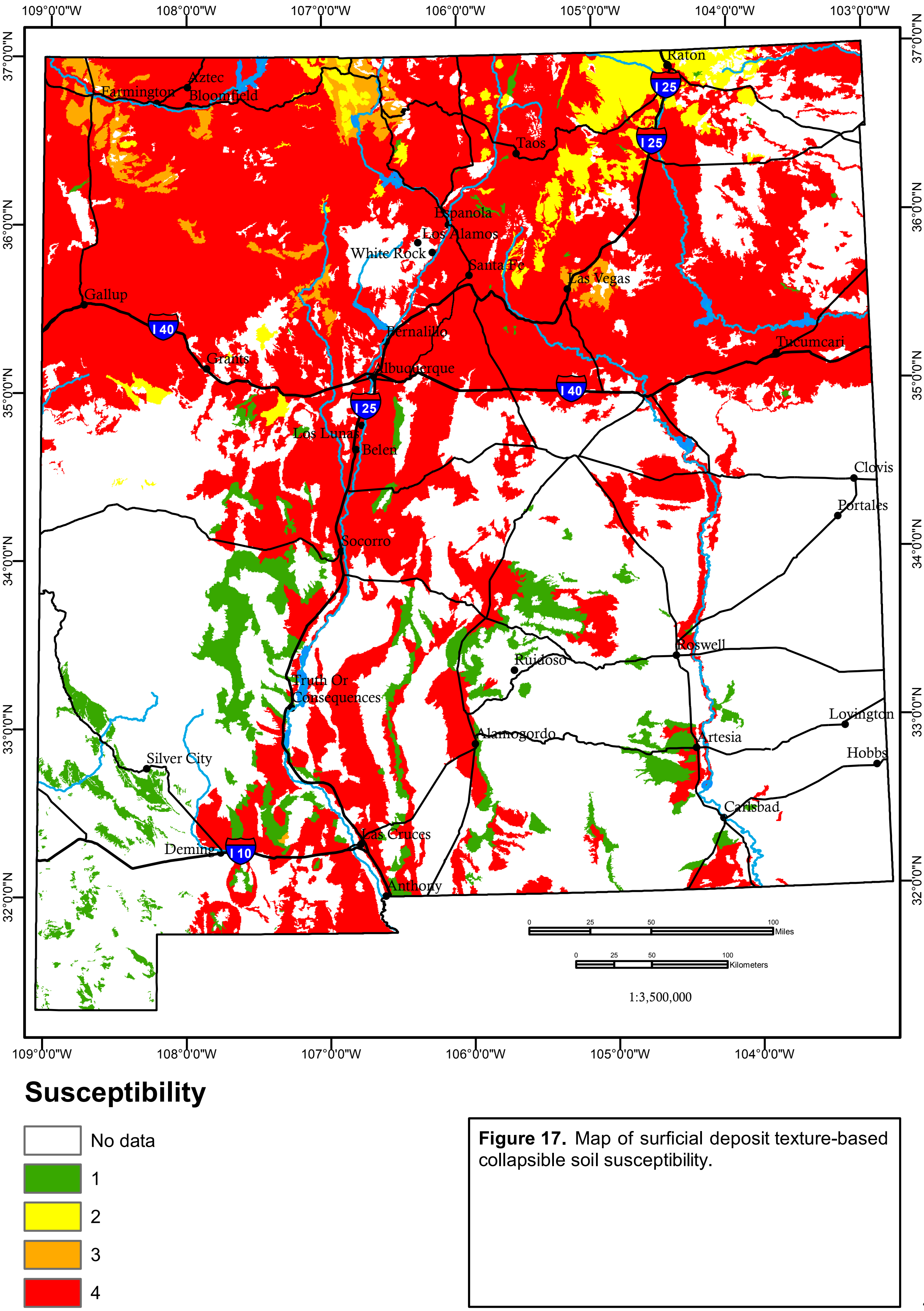


Figure 17. Map of surficial deposit texture-based collapsible soil susceptibility.

As discussed previously, composition and texture classes are only locally defined in the landform map of Hawley et al. (2005), and as a consequence the two derivative susceptibility maps show large areas of “no data” (Figs. 16-17). Where defined, the composition-based susceptibility map highlights areas underlain by sedimentary rocks, and particularly those areas underlain by weakly-cemented sedimentary rocks. Most other areas show low susceptibilities on this map. In contrast, in the areas where texture classes were defined, most show a high susceptibility in the texture-based map (Fig. 23). This results from the application of our conservative approach to texture map units that often include multiple texture classes within a mapping unit. For example, a texture map unit of “gm2,” or “cobbly gravel and loam,” results in the highest susceptibility rating due to the presence of loam anywhere in the map unit designation. Since many texture map units contain at least one high-susceptibility element, most texture map units show high susceptibility in the texture-based map.

3.4 SSURGO and STATSGO soil texture-based susceptibility

Figure 18 shows the susceptibilities from the SSURGO and STATSGO soil texture datasets. Many parts of the state show the highest susceptibility rating, likely due to our conservative method of determining a single susceptibility factor for each map unit. Our approach skews results toward the higher classes occurring in any given map unit, an effect that is particularly prominent in the areas where STATSGO data was used. Here, map units are particularly broadly-defined and incorporate a wide range of soil types, as a consequence of the coarser resolution of the dataset. As a result, most map units from STATSGO include components with high susceptibility factors, resulting in map units with similarly high factors (compare Figs. 8 and 24). Some differentiation is apparent in the soil texture-based susceptibility map, however. In particular, many shallow soils in bedrock areas, such as between Ruidoso-Alamogordo and Roswell-Artesia, east of Socorro and Truth or Consequences, and west of Las Cruces show low susceptibility classes; sand- and gravel-rich alluvial deposits along the Rio Grande and San Juan River show moderately low classes; and poorly-sorted sandy soils along tributaries to the Rio Grande show moderately high classes. Some areas of “no data” persist despite the combining of SSURGO and STATSGO datasets; these areas occur in predominantly bedrock locations, such as the Guadalupe Mountains and hills west of Silver City and Gallup.

