NM WRRI Student Water Research Grant Final Report

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Debris Flow Potential Following Wildfire in the Upper Santa Fe Municipal Watershed

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Research problem and research objectives

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. This destructive form of mass wasting in landscapes that have otherwise been stable throughout recent history creates significant hazards for people and challenges for natural resource managers. 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 through analyzing USGS-developed geospatial modeling outputs. This approach addresses two fundamental questions in debris-flow hazard assessment: where might debris flows occur and how big might they be? In this study, we will create a series of GIS produced maps and accompanying data that show the estimated probability and volume of post-fire debris flows for the Santa Fe, New Mexico watershed given a 2-, 5-, and 10-year, 30-minute rainfall event following a moderate to high severity wildfire. We hypothesize watershed basins with slopes greater than 30% will be identified as potential debris-flow zones.

Methodology

We employed previously established methods by Cannon and others (2010) and Verdin and others (2012) developed for modeling post-wildfire debris flows 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 flow and estimation of debris flow volume in a given drainage basin influenced by fire. The regression equation for debris flow probability is as follows:

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

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%;
R is drainage-basin ruggedness: the change in drainage-basin elevation (meters) divided by the square root of the drainage-basin area (square meters);
%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);
%*C* is clay content of the soil (percent);
LL is the liquid limit of the soil (percentage of soil moisture by weight)

Cannon and others (2010) then developed an empirical model for the estimation of debris flow volume following a wildfire:

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

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.

We continue to analyze the factors identified by Cannon and Reneau (2000) in a post wildfire burned basin through modeling. We have then applied these modeling techniques within the Santa Fe Municipal Watershed (SFMW) to identify tributaries with the potential for producing debris flows within 44 sub basins (Figure 1).

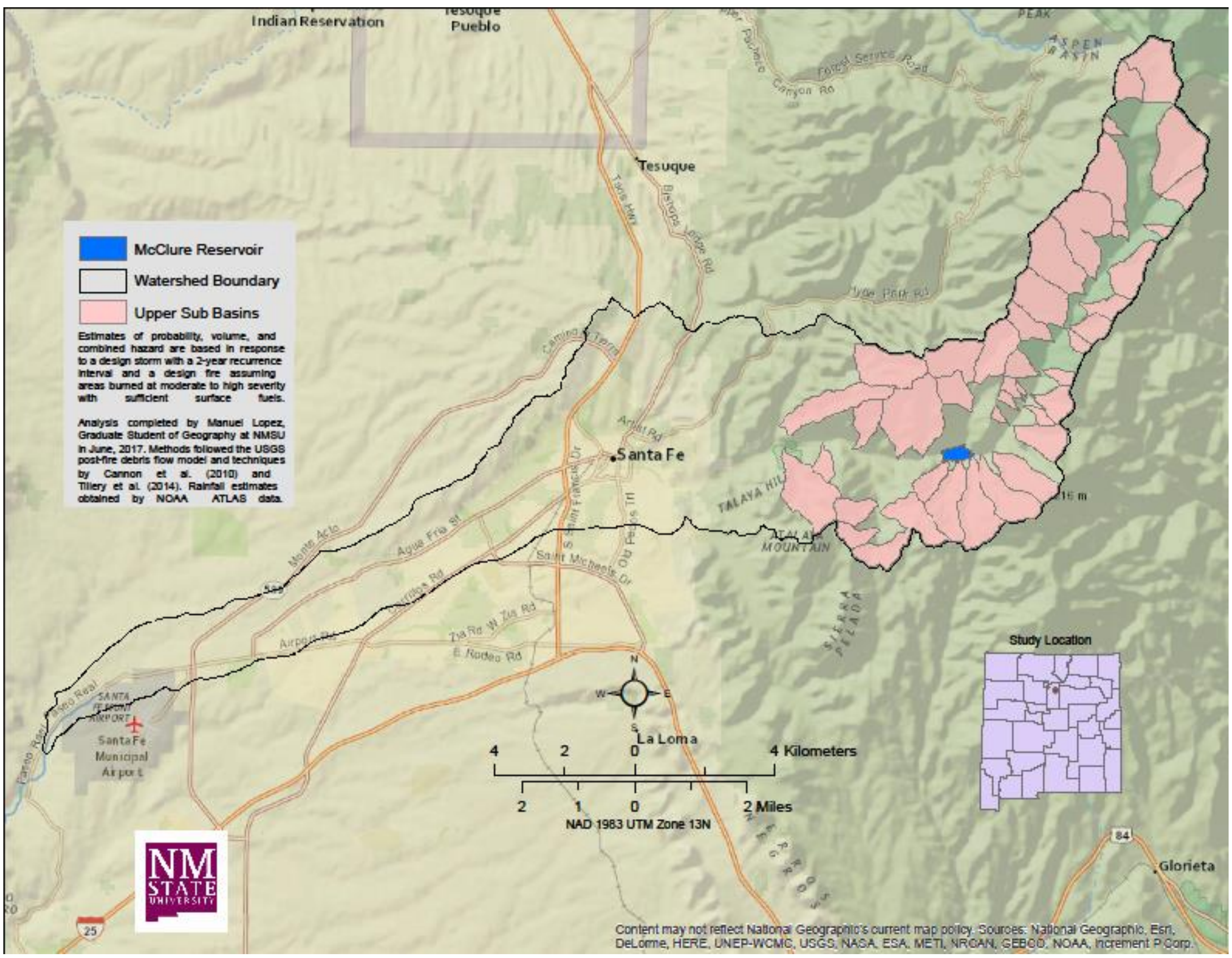

Figure 1. Forty-four sub basins in the upper SFMW

We examined slope angle, channel width and depth, and burn intensity, among other important factors, we can verify if the same information and techniques used by Cannon and Reneau (2000) are true for other tributaries.

Once delineating debris flow probability and potential volume in various tributaries, identification of debris flow probability and volume at the sub-basin level is needed to identify the most hazardous basins. We used the field calculator in ArcGIS, the above equations aid in creating a probability and volumetric index per sub-basin. We combined both indices and arrived at a final hazard index per sub-basin.

A burn severity raster was computed for debris flow analysis. We used Finney and Stratton's fire mapping and analysis program FlamMap (2006) of the United States Forest Service. FlamMap is a fire mapping and analysis program that describes potential fire behavior based upon environmental conditions such as weather and fuel moisture. The designed fire included variables consistent with previous fire years, such as the active 2011 fire year in which the Las Conchas and Pacheco fires burned, to create a burn severity raster. The design fire assumed an uphill wind direction with 20-foot wind speeds of 21 mph.

