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Ann Youberg

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Ann Youberg

Arizona Geological Survey

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416 West Congress, Suite 100
Tucson, AZ 85701

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Cover Photo: Bray Creek Ranch post-fire debris flow following the 2006 February Fire. Post-fire debris flows also occurred in Bray Creek following the 1990 Bray Fire. Photo taken by A. Youberg, October 18, 2007.

INTRODUCTION

Arizona has experienced a dramatic increase in area burned by wildfires during the drought of the past decade. Over 1.8 million acres of Arizona wildlands burned during the four-year period between 2002 and 2005, of which almost one million acres were burned by only five fires (Southwest Coordination Center, 2006). In addition to increased fire size, recent wildfires have burned with higher intensity, in part due to fuel loading as a result of a century of fire suppression (Schoennagel et al., 2004). High severity burns denude watersheds and may generate hydrophobic (water-repellent) soils, resulting in dramatic increases in runoff and soil erosion in upland areas. Because of these increases in post-fire runoff and erosion, fairly common rainfall events may generate sizable floods or debris flows. Although debris flows are less common than floods after fires, debris flows can be significantly more destructive than floods (Cannon et al., 2004). Post-fire hazards in burned areas are evaluated after containment of the wildfire is achieved through the Burned Area Emergency Response (BAER) program, but potential debris flow hazards typically are not assessed. Even if potential flooding and debris flow hazards are identified through the BAER process there is little time to design, plan and implement hazard mitigation efforts.

The debris flow hazard in Arizona is increasing due to larger and more frequent wildfires denuding hillsides of protective vegetation. Mitigation strategies must be developed and implemented prior to wildfires in order to decrease the likelihood of damaging and life-threatening debris flows. The goal of this study is to develop a method for identifying potential post-fire debris flow hazard areas prior to the occurrence of wildfires, providing more time for local governments and emergency planners to develop and execute hazard mitigation strategies. This pilot study focuses on the communities of Pine and Strawberry, which are located in forested canyons at the base of the Mogollon Rim in north-central Arizona. The vast forests along the Mogollon Rim have experienced many of Arizona's largest historical wildfires, including the Dude Fire of 1990 and the Rodeo-Chediski Fire of 2002. The steep terrain associated with the Rim is conducive to the generation of debris flows, and debris flows have occurred after several recent fires in the area. Results from this project will provide local agencies, emergency planners and land managers more effective tools for prioritizing watershed treatment areas and implementing mitigation measures to alleviate potential impacts and threats from post-fire debris flows to infrastructure, human life and property in a timely and cost-effective manner.

Background – Wildfire and Debris Flows

Over the last century annual area burned by wildfires in Arizona has increased dramatically (Grissino-Mayer and Swetnam, 2000). Indeed, five of Arizona's largest historic wildfires occurred between 2002 and 2005, burning almost one million acres (Southwest Coordination Center, 2006). The occurrence of large wildfires in Arizona is not a new phenomenon however. Swetnam and Betancourt (1998) found in the tree-ring record regionally synchronous fires have recurred for centuries. The difference between historical and modern fires is an increase in fire intensity and burn severity. Ponderosa Pine forests historically burned by frequent, low intensity surface fires, but now tend to burn by high intensity crown fires that kill trees and leave a denuded landscape (Schoennagel et al., 2004). Several factors may have contributed to this change including fire suppression efforts, fuels buildup, and climate change. Fuels build up and time since last fire were identified as the most important factors for fire severity in Ponderosa Pine forests while climate was the most important factor in mixed conifer forests (Schoennagel et al., 2004). Key climatic factors varied by forest type and included long-term drought, or wet year(s) followed by a dry year (Grissino-Mayer and Swetnam, 2000). The most important factors for the severity of the Rodeo-Chediski Fire were found to be fire suppression and increased stand density rather than climatic influences (Schoennagel et al., 2004).