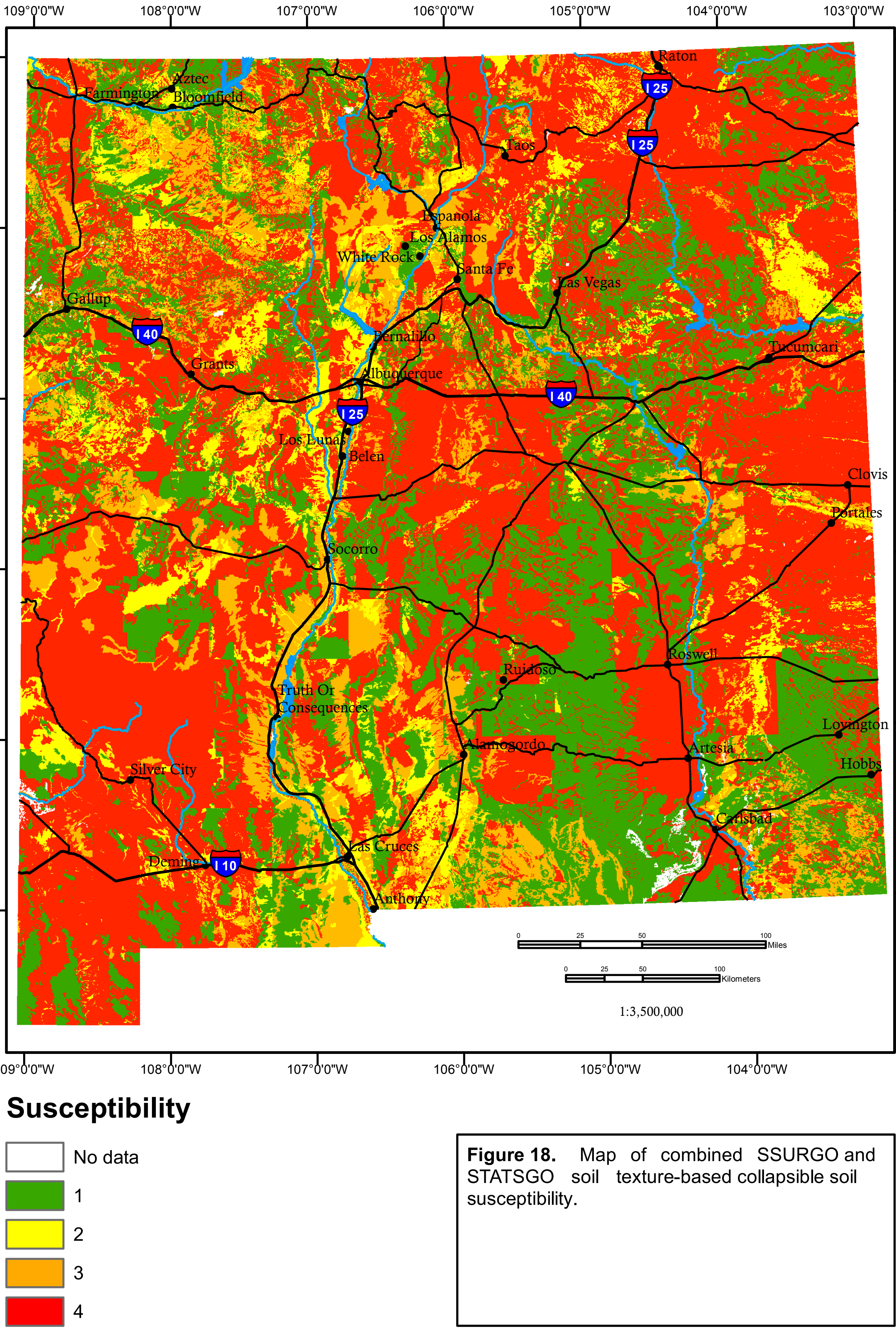


Figure 18. Map of combined SSURGO and STATSGO soil texture-based collapsible soil susceptibility.

3.5 SSURGO soil taxonomy-based susceptibility

Figures 19-21 show the hydrocompaction susceptibilities based on SSURGO-derived soil taxonomic order, suborder and great group. This layer was not merged with the STATSGO dataset, given the large variability in mapping classifications already present in much of the SSURGO dataset. For all three taxonomic levels, not all map units provided valuable information about hydrocompaction susceptibility, creating additional blank spaces in all three estimates. In the case of the taxonomic order-based susceptibilities, these 'no-information' regions generally correspond to regions without developed soils, i.e., rocky regions. For the sub-order susceptibilities, the 'no-information' regions correspond either to rock regions, or regions with the sub-order 'orth-', implying that the properties are typical of whatever the greater order was. For the great group-based susceptibility, the features or horizons leading to the classification either were meaningless for collapse susceptibility or added no additional information from the order and suborder levels.

Taxonomic order-based susceptibilities reflect that most of the state has Aridosols, or soils forming under arid climates, and young soils forming on flat surfaces (Entisols). Soils associated with playas (Vertisols), young soils on slopes (Inceptisols), and more moist and upbuilding grassland soils (Mollisols) have susceptibilities of two. Soils associated with wetter conditions, either in grasslands or forests, have the lowest susceptibility

In general, we did not find assigning high (three) susceptibilities to the suborder taxonomic classes justified, except for classes that indicated very dry climate or salt build-up, or young and rapidly upbuilding soils. This is because the suborder level begins reflecting horizon types, not just profile types (Johnpeer et al., 1985). Horizons indicating moderately dry climate but older age or the presence of clay minerals have an intermediate susceptibility. Suborders indicating humid climates, repeated saturation, plowing or other human impacts, or strong organic horizon development were assigned a susceptibility of one. The particular choice to associate calcic soils, which take a significant time to develop, and slightly wetter conditions with a susceptibility of two leads to a broad assignment of a susceptibility of two. Lowest risks are again associated with highlands and regions that receive frequent flooding. Highest risks are associated with the driest regions and with small fluvial deposits.

Similar to the other, higher taxonomic levels, we chose to assign the highest susceptibilities of three to soils with horizons indicating arid and dry climate, and recent and rapid upbuilding. We used a susceptibility of two for soils with secondary clay-rich, calcite-rich or mollic horizons indicating semi-arid conditions, and less hot and dry climate. The lowest susceptibility (one) was assigned to great groups indicating wetter conditions.

For all three taxonomic levels, the challenge was to assign a susceptibility based on pedogenic classification that is overprinting on the sedimentary deposit—our primary interest was the age and type of sedimentary deposit. For all three taxonomic levels, we had focused higher susceptibilities on classifiers indicating aridity, weak soil development and presence of clays; intermediate susceptibilities on still arid but slightly wetter or older deposits; and the lowest susceptibilities on humid region soils. Nonetheless, we did not assign extreme susceptibility (four) to any soil taxonomic classification, because of the lack of a direct link between soil classification and sedimentary deposit type.

3.6 Vegetation and land-use-based susceptibility

Vegetation and land-use, again, is an indirect proxy for hydrocompaction susceptibility. The map of vegetation- and land-use-based susceptibility is shown in Figure 22. Pixels that were grasslands, desert shrubs, or barren had a susceptibility of three. This is most of the state. Cultivated agricultural land was given a susceptibility of two. Forested or forest-like shrublands (such as mountain 'scrub' oak) pixels received susceptibilities of one. These are usually in mountainous areas and receive enough water to have collapsed the soils.

3.7 Depth-to-water-based susceptibility

Because of the collocation of wells with people, much of the state was not covered by DTW-based susceptibilities (Fig. 23). However, the regions that were covered were generally near population centers, making the susceptibility information from this proxy more valuable for decision makers.

The lowest susceptibility (one) regions are commonly associated with river valleys, though susceptibilities of one are also found scattered through much of eastern New Mexico, where historical water levels were much shallower than today or where aquifers are shallow, perched systems. Because the date of measurement of static water levels begin in the 1920s and continue to 2016, this dataset is an integrative measurement, so declining groundwater levels in parts of the state are not overemphasized. Moderate susceptibility (two) generally were located along valley flanks. The highest susceptibilities (three) are found in closed basins, such as near Deming, near Alamogordo, or in the Estancia Basin, or in upland or mountainous regions.

For the final susceptibility estimate, however, the low density regions of the state receive low (three) quality factors (Fig. 24), while urban and intensely irrigated regions have high quality factors. Once again, the sliding scale was used to account for both water level spatial and temporal variability, and for changing well density. The susceptibilities are most trustworthy around population and irrigated agricultural centers.

3.8 Total susceptibility, quality and number of layers used

Using Equation (1) and all of the proxies above, a 500-m resolution total susceptibility for the state was developed (Fig. 25), along with maps of quality (Fig. 26) and the number of valid proxies for each grid cell (Fig. 27). The range of susceptibilities ranges from 0.5 to 3.7—more restricted than the input values. Despite the many straight, mapping-related boundaries seen in the soil texture, soil taxonomy and landform-based maps (Fig. 13-21), the final total susceptibilities appear to mostly mimic landscape boundaries. The mapping boundaries are averaged out by the multiple proxies used, though a few still exist especially in southeastern New Mexico.

