DEBRIS-FLOW POTENTIAL FOLLOWING WILDFIRE

IN THE UPPER SANTA FE MUNICIPAL WATERSHED, NEW MEXICO

BY

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A thesis submitted to the Graduate School

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“Debris-flow potential following wildfire in the upper Santa Fe Municipal Watershed, New Mexico” a thesis prepared by Manuel Lopez in partial fulfillment of the requirements for the degree, Master of Applied Geography, has been approved and accepted by the following:

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DEDICATION

This thesis is dedicated to my family here in New Mexico. The people who live and breathe this place we call home and who understand the importance of our culture, mountains, and the water that gives life to all of it.

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ABSTRACT

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In the southwestern Rocky Mountains, moderate to severe forest fires can increase the likelihood of debris-flow events by consuming rainfall intercepting canopy, generating ash, and forming water-repellant soils resulting in decreased infiltration and increased runoff and erosion. Debris flows, a destructive form of mass wasting, create significant hazards for people, and cause severe damage to watersheds and water resources. Although there is no way to know the exact location and severity of wildfire, or intensity and duration of a subsequent precipitation event before it happens, probabilities of debris-flow occurrence and volume can be estimated using empirical models. This study addresses two fundamental questions in debris-flow hazard assessment: where might debris flows occur and how big might they be. We generated a series of geographic information system produced maps and accompanying data that estimated the probability and volume of post-fire debris flows for the upper Santa Fe Municipal Watershed given a 2-, 5- and 10-year, 30-minute rainfall events following moderate to high severity wildfire. We hypothesized debris-flow potential would correlate with increasing fire severity and rainfall precipitation given slopes greater that 30%. Burn severity simulation given low fuel moistures and windy conditions seasonally common to the region indicated generally moderate severity fire throughout the watershed. Sub-basins with prior forest treatments yielded the lowest burn severities as well as the lowest debris-flow probabilities and estimated sediment volumes for each model storm. Results and implications from this work can help inform city planners and forest managers, and give them an opportunity to prepare and mitigate potential negative effects associated with wildland fire and subsequent debris flows.

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SFMW Santa Fe Municipal Watershed

USGS United States Geological Survey

Chapter 1: Introduction

In the Rocky Mountains of the southwestern United States, fire historically was a natural process impacting forest structure and composition. Due to fire suppression policies implemented over the past century, stand structure and fuel loads of southwestern forests were altered (deBuys 1985). This change in forest structure has presented forest managers with a multitude of challenges related to fire behavior and post-fire mitigation response. Given current climate change trends in the Southwest, fire frequency and severity are likely to increase and forested landscapes, including watersheds, are likely to be impacted by debris flows, which can have a destructive impact on civil structures. As populations continue to increase and move into the wildland urban interface prone to wildfires, there is a need to identify potential hazards caused by debris flows originating from recently burned areas.

1.1 Debris Flows

Debris flows are triggered by initial failure of sediment masses sliding downslope (Bridge and Demicco 2008). Gravity aids in debris-flow mass movement in conjunction with precipitation infiltration and slopes greater than 10 degrees (Costa 1984). Long-duration storm events increase pore-water pressure within the soil until the shear strength is compromised (Iverson 2000). Further conditions adequate for debris-flow initiation include ample amount of unconsolidated fine-grained rock, soil debris, and sparse vegetation (Costa 1984). Moisture necessary for debris-flow occurrence increases the soil liquid limit creating higher viscosities compared to flowing water. In contrast to flowing water, debris flows contain a higher internal shear strength, thus enabling the flow to move as a relatively rigid plug (Ritter *et al.* 1995).

1.2 Fire and Erosion

There have been many instances of debris-flow occurrence following wildfires throughout the western United States (Cannon *et al.* 2009). Once rainfall deposits on a burn area surface, the result is often the transport and deposition of sediment within and downstream of burned areas. This process can occur in areas which have not experienced debris flows in the past and can sometimes be the result of a low-magnitude rainfall.

In the temperate region of northern New Mexico, landscape vegetation variability is greatly determined by the steep elevational gradient that exists. Lower elevations begin around 1705 m and are characterized by Colorado pinyon pine (*Pinus edulis*), Rocky Mountain juniper (*Juniperus scopulorum*), and Gambel oak (*Quercus gambelii*). Historically, grasses and forbs provided herbaceous ground cover connecting lower elevation trees to mixed conifers in the upper elevations (2400–3300 m) (Allen 2007). This vegetation coverage is important for the prevention of erosion in steep, mountainous landscapes. Disturbances on the landscape such as timber harvesting, grazing, and fire can decrease rooting strength in the soil mantle due to the lack of root structure (Sidle and Ochiai 2006).

With the introduction of railroads to northern New Mexico in 1880, cattle ranching became a valuable and common practice (Rothman 1992). Intensive livestock grazing in the southwest removed native foliage, compacted soil, and altered spatial density and patterning of land cover types. This loss in surface fuels also removed the connectivity of surface fires at local to regional scales, thus reducing surface fire occurrence on the landscape (Swetnam, Allen, and Betancourt 1999). Soil and vegetation canopy in an unburned forest aid in rainfall absorption and storage resulting in minimal runoff (Moody *et al.* 2008). Severe wildfires disrupt this function by decreasing vegetation cover, understory litter, forest canopy, as well as changing soil properties to become less porous (Meyer 2002). When precipitation falls in an area lacking herbaceous cover, runoff and overland flow can occur. Moreover, bare-soil patches become a connected matrix, accelerate water runoff and increase erosion rates (Wilcox *et al*. 2003). With high severity fires occurring in these same areas, erosion is a typical occurrence due to an impermeable layer of soil developed by the burn (Robichaud 1996). An increase in progressive sediment-laden runoff creates a positive feedback for post-wildfire debris flows (Cannon, Bigio, and Mine 2001). Post-wildfire debris-flow initiation rates decrease with time depending on vegetation recovery in the burn area and corresponding storm intensities.

1.3 Fire History

A region's fire history is linked to its fire regime, or the size, frequency and severity of wildfire over time (Agee 1996). Fire regimes differ between forest type and composition. Ponderosa pine forests exhibit a low severity, high frequency fire regime and are located at the lower elevations (up to 2900 m) (Swetnam and Baisan 1996). Ponderosa pine forests diffuse into mixed-conifer forests towards higher elevations. Mixed conifer forests are comprised of Douglas-fir (*Pseudostsuga* *menziesii)*, ponderosa pine (*Pinus ponderosa*), southwestern white pine (*Pinus strobiformis*), quaking aspen (*Populus tremuloides*), white fir (*Abies concolor*), and Englemann spruce. High elevation forests exhibit a high severity, low frequency fire regime (Margolis and Balmat 2009). Northern New Mexican forests and watersheds contain both fire regimes and wildfire is an intricate part of the ecosystem.

In the Rito de los Frijoles watershed in the Jemez Mountains of northern New Mexico, fire scars were sampled throughout a 20 km^2 area and showed fires burned every 5-16 years from 1598-1899 (Allen 2007). Touchan and others (1996) collected fire-scarred samples from 13 sites, acquiring cross-sections from fire-influenced boles of downed logs, snags, and stumps. Their findings suggested early reductions in fire frequency were potentially related to sheep grazing by native people. Specifically, grazing animals consumed fine fuels such as grasses and shrubs which were the surface fuels necessary for facilitating fire spread. Introduction of domestic cattle on the landscape further reduced fine fuels necessary for surface fire spread. Intensive livestock grazing from 1880–1935 disrupted the connectivity of surface fuels from forest patches to the overall matrix of the region, and surface fires were reduced (Allen 1989). Following a reduction in surface fires, sapling tree mortality was reduced and a higher density of young trees began to dominate forest landscapes (Moore, Covington and Fule 1999). Encroachment increased the vertical and horizontal connectivity between young and mature trees. In recent decades, we have seen an increase in high severity crown fires (Stephens *et al.* 2014).

Dendrochronological research performed in the Santa Fe Municipal Watershed (SFMW) yielded past wildfire size, extent, and seasonality (Margolis and Balmat 2009). Researchers logged a total of 442 fire scars from 76 trees within the ponderosa pine forested region (1600 ha area). The scars indicated that 81% of the fires occurred in the growing season from May through June. Widespread fires occurred every 18-21 years between 1550 and 1880 and have not been recorded since (Margolis and Balmat 2009). Similar to ponderosa pine wildfire reconstruction, between 1495 and 1880 72 % of mixed conifer fire seasonality predominantly occurred in the growing season (May through June) ((Margolis and Balmat 2009). Fire scar samples were obtained from 65 trees in 21 locations throughout a 1200 ha search area and had a maximum fire interval of 31 years. Age structure records from tree core samples in the mixed conifer and in the highest elevations dominated by Englemann spruce and corkbark fir (*Abies lasicarpa*), showed a tree recruitment period in the late-1600's and mid-1800's. These indicated stand replacing fires which cross-dated with fire scars throughout the region as the years 1685 and 1842 (Margolis and Balmat 2009).

1.4 Climatic Influence on Fire Behavior

The majority of southwestern wildfires occur in the growing season (May-June) and the southwestern monsoon follows from July through August, depositing over half of the annual precipitation and increasing the probability of post wildfire debris-flow.

The southwest climate correlates closely with the El Niño-Southern Oscillation (ENSO), which varies between moist El Niño and dry La Niña events every 2-6 years (Kitzberger *et al.* 2001). When an El Niño year occurs, above normal precipitation is predicted to provide abundant snowpack in the winter and moist spring conditions, creating an increase surface fuel growth. When a La Niña pattern occurs, dry conditions and gusty wind patterns allow for combustion of the ample surface fuels.

1.5 Capulin Canyon Debris-Flow - A Case Study

In 1999, the United States Geological Survey's (USGS) Geological Hazards Team in conjunction with Los Alamos National Laboratory's Geology and Geochemistry group studied the response of three drainage systems to the Dome Fire of 1996 in the Jemez Mountains of northern New Mexico (Cannon and Reneau 2000). Their objectives were to identify channel, hillslope and burn characteristics which might identify susceptibility to post-wildfire debris-flow. The morphology of the three drainages (Capulin Creek and the north and south tributaries) varied considerably. Capulin Creek was much larger than the north and south tributaries, which were similar in size to one another. Hillslopes of the tributaries were considerably steeper and covered in rocks and boulders, whereas Capulin Creek was less rugged with a gentle, smooth channel gradient. Each drainage had different percentages affected by moderate to high burn severities. Capulin Canyon contained 36% moderate to high burn severity, north tributary 22%, and south tributary 3%. Results indicated Capulin Creek responded to precipitation with severe flooding while the south tributary lacked significant sediment yield or flooding. However, the north tributary, which had significantly more moderate to high severity burn area than the topographically similar south tributary, responded with a debris flows of sediment with deposits of large cobbles and boulders. This study concluded that steep slope (i.e., >22%), large cobbles on top of sediment, all contained within high and moderate severity areas were characteristics necessary for debris-flow to occur in the Jemez mountains volcanic region.

1.6 Soil Black Carbon

Communities in the southwestern United States depend heavily on sparse water resources, especially water derived from mountain watersheds. This is important since forest fires have increased in severity and frequency in the southwest since 1980 (Dillon *et al.* 2011). There is further prediction on a continued increase of southwestern fires because of fire suppression, climate change, and the continued shift in land use (Litschert *et al*. 2012). With potential impacts from wildfire, it has become increasingly important to understand the effects that black carbon can have on water quality (Smith *et al.* 2011).

Black carbon is the result of partial combustion of organic matter which typically comprises near 4% of total soil carbon (Cornelissen *et al.* 2005). This percentage can vary greatly with different fire severity. Soil BC has potential for being a part of the global carbon cycle because of its resistance to microbial attack or degradation (Forbes *et al.* 2006). The lifespan of soil BC can be between centuries and millennia dependent upon how it is consumed, whether it is by further fire, biological factors or chemical solution such as water (Certini 2005; Hockaday *et al.* 2006; Jaffe *et al.* 2013). An important issue with soil BC is its ability to retain soil nutrients. Depending on the soil makeup of a region, soil BC may sequester contaminants from heavy metals such as lead and chromium (Qiu *et al.* 2008; Wang *et al.* 2010). If flow events occur, soil BC and the absorbed contaminants may be deposited into watersheds and stream systems, contaminating components of the hydrologic cycle.

Chapter 2: Problem Statement

The City of Santa Fe depends on water from the Santa Fe Municipal Watershed. The potential for severe wildfire and subsequent debris-flow places the watershed and its water quality at risk. The Southwest is predicted to have longer periods of hot and dry climate, and the summer monsoons will bring shorter, more intense durations of storms (IPCC 2007). This combination of factors makes the mountainous region of the watershed vulnerable to severe wildfire and potentially damaging debris flows. Forest treatments in the form of thinning and burning have occurred below the wilderness boundary whereas no treatments have been conducted in the wilderness. It is necessary to analyze the mountain slopes in the basin to verify if they exhibit the characteristics for creating debris flows pending damaging wildfire in the area. I will address the following questions:

- Is the upper Santa Fe Watershed at risk for severe wildfire?
- Are there potential debris-flow locations (i.e., probability) and what are their estimated volumes?
- What are the potential ramifications of debris flows in the SFMW?

CHAPTER 3: STUDY AREA

The upper Santa Fe Municipal Watershed (SFMW) is located in the Santa Fe National Forest (N35.68903°, W-105.8302°) and partially provides drinking water for the city of Santa Fe. The city is nestled between two mountain ranges, the Jemez Mountains to the west, which rise to an elevation of 3505 meters, and the Sangre de Cristo Mountains to the east, forming the tail end of the Rocky Mountains and rising to an elevation of 3990 meters (Figure 1).

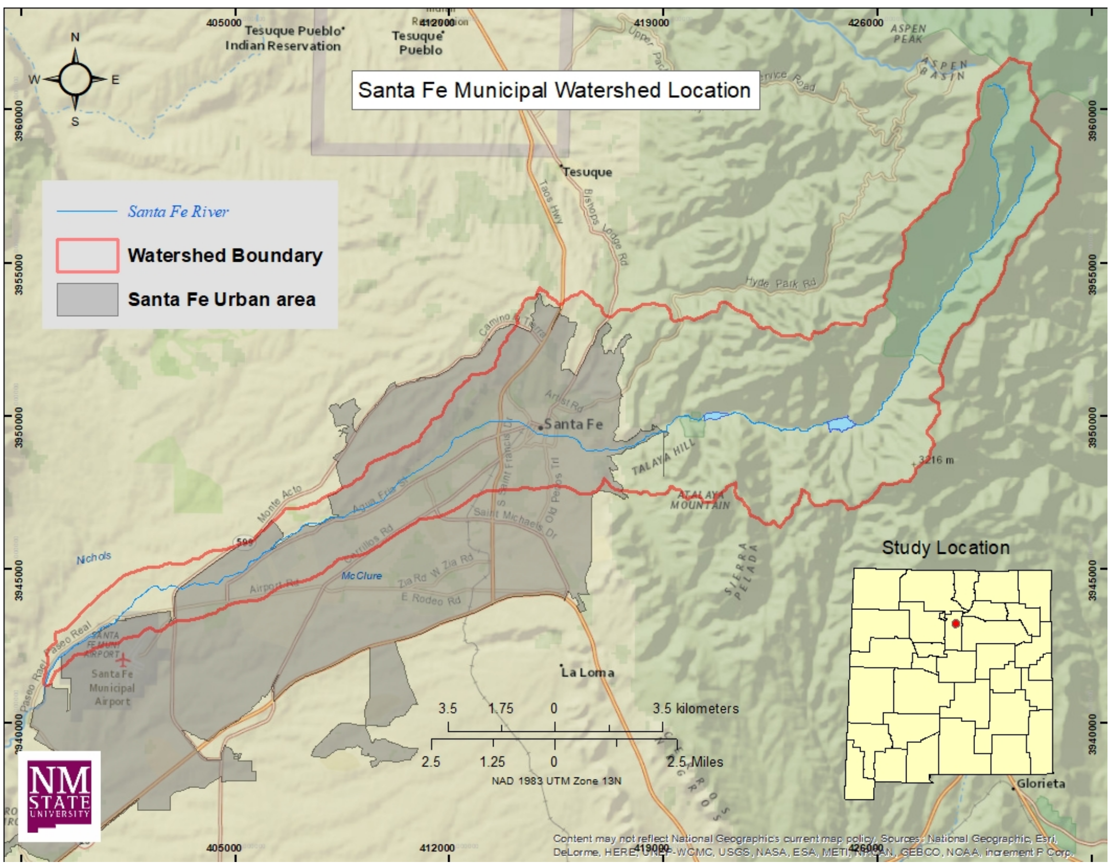

Figure 1. Santa Fe River, Urban Area, and the Santa Fe Municipal Watershed. Dark green represents Pecos Wilderness boundary and light green representing Santa Fe National Forest land.