This model was modified by utilizing the characteristics identified in the field, and implemented on a Digital Elevation Model of the upper Santa Fe watershed. The resulting maps would give insight to potential risk areas in the SFMW and would aid watershed managers in addressing future forest treatment decisions.

Results, conclusions, and recommendations for further research

Site visits to the SFMW prior to the winter snow pack provided evidence of past debris flows in the non-treated wilderness region as well as the treated (thinned and burned) non-wilderness portion. This evidence validated our hypothesis that the watershed has been capable of producing debris flows.

35 of 44 sub basins have a 40% probability of debris flows occurring in a particular stream segment during a design fire in the SFMW regardless of the rainfall event (Figures 1-3). The sub basins with the lowest probability and volumes (sub basins 1, 2, 6, 7, 12, 13, 15, 33, and 34) have lower percentages of basin area with slopes greater than 30 degrees. They also have low percentages in area burned by the design storm due to less vegetation, either from high elevation or from forest treatments (Table A).

Table A. Sub basin area with slopes greater than 30° and percent area burned at moderate to high severity.

Sub basins	% slope area >30°	% area burned
1	28.9740009	72.1158981
2	20.0529003	64.1243973
3	16.3817005	87.1415024
4	9.3062601	83.8917999
5	15.6196003	75.4045029
6	37.1679993	54.0652008
7	25.3220997	68.8828964
8	20.6982994	81.9644012
9	27.4020996	89.9705963
10	31.1343002	75.6964035
11	23.3973999	87.4473038
12	28.3075008	39.2887993
13	10.5593004	43.2779999
14	19.7301006	93.9725037
15	23.3208008	38.3764
16	14.1077003	68.2388992
17	19.6718006	77.4337997
18	30.6914005	85.223999
19	36.6414986	85.1146011
20	41.5928001	80.9912033
21	20.6793003	91.6617966
22	48.1988983	87.8310013
23	49.4452019	87.017601
24	14.9418001	97.4515991
25	29.2831001	90.3259964
26	28.2033005	91.4440994
27	15.3778	91.0634995
28	24.0307999	98.1455994
29	31.6683006	96.5728989
30	20.7584	97.5522003
31	27.1264	88.0494995
32	23.5501995	81.7266006
33	36.7653008	49.2224998
34	27.2143002	65.5225983
35	32.1488991	92.1503983
36	25.2766991	99.7173996
37	46.5461006	79.3546982
38	48.2342987	89.8962021
39	19.4025993	88.1339035
40	35.8084984	87.4658966

41	40.8600998	84.9163971
42	36.1335983	86.6278992
43	48.2855988	78.7464981
44	34.7853012	96.7085037

Execution of the debris flow model yielded the following segment probability results with regards to 2-year, 5-year, and 10-year recurring storms:

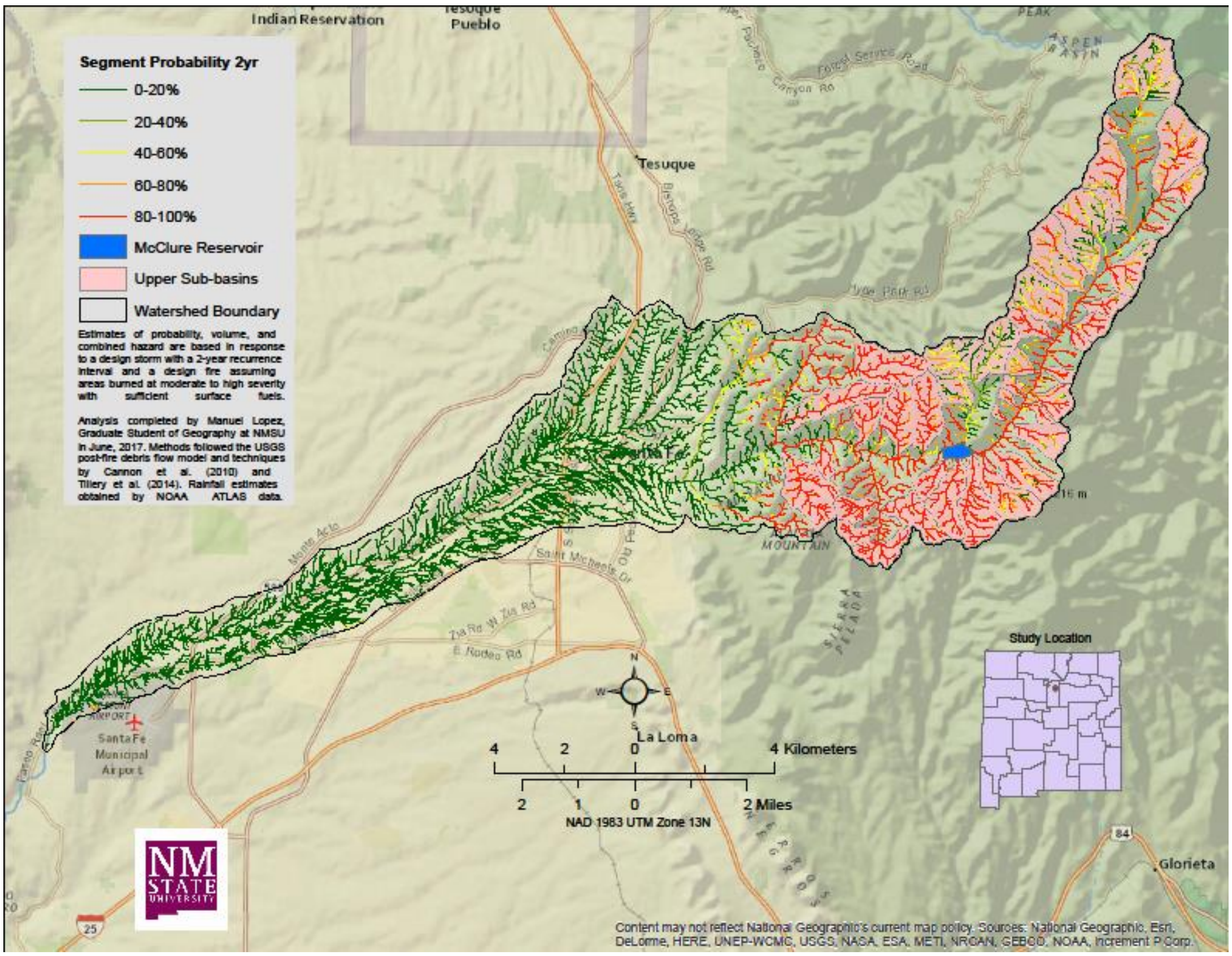

Figure 2. Segment probability for a 2-year storm recurrence. NOAA rainfall averages for a 2-year storm in this region have a total of 18mm/30min, or 36mm storm intensity.