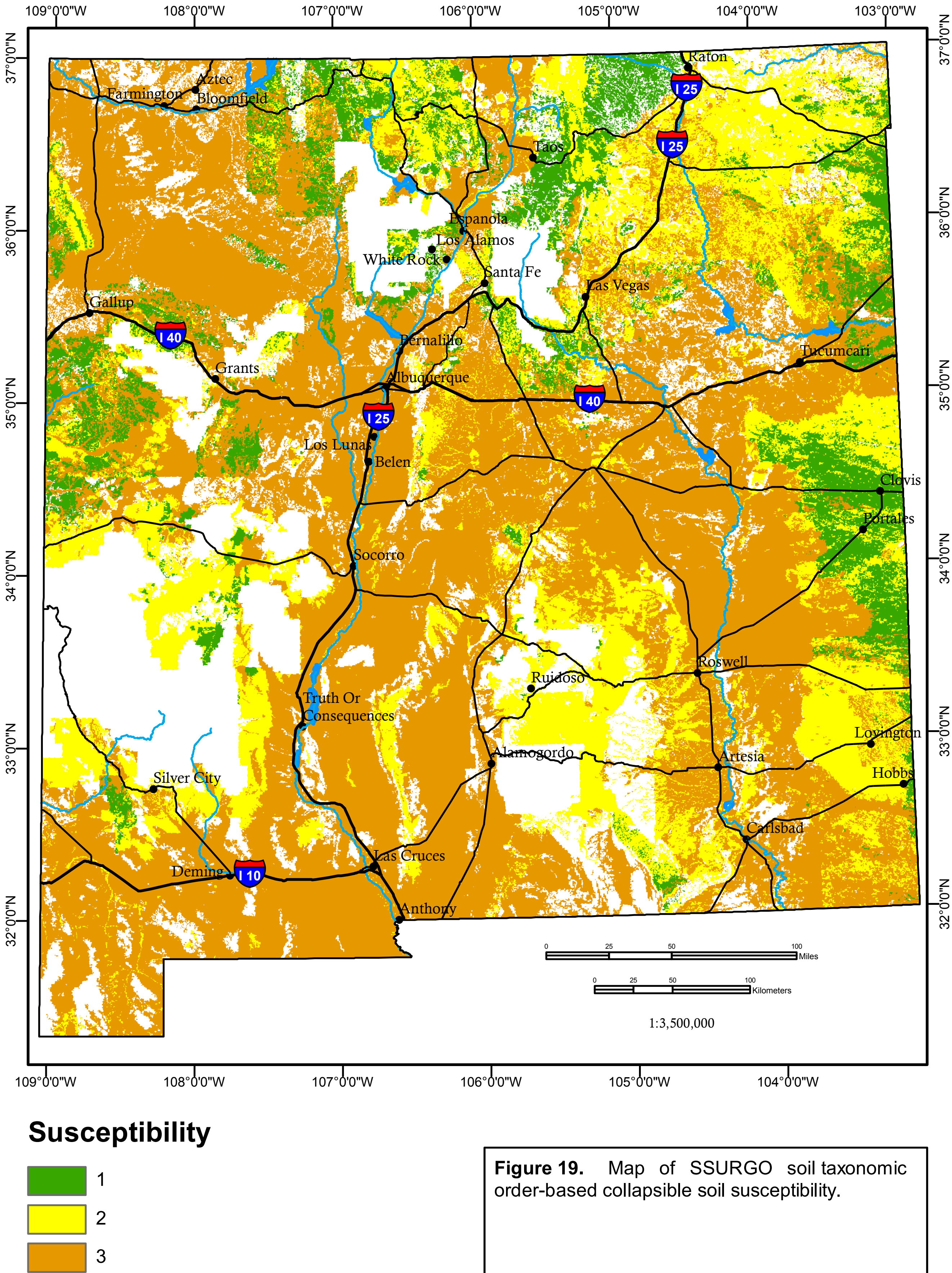


Figure 19. Map of SSURGO soil taxonomic order-based collapsible soil susceptibility.

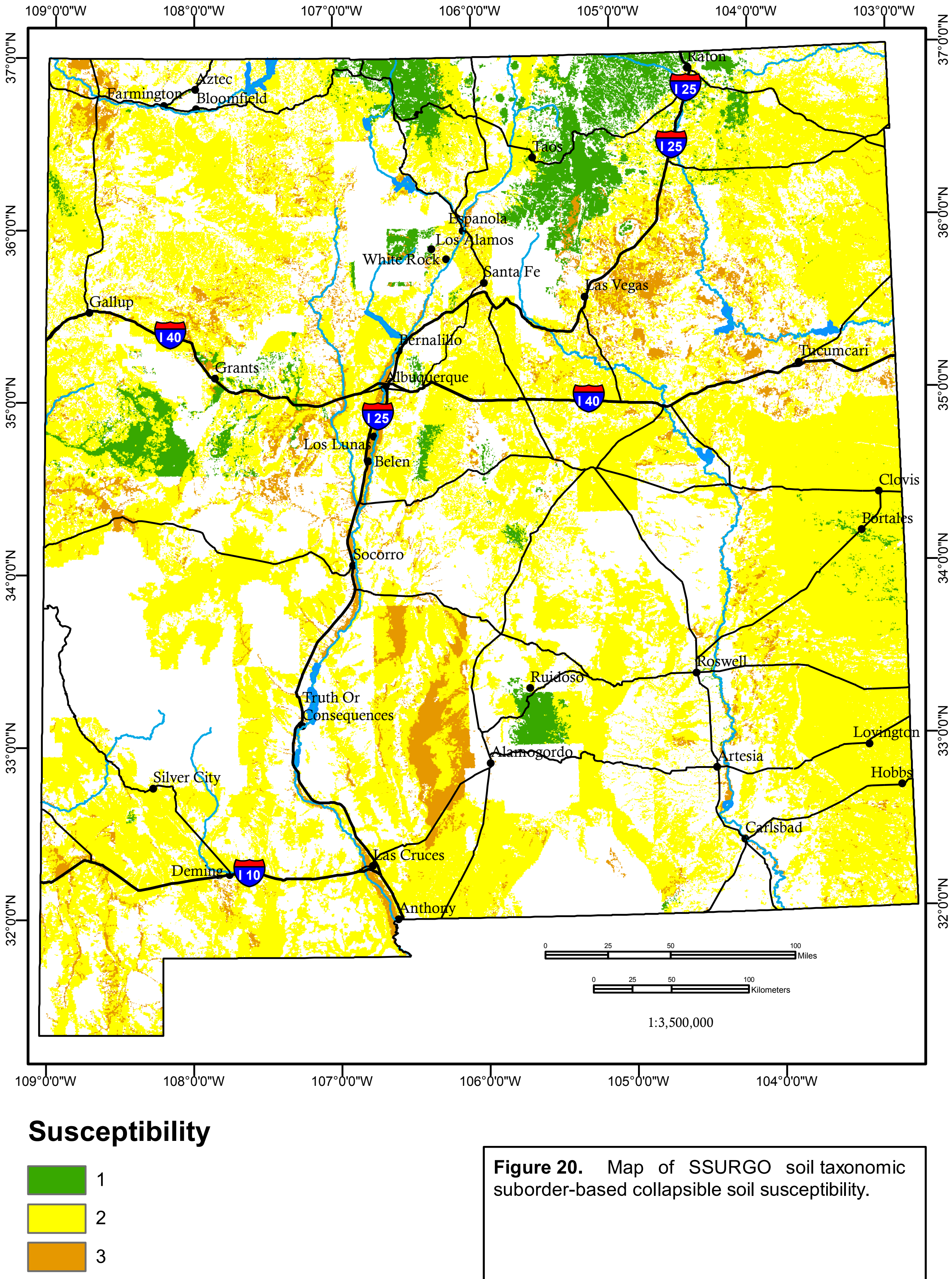


Figure 20. Map of SSURGO soil taxonomic suborder-based collapsible soil susceptibility.