The SFMW provides water for over 70,000 people residing within the city of Santa Fe and surrounding communities. The upper region of the watershed makes up 70 square kilometers of the Santa Fe River Basin. There are two reservoirs contained in the watershed, Nichols and McClure, together holding a water storage capacity of 3,939.8 acre-feet, allotting 40% of the city's annual use. The higher elevations of the watershed contain 40 ha of mixed conifer and spruce-fir forests contained within the Pecos Wilderness. The lower 29 ha of the upper region is characterized by ponderosa pine and piñon pine-juniper woodlands (Santa Fe Municipal Watershed Plan 2013). Annual precipitation ranges from 41 inches (104.1 cm) at the uppermost elevation to 18 inches (45.7cm) at the lower elevations of the upper watershed (Figure 2). The robust elevation change in the watershed promotes orographic lifting leading to the wide range in precipitation values. The Santa Fe Watershed receives most of its precipitation in the form of monsoons; high-intensity, short duration afternoon thunderstorms (36mm(1.4in)/hour, NOAA 2016), and in the winter in the form of snow. The southwestern monsoon season usually takes place in the months of July and August following a dry and windy spring season. The vegetation cover types within the watershed starting at lower elevations (i.e., < 8500 feet) are characterized by ponderosa pine (*Pinus ponderosa*), piñon pine (*Pinus edulis*), juniper (*Juniperus* spp.) and oak (*Quercus* spp.). The upper elevations are dominated by Douglas-fir (*Pseudostsuga menziesii)*, ponderosa pine, southwestern white pine (*Pinus strobiformis*), quaking aspen (*Populus tremuloides*), white fir (*Abies concolor*), Engelmann spruce (*Picea engelmannii*.), and corkbark fir (*Abies lasicarpa*) (figure 4).

The greatest threat to the watershed is wildfire, which in turn could significantly impact the city's drinking water facility due to subsequent flooding, sedimentation, and potentially debris flows following a wildfire. While significant amounts of planning, funding, and forest restoration have occurred in the lower watershed, (over 2209 ha thinned and burned between 2003 and 2009), no forest treatments have been conducted in the wilderness area above McClure Reservoir to address critical fuel loads that create a risk to the city's water supply due to post-fire flooding and debris-flow (Lewis et al 2013).

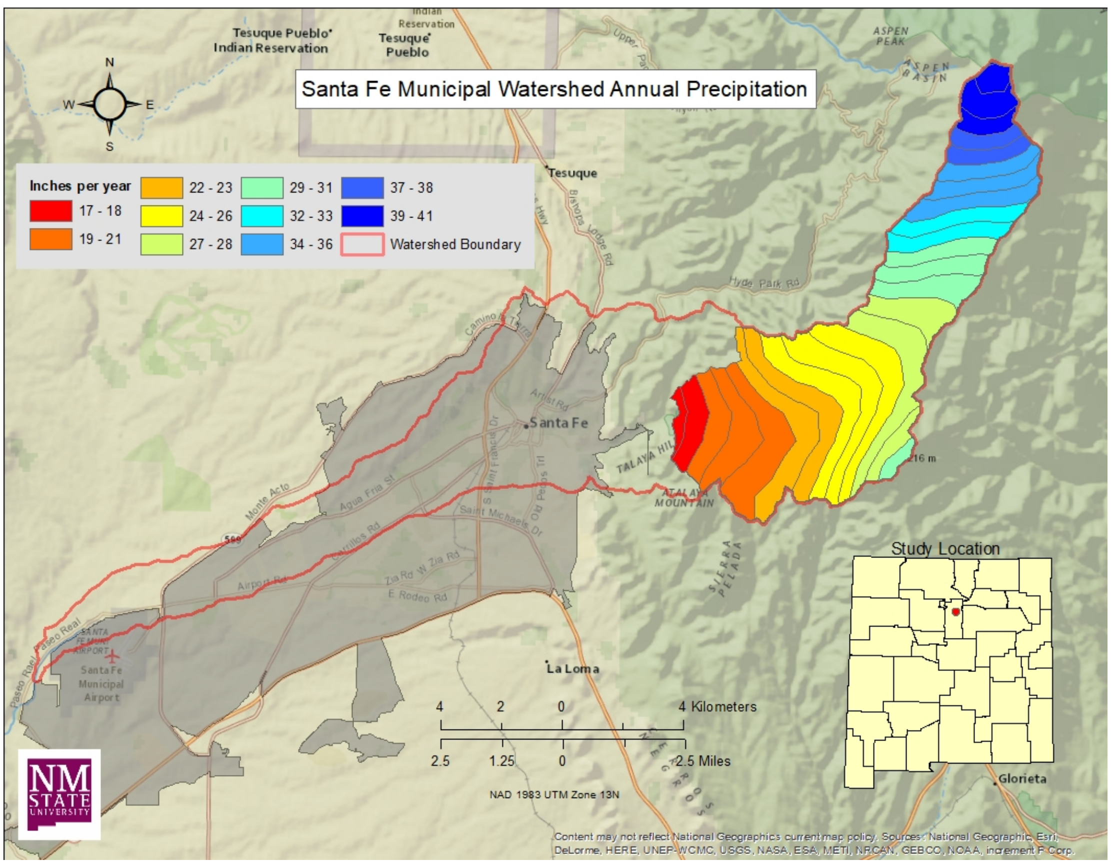

Figure 2. Annual precipitation map for the upper Santa Fe Municipal Watershed between 1981 - 2010. Values range from 406 mm (16 inches) at the lower elevations and up to 1041.4 mm (41 inches) at Lake Peak (USDA NRCS Annual Precipitation by State, 2012).

Sub-basins within the SFMW were delineated utilizing RiverTools (Peckham 2009) which identifies major drainage basin outlets throughout the stream network. Being that the upper watershed has the elevation necessary for forest vegetation and the highest potential for wildfire, our focus study area encompassed 70 km^2 above Nichols reservoir, outlining 44 sub-basins (Figure 3).

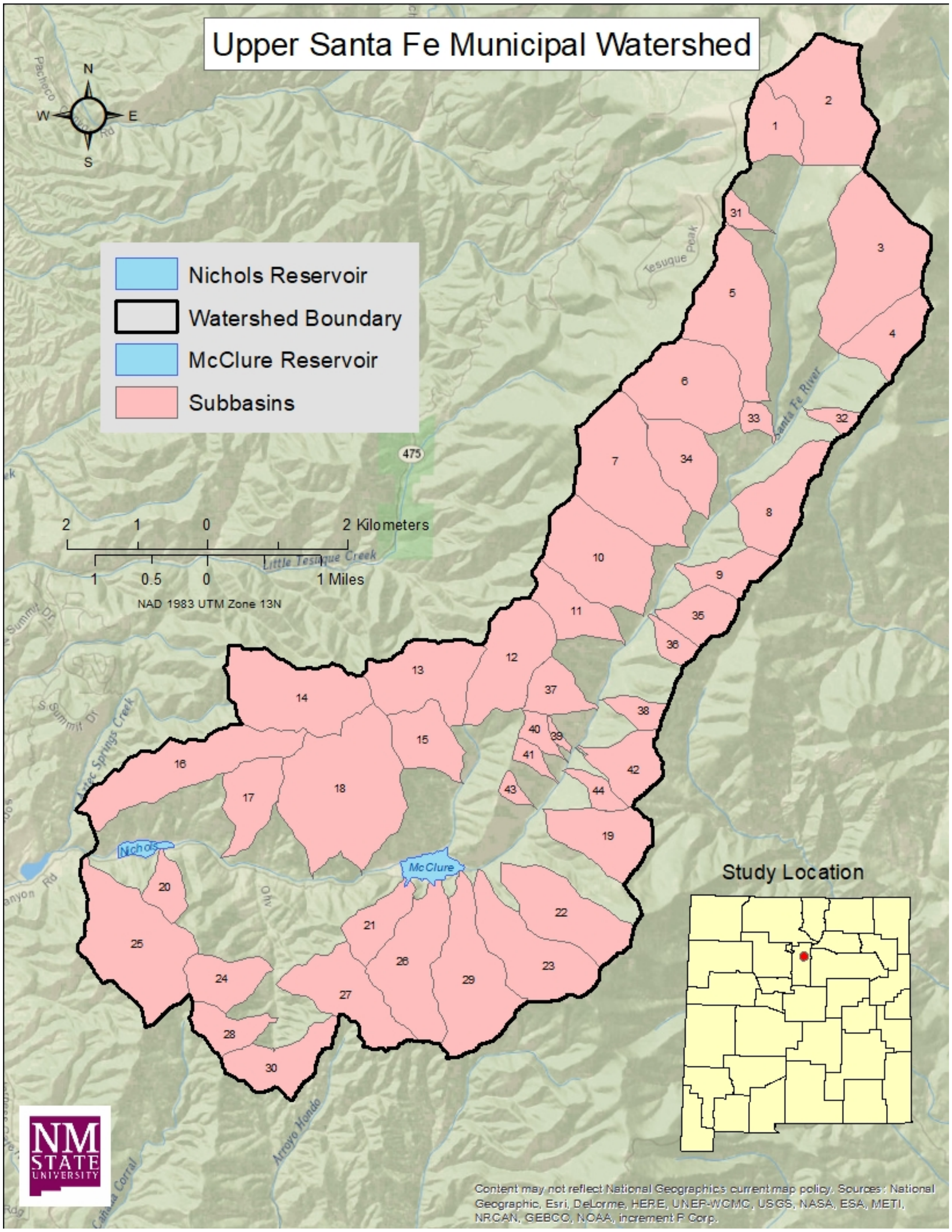

Figure 3. Upper Santa Fe Municipal Watershed with 44 delineated sub-basins and their corresponding ID numbers.

Chapter 4: Methods

Although there is no way to know the exact location, extent, and severity of wildfire, or the subsequent rainfall intensity and duration before it happens, probabilities of fire and debris-flow occurrence for different locations can be estimated with geospatial analysis and modeling efforts. This project addresses two fundamental questions in debris-flow hazard assessment: where might debris flows occur and how big might they be? The purpose of this project was to provide information to the city on how the watershed might respond in terms of a debris-flow in the event of a large-scale wildfire and subsequent rainfall. This information will provide managers an opportunity to prepare for and potentially mitigate such an event.

In an effort to quantify the hazard of post-wildfire debris flows in the SFMW, two empirical models (equations) were used to estimate probability, volume, and combined relative hazard. Research by Cannon and others (2010) and Verdin and others (2012) have analyzed numerous post wildfire basin locations in the intermountain western United States. They have created different empirical models derived from the statistical evaluation of numerous burned basins and used it to create probability of debris flows and estimation of debris-flow volume in a given drainage basin influenced by fire. The models were designed to be utilized in a geographic information system (GIS) by managers prior to or after a wildfire event.

4.1 PROBABILITY MODEL

The regression equation for debris-flow probability is:

$$P=e^x/(1+e^x)$$

Where: *P* is the probability of debris-flow occurrence in fractional form;

And x = *–0.7 + 0.03(%SG30) – 1.6(R) + 0.06(%AB) + 0.07(I) + 0.2(%C) – 0.4(LL);*

- Where: *%SG30* is the percentage of the drainage-basin area with slope equal to or greater than 30% (using 10-m digital elevation models) (Gesch *et al.* 2002);
- *R* is drainage-basin ruggedness: the change in drainage-basin elevation (meters) divided by the square root of the drainage-basin area (square meters) (Melton 1965);
- %AB is the percentage of drainage-basin area burned at moderate to high severity
- *I* is average storm intensity (calculated by dividing total storm rainfall by the storm duration, in millimeters per hour) (Bonnin *et al.* 2006)
- %*C* is clay content of the soil (percent) (State Soil Geographic dataset [STATSGO]); Schwartz and Alexander 1995); and
- *LL* is the liquid limit of the soil (percentage of soil moisture by weight)

Probabilities predicted by the equation potentially ranged from 0 (least likely) to 100 percent (most likely). The predicted probabilities were assigned to 1 of 5 equal (20 percent) interval classes for cartographic display. The debris-flow input values per sub-basin can be seen in table 1.

Table 1. *Watershed inputs for debris-flow model.*

Basin ID	Area (km^2)	Percentage of area with slope ≥ 30%	Ruggedness	Clay Content (%)	Liquid Limit (%)
1	0.71	28.97	0.44	28	31
2	1.87	20.05	0.35	28	31
3	2.42	16.38	0.46	28	31
4	0.81	9.31	0.47	28	31
5	1.82	15.62	0.43	28	31
6	1.67	37.17	0.53	28	31
7	2.16	25.32	0.54	28	31
8	1.15	20.70	0.41	28	31
9	0.55	27.40	0.56	28	31
10	1.72	31.13	0.48	28	31
11	0.75	23.40	0.46	28	31
12	1.41	28.31	0.31	28	31
13	1.39	10.56	0.28	28	31
14	1.86	19.73	0.25	14	22.5
15	0.79	23.32	0.42	14	22.5
16	1.84	14.11	0.37	14	22.5
17	0.81	19.67	0.46	14	22.5
18	2.98	30.69	0.31	14	22.5
19	1.06	36.64	0.60	28	31
20	0.39	41.59	0.57	14	22.5
21	0.63	20.68	0.34	14	22.5
22	1.39	48.20	0.65	28	31
23	1.53	49.45	0.65	28	31
24	0.70	14.94	0.43	14	22.5
25	2.22	29.28	0.35	14	22.5
26	1.62	28.20	0.30	14	22.5
27	1.27	15.38	0.32	14	22.5
28	0.51	24.03	0.42	14	22.5
29	1.80	31.67	0.45	14	22.5
30	0.91	20.76	0.25	14	22.5
31	0.20	27.13	0.87	28	31
32	0.18	23.55	0.86	28	31
33	0.18	36.77	0.61	28	31
34	0.93	27.21	0.63	28	31
35	0.61	32.15	0.50	28	31
36	0.26	25.28	0.70	28	31
37	0.52	46.55	0.53	28	31
38	0.27	48.23	0.77	28	31
39	0.06	19.40	1.00	28	31
40	0.22	35.81	0.84	28	31
41	0.16	40.86	0.84	28	31
42	0.73	36.13	0.49	28	31
43	0.12	48.29	0.90	28	31

44	0.23	34.79	0.88	28	31

4.2 Volume Model

The debris-flow volume estimates for both the basin outlet and along the drainage network are predicted using multiple linear regression models for region-specific databases. These are used to estimate the volume (m^3) of eroded material emanating from drainage outlets along the stream network during a certain rainfall intensity. The volumetric outputs of the equation have four classes in order of magnitude with ranges of 0-2,000 m^3; 2,000-5,000 m^3; 5,000-10,000 m^3; and greater than 10,000 m^3. This classification is displayed with a color scheme per stream segment.