Watersheds burned by intense fires result in high burn severity, the formation of hydrophobic soils, mortality of the majority of trees or vegetation, and complete consumption of the litter layer. These denuded watersheds have decreased infiltration rates, increased runoff, and increased erosion due to rainsplash and overland flow (Inbar et al., 1998; Meyer, 2002). Excess runoff and erosion results in sediment-laden flows that may be either flood flows or debris flows (Inbar et al., 1998; Moody and Martin, 2001a). Post-fire sediment-laden flood flows occur more frequently than debris flows, but debris flows can be significantly more destructive than floods (Cannon et al., 2004). Factors effecting the occurrence of debris flows and floods include burn severity, geology, catchment size and gradient, and storm intensity, duration and movement through the basin (Cannon et al., 2004; Wells and Harvey, 1987; Wohl and Pearthree, 1991). Debris flows tend to form in smaller, very steep basins and transition into sediment-laden (hyperconcentrated) flows or flood flows downstream as contributing area and runoff increase (Melis et al., 1997; Wells and Harvey, 1987). Short-duration, high-intensity precipitation intensity is also an important factor for debris flow generation (Cannon et al., 2007; Cannon et al., 2001). Post-fire debris flows can vary in coarseness from primarily sand, silt, clay and ash, to coarser materials up to and including large boulders (Cannon, 2001). Logs and other organic debris may also be an important component of debris flows.

Although debris flows may generated by extreme precipitation in the absence of fire (Pearthree and Youberg, 2006), most of the recent debris flow activity in Arizona has been linked to wildfires (Pearthree and Youberg, 2004). There are some significant differences between debris flows initiated in unburned (undisturbed) areas versus burned areas. Debris flows in undisturbed areas may be triggered by rare, extreme precipitation events when soils with high antecedent moisture conditions receive long, sometimes intense, periods of precipitation resulting in failure of saturated soil (Anderson and Sitar, 1995; Wieczorek and Glade, 2005). Post-fire debris flows, on the other hand, usually occur due to runoff during the first significant storm after the fire when antecedent soil moisture is low or absent (Cannon, 2001; Cannon and Gartner, 2005; Cannon et al., 2007; Moody and Martin, 2001b; Parrett et al., 2004). Post-fire debris-flows tend to be generated by relatively common, 2- to 5-year frequency storms. Cannon and others (2007) analyzed rainfall intensities from convective storms that generated 25 post-fire debris flows in southwestern Colorado, and frontal storms that generated 68 post-fire debris flows in southern California. Results showed that return intervals for these storms were typically two years or less with average intensities ranging from 1.0 to 32.0 mm/h in Colorado and 1.3 to 20.4 mm/h in California (Cannon et al., 2007). Post-fire debris flows tend to scour and erode channel bottoms and banks downslope entraining most of the mass well below the initiation zone (Santi et al., 2007).

Debris flows differ from flood flows by the amount of sediment carried in the flow, which is reflected in deposited sediment. Debris flows are part of a continuum between water floods and sediment-rich slurries (debris flows), with hyperconcentrated flows in the middle. There are no fixed boundaries between floods, hyperconcentrated flows, and debris flows. These flows are generally broken out by the amount of sediment in the flow along with flow rheology (Pierson, 2005b; Pierson and Costa, 1987). Flood flows typically contain less than 40% sediment by volume and are turbulent Newtonian flows (Pierson and Costa, 1987). Hyperconcentrated flows have around 40-60% volume of sediment and a strong enough granular interaction to keep sediment in suspension as long as velocities are maintained (Pierson, 2005b). Both flood and hyperconcentrated flows exhibit sorting by grain size in deposits (Pierson, 2005a). Debris flows are a two-phased flow (fine sediment and water slurry, and coarse particles) which typically contain more than 60% by volume of sediment. The fine-grained portion (matrix) is composed of clay, silt and sand. The interaction of the matrix, driven by high pore pressure, with the coarse-fragments, influenced by frictional and gravitational forces, keeps larger particles from settling even at low velocities. Hence debris flow deposits exhibit little or no sorting (Iverson and Vallance, 2001; Pierson, 2005b).

Ongoing Mitigation Efforts

Arizona Division of Emergency Management (ADEM), in conjunction with the consulting firm of URS, developed a multi-hazard State of Arizona All Hazard Mitigation Plan (AZ HMP) to comply with the Disaster Mitigation Act of 2000. This plan identifies mitigation measures to reduce or eliminate the effects of future disasters within the state (URS, 2004). ADEM, along with Arizona State Land Department (ASLD), also developed a wildfire mitigation plan for the state of Arizona. With support from ADEM and ASLD, Gila County developed a site-specific wildfire mitigation plan, entitled Rim Country Community Wildfire Protection Plan (CWPP), targeting the northern 450 square miles of Gila County (Gila County, 2004).