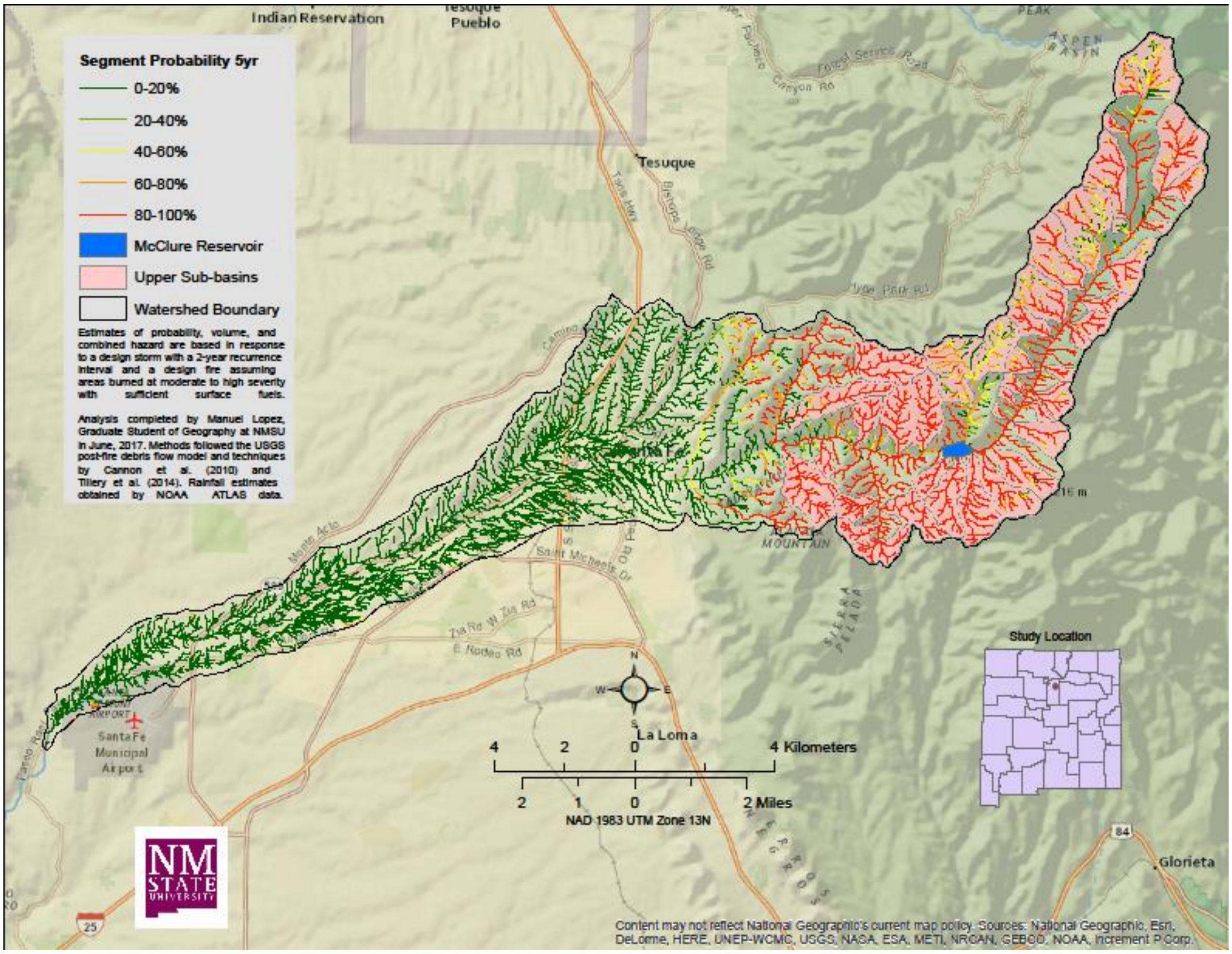

Figure 3. Segment probability for a 5-year storm recurrence. NOAA rainfall averages for a 5-year storm in this region have a total of 24mm/30min, or 48mm storm intensity.