Cannon and others (2010) developed an empirical model for the estimation of debris-flow volume following a wildfire and a given storm event. The equation is:

$$ln(V) = 7.2 + 0.6(\ln SG30) + 0.7(AB)0.5 + 0.2(T)0.5 + 0.3$$

- Where: *V* is the debris-flow volume, including water, sediment, and debris (cubic meters);
- *SG30* is the area of a drainage basin with slopes equal to or greater than 30 percent (square kilometers);
- *AB* is the drainage-basin area burned at moderate to high severity (square kilometers);
- *T* is the total storm rainfall (millimeters);
- and 0.3 is a bias-correction factor that changes the predicted estimate from a median to a mean value.

4.3 Combined Hazard

After segment debris-flow probability and potential volume were calculated, identification of debris-flow probability and volume at the sub-basin level was generated. Using the field calculator in ArcGIS, the above equations were used to create a debris-flow hazard index per sub-basin (Table 1). The most hazardous basins include a combination of high debris-flow probability of occurrence and large potential volume of eroded material. Basins with a lower hazard index will contain an offset of the two factors, either lower probabilities with high potential volumes, or high probabilities with low potential volumes. The least hazardous basins will include those that contain both low probabilities and low potential volumes.

Cannon and others (2010) outlined the methods necessary for hazard calculation. For each debris-flow probability class, a ranking was assigned from 1 to 5 in ascending order, and an ascending rank of 1 to 4 for the volumetric classes. When ranks from both classes were added together the sub-basins displayed their relative hazard ranking in a cartographic map (in ascending order, with 9 representing the most hazardous) (Table 2).

Table 2. Hazard ranking system (Source: Robert Sabie Jr., NM WRRI)

	Probability					
Volume	Rank	1	2	3	4	5
	1	2	3	4	5	6
	2	3	4	5	6	7
	3	4	5	6	7	8
	4	5	6	7	8	9

4.4 Model Application

One of the most influential variables in the debris-flow model is total storm rainfall and intensity. Debris-flow probability and potential volumes depend on the precipitation-frequency estimates for the study area (Bonnin *et al.* 2006). Precipitation-frequency is measured in year intervals and expressed as a percent chance of occurrence. For example, a 2-year storm recurrence has a 50% chance of occurring per year. The Southwestern monsoon season, which usually arrives in the summer month of July and lasts through September, is characterized by short recurrence intervals with high-intensity convective thunderstorms (Sheppard *et al.* 2002). Cannon and others (2008) found debris flows occurred within 2 years after wildfire in response to short recurrence interval storms (from 2 to 10 years). Similar research in the southwestern US by Tillery and others (2011) showed that short recurrence, high intensity storms with storm durations less than 30 minutes were likely to produce debris flows and aided in predicting post-fire debris-flow probability. Using the same methods, the storm events used for this research were selected to portray the most frequently occurring storm possibilities in the region. The storms included: 1) 2-year recurrence, 30 minute duration rainfall of 1.41 inches/hour (36 mm/hr)(18 mm accumulation), representing a 50-percent chance of occurring in any given year; 2) 5-year recurrence; 30 minute duration rainfall of 1.88 inches/hour (48 mm/hr)(24 mm accumulation), representing a 20-percent chance of occurring in any given year; and 3) 10-year recurrence; 30 minute duration rainfall of 2.20 inches/hour (56 mm/hr)(28 mm accumulation), representing a 10 percent chance of occurrence in any given year. These design events were defined from data and methods detailed in the National Oceanic and Atmospheric Administration's Precipitation-Frequency Atlas of the Western United States (Miller et al. 1973, Bonnin et al. 2006). Data location for rainfall intensity: Latitude: 35.6982°; Longitude: -105.8128°; Elevation: 8058.03 ft.

Model outputs of debris-flow probability, volume, and combined hazards were calculated along the stream network and at the drainage-basin scale. Once the basin outlets were determined, debris-flow probability and volume are a factor of the landscape characteristics upstream and delineated per pixel. Independent variables of model equations represented continuous surfaces over the potential burn area. After these surfaces were developed using a geographic information system, execution of the model equations with map algebra per pixel yielded debris-flow probability and volume at the stream segment scale.

Forty-four sub-basins were delineated within the SFMW for debris-flow probability, volume estimation, and hazard. The Santa Fe River's flow is disrupted by the McClure Reservoir and prevents stream connectivity for debris-flow probability and volume. Therefore, drainage basin outlets contributing to the Nichols Reservoir only reside below McClure Reservoir as a separate stream network. The basins were identified within a 10-meter digital elevation model of the SFMW where topographic properties were also analyzed. Basin sizes ranged from 0.06 – 2.98 km^2. Potential debris-flow volumes are dependent on percentage of soil clay content and liquid limit. Clay content and liquid limit were obtained from the State Soil Geographic database (Schwartz and Alexander 1995) at 1km resolution Natural Resources Conservation Service's State Soil Geographic dataset (STATSGO2). STATSGO2 has a coarse spatial resolution at 1km but was necessary to use instead of the finer Soil Survey Geographic Database (SSURGO) due to the latter not having coverage of the SFMW. STATSGO soils data arrives in a coarse resolution and had to be resampled to 10m pixels. Clay content and liquid limit per sub-basin were outlined in Table 1. Resampling from a larger pixel size to a smaller size does not result in a loss of spatial information and was considered acceptable.

4.5 Fire Behavior Modeling

To execute the debris-flow model in an area which has not recently experienced fire the selected watershed must have a burn severity estimate. Keeley

(2009) defines burn severity as a measure of changes in vegetation cover from pre-wildfire to post-wildfire. This is represented as a percentage of area burned at the basin level for both debris-flow probability and volume estimation. In regard to forest canopy, a moderate severity burn will scorch only a portion of the tree canopy, but not consume all of its needles. A high severity fire will completely burn and kill over story tree canopy as well as consume most if not all surface litter (Keeley 2009).

A burn severity raster was computed using Finney's (2006) fire mapping and analysis program FlamMap. FlamMap is a fire mapping and analysis program that describes potential fire behavior based upon environmental conditions such as weather and fuel moisture. Data was extracted from LANDFIRE (Ryan and Opperman 2013), a planning project that allows forest managers in multiple agencies to have current geospatial data on fuels and terrain. FlamMap imports LANDFIRE data such as slope, aspect, and elevation, and fuels layers such as canopy cover, stand height, canopy base height, canopy bulk density, and fuel-loading (Ryan and Opperman 2013). LANDFIRE fuels data and the FlamMap crown-fire outputs arrive in 30m spatial resolution and had to be resampled to 10m using the nearest neighbor technique (Tillery *et al.* 2014). After a burn severity run is completed (using weather and fuels data) the resulting raster is exported as a .tif file to ArcMap, and a classification scheme created to decipher moderate to high severity (low=0, m-h=1).

Mean weather and fuel moisture parameters were taken from June 26, 2011 and can be considered as representative of conditions observed during the 2011 Las Conchas Fire (Table 3).

Table 3. Weather and fuel inputs were taken from the Coyote Remote Automated Weather Station during June 26, 2011 to represent fuel and weather conditions as observed during the Las Conchas Fire (source: MesoWest).

FlamMap Parameters	Input Values
20-foot wind speed	21 mph
Wind direction	211 degrees
1-hour fuel moisture	5%
10-hour fuel moisture	7%
100-hour fuel moisture	8%
Foliar moisture content	90%
Live herbaceous fuel moisture	53%
Live woody fuel moisture	65%

Chapter 5: Results

5.1 Burn Severity Simulation Results

The existing vegetation types and the presence or absence of forest treatments in the SFMW had varying influences on the FlamMap burn severity results. Figure 4 displays the various vegetation types within the watershed. The areas with ponderosa pine and Douglas-fir forests burned at a moderate severity. Areas with pinyon/juniper vegetation and sparse vegetation/grassland burned at a low severity. The Pecos Wilderness, comprised of mixed conifer trees, burned at a mix of low to moderate severities (Figure 5). The highest burn severities occurred at varying elevations, aspects, and slopes. High levels of canopy bulk density attributed to moderate burn severities (Figure 6). Both surface and crown fire (low vs high severities) were represented in the FlamMap simulation. Torching and crown fire were apparent in areas that lacked thinning and burning treatments (Figure 7). The lowest severities with surficial fire burned in areas which had previous forest treatments. All forest types in the SFMW were predicted to have active torching and crown fire given fuel and fire weather conditions similar to those observed during the Las Conchas Fire. The FlamMap simulation predicted 81 percent of the watershed would burn at moderate and high severity given these conditions.

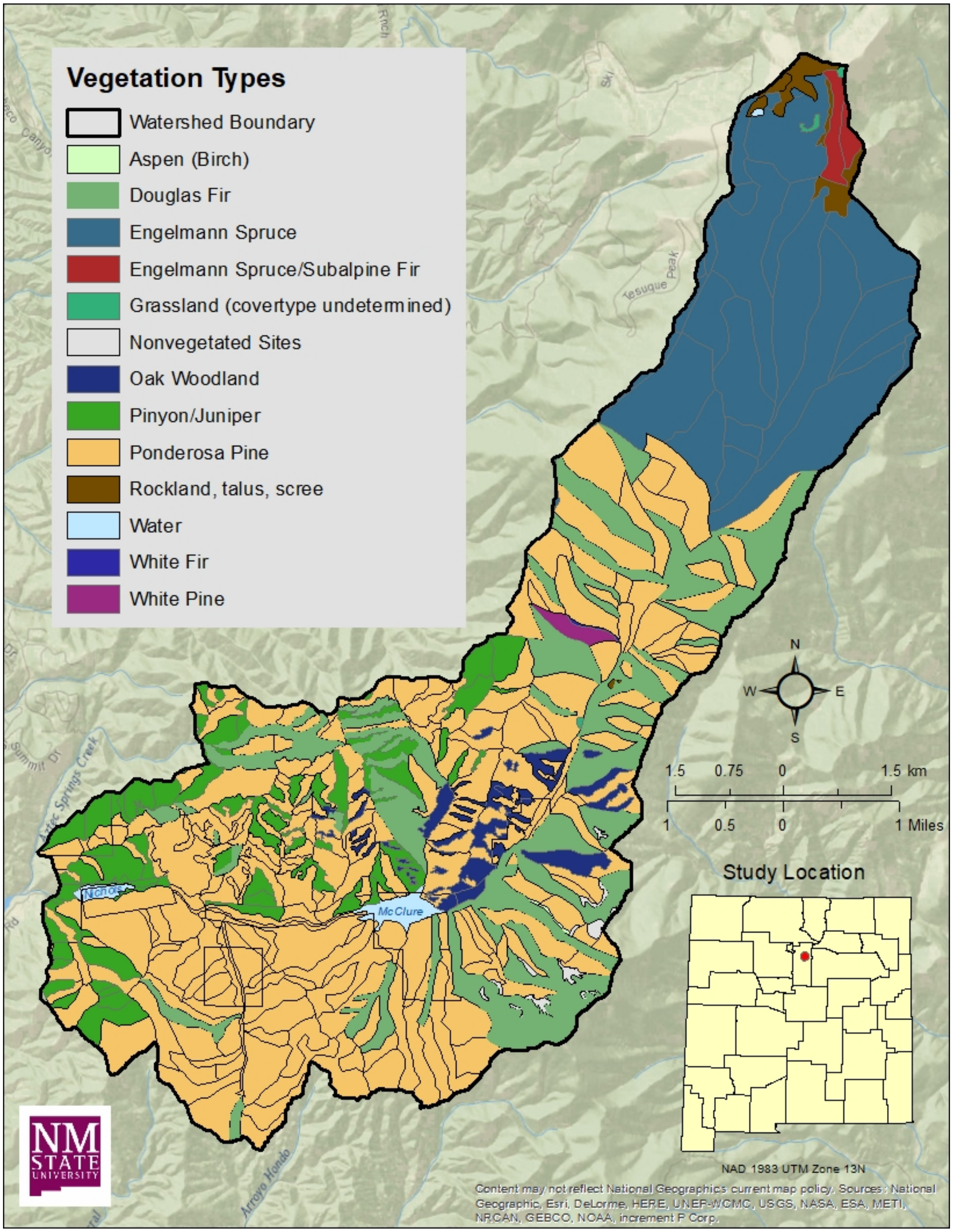

Figure 4. Vegetation types of the Santa Fe Municipal Watershed (source: USDA, Santa Fe National Forest GIS Data).

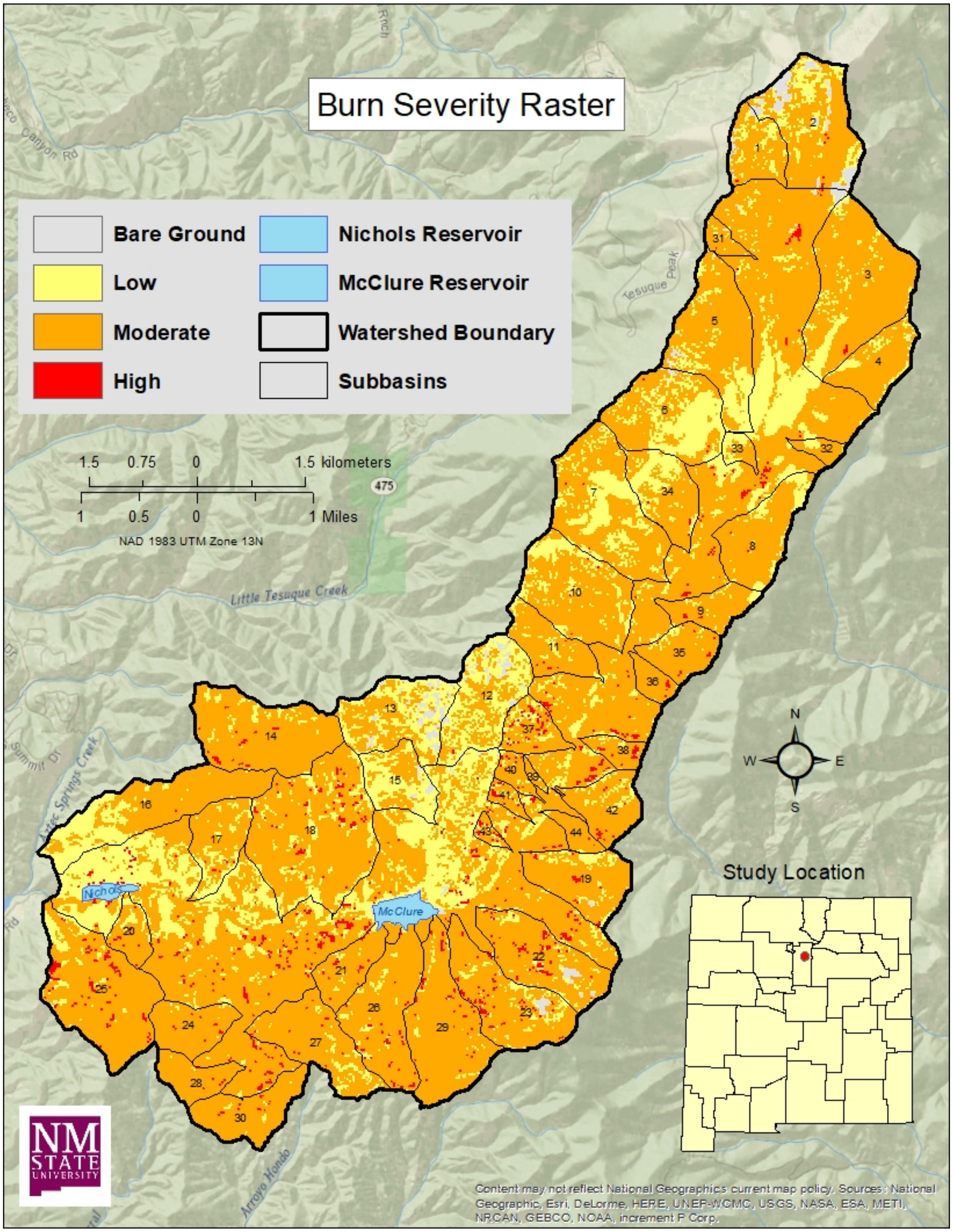

Figure 5. Burn severity raster developed in FlamMap displaying moderate to high severity burn with corresponding input variables shown in Table 1.