Gila County has been affected by three of the five very large recent fires in Arizona. AZ HMP rates 70% of Gila County as extreme wildfire hazard risk, 19% and as high to medium risk (Figure 1, URS, 2004). These areas encompass many wildland urban interface (WUI) communities which ADEM identifies as areas of increasing significant risks of major loss from wildfires. ADEM estimates 75 percent of the 50,000 residents of Gila County are potentially exposed to risks from wildfires. Pine and Strawberry are WUI communities at the base of short, steep basins formed along the edge of the Mogollon Rim that lie within the extreme wildfire hazard risk zone (Figure 1).

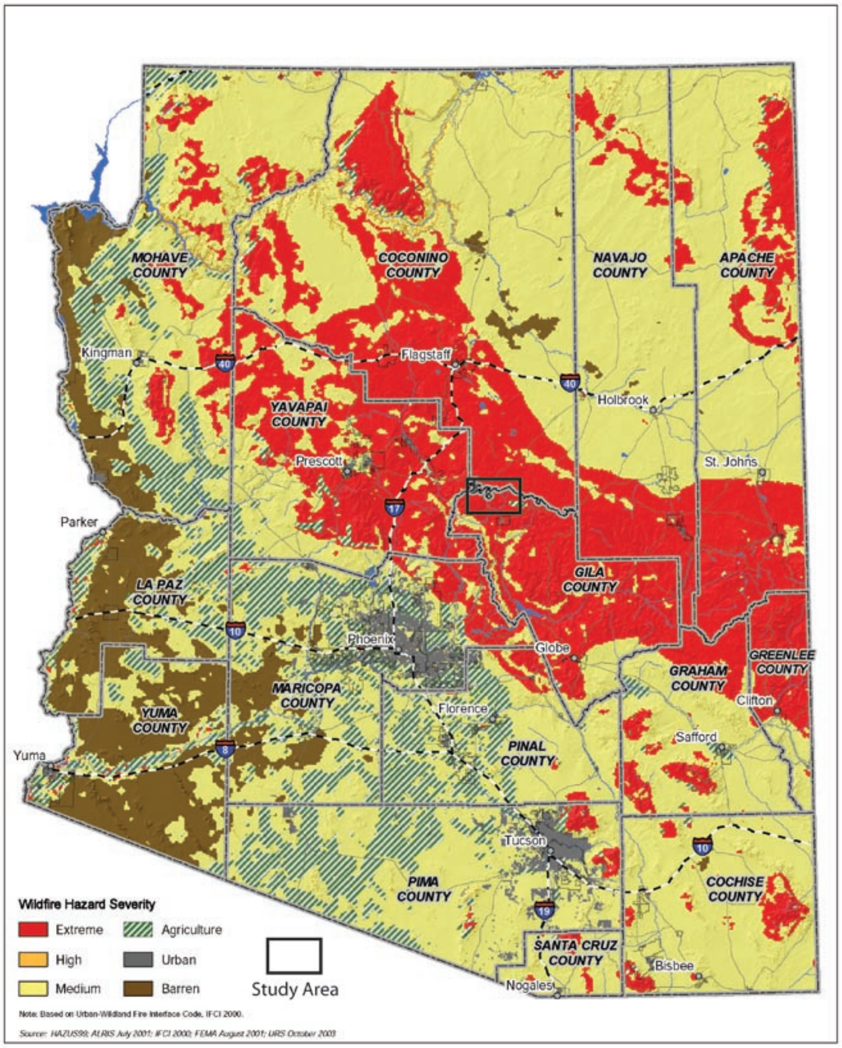

Figure 1. Statewide wildfire hazard risks from AZ HMP (from URS, 2004) with study area location.

Approximately 90% the land covered by the Rim Country CWPP is in Tonto National Forest. Another 6% is under other federal jurisdiction and the remaining 4% is privately held . The Healthy Forest Restoration Act requires the Forest Service to support and work with communities that have developed a Community Wildfire Protection Plan. The CWPP classifies forests within Gila County as fire hazard condition class 3, with at least three missed normal fire events and large accumulation of fuels. In addition, the region is facing a protracted drought and massive tree mortality due to bark beetle infestation. Based on these assessments, the overriding concern and mitigation goal, as stated in the CWPP, is fuels reduction. Additional mitigation measures that were not addressed in the CWPP could include acquiring flood-prone land or rezoning to prevent building within hazard areas, resizing culverts in developed basins found to have a high likelihood of post-fire debris flows, and removing features such as sediment filled stock tanks to reduce potential hazards.