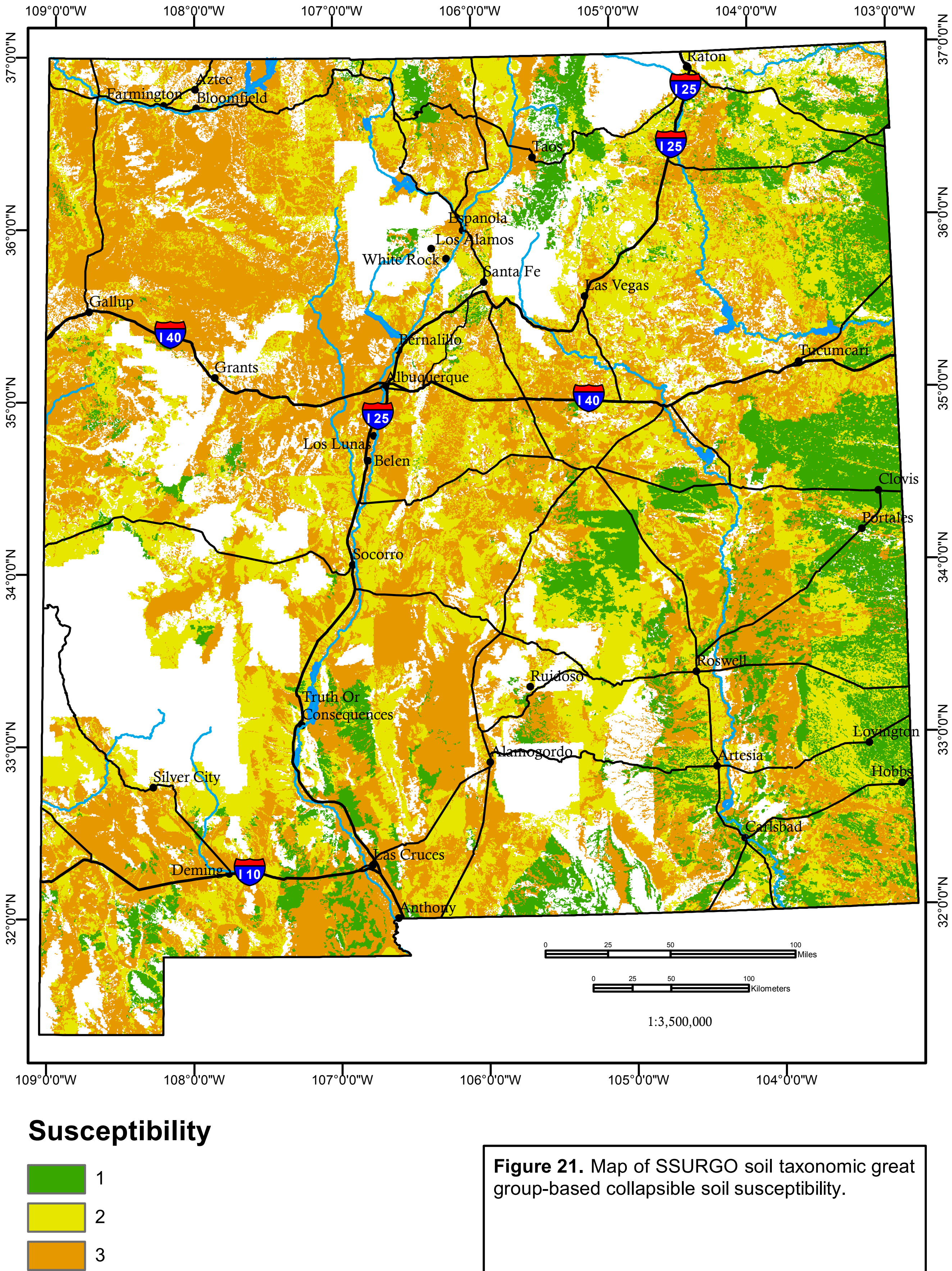


Figure 21. Map of SSURGO soil taxonomic great group-based collapsible soil susceptibility.

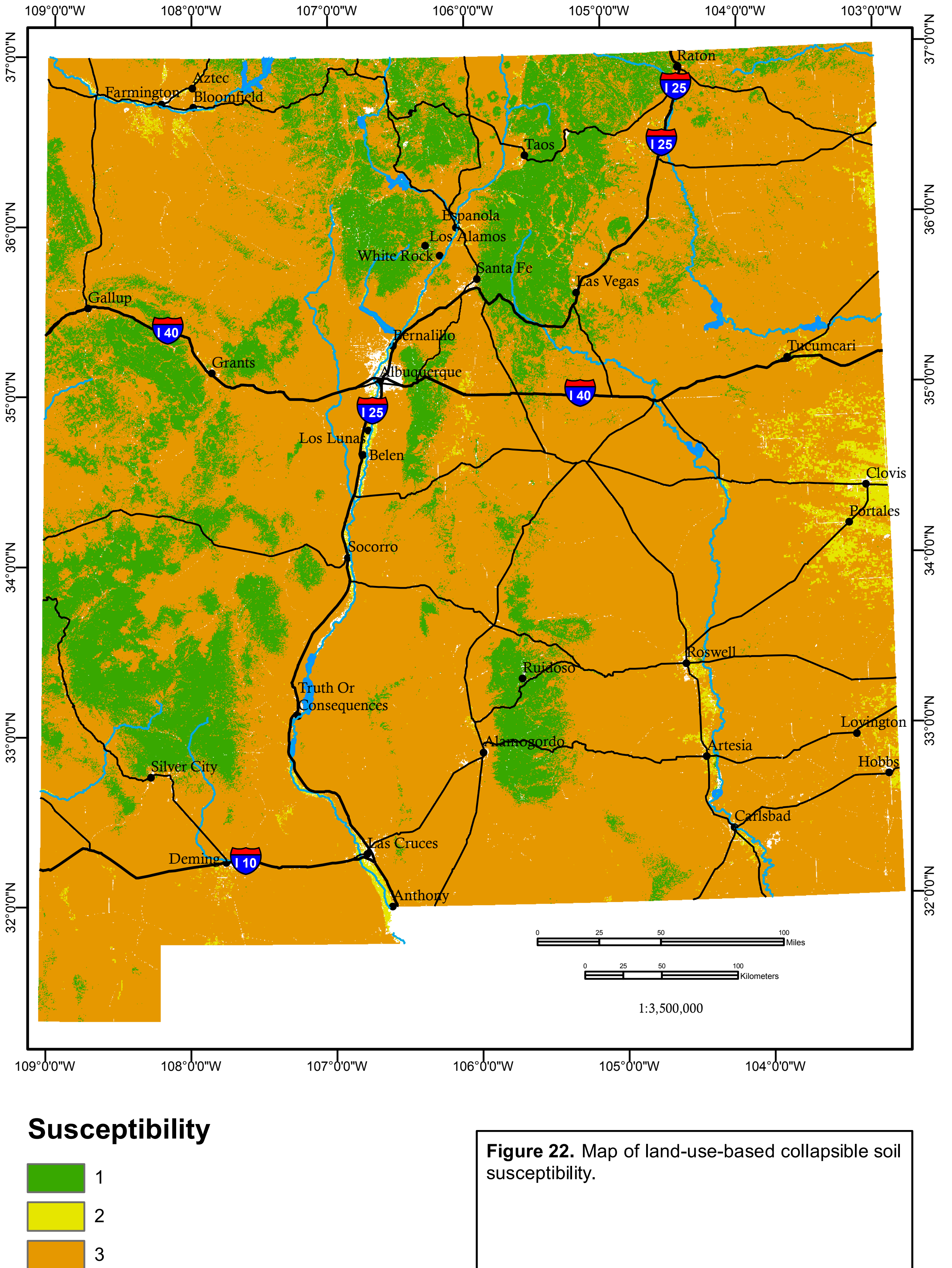
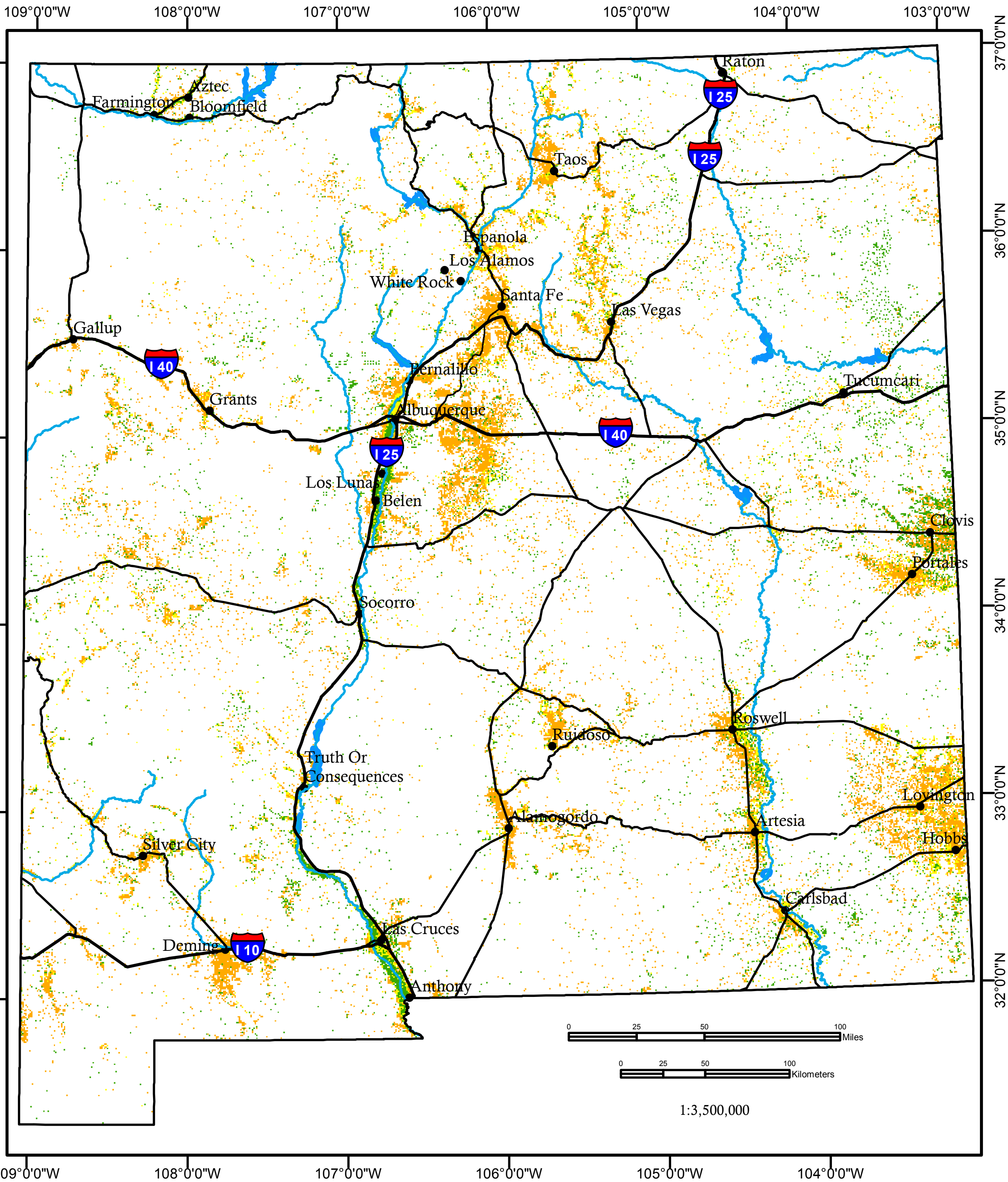