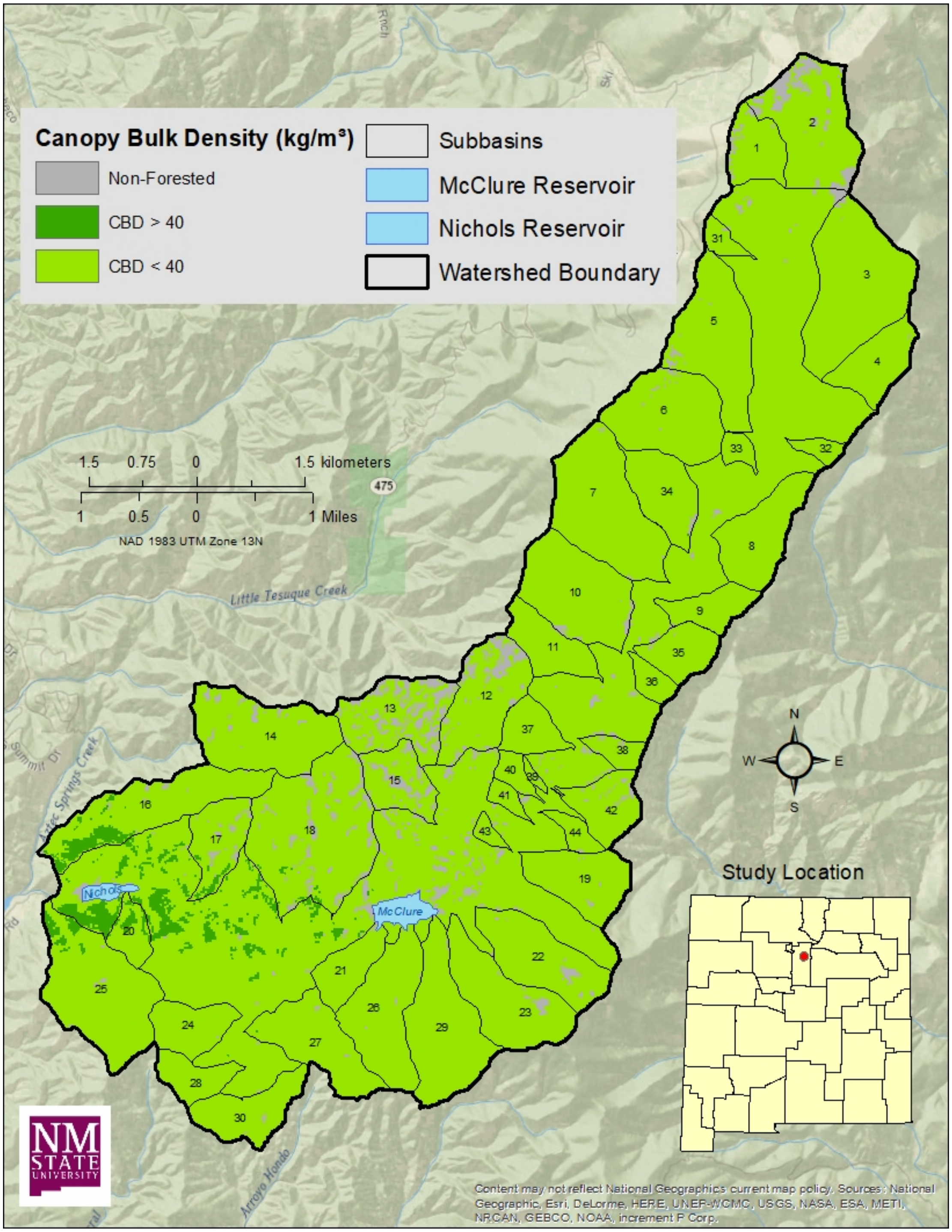

Figure 6. Canopy bulk density of the Santa Fe Municipal Watershed (source: LANDFIRE dataset).

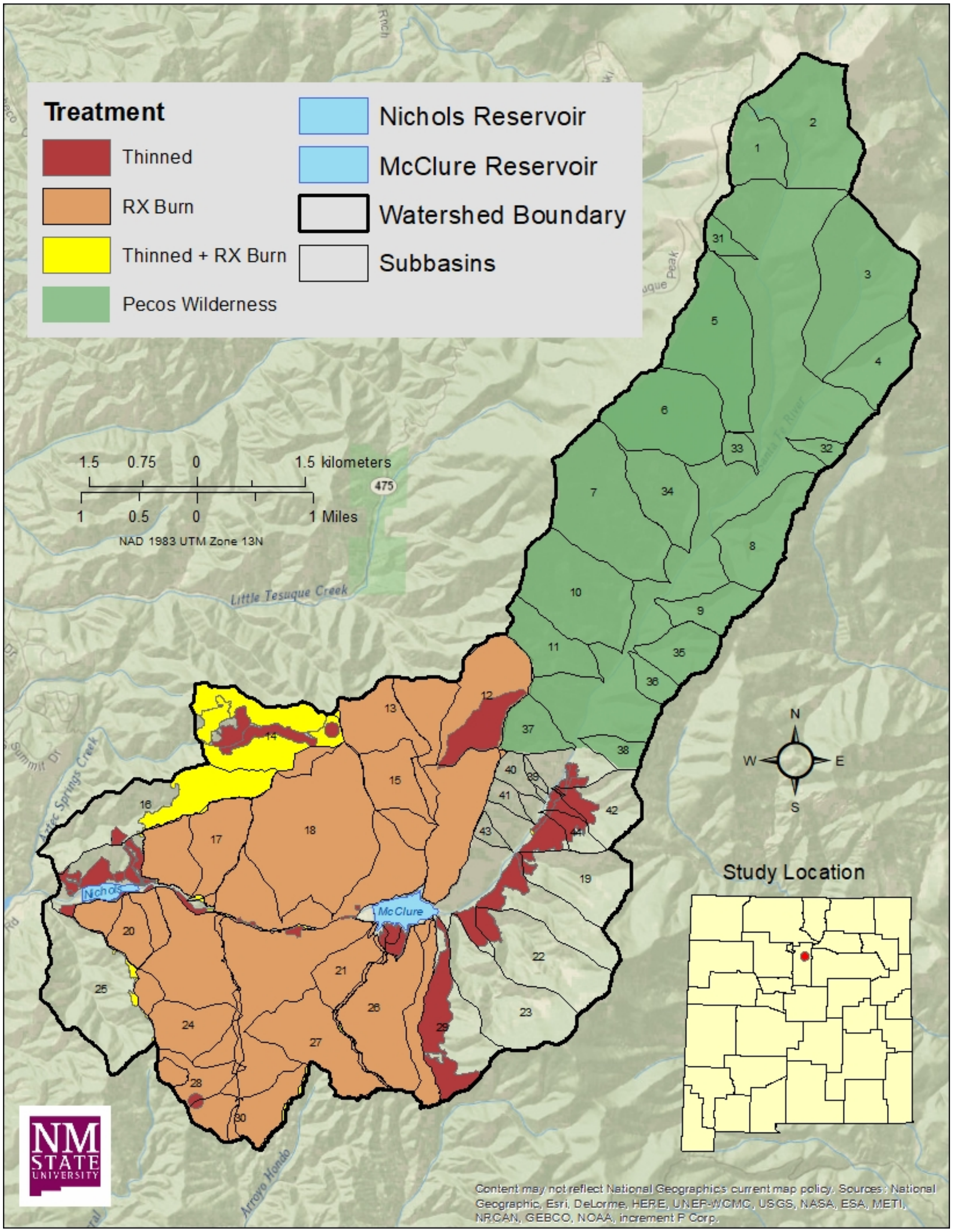

Figure 7. Previous forest treatments within the Santa Fe Municipal Watershed (source: USDA, Santa Fe National Forest GIS Data).

5.2 Debris-Flow Probability Estimates (Basin and Segment)

In a 2-year storm recurrence, around 41 percent of the sub-basins within the watershed had 60 to 100 percent probability of exhibiting debris flows (Figure 8). Basins 3, 12, 13, 15, and 33 had the lowest probabilities at 0 to 20 percent and contained forest stands which had been thinned and burned reducing available fuels for combustion (Figure 7). In the burn severity results (Figure 5), these basins encompassed the lowest burn severities given weather and fuel input variables for Las Conchas fire conditions. Basins 31 and 39, the smallest basins with regards to area, had higher debris-flow probabilities (40-60% and 20-40%) given their extreme ruggedness and moderate burn severities.

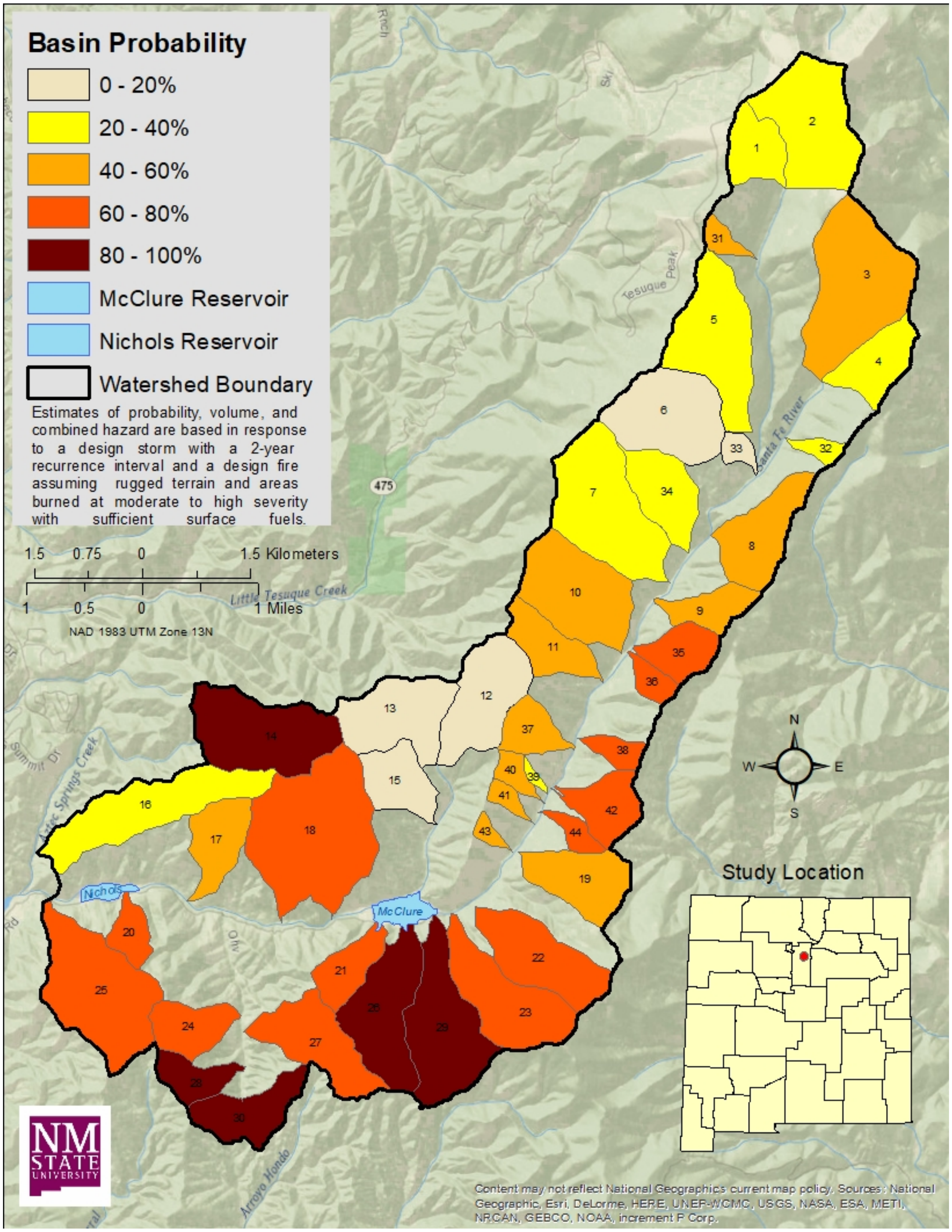

Figure 8. Upper SFMW basin probabilities following a 2-year, 1.41 inches/hour (35.92 mm/hr) storm recurrence.

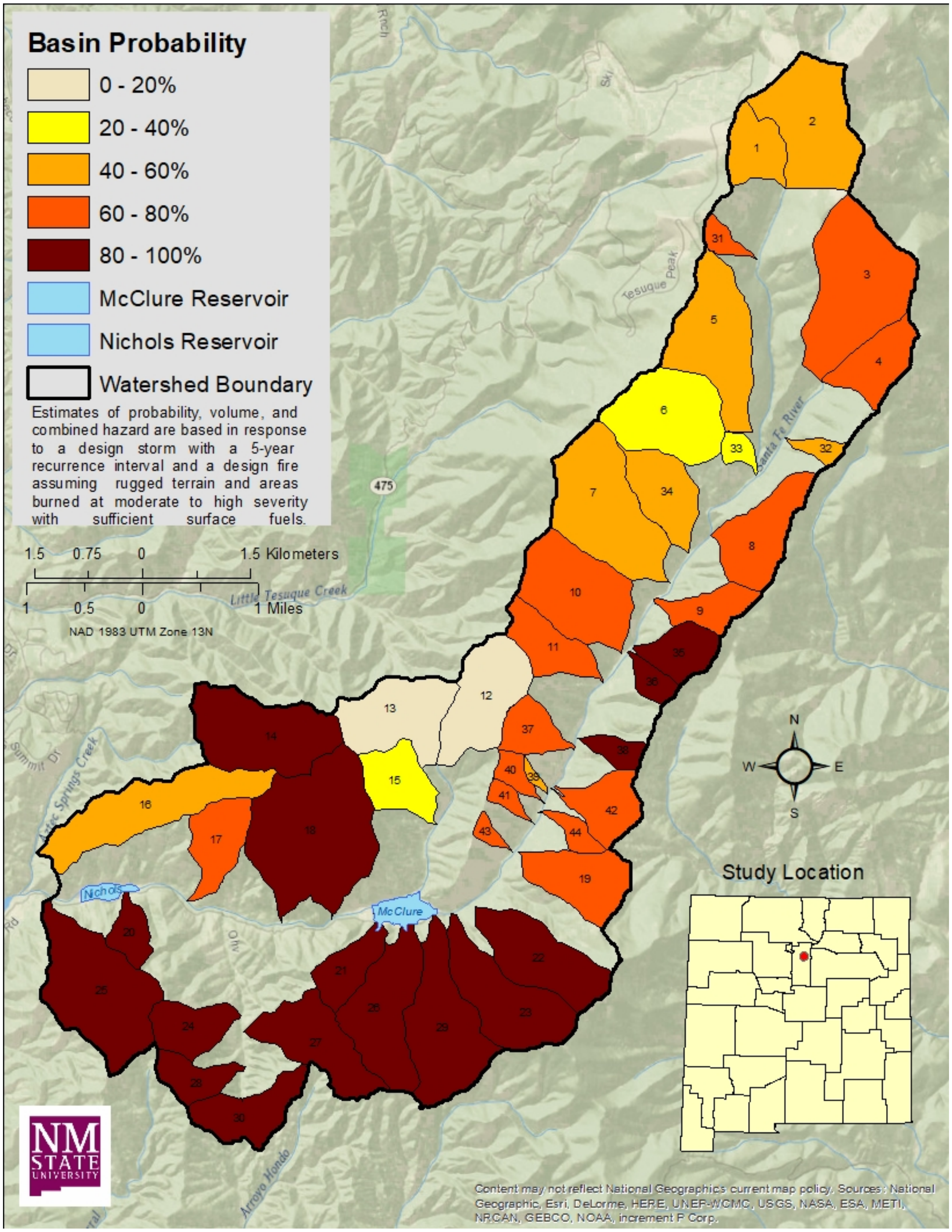

Figure 9. Upper SFMW basin probabilities following a 5-year, 1.88 inches/hour (48 mm/hr) storm recurrence.