Debris Flow Models

The USGS has developed several models to predict hazard risks from post-fire debris flows based on the probability of debris-flow occurrence and potential volume of material generated. The models incorporate average rainfall intensity and percent of the basin burned at high and medium severity with combinations of additional factors describing basin shape and size (morphometrics) and soil parameters. The most commonly used basin morphometric parameters are basin ruggedness and percent of basin with greater than 30% slopes. Basin ruggedness, or the Melton Ratio, is a ratio of the watershed length to the square root of basin area (Wilford et al., 2004). Soil parameters include clay content, organic matter, liquid limit of soil material, and the soil hydrologic group, a measure of soil infiltration capacity (Cannon et al., 2004). Evaluation of these models in other parts of the western US indicate that the most important variables for predicting post-fire debris flows are percent of the basin burned at high and moderate severity, percent of the basin with greater than 30% slopes, and lithology (Cannon, 2001; Cannon et al., 2004). More recent work by the USGS has suggested that basin area and average basin gradient may also be a good indicator of debris-flow potential (Cannon and Gartner, 2005). This relates well to other studies that have found the Melton Ratio and length of watershed to be good indicators debris-flow prone basins (Wilford et al., 2004).

The USGS models were developed to evaluate areas after a wildfire to define the potential risk of post-fire debris flows from recently-burned basins. The models combine various basin morphometrics and soil parameters with burn severity and a range of average rainfall intensities to estimate the probability of a debris flow. The models then estimate potential debris-flow volumes from each basin. Basins are ranked for probability and likely magnitude of debris flow. Probability and magnitude rankings are combined and re-ranked to derive a final hazard ranking for each basin.

A significant problem with using the USGS models in Arizona is the requirement for soil parameters. These models utilize soil data from the Natural Resource Conservation Services (NRSC) soil survey STATSGO database. The STATSGO database in Arizona does not cover federal lands, unlike other parts of the western US. The US Forest Service has been tasked to map their lands as part of the Terrestrial Ecosystem Surveys (TES). TES maps vegetation type, soils information, some topographic indexes such as slope steepness, and land-use suitability data. Most, but not all, of the forests in Arizona have completed their TES surveys and the data are available to the public. Terrestrial Ecosystem Surveys, however, do not measure the same soil parameters as those found in the STATSGO database or NRCS soil surveys. For example, hydrologic soils groups are not classified in a TES database, organic matter is rarely measured, and clay content, although calculated during a TES, is not necessarily included as a parameter within the TES database. Liquid limit is the only soil parameter that seems to be consistently measured and entered into TES databases.

In addition to the limitation of soil data, the USGS models are based on an average triggering rainfall intensity. Precipitation in Arizona is extremely variable both spatially and temporally. Rain gages are sparsely located and thus may miss the highest intensity events. In addition, triggering rainfall thresholds for debris flow initiation have not been developed for anywhere in Arizona. These models, by necessity, assume precipitation falls equally over the entire study area.

A recent study in Arizona investigated post-fire debris flows that occurred after the 2000 Pumpkin Fire that burned Kendrick Mountain, northwest of Flagstaff, Arizona (Jenkins, 2007). A goal of this study was to evaluate factors effecting post-fire debris flows on the southern Colorado Plateau. Jenkins (2007) found that aspect, percent of basin with slopes less than 40%, and maximum basin elevation were the most insignificant factors for predicting post-fire debris flows. These parameters may be proxies for other important variables. For example, aspect may reflect denser vegetation that grew as a result of cooler growing temperatures and moister soil conditions, and paradoxically resulted in hotter fire behavior (Jenkins, 2007). Maximum basin elevation may reflect orographic effects and rainfall patterns, and percent low basin gradient may be a proxy for short, steep upper reaches where debris flows may be initiated more easily, or it may indicate sediment availability. Lithology was not found to be a key factor on Kendrick Mountain, unlike other studies showing a significant difference with lithology (Cannon and Gartner, 2005). This is most likely due to the fact that while Kendrick Mountain has many different rock units all of the rocks are volcanic. Jenkins (2007) was not able to quantify or model triggering rainfall events due to the lack of detailed precipitation data for the storms that generated the debris flows.