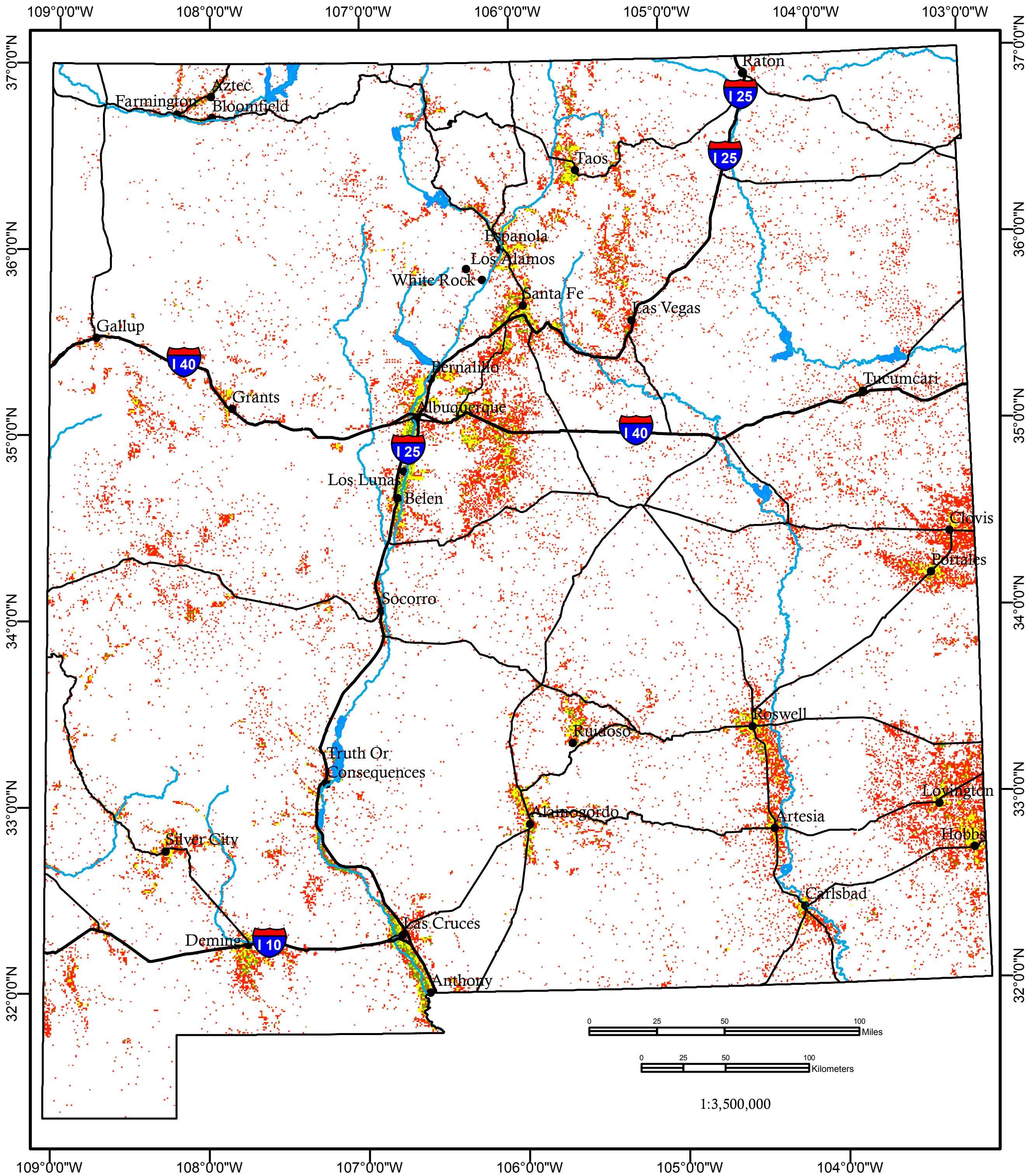
Figure 22. Map of land-use-based collapsible soil susceptibility.



Susceptibility

- 1
- 2
- 3

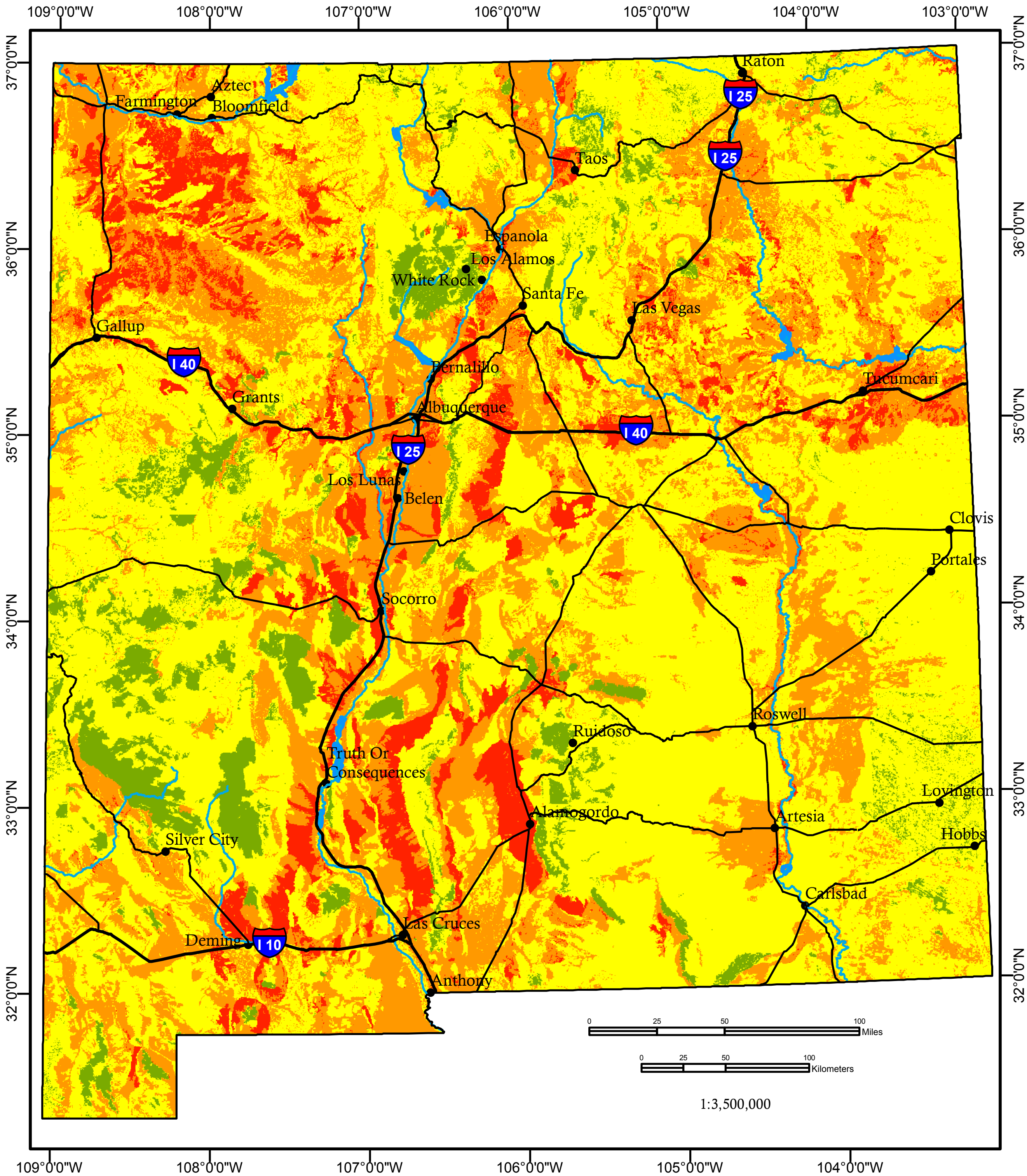
Figure 23. Map of depth-to-water-based susceptibility.