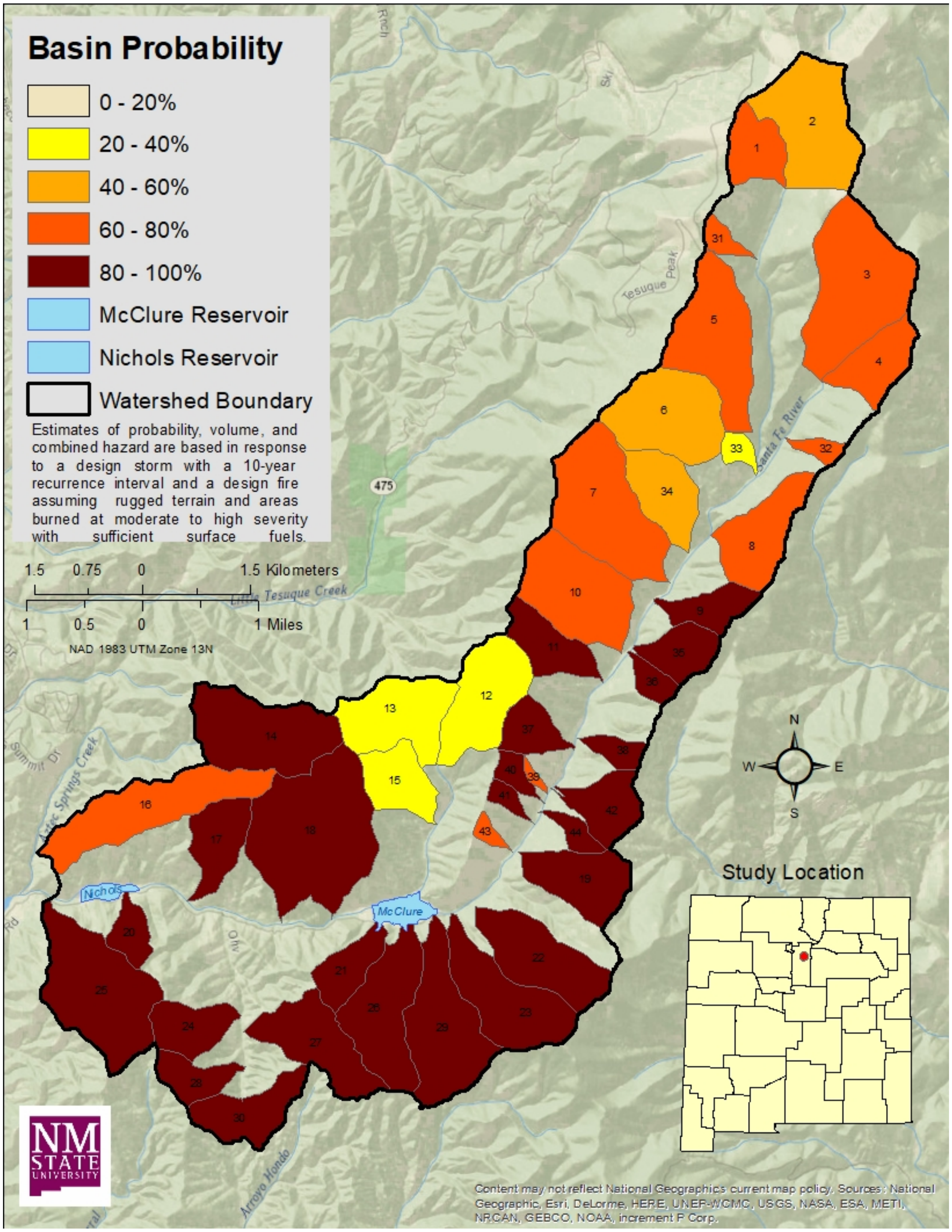

Figure 10. Upper SFMW basin probabilities following a 10-year, 2.20 inches/hour (55.98 mm/hr) storm recurrence.

Basin probabilities increased in each sub-basin with an increase in precipitation. Basins 12, 13, and 15, located in the lower watershed and exhibiting previous forest treatments, maintained the lowest probabilities throughout each storm recurrence. Basin 33 was the only sub-basin containing low probabilities in the upper watershed during the 10-year storm recurrence. Table 4 provides percentage probability of debris flow within every sub-basin.

Table 4. *Debris-flow probability per sub-basin with storm intensity increase*

Basin ID	2-Year storm(36mm)	5-Year storm(48mm)	10-Year storm(56mm)
1	0.379832	0.587911	0.713805
2	0.250137	0.437263	0.575987
3	0.501574	0.700965	0.803843
4	0.395675	0.603981	0.727243
5	0.336249	0.541292	0.673519
6	0.185491	0.346609	0.481165
7	0.277546	0.472262	0.610053
8	0.474144	0.677451	0.785949
9	0.582371	0.764608	0.850269
10	0.430567	0.637854	0.754852
11	0.558266	0.746443	0.837308
12	0.0937274	0.194137	0.296349
13	0.0742388	0.157396	0.246173
14	0.810205	0.908623	0.945604
15	0.114137	0.230843	0.344125
16	0.388866	0.597129	0.721541
17	0.530016	0.724283	0.821187
18	0.760971	0.881176	0.92839
19	0.565809	0.752198	0.841438

20	0.692903	0.840147	0.901847
21	0.767846	0.885115	0.930887
22	0.667593	0.823889	0.891051
23	0.661986	0.820208	0.888584
24	0.772159	0.887568	0.932437
25	0.793707	0.899621	0.940005
26	0.812394	0.909804	0.946335
27	0.736992	0.86715	0.919427
28	0.825933	0.917031	0.950793
29	0.836605	0.922641	0.954235
30	0.844731	0.926862	0.956813
31	0.429657	0.636996	0.754165
32	0.318878	0.521653	0.655943
33	0.128803	0.256168	0.375808
34	0.222676	0.400221	0.538438
35	0.670981	0.826099	0.892528
36	0.652153	0.813683	0.88419
37	0.581877	0.764242	0.85001
38	0.651476	0.813229	0.883883
39	0.328149	0.532213	0.66544
40	0.499209	0.698978	0.802349
41	0.496511	0.696702	0.800631
42	0.625636	0.79562	0.871886
43	0.43673	0.64363	0.759465
44	0.610552	0.785031	0.864576

Given a 10-year storm, there were no basins in the 0-20 percent range for debris-flow probability, and over 90 percent of all the sub-basins exhibited high debris-flow probabilities (60-100%). Basins 14, 26, 28, 29, and 30 had the highest probabilities in all three scenarios. Their attributes are reported in Table 5. These basins have high elevational gradients and are over 90 percent burned at moderate and high severity.

Table 5. *Sub-basins with the highest debris-flow probabilities in each storm recurrence and their corresponding attributes.*

Basin ID	Area (km^2)	Max Elevation (meters)	Ruggedness	% Burned at High and Moderate Severity
14	1.86	2875	0.25	94
26	1.62	2787	0.30	91
28	0.51	2744	0.42	99
29	1.80	3013	0.45	97
30	0.91	2707	0.25	98

Segment probabilities for 2-,5-, and 10-year storm recurrence results were similar to basin probabilities in that the sub-basins north of McClure reservoir had the lowest probability for debris-flow occurrence in every storm scenario (figures 11 – 13). Basins 12, 13, and 15 have high elevations and large areas (Table 6), but lack one of the driving factors for post-fire debris-flow initiation, that is, percent area burned at moderate and high severity as a result of previous forest treatments.

Table 6. *Sub-basins with the lowest segment probabilities in each storm recurrence and their corresponding attributes.*

Basin ID	Area (km^2)	Max Elevation (meters)	Ruggedness	% Burned at High and Moderate Severity
12	1.41	2908	0.31	39
13	1.39	2875	0.28	43
15	0.79	2829	0.42	38

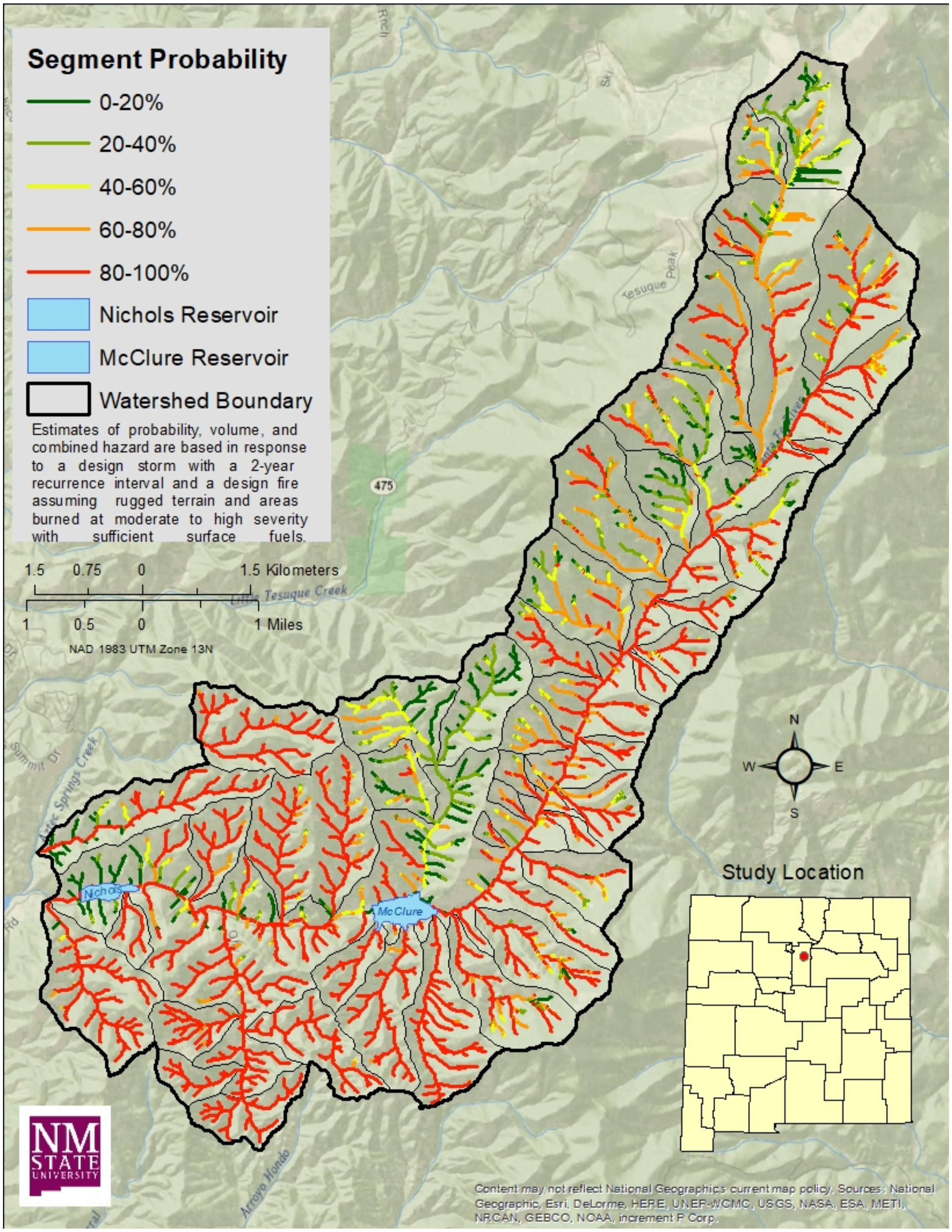

Figure 11. Upper SFMW segment probabilities following a 2-year, 1.41 inches/hour (35.92 mm/hr) storm recurrence.

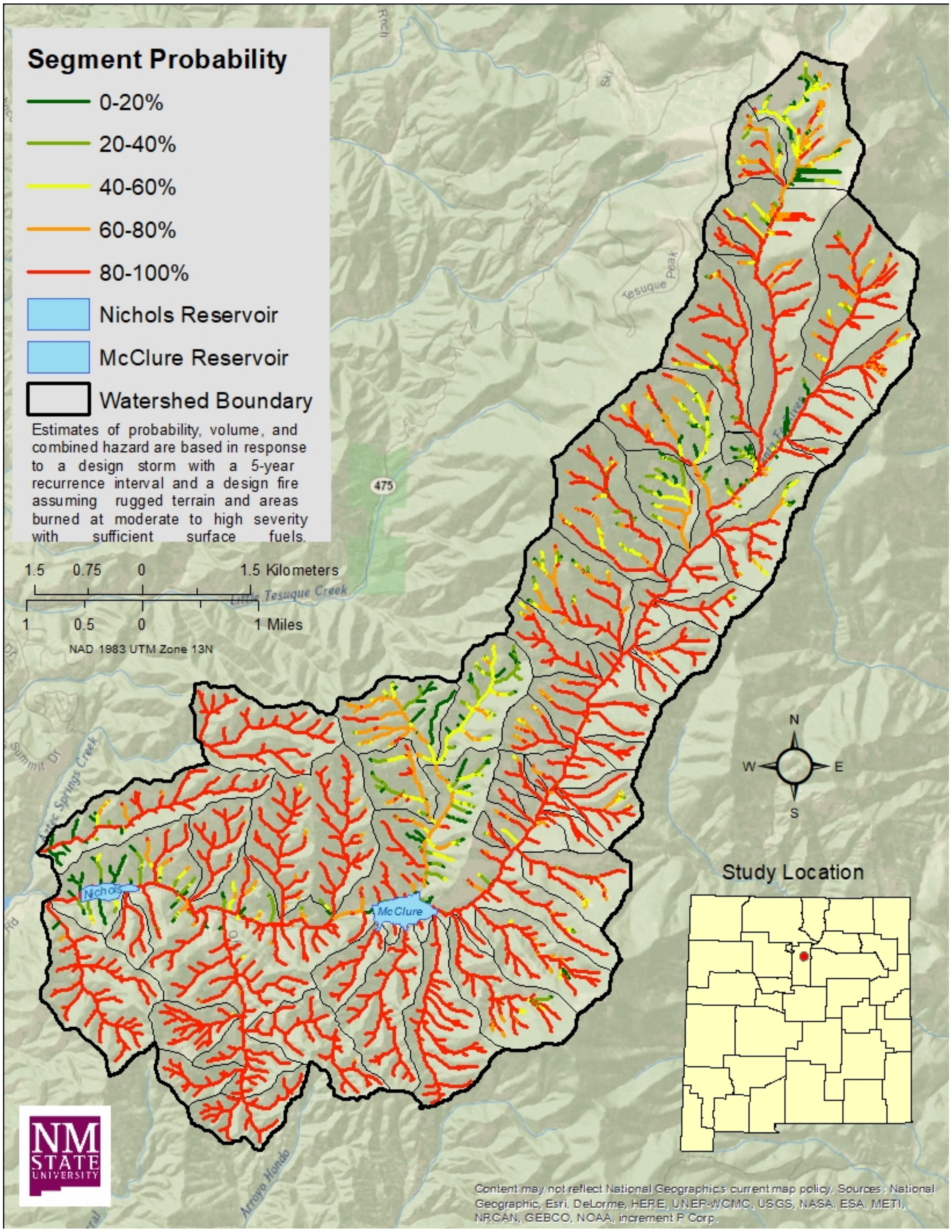

Figure 12. Upper SFMW segment probabilities following a 5-year, 1.88 inches/hour (48 mm/hr) storm recurrence.