A recent Canadian study used only basin morphometrics over diverse lithologies to identify basins prone to debris flows (Wilford et al., 2004). This study found the Melton Ratio, a measure of basin relief to basin area, in conjunction with basin length to be the most reliable indicator of debris flow basins (Wilford et al., 2004).

Study Area

The study area encompasses the unincorporated villages of Pine and Strawberry. These communities are located within canyons extending south from the Mogollon Rim in north-central Arizona (Figures 2 and 3). Although Pine and Strawberry Canyons have not been recently burned by wildfires, much of the Mogollon Rim to the east has (Figure 3). Recent wildfires within or adjacent to the study area include the 2007 Promontory Fire, 2006 February Fire which re-burned a portion of the 2004 Webber Fire and the entire area burned by the 1990 Bray Fire, 2002 Pack Rat Fire, and one of the first large fires in Arizona, the 1990 Dude Fire. Farther to the east along the Mogollon Rim, Arizona's largest and most destructive historical fire, the 2002 Rodeo-Chediski fire, burned almost half a million acres.

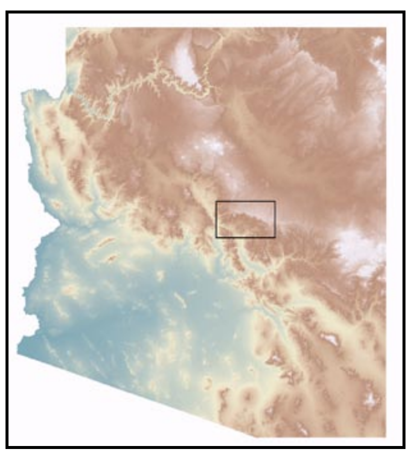

Figure 2. Area of study location. The box encompasses the Mogollon Rim and the steep slopes below it, including the communities of Pine and Strawberry.

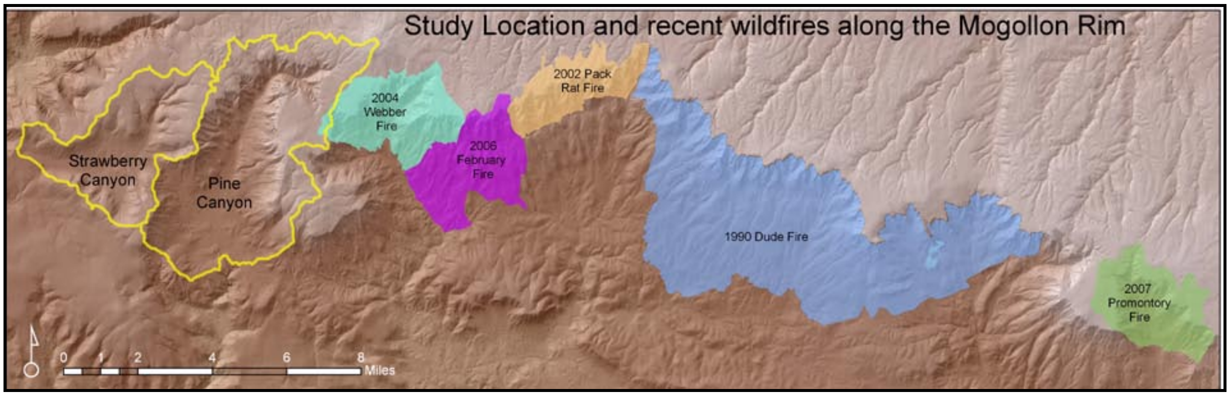

Figure 3. Location of Pine and Strawberry Canyons outlined in yellow, along with adjacent recent wildfires.