Quality

- 3
- 4
- 5
- 6

Figure 24. Map of depth-to-water-based quality.



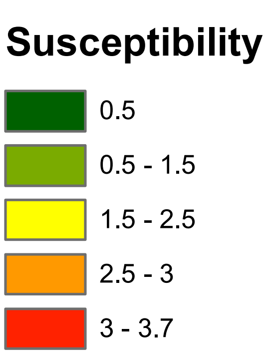
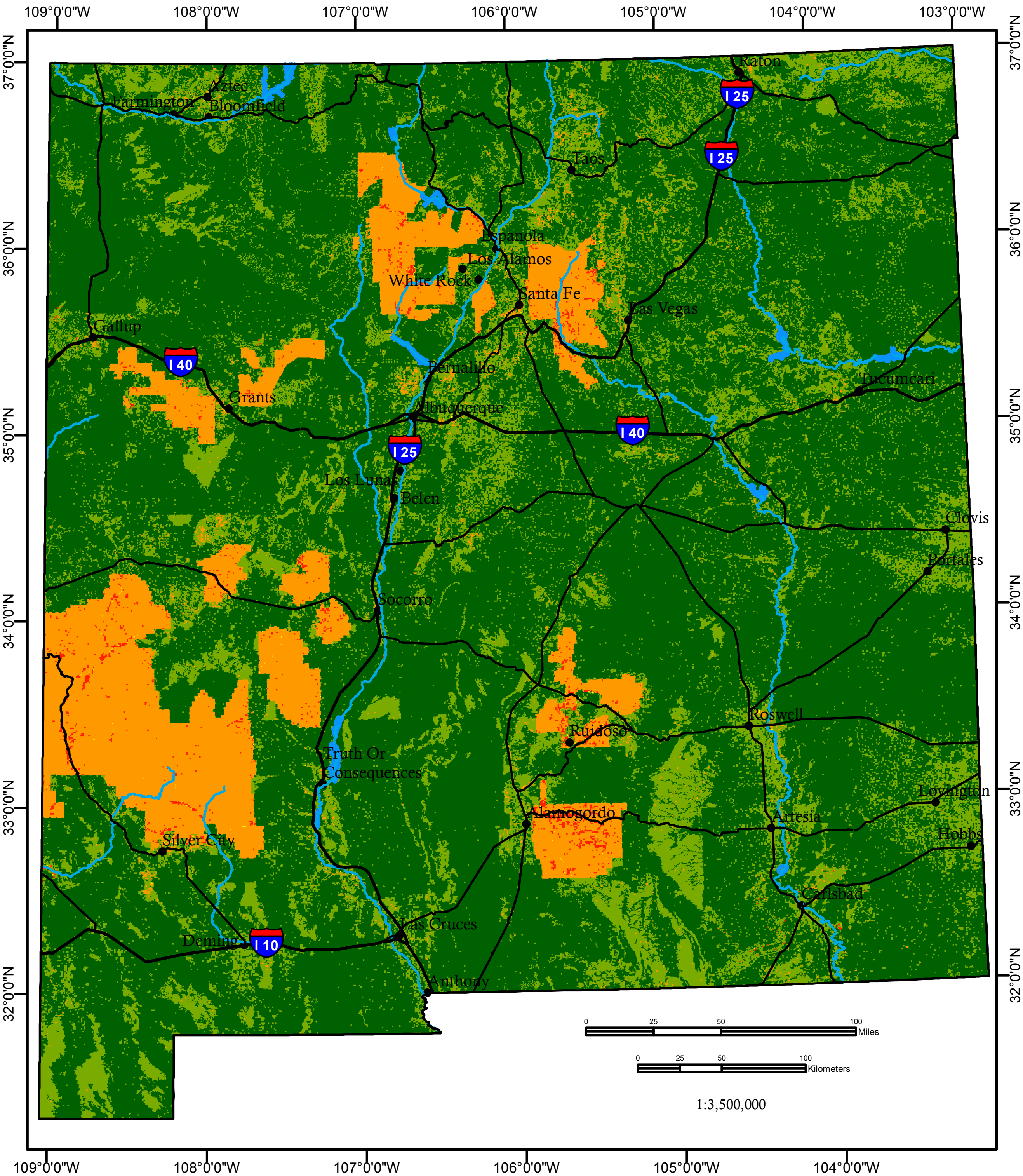


Figure 25. Map of collapsible soil total susceptibility.



Quality

	4.0 - 6.3
	6.3 - 6.5
	6.5 - 6.6
	6.6 - 6.9
	6.9 - 7.3

Figure 26. Map of mean quality of collapsible soil susceptibility.