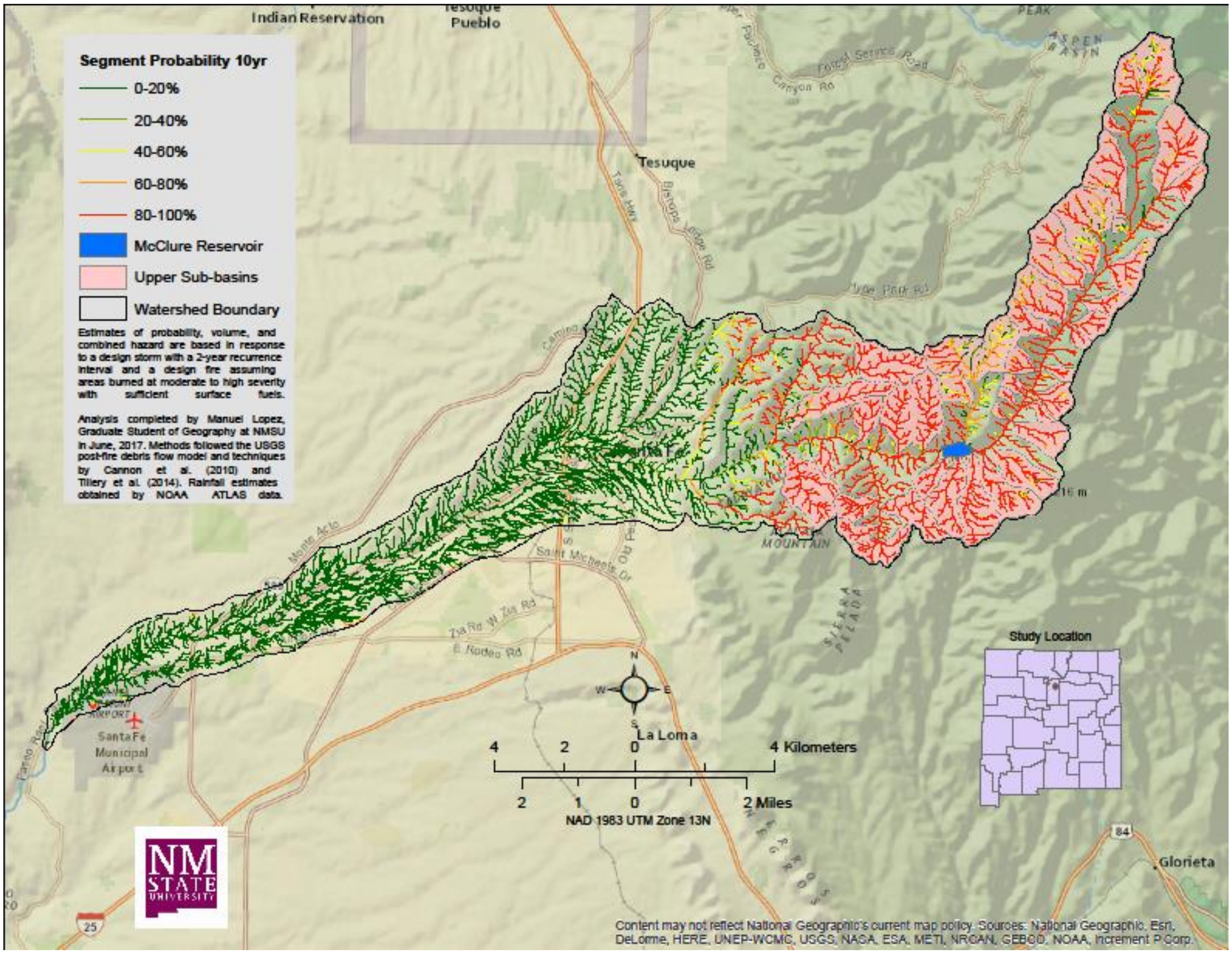

Figure 4. Segment probability for a 10-year storm recurrence. NOAA rainfall averages for a 10-year storm in this region have a total of 28mm/30min, or 56mm storm intensity

This analysis is primarily focusing on the upper SFMW, the area with the rose hued sub basins in the above figures. The results of the segment probability have subtle differences for the yearly progression. As the storm intensity increases, the probability also increases. We can better see changes in segment probability relative to storm intensity in the sub basin directly north of the McClure reservoir. At the sub basin level, we can see a marked increase in debris-flow probability with an increase in storm intensity (Table B).

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

Sub basins	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

The next set of figures correspond to the potential volumes per stream segment for the same storm events:

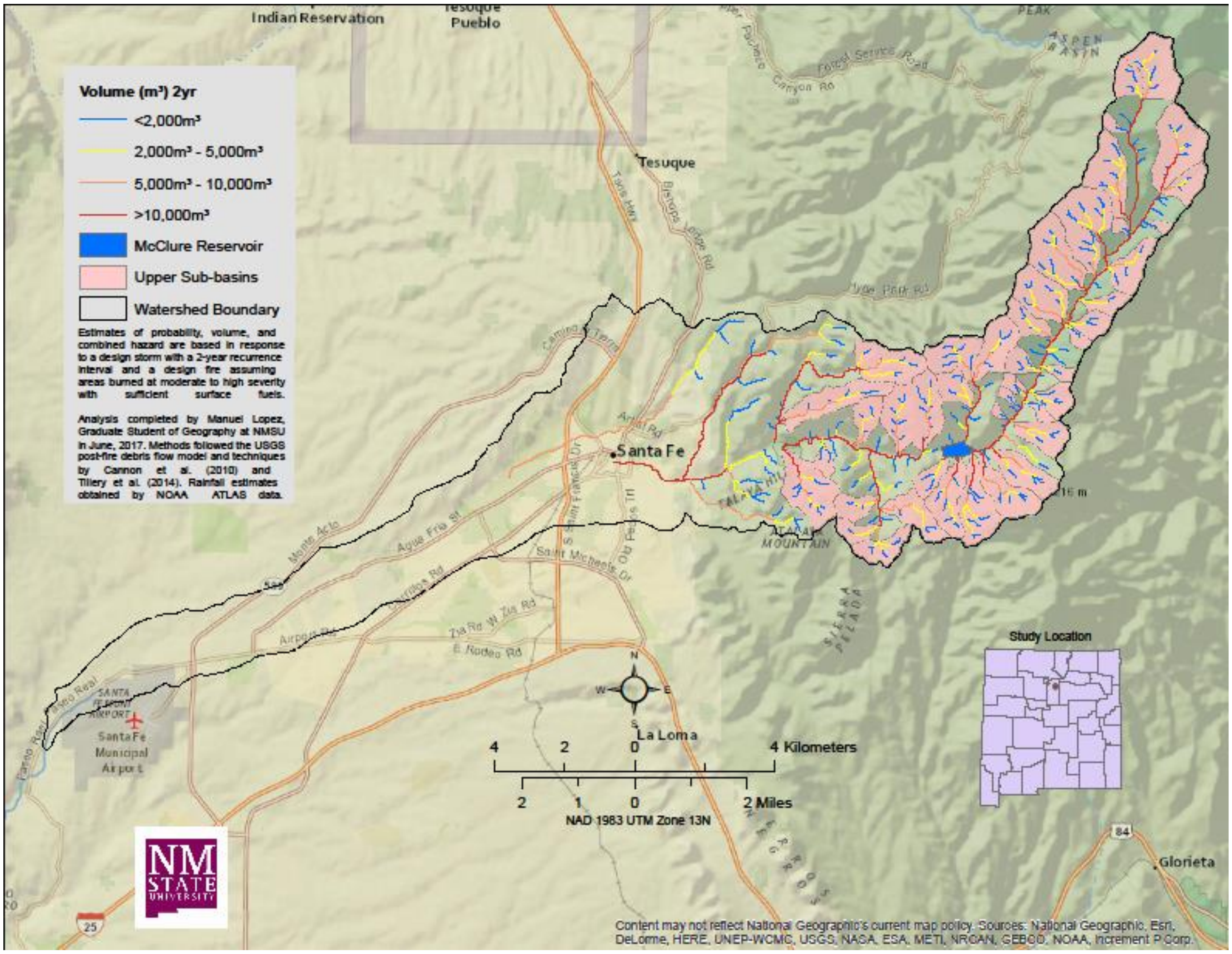

Figure 5. Potential sediment volumes from debris-flow generation after a 2-year storm recurrence with a total rainfall of 18mm/30min, or 36mm storm intensity.