The Mogollon Rim forms the southern edge of the Colorado Plateau. The elevation drop from top of the Mogollon Rim to the floor of adjacent canyons is approximately 1000 feet in the study area. The geology of the Mogollon Rim consists of gently north-dipping, Paleozoic and Mesozoic sedimentary rocks discontinuously capped by Tertiary basalts (Holm, 2001). The Coconino Sandstone is a sandstone unit that forms steep slopes and cliffs along the upper edge of the Rim (Figure 4). The Supai Group underlies the Coconino Sandstone and forms the lower part of the Rim (Blakey and Knepp, 1989; Peirce, 1989). The Supai Group consists primarily of red mudstone and sandstone beds, but also includes the Fort Apache Member, a distinctive limestone seen throughout the study area (Weisman, 1984). Below the Supai Group is the carbonate-rich Naco Formation (Richard et al., 2002; Wilson et al., 1969).

Figure 4. Two views of the Coconino Sandston and Supai Group at the Mogollon Rim. The left photograph is above Webber Creek, just west of Poison Canyon. The right photograph is the west canyon wall above the town of Pine, north of Highway 87.

To evaluate the potential for post-fire debris flows in Pine and Strawberry canyons, we delineated tributary watersheds above the developed areas (Figures 5 and 6). Basin outlets were selected to reflect the highest degree of risk to the developed area if a debris flow were to occur. Study watersheds have several common features due to the nature of the Mogollon Rim. Most basins extend onto the flat-lying Rim resulting in very gently-sloping upper watersheds, with extremely steep (cliffs) to moderately steep slopes over the Coconino Sandstone in the mid-basins, and moderately to gently sloping lower basin. Tributary basins in the two study canyons upstream of the developed areas were not delineated separately but as one large basin (Pine15 and Straw5). There are two reasons for this. First, these areas lie entirely within forest service lands so development will not occur and mitigation options are limited to forest thinning. Second, although the potential for post-fire debris flows in these areas is high, it is unlikely debris flows will have the momentum to move down the low-gradient main channel into the developed areas, although floods and hyperconcentrated flows along the main channels may affect developed areas.

METHODS

The goal of this study is to develop a method for identifying basins most likely to produce post-wildfire debris flows prior to the occurrence of fire. The objective is to provide ample time for local agencies, emergency planners and land managers to identify and employ mitigation options to reduce the likelihood or extent of damage from post-fire debris-flow events. Results from USGS models, and from basin morphometrics analysis, were evaluated to design an effective approach for ranking hazard potential for each study basin.

GIS Analysis

Geographic information systems (GIS) make it possible to analyze large amounts of data over large geographic areas. This study heavily utilized GIS to evaluate the study basins. All measures of basin morphometrics can be extracted using GIS (Table 1, Appendix A). Basin morphometrics were derived from 10-m digital elevation models (DEMs) in ArcMap 9.2 (ESRI, 2006) using a tool called Terrain Analysis Using Digital Elevation Models (TauDEM)(Tarboton, 2005). TauDEM extracts basin characteristics using 8-directional and infinite-directional flow models to derive flow paths and basin extent. This method tends to derive more realistic flow paths, and hence stream channels, then the ESRI ArcHydro tool which uses only a 4-directional flow model to derive streams and basins.

Table 1. Basin morphometrics definitions.

Parameter	Definition
Ruggedness	Basin relief/square root of basin area (the Melton Ratio)
Planimetric Length	Straight line length of watershed from outlet to a point at the basin divide that is hydrologically the furthest point from the outlet (in GIS Planimetric length = 2 x Major Axis, which is the eigenvector of an ellipse describing basin area)
Relief Ratio	Basin relief/basin length (planimetric length)
Shape	Basin area/(basin length)^2

In addition to the 10-m DEMs, analytical datasets included Tonto and Coconino National Forests TES databases, and several GIS layers from the Tonto National Forest including burn severity of recent fires, extent of developed areas in Pine and Strawberry, and areas recently treated through forest thinning around Pine and Strawberry. GIS layers showing fire risk and projected fire behavior were obtained from Northern Arizona Universities' Forest ERA website and were used to understand possible fire scenarios in Pine and Strawberry. Geologic data was extracted from the Arizona Geologic Survey digital geologic map of Arizona (Richard et al., 2002) and an older, more detailed geologic map of the area by Wilson(Wilson et al., 1969).

Basin morphometrics were derived for drainages in Pine and Strawberry canyons (Figures 5 and 6) to delineate post-fire debris flow hazards, and in Webber Canyon which includes upper Webber, Poison, Cow and Bray canyons (Figure 7) to evaluate basin responses from past fires. Databases were created for each study basin with data describing basin morphometrics, vegetation, soils and geology information, and burn severity where previous fires occurred (Appendix A).