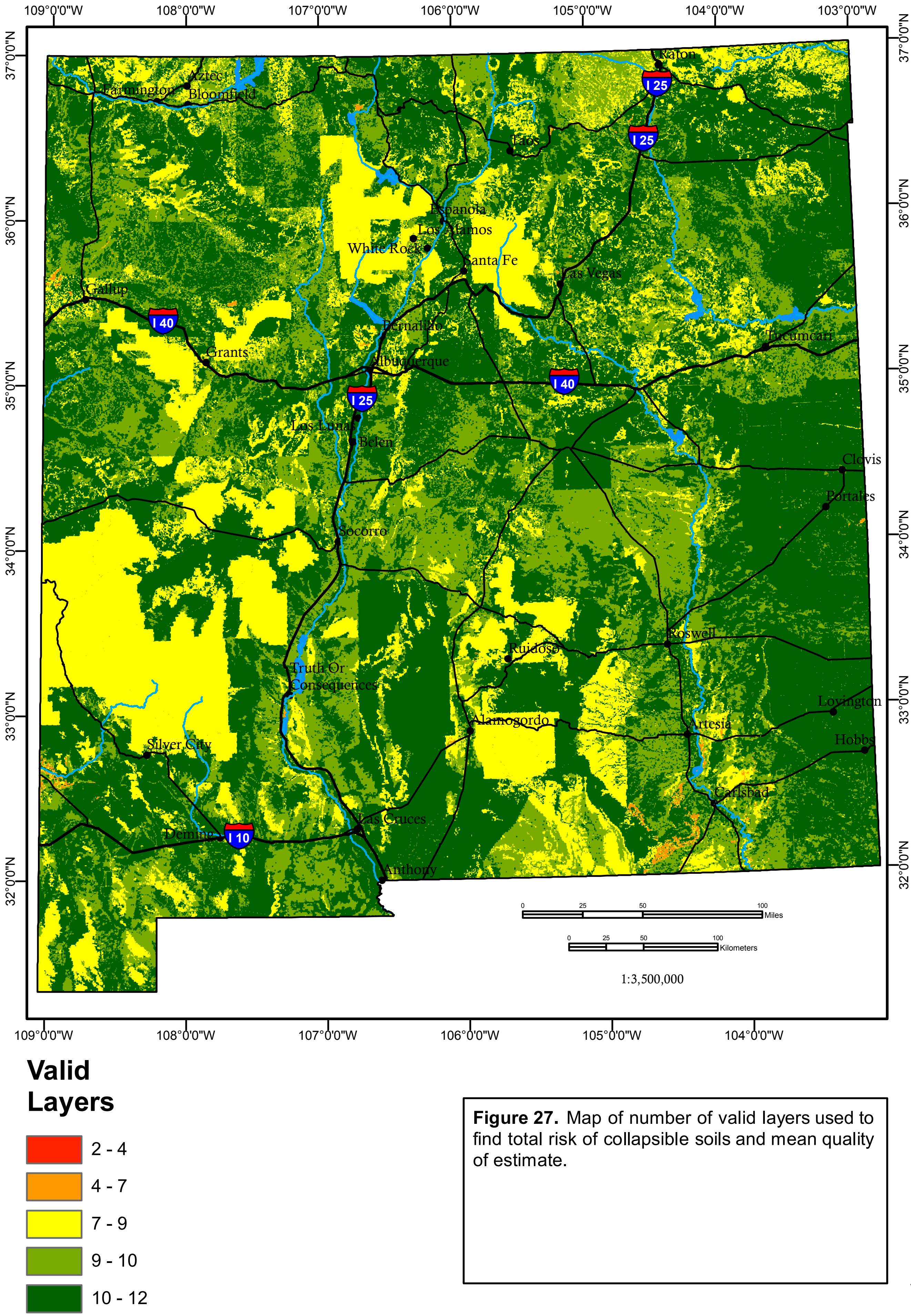


Figure 27. Map of number of valid layers used to find total risk of collapsible soils and mean quality of estimate.

Areas of high susceptibility were associated with medial to distal alluvial fans downslope of mountains, narrow floodplains, eolian deposits, and regions with poorly clay-cemented sandstones. In some regions, single cells had significantly higher or lower values than their neighbors. This was likely caused by locally dense DTW measurements with high values.

Figure 26 shows the statewide map of total quality (average of quality factors at each point). This map shows strong mapping bias, where regions not covered by the NRCS soils data or by the landform map appear clearly to have lower total qualities. Additionally, urban regions have in general lower qualities because of the loss of meaningful land-use data. Few points, however, have low total quality (<6.5). Most areas have good to excellent quality (>6.6). Some of the good but not excellent areas show a lower quality simply because some of the soil taxonomic codes were not relevant to assessing collapse susceptibility, lowering the overall quality of the pixel.

Lastly, Figure 27 shows the number of layers used to estimate total susceptibility. This is another metric of the robustness of susceptibility estimate: the greater the number of layers, the more reliable the susceptibility estimate is. Much of the state has good to excellent (>8) coverage. With only a handful of pixels of low to poor counts (< 7), the remainder of the state has a moderately high number of layers.

The number of layers largely show mapping boundaries from the landform map or from the SSURGO dataset. Complicating the pattern, not all taxonomic codes provided meaningful information about collapse susceptibility, leading to well-mapped soil units to nonetheless have a lower number of layers used.

3.9 Comparison of susceptibilities with known locations

Figure 28 shows the layer-by-layer susceptibilities in regions with hydrocompactive soils or in the neighboring pixels. Climate-based susceptibilities are all three (high), corresponding to all known values occurring in arid climates (Fig. 28a). Landform emplacement and landform depositional environment (Fig. 28b,c) both have more than two-thirds of known regions with susceptibilities of three or high, but do have some with low or moderate (one or two) susceptibilities. These lower values are due to some poorly predicted regions in basalt-capped mesas north of Española and due to neighborhoods falling into floodplains. Landform age (Fig. 28d) and landform composition (Fig. 28e) have bimodal distributions. In the case of landform age, the vast majority of known locations do correspond with high to extreme susceptibilities. Landform composition, however, has roughly equal parts low and extreme susceptibility, meaning that this layer is not reliable. Landform composition does, however, serve to shift the susceptibility away from the background levels of high susceptibilities and is therefore kept. Landform texture is a good predictor, with almost all known regions having extreme susceptibility (Fig. 28f), though this could be caused simply by having almost no coverage at less than extreme susceptibility for this layer (Fig. 17). Soil texture from the NRCS soil survey data has mostly high to extreme susceptibilities in known regions, though roughly 20% are predicted as low to moderate susceptibility (Fig. 28g). Soil taxonomic order groups most known areas into high susceptibility (three), with few pixels corresponding to moderate (two) susceptibilities (Fig. 28h). Soil taxonomic sub-order has roughly twice as many high (three) susceptibilities than moderate (two) susceptibilities (Fig. 28i). Soil taxonomic great group shows susceptibilities roughly split between moderate (two) and high (three) in known areas (Fig. 28j). The NLCD layer shows over two-thirds of areas with or around known hydrocompactive soils have high susceptibilities (Fig. 28k). Finally, the depth-to-water-based susceptibilities around known sites mostly group around moderate to high susceptibility, with slightly more high susceptibilities than moderate (Fig. 28l).

The total (quality-weighted) susceptibilities (Fig. 29) around known regions of collapsible soils show that more than 95% of known locations occur above total susceptibilities of 2.5, with a roughly linear decline from 2.5 to 3.5 and a maximum susceptibility of 3.7 (Fig. 29). We roughly classify susceptibility classes as low (less than 1.5), moderate (1.5 to 2.5), high (2.5 to 3), and extreme (greater than 3). These correspond to the color bins used in the total risk maps (Fig. 25).