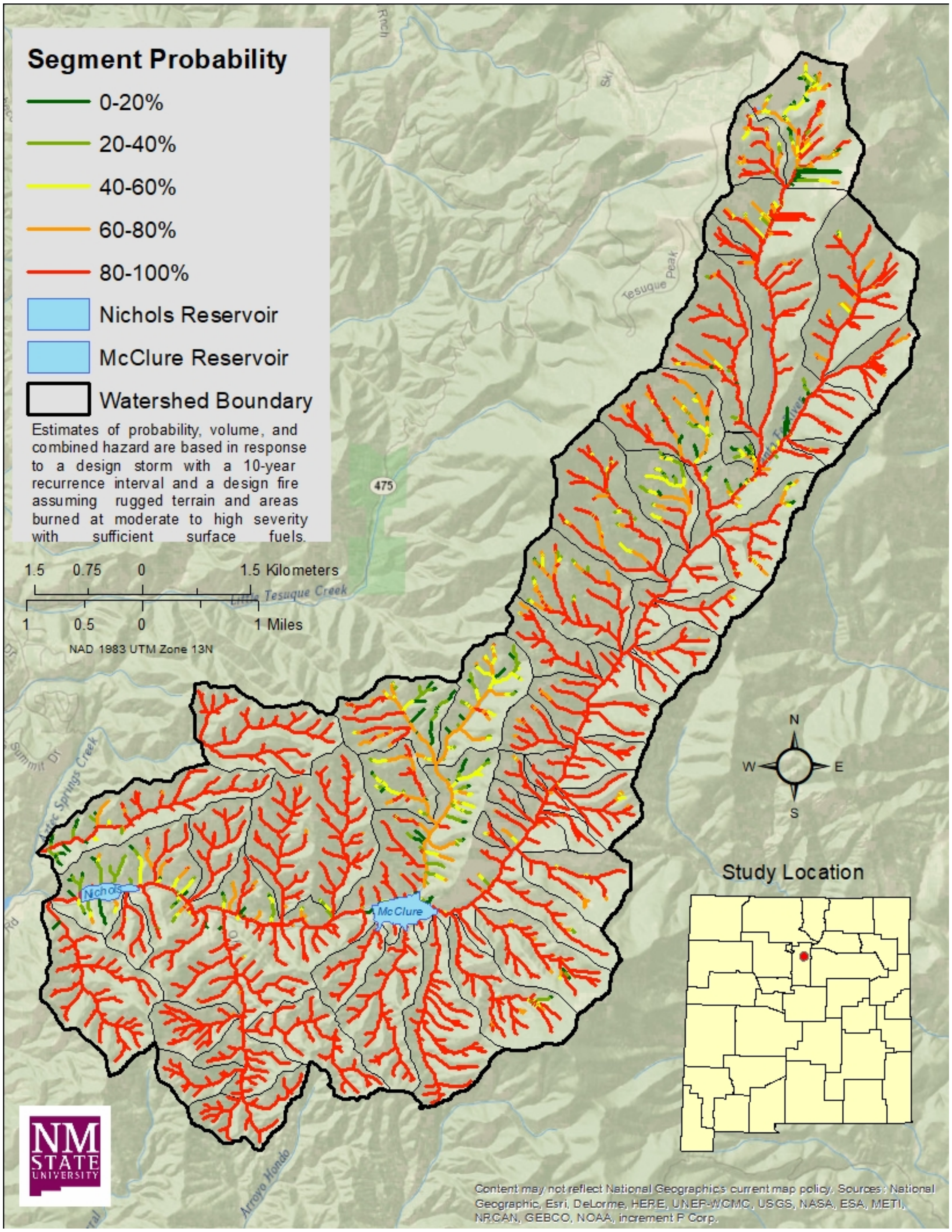

Figure 13. Upper SFMW segment probabilities following a 10-year, 2.20 inches/hour (55.98 mm/hr) storm recurrence.

The Santa Fe River had an 80-100 percent probability of producing debris flows in every model storm (figures 11-13), including the regions above and below McClure reservoir. Similarly, every main channel of the side tributaries exhibited high percentages of probability as well. Every instance where lower probability stream segments converged with another tributary, the probability for debris flow increased. Given a Las Conchas burn scenario for the SFMW, the majority of the stream segments in the watershed have high probabilities in the most commonly occurring storm events. This is also seen in the uppermost elevations during a 10-year storm recurrence where precipitation rates are normally the highest and forests have a low frequency, high severity fire regime.

5.3 Debris-Flow Volume Estimates

Estimated debris-flow volumes were calculated at the basin and segment levels. These values are independent of the probability model and are important to consider since a high probability basin may actually yield low sediment volumes. The results of the estimated debris-flow volumes pending a 2-, 5-, and 10-year recurring storm are reported in figures 11 through 13.

Volume model classification values as outlined by Canon et al. (2010) included four categories from 0 to over 100,000 m^3. However, model output volumes in this analysis did not exceed over 11,153 m^3 (basin 18). Thus, model output for this project identified volumes greater than 10,000 m^3 as the largest potential volumes (indicated in dark red).

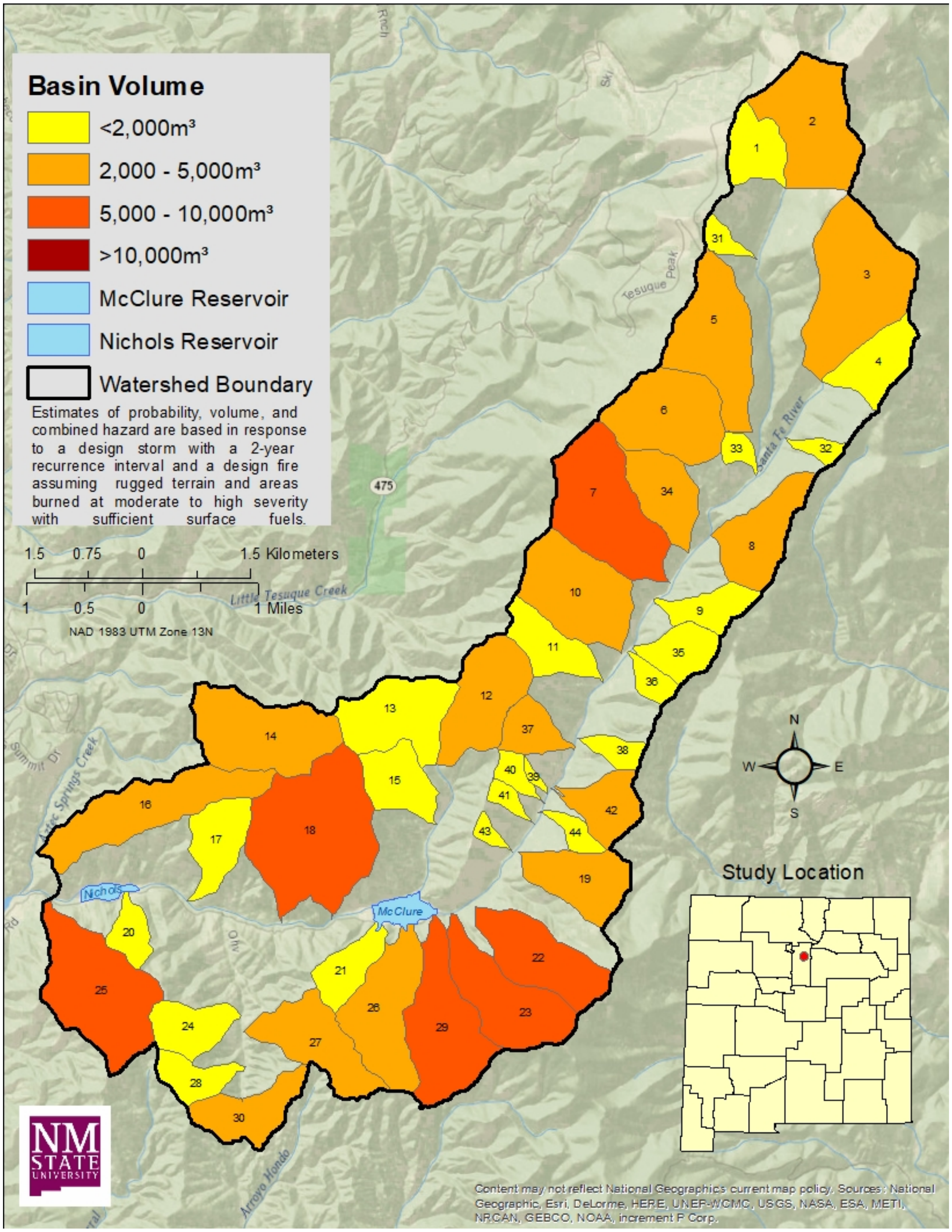

Figure 14. Upper SFMW estimated basin volumes following a 2-year, 1.41 inches/hour (35.92 mm/hr) storm recurrence.

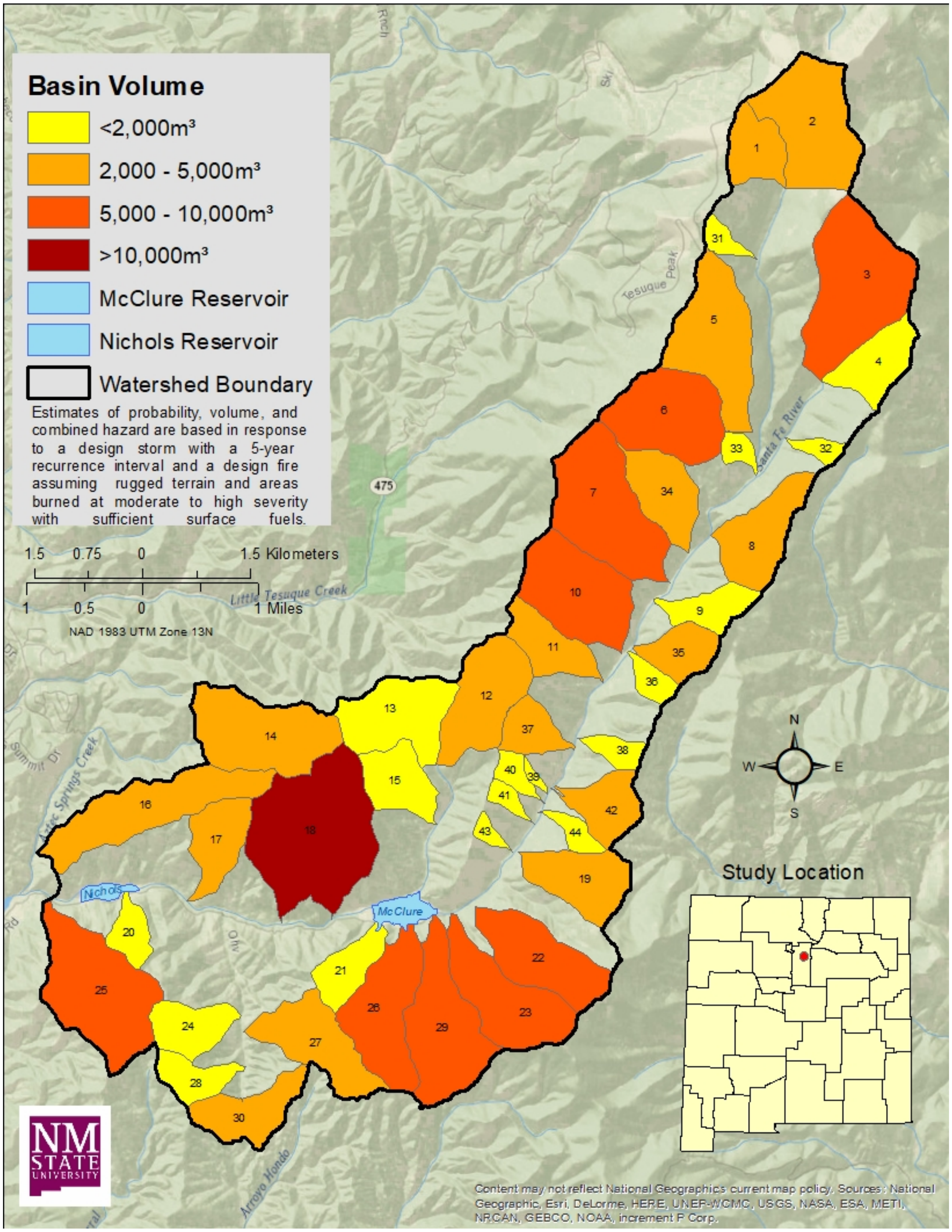

Figure 15. Upper SFMW estimated basin volumes following a 5-year, 1.88 inches/hour (48 mm/hr) storm recurrence.

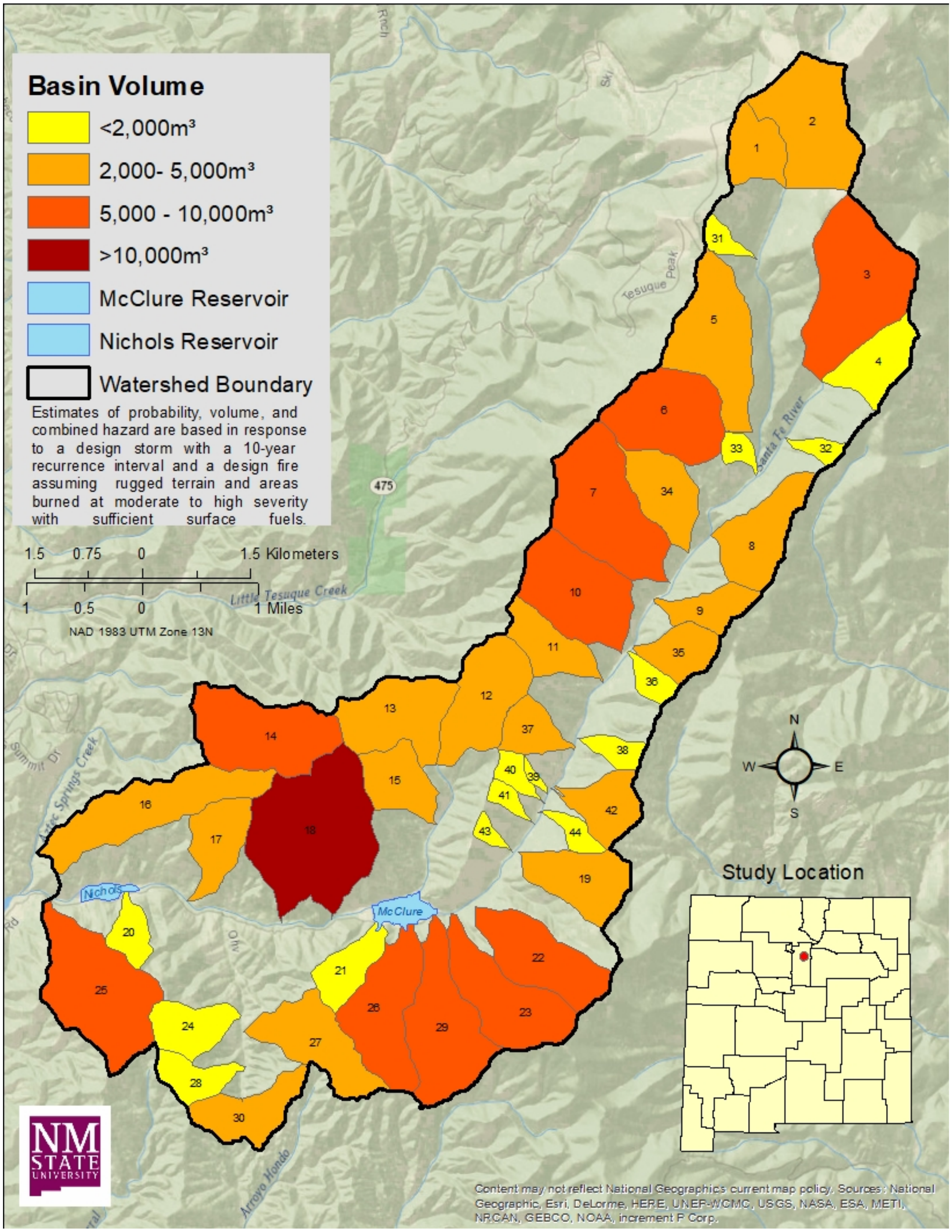

Figure 16. Upper SFMW estimated basin volumes following a 10-year, 2.20 inches/hour (55.98 mm/hr) storm recurrence.