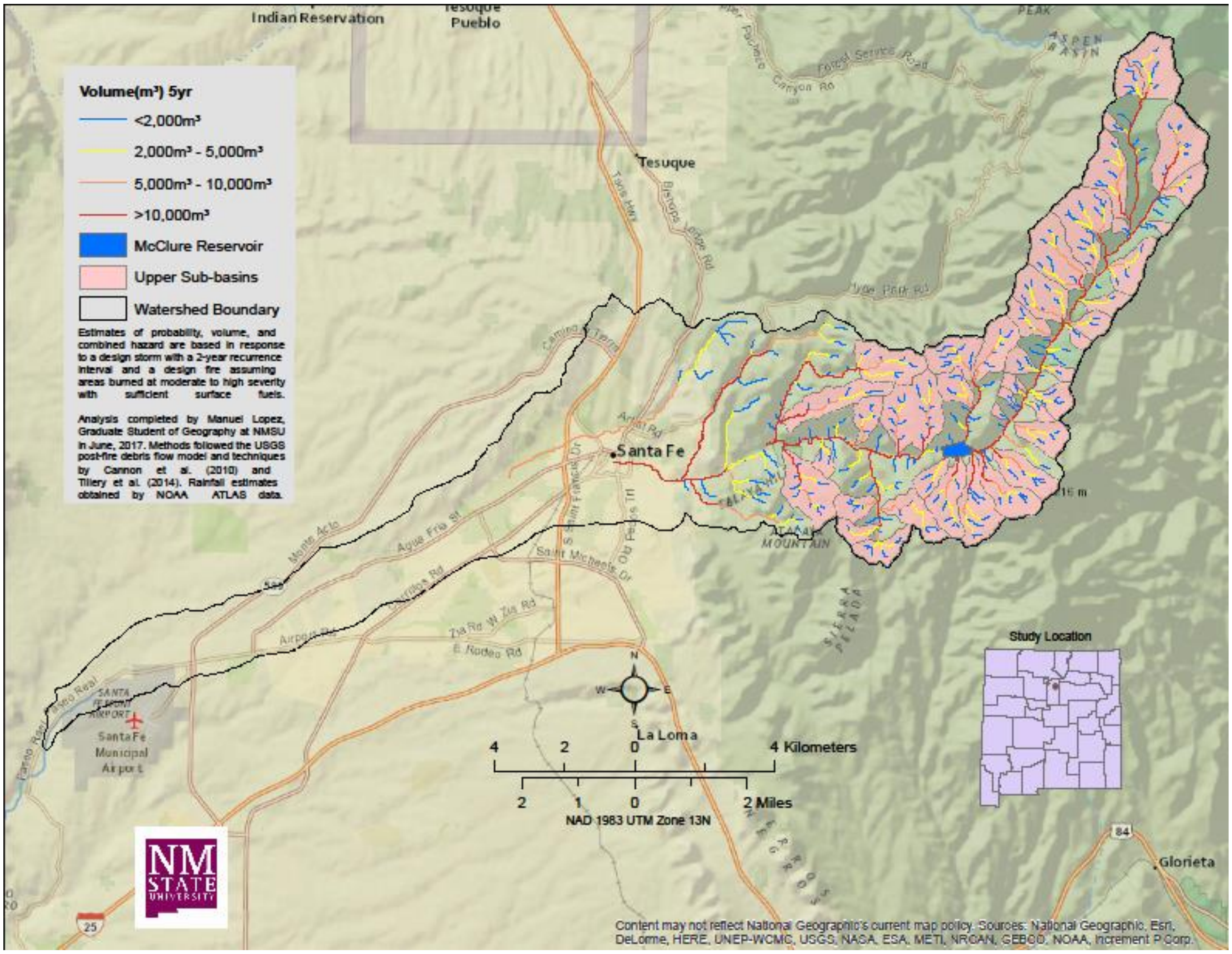

Figure 6. Potential sediment volumes from debris-flow generation after a 5-year storm recurrence with a total rainfall of 24mm/30min, or 48mm storm intensity.