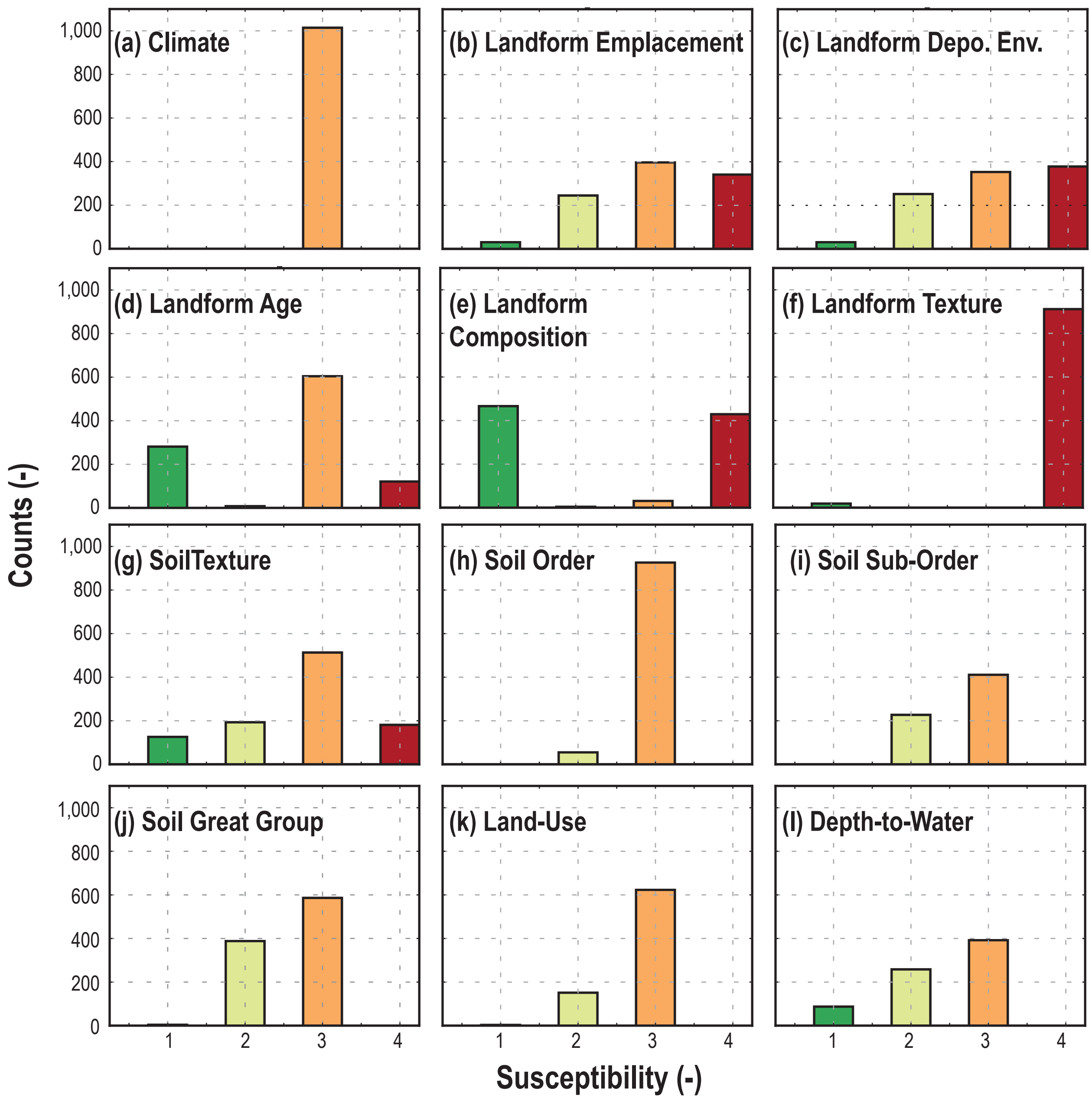


Figure 28. Histogram of number of cells either in known sites with collapsible soils or within 500 m of a known location, for susceptibilities based on (a) climate, (b) landform emplacement, (c) landform depositional environment, (d) landform age, (e) landform composition, (f) landform texture, (g) NRCS-based texture, (h) soil taxonomic order, (i) soil taxonomic sub-order, (j) soil taxonomic great group, (k) NLCD, and (l) depth-to-water.

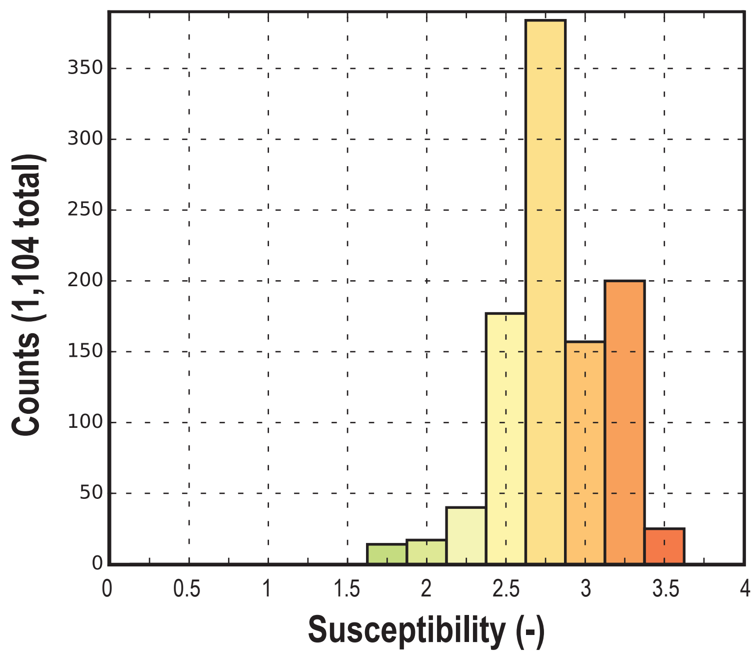


Figure 29. Histogram of total susceptibility at and within 500 m of known collapsible site locations.

4 Discussion

Our final total, or quality-weighted, susceptibilities both match the expected map patterns associated with distal alluvial fans and eolian deposits, and show a strong correlation with known locations with hydrocompactive features (Fig. 25 and 29). However, some individual layers either correlated well through simply having overwhelming spatial coverage (climate, landform texture, soil taxonomic order, and land-use; Fig. 12, 17, 19 and 23) or had surprisingly bimodal distributions (landform age and composition; Fig. 15 and 16) of susceptibilities at known locations. Largely, the higher quality layers showed good correlation (most susceptibilities of at least three) between predicted susceptibility and known locations. Because of the sparsity of known locations (Fig. 11), we have chosen to still include the layers that overpredict susceptibility. Deposits below the scale of the map or in regions where high quality proxies are unavailable exist and need to be accounted for during planning. By using all of the data, the misfits from the different layers—some of which are very significant—are averaged out by other layers, as seen in the clear grouping of total susceptibilities above 2.5 in known collapsible soil regions (Fig. 29).

However, some layers were more reliable than others and not all layers had coverage over the entire state. This was especially the case for landform texture, soil taxonomic suborder, and soil taxonomic subgroup (Fig. 19-21), which all had significant gaps in coverage but good correlation. When interpreting the total susceptibility map, it is important to consider the average quality and the number of layers used. In regions where most high quality layers are present (quality more than six and more than nine layers), the total susceptibility was strongly weighted toward high quality—and highly correlated—layers. However, in regions with lower qualities or a lower number of layers, it is important to see which layers are included, no matter the predicted susceptibility.

When considering the resolution of these maps for planning purposes, buffers around areas of high or extreme risk of one raster cell are appropriate. This is consistent with considering areas of greater than 10 km^2. During planning, areas with high (total susceptibilities of 2.5 and greater) susceptibilities should be the subject of detailed study including geotechnical surveys. This is even more critical in regions with extreme susceptibility. However, the comparison of total susceptibility with known regions with collapsible soils shows that susceptibilities above 2.5 are strongly correlated with collapsible features.

Most of the state has moderate susceptibilities (1.5 to 2.5), and a high quality and number of layers. This reflects a bias of the authors. Early in the design process, we decided to not assign susceptibilities less than one in layers, except in areas with standing water or wetlands. This is because the landscape is extremely heterogeneous and small features may host collapsible soil deposits. For example, in housing developments west of Los Lunas, NM, multiple homes have suffered damage from collapsible soil-caused subsidence. This development was screened for hydrocompactive soils before construction, but buried arroyos filled with hydrocompactive deposits were missed; these are the features causing subsidence (J. Hawley, personal communication). These types of small but high susceptibility features, whether buried or not, led us to the decision to almost always assign a low risk.

During the planning process, the risk of hydrocompactive soils should be considered by planning engineers. In regions with high to extreme susceptibilities, geotechnical surveys should be planned. In low to moderate susceptibility areas, smaller features that are high risk (eolian sand and loess deposits, small alluvial fans, and back-filled channels, for example) should be identified and assessed.

With planners in mind, we present several heuristics for using these maps:

- Regions with total susceptibilities greater than 2.5 (high) should be carefully assessed for the presence of collapsible soils, regardless of the number of layers or mean quality.
- Which layers are present and what their risks are should be assessed when mean quality is less than six and number of layers is less than nine. Higher correlated layers should then be weighted more by planners.
- When considering the susceptibility maps, a buffer of one pixel (500-m) away from high to extreme susceptible regions should be included to account for the map scale.
- In regions with low to moderate susceptibility, and high quality and number of layers, small collapse-prone features should be identified during planning.

In this study, we developed a method to estimate maps of hydrocompaction susceptibility across the state of New Mexico at scales of 1:750,000. Because of the logistical impossibility of conducting geotechnical surveys at this scale and the fact that collapsible soils are not known to exist until they are both wetted and loaded (i.e., a structure is constructed on them or an in situ test is conducted), we chose to use an overlay method, bringing together multiple indirect proxies of variable quality and strengths of correlation. This approach used climate, landform, soil, land-use and depth-to-water proxy measurements to estimate the total susceptibility and the quality of the estimate. Additionally, not all layers are present across the state, so the number of proxies used in the final estimate is also reported. The total susceptibility shows a strong, but not perfect, correlation with known hydrocompaction features. This work provides a new tool for understanding and planning for collapsible soils across New Mexico.

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6 Appendix: Electronic Supplement

The transformations from proxy data (e.g., Quaternary landform age, NRCS soil taxonomic great group, or NRCS soil texture) to susceptibilities were done using scripts in Python 2.7, and are available upon request. Additionally, all map layers used in this report are available online at:

http://geoinfo.nmt.edu/publications/openfile/home.cfml

under OFR-593. This includes layers for total susceptibility, mean quality, number of proxies, known locales, and all of the individual susceptibility and quality layers. Additionally, the Köppen-Geiger climate zone layer derived for this study is included with a table correlating the numbers in the layer with the qualitative climate zone.