Models for the three different storm intensities show subtle differences. Potential debris-flow volumes are presented in Table 7.

Table 7. *Potential debris-flow volumes per sub-basin with storm intensity increase (values in m^3). Red = highest totals, Yellow = lowest totals*

Basin ID	2-Year storm(36mm)	5-Year storm(48mm)	10-Year storm(56mm)
1	11986	2266.6599	2448.9900
2	3737	4265.7202	4608.8599
3	4957	5657.8398	6112.9702
4	1183	1350.5800	1459.2200
5	3329	3800	4106
6	4564	5209	5628
7	5109	5831	6300
8	2599	2966	3204
9	1643	1876	2027
10	4784	5460	5900
11	1941	2215	2394
12	3035	3464	3742
13	1705	1946	2102
14	4311	4921	5317
15	1660	1894	2047
16	3042	3472	3751
17	1800	2054	2219
18	9045	10323	11154
19	3459	3948	4265
20	1562	1782	1926
21	1561	1781	1924
22	5316	6067	6555

23	5912	6748	7291
24	1433	1636	1768
25	6495	7413	8009
26	4571	5218	5637
27	2494	2846	3075
28	1454	1660	1793
29	5632	6428	6945
30	2218	2531	2735
31	736	840	908
32	611	697	753
33	759	866	936
34	2370	2705	2923
35	1994	2276	2459
36	870	992	1072
37	2096	2393	2585
38	1296	1480	1599
39	256	292	316
40	922	1052	1137
41	786	897	969
42	2460	2807	3033
43	700	799	863
44	952	1086	1174

Basin 18 had the highest potential debris-flow volume in every storm configuration. In contrast to probability, basin size directly influenced potential debris-flow volumes (i.e., the smallest basin areas yielded the lowest potential volumes, e.g., < 2,000 m^3). The basins above the McClure reservoir (12, 13, and 15) which the model indicated have the lowest probabilities for debris-flow due to forest treatments, also had lower estimated volumes, ranging from less than 2,000m^3 in the 2-year storm, up to 3,742m^3 in the 10-year storm for basin 12. All sub-basins increased their estimated yields with an increase in storm intensity.

Estimated segment volumes for 2-, 5-, 10-year storms are illustrated in figures 17 through 19. The main channel of the Santa Fe River contained the largest amount of predicted sediment volume (>10,000 m^3) in every storm recurrence. There is a significant distance and area above the McClure Reservoir that the Santa Fe River travels from its inception and there are more than ten tributaries in the 5- and 10-year storm recurrence representing potential volumes greater than 10,000 m^3. This indicates the Santa Fe River feeding into the McClure Reservoir is capable of debris-flow volumes up to 100,000 m^3 (figures 18 and 19). The Nichols Reservoir is also impacted by the main channel of the Santa Fe River, with volumes greater than 10,000m^3 in 5-, and 10-year storm recurrence. The difference in volume as portrayed in the figures are subtle, but increases occur upstream in every tributary given an increase in storm intensity.

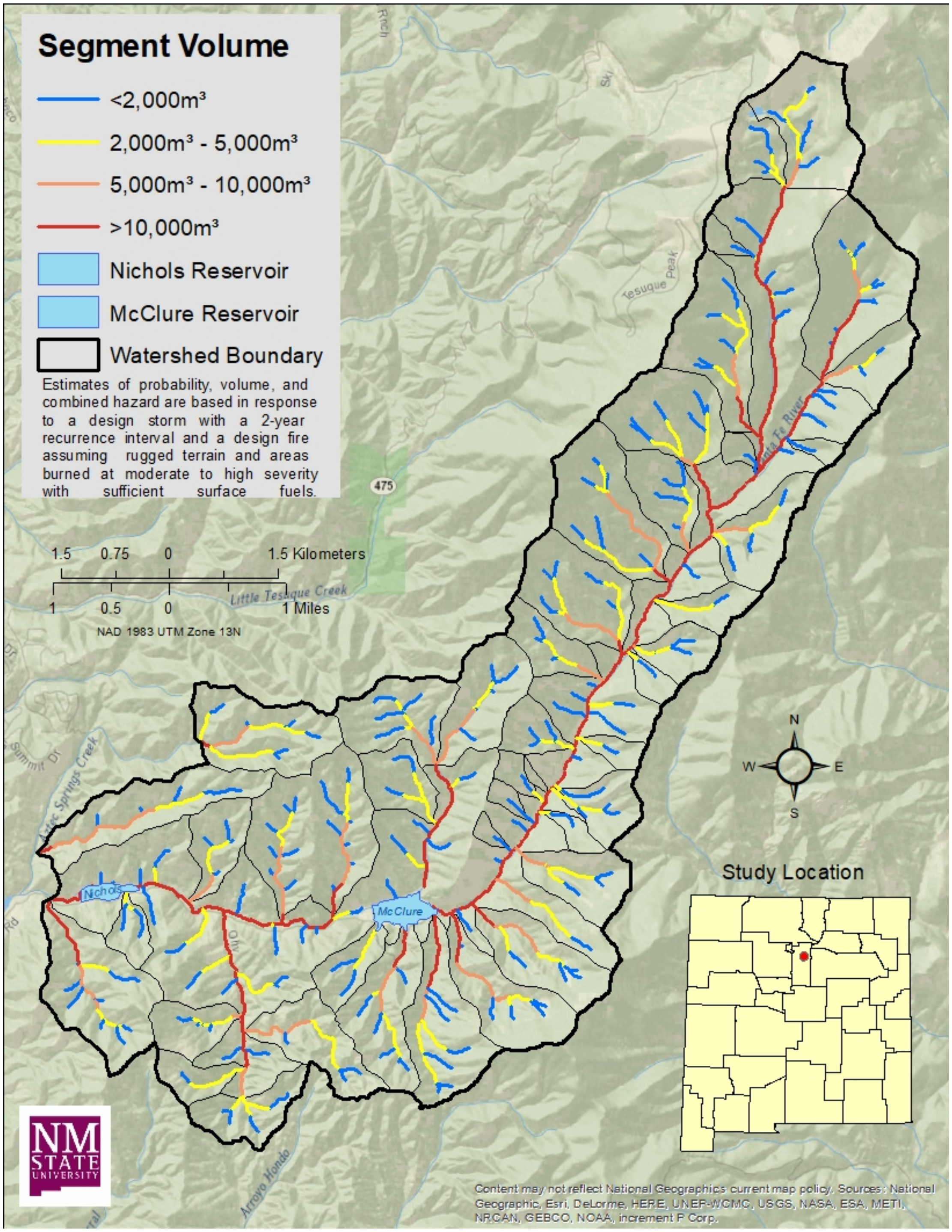

Figure 17. Upper SFMW estimated segment volumes following a 2-year, 1.41 inches/hour (35.92 mm/hr) storm recurrence.

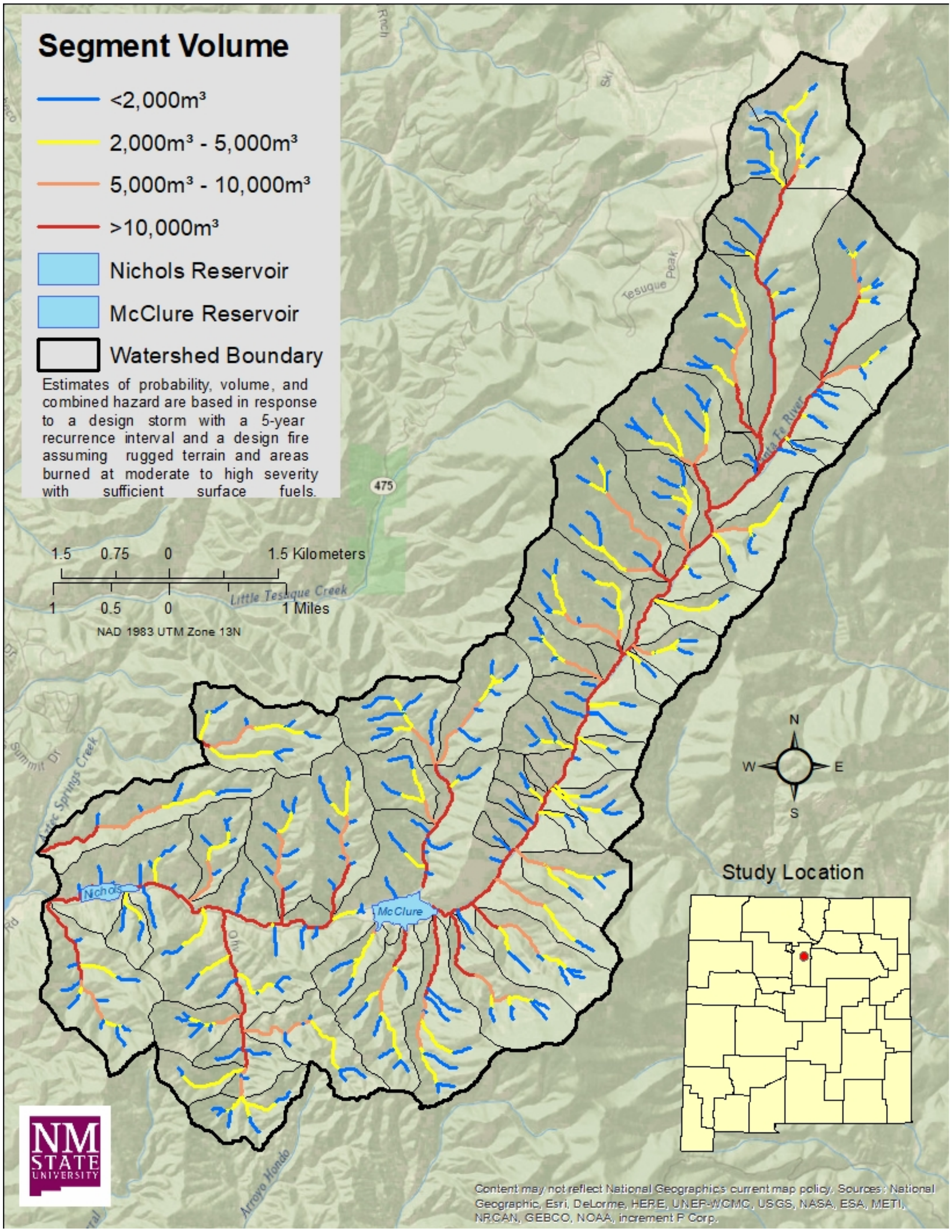

Figure 18. Upper SFMW estimated segment volumes following a 5-year, 1.88 inches/hour (48 mm/hr) storm recurrence.

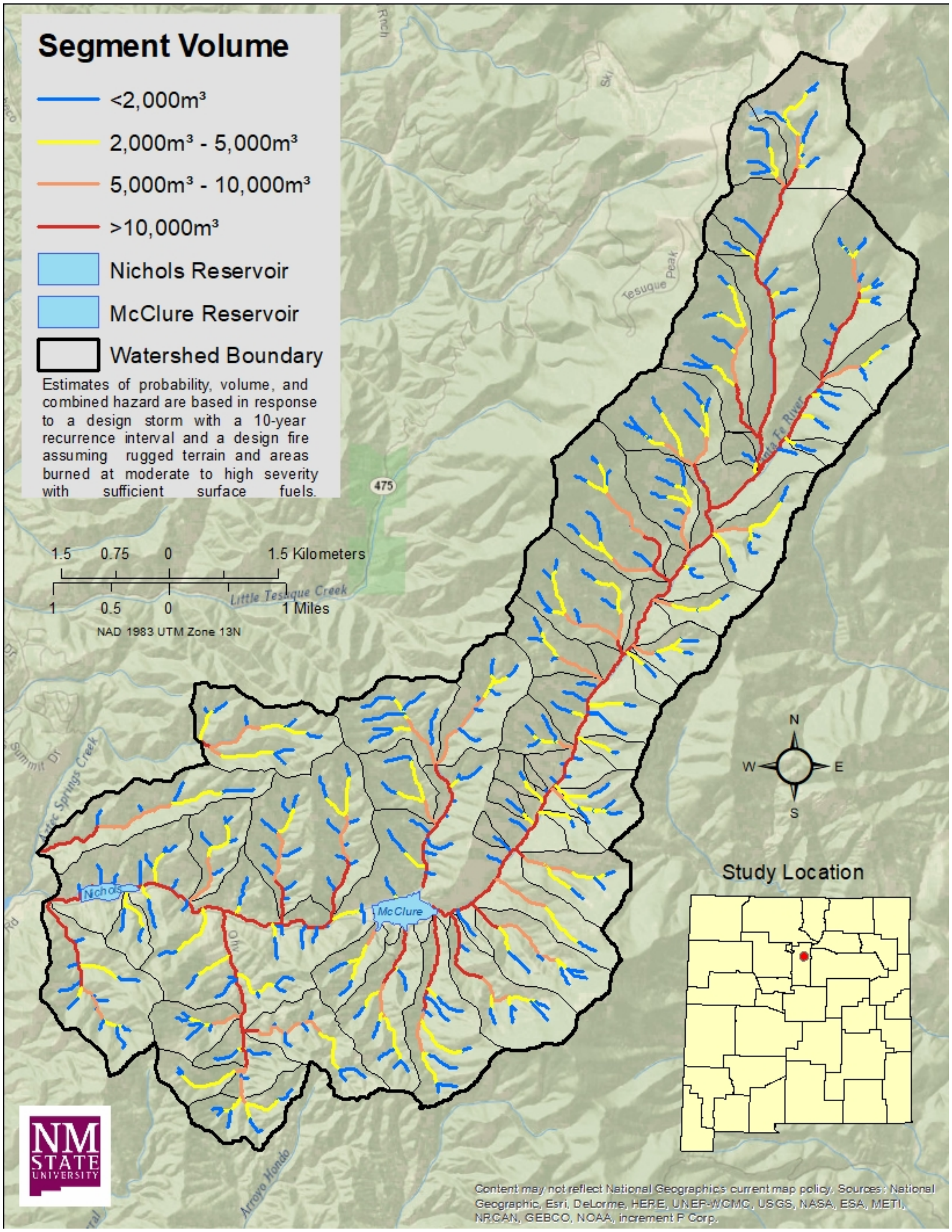

Figure 19. Upper SFMW estimated segment volumes following a 10-year, 2.20 inches/hour (55.98 mm/hr) storm recurrence.

5.4 Debris-Flow Hazard Estimates

Overall hazard estimates were made at the basin level by combining probability and volume rankings into the hazard index. Figures 21 through 23 illustrate a similar trend with our probability and volume estimates, that is, with an increase in storm intensity, hazard rankings per basin also increase. Basins 12, 13, 15, and 33 were the only basins that maintained a low hazard ranking with each storm recurrence. The number of basins with a high hazard index increased from 11.3 percent in the 2-year storm recurrence to over 54 percent in the 10-year storm recurrence. With conditions similar to those that created the high severity Las Conchas fire coupled with common re-occurring storms, the SFMW sub-basins are prone to high hazard events.