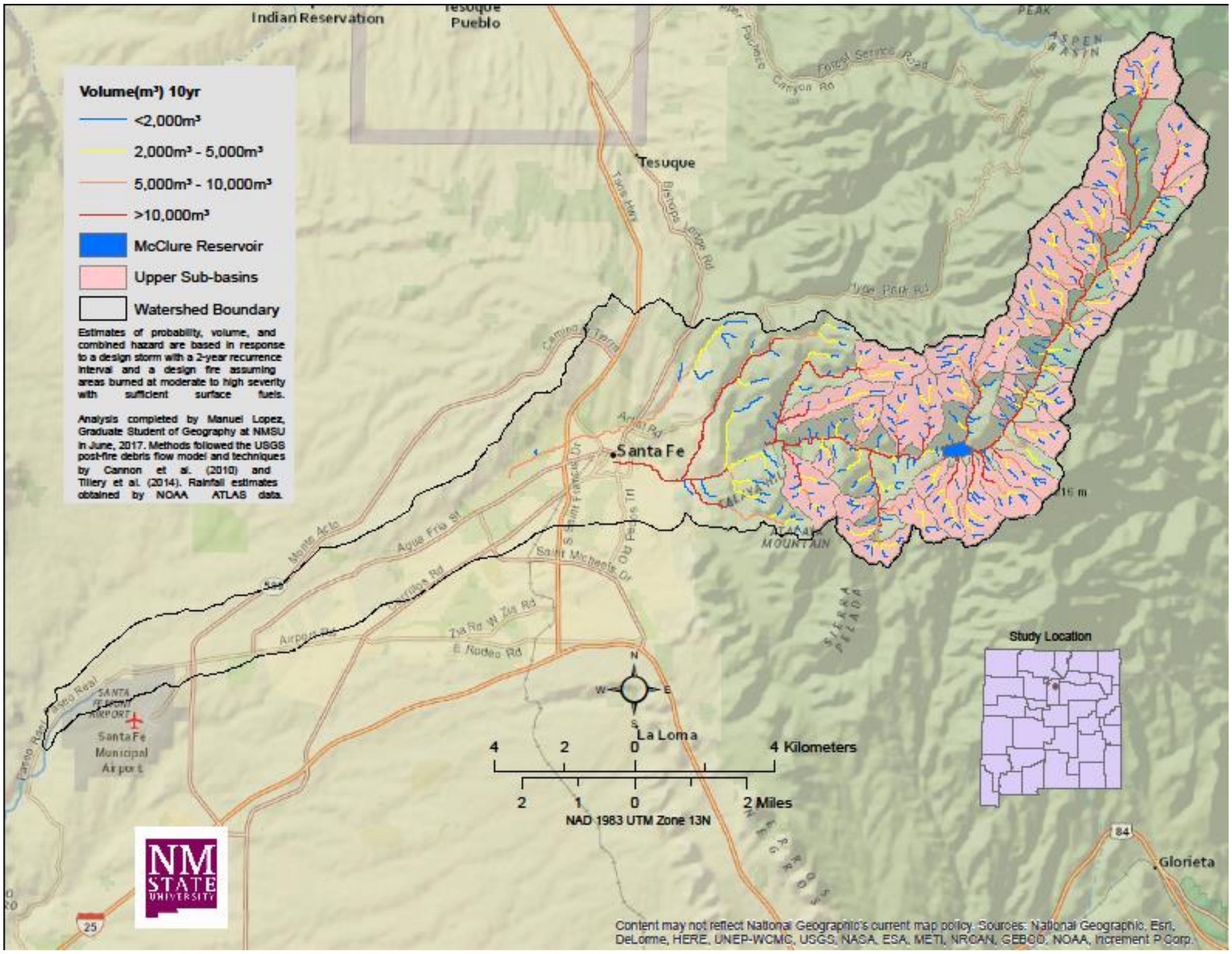

Figure 7. Potential sediment volumes from debris-flow generation after a 10-year storm recurrence with a total rainfall of 28mm/30min, or 56mm storm intensity.

Potential debris-flow volumes are dependent on percentage of soil clay content and liquid limit. Soils data was obtained from the Natural Resources Conservation Service's State Soil Geographic dataset (STATSGO2) with a spatial resolution of 1 km. The models for the three different storm intensities show subtle differences, but we can view these changes in sediment volume in Table C.

Table C. Potential debris-flow volumes per sub basin with storm intensity increase (values in m³)

Sub basins	2-Year storm(36mm)	5-Year storm(48mm)	10-Year storm(56mm)
1	1985.9399	2266.6599	2448.9900
2	3737.4399	4265.7202	4608.8599
3	4957.1499	5657.8398	6112.9702
4	1183.3199	1350.5800	1459.2200
5	3329.3401	3799.9399	4105.6201
6	4564.1099	5209.2500	5628.2900

7	5108.8599	5830.9902	6300.0498
8	2598.5200	2965.8201	3204.3999
9	1643.3600	1875.6500	2026.5300
10	4784.1699	5460.4102	5899.6602
11	1940.9700	2215.3201	2393.5300
12	3034.7100	3463.6699	3742.2900
13	1704.6801	1945.6300	2102.1399
14	4311.4102	4920.8198	5316.6602
15	1659.8600	1894.4800	2046.8700
16	3041.6001	3471.5300	3750.7900
17	1799.5601	2053.9199	2219.1399
18	9044.8203	10323.2998	11153.7002
19	3458.6699	3947.5601	4265.1001
20	1561.7300	1782.4800	1925.8700
21	1560.5900	1781.1801	1924.4600
22	5315.6099	6066.9702	6555.0098
23	5912.2598	6747.9600	7290.7798
24	1433.3700	1635.9800	1767.5800
25	6494.9399	7412.9902	8009.3101
26	4571.4302	5217.6001	5637.3101
27	2493.5000	2845.9600	3074.8899
28	1454.2300	1659.7900	1793.3000
29	5631.7798	6427.8301	6944.8999
30	2217.7300	2531.2000	2734.8101
31	736.3720	840.4580	908.0660
32	610.6480	696.9630	753.0280
33	759.1780	866.4870	936.1890
34	2370.0701	2705.0801	2922.6799
35	1994.1899	2276.0601	2459.1499
36	869.5650	992.4770	1072.3101
37	2096.3701	2392.6899	2585.1599
38	1296.4900	1479.7500	1598.7800
39	256.1730	292.3830	315.9030
40	921.8200	1052.1200	1136.7500
41	786.0970	897.2110	969.3840
42	2459.5200	2807.1699	3032.9900
43	699.8130	798.7310	862.9830
44	951.8780	1086.4301	1173.8199

Increase in storm intensity increases yield in potential debris flow volumes. The highest values are located in the main stream channels, most notably the Santa Fe River. As side tributaries converge and gather further debris, the main channel could carry tens of thousands of cubic meters of debris into the McClure reservoir. If we combine the total volumes per sub basin for a 2-year recurrence storm, a sum of 119,343m^3 of sediment will enter the Santa Fe river. For a 10-year recurrence storm the sum of all sub basin sediment volume is 147,170m^3.

A hazard index was generated by assigning a rank from 1-5 to probability percentages and to debris flow volumes. These were then added together to provide the final sub basin debris flow hazard ranking (figure 8).

	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

Figure 8. Hazard ranking system (Source: Cannon and others, 2010)

The hazard ranking at the sub basin level resulted in the following figures:

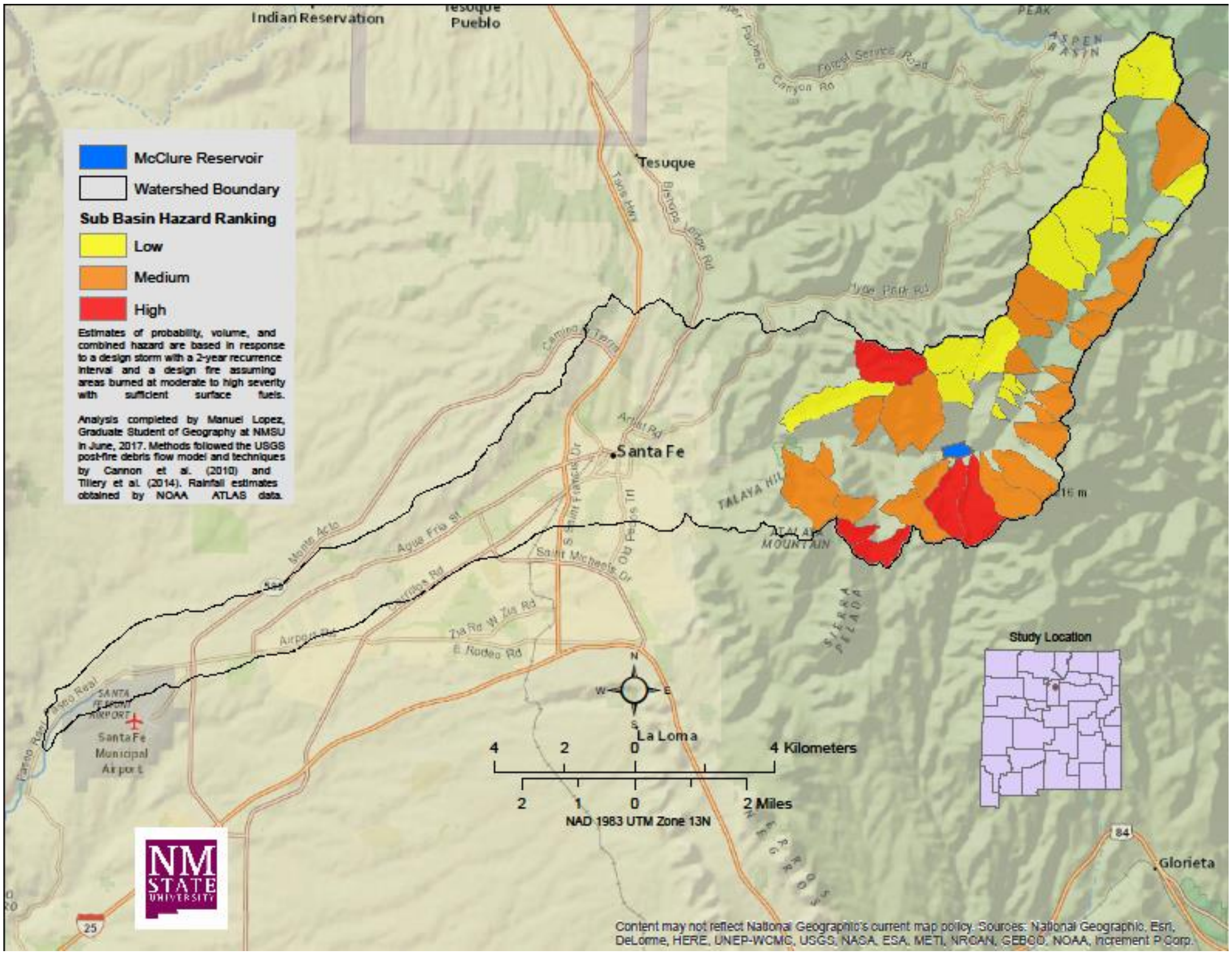

Figure 9. Sub basin hazard rankings for a 2-year storm recurrence.