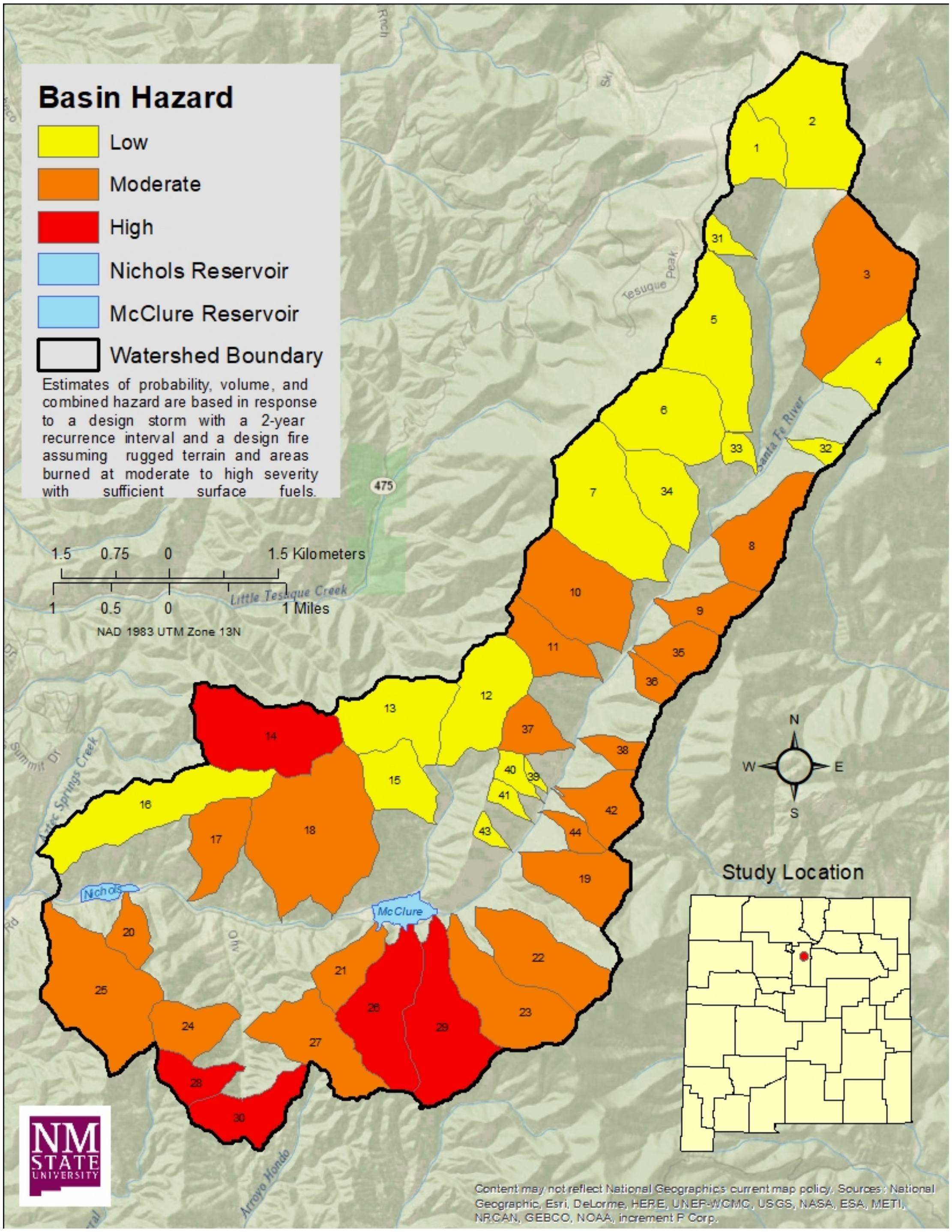

Figure 20. Upper SFMW basin hazard following a 2-year, 1.41 inches/hour (35.92 mm/hr) storm recurrence.

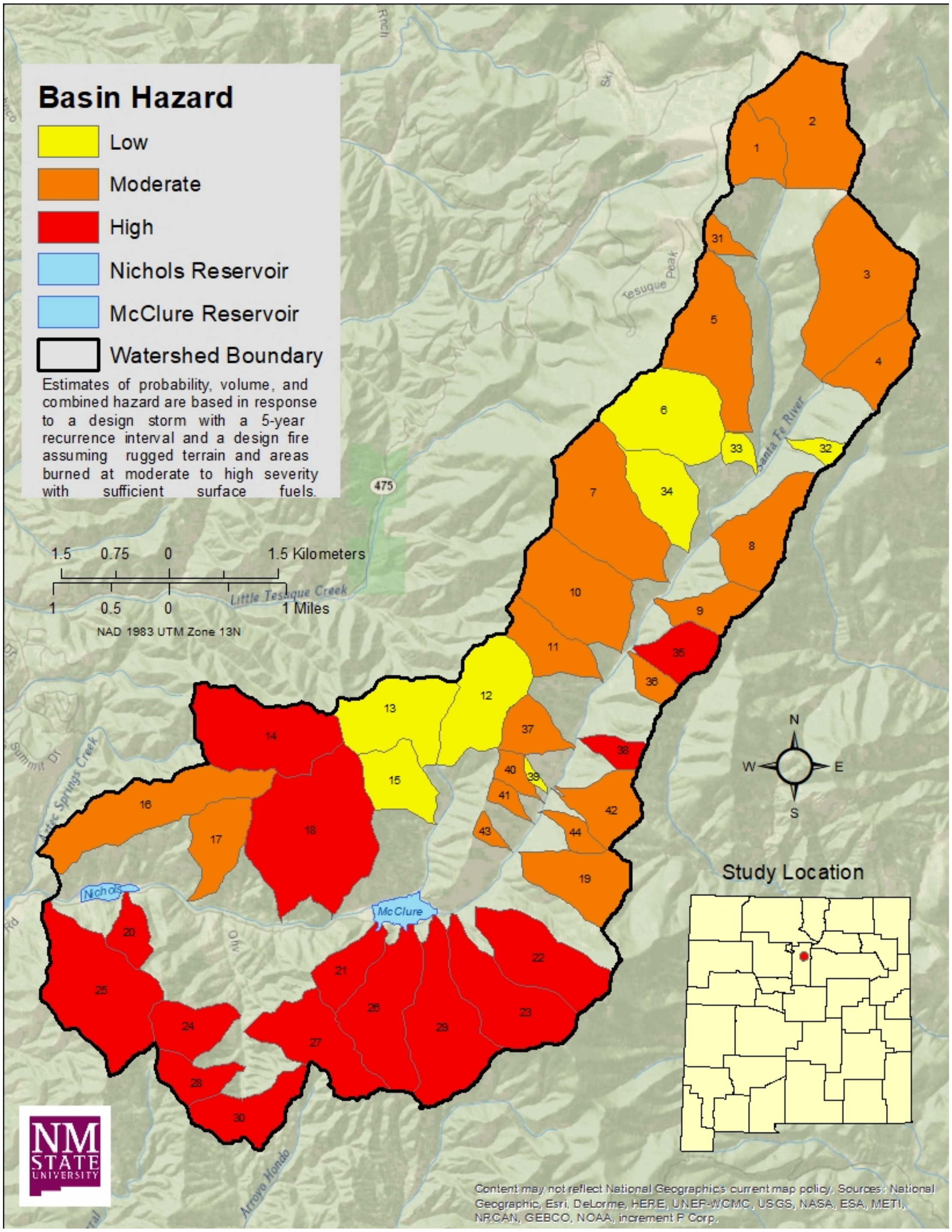

Figure 21. Upper SFMW basin hazard following a 5-year, 1.88 inches/hour (48 mm/hr) storm recurrence.

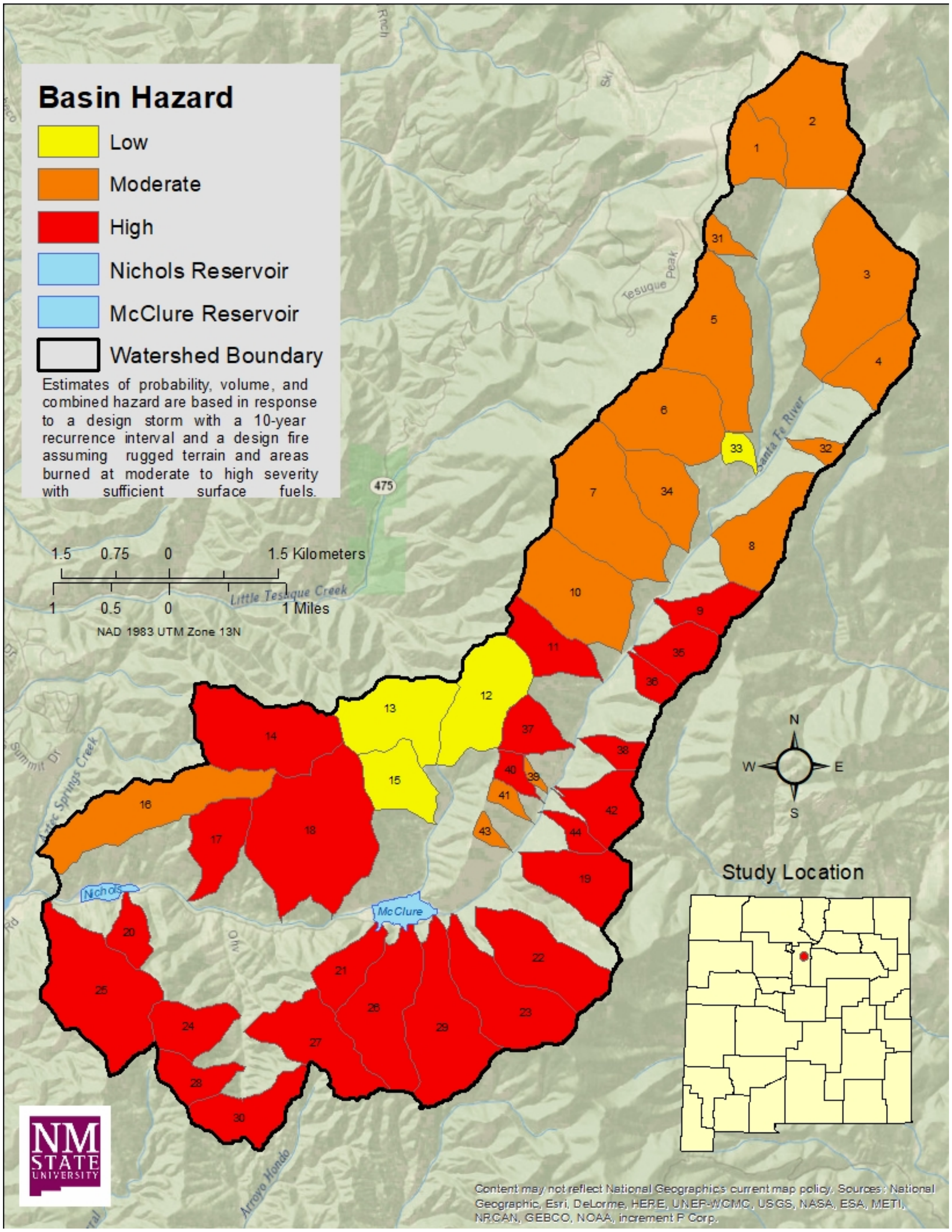

Figure 22. Upper SFMW basin hazard following a 10-year, 2.20 inches/hour (55.98 mm/hr) storm recurrence.

CHAPTER 6: DISCUSSION

Given that 81 percent of the SFMW was burned at moderate to high severity, it is expected that debris flows would occur following model storm events. By implementing model storms that have the most common occurrence in the region, we can begin to understand the ramifications of forest treatments and moderate and high fire severity (Figures 5-7).

The utilization of models for forecasting dangerous events aids managers and the public in making future decisions regarding hazard mitigation. Models however, are our attempt at representing reality, in this case, multiple dynamic natural processes. By implementing specific scenarios into these models for dynamic events, we inevitably will encounter limitations and potential errors. The intention was to outline the potential effects that moderate and high severity fire can have on the SFMW. There exists much variability in the topography of the SFMW and this will inevitably influence the spatial extent and severity that a wildfire will have within the watershed. Nevertheless, by implementing the tools and data provided by multiple agencies, specific areas have been mapped which would likely be impacted by moderate to high severity fire. Locations were identified by topographies and soil types coupled with common storm recurrence intervals that trigger post-wildfire debris flows. The results can aid planners and forest managers in mitigation efforts by identifying specific problematic locations with regards to fuel abundance or potential debris-flow proximity to important reservoirs.

Multiple models were used in the analysis: 1) RiverTools to delineate the stream network; 2) FlamMap to create a proxy for burn severity; and 3) USGS debris-flow models by Cannon and others (2010) to generate debris-flow probability and volume. These datasets needed to be similar in grid size (10m) for the debris-flow model to function. Analysis in the future would benefit from multiple fire scenarios. Las Conchas fire parameters were taken as a worst-case scenario event, but multiple burn severity scenarios typical of the Sangre de Cristo Mountains and their forests would give further insight to post-fire debris flows and their locations.

Due to the destructive nature of debris flows and the unpredictable timing of their occurrence, there is a lack of empirical observations in the research (Smith *et al.* 2011). This limitation is also present geographically. Whereas the model designed by Cannon and others (2010) has been widely used and accepted, as well as implemented in many areas within New Mexico, the model origin is based on northern Rocky Mountain and Californian post-fire debris-flow occurrences. Southwestern debris flows might have differences with regards to vegetation, topography, and the regional monsoonal precipitation patterns. Examining this would require further research.

Future studies for debris-flow occurrence in the southwestern United States will benefit from research into region specific precipitation characteristics. There is a strong correlation in the Southwest with monsoon and fire occurrence. Periods of one to two wet cool seasons followed by cool-season drought has been a consistent pattern for inducing landscape fire in the southwestern US (Swetnam and Betancourt, 1998). North American monsoon compounds the climate variability with fire occurrence by bringing over 50 percent of the annual moisture to the southwestern US, and by increasing fine fuels in the summertime months. Margolis and others (2017) found that large fires occurring in the early growing season months (April – June) were associated with a wet-cool season 2-3 years prior to the fire, increasing fuels, and a dry cool season the year of the fire. The north American monsoon influenced fire seasonality, by shifting large fire occurrences to later months (September – October). Where north American monsoon usually aids in suppressing early season fires, if monsoonal drought follows a dry-cool period, late season fires generally occur. These differences in fire seasonality and north American monsoon occurrence from other geographic locations would naturally create different debris-flow seasonality and recurrence times. If debris-flow occurrence is most likely 1-3 years following a fire (Tillery and Haas 2016), then special attention must be made to the high frequency, high intensity north American monsoon.

CHAPTER 7: CONCLUSIONS

Burn severity throughout the watershed was predicted to be mostly moderate given the weather inputs. A moderate severity fire coupled with the most common storm recurrences in the region provided for high debris-flow probabilities and hazards. These hazards include contamination of the Nichols and McClure reservoirs with debris and soil black carbon, possible breach of reservoir dams, and detrimental impacts to natural resources, waterways, and urban resources downstream.

Noting that many basins which exhibited prior treatments had lower probabilities and volumes further validates the need for forest managers to continue fuel reduction treatments within the where appropriate. This information will provide city and forest managers an opportunity to prepare and mitigate potential negative effects associated with wildland fire and subsequent debris flows. Ultimately, this knowledge will benefit water quality for the city of Santa Fe and forest management in the watershed.

Fire is an important process which regulates the generation of surface fuels in forest systems. Anthropogenic influences have altered the natural interaction between forests and fire. With a predicted future of increased temperature, dry conditions, and intensification of southwestern monsoons, the alterations already established by humans may negatively impact southwestern Rocky Mountain regions even further. Forest managers need further scientific inquiry on the effects that high frequency and high severity fires have on geomorphic changes and hydrologic impacts. When these characteristics are further analyzed, nearby communities will be better informed to make planning and management adjustments as necessary.

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