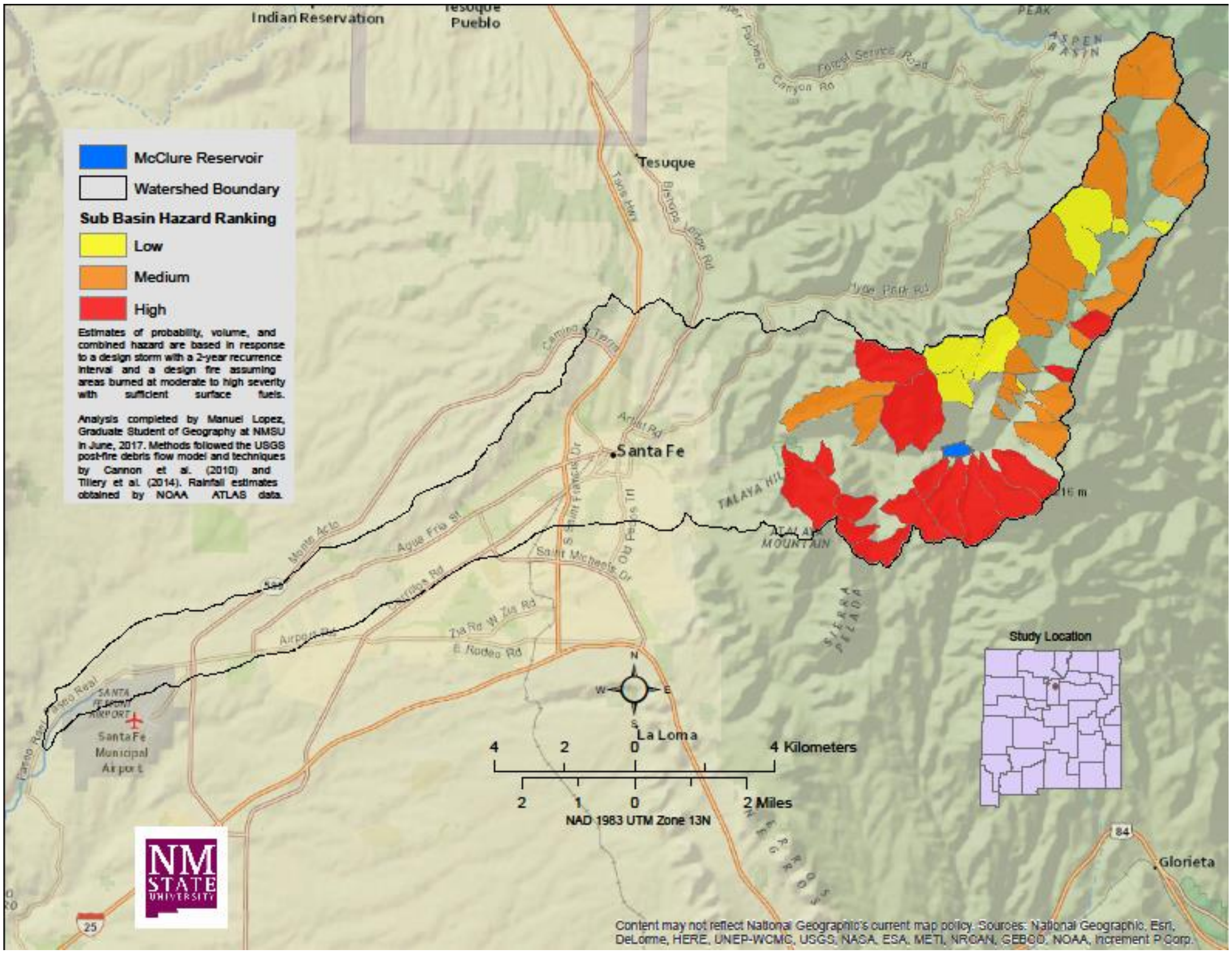

Figure 10. Sub basin hazard rankings for a 5-year storm recurrence

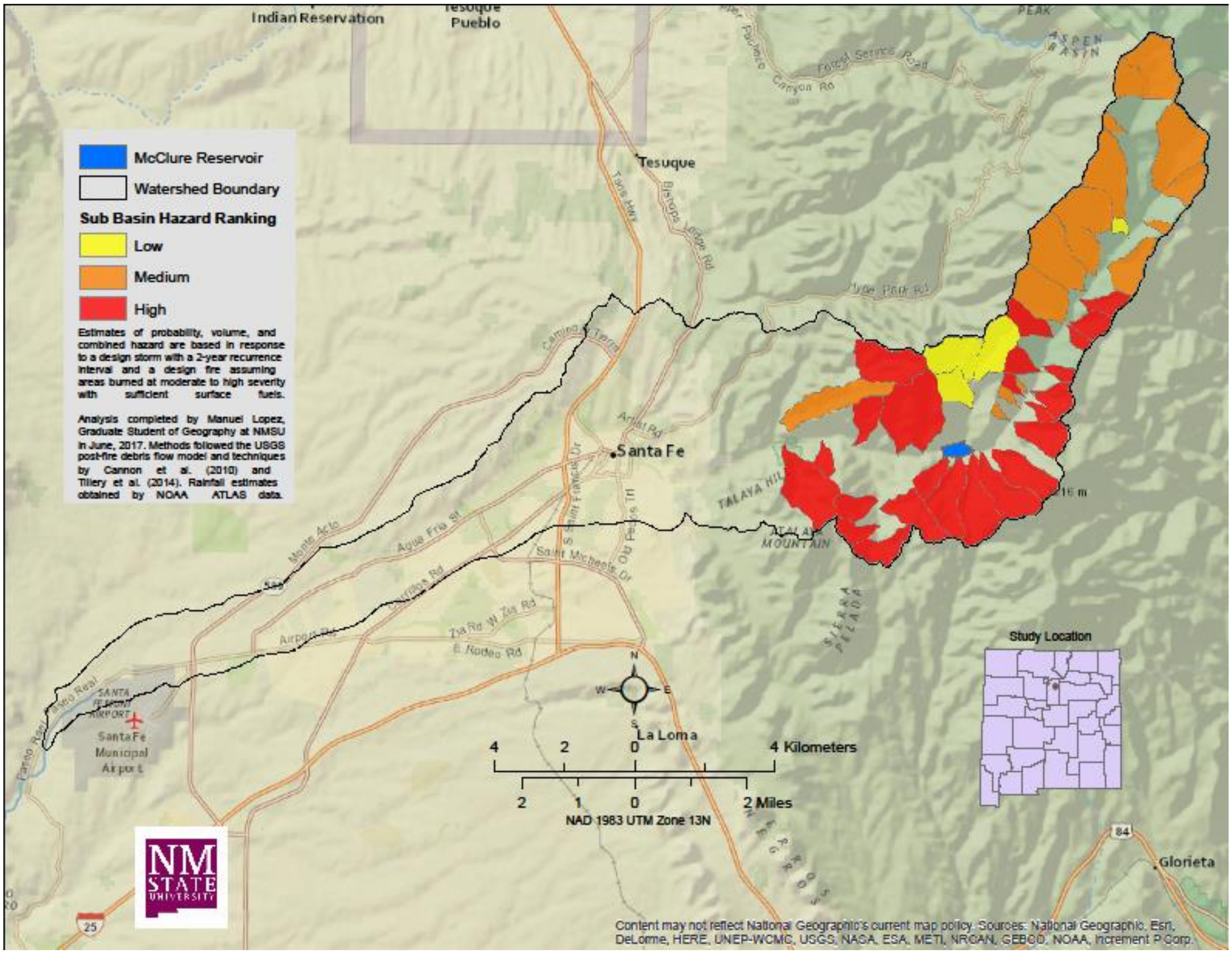

Figure 11. Sub basin hazard rankings for a 10-year storm recurrence

Figure 8 through 10 combine the probability and volume rankings into a low, medium, and high hazard result. These results vary and do not appear to correlate with basin size. The sub basins directly north of the McClure reservoir (basins 11, 12, and 14) have a thinned forest cover according to the Landsat imagery, possibly attributing to the lower debris flow probability and volume statistics. The basins below the McClure reservoir to the west, have had some fuel treatments such as prescribed burning and mechanical thinning, whereas the upper basins have not experienced any such treatments. Treatments do not appear to influence the high hazard ranking for debris flows following a high intensity storm in the model. Field visits are required to validate our hypothesis of slope angle and vegetation cover attributing to the varied hazard index results.

To further analyze the differences between basin results beyond the aspect of remote sensing and GIS analysis involves further exploration in the field. Access to the SFMW is closed to the public and for this reason I have obtained a position with the USGS in Santa Fe, NM studying fire regimes in the Sangre de Cristo mountains, allowing ease of access to the SFMW. All remaining analysis for our research will be in the field the remaining summer of 2017.

We are confident that if a severe wildfire occurs in the wilderness portion, debris flows have a high probability of occurrence pending a large storm event. The impact on the freshwater supply for the city could be negatively impacted as well as the costs for dredging the McClure reservoir. Field analysis is required to understand the extent of forest treatments in the basins below the McClure reservoir to validate whether those stands remain congested or are adequately spaced.

Beneficiaries of research

Results will provide city and forest managers an opportunity to prepare and mitigate potential issues associated with debris flows. Agencies that are involved in the Santa Fe Municipal Watershed management are United States Forest Service and the City of Santa Fe.

List of presentations

NMSU University Research Council Fair (Las Cruces, NM)
NM WRRI Annual Water Conference (Silver City, NM)
Southwest Association of American Geographers annual conference (Denton, TX)

List publications or reports

N/A

List of other students or faculty members involved

Doug Cram, Extension Forestry and Fire Specialist, New Mexico State University
Robert Sabie Jr., GIS Analyst, New Mexico Water Resources Research Institute

Special recognition awards or notable achievements

Richard D. Wright Award for Excellence in Applied GIS

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