Field Observations

Field observations were conducted to determine hydrologic responses of basins burned by the 2004 Webber and 2006 February Fires, and to evaluate if study drainages in Pine and Strawberry Canyons had evidence of past debris flows in the form of debris-flow deposits. Observations of basins within Pine and Strawberry were limited to due access issues.

Models

USGS models were tested using past responses to fires in the canyons just to the east of Pine, and to estimate responses based on two different burn severities in Pine and Strawberry. Three of six models produced results that could be evaluated; the other three models required soil data that was not available. These models first calculate the probability of a debris flow and the potential volume from each subbasin. The probability of debris flow occurrence and potential debris flow volume from each subbasin are ranked, then the rankings are combined and re-ranked for a final hazard probability.

Probability of debris flow is calculated by:

$$P = \frac{e^x}{1+e^x} * 100$$ where x is calculated from one of the six different models:

Three of the six models for finding x produced results and are shown:

Model2a =-0.679 + 0.025*(%area ge 30%) - 1.555*(Ruggedness)+0.056*(% bs med + high) + 0.062*(Av Rainfall Intensity) +0.231*(Clay Content)-0.398*(Liquid Limit)

Model7a = 4.809+0.048*(% bs med + high) + 0.07*(Av Rainfall Intensity) +0.235*(Clay Content) - 1.461*(Hydro Group) -0.427*(Liquid Limit)

Model10a=-7.093 + 0.027*(%area ge 30%) - 1.248*(Ruggedness) +0.053*(% bs med + high) +0.038*(Av Rainfall Intensity), Where:

%area ge 30% = percent of area with slopes greater than 30%
Ruggedness = Melton Ratio (basin length/square root basin area)
% bs med + high = percent of basin with medium and high burn severity
Av Rainfall Intensity = average rainfall intensity over the entire area (2 in/hr this study)
Clay Content = derived from Tonto TES database
Hydro Group = hydrologic soils group estimated from soils information in TES and geology
Liquid Limit = derived from Tonto TES database

The boundary between the Tonto and Coconino National Forests runs along the top of the Mogollon Rim, with the Tonto below the Rim and the Coconino on top. The Tonto TES lists clay content, organic matter and liquid limit in their database while the Coconino lists only liquid limit. Neither TES database has hydrologic group classification. To run these models, the hydrologic group was estimated from soil and geologic information; other soil parameters for each basin were assumed to be represented by data in the Tonto TES. (Soil parameters for each basin are in Appendix A).

In addition to the limitation of soil data, the USGS models are based on an average triggering rainfall intensity. For this modeling exercise, an intensity of 2 in/hr was assumed. This value is roughly a 10- to 20-year return period rainfall for this area based on NOAA Atlas 14 data (National Weather Service, 2008). This value was also used after the 2006 Brins Fire to conservatively evaluate post-fire debris flow potential in Oak Creek Canyon (Cannon and Youberg, unpublished data).

In addition to the USGS models, GIS-derived basin measurements were evaluated in different combinations to determine the effectiveness of morphometrics for identifying basins most likely to have post-fire debris flows. Each morphometric was ranked and then different combinations were evaluated. The effectiveness of this method was evaluated based on how well it predicted post-fire debris flows in basins that have previously burned.

RESULTS

Field Observations

To evaluate basin response to wildfire along the Mogollon Rim, observations were made in several canyons from unburned Strawberry Canyon on the west to the Promontory Fire, in Christopher Creek drainage, on the east (Figure 2). Most canyons had at least some debris-flow deposits whether they had burned recently or not. Most of the observed debris flow deposits were not fresh-looking, especially along trunk streams, but it is nevertheless apparent that a major geomorphic process occurring in these canyons is erosion and deposition by debris flows.

More detailed observations were conducted in the burned areas just east of Pine and Strawberry Canyons. Post-fire watershed responses were evaluated at Camp Geronimo (2004 Webber Fire), and Bray and Cow Canyons (1990 Bray Fire and 2006 February Fire) (Figure 8). Techniques for identifying burn severity and burned areas within a fire perimeter have improved in recent years. In 2004 all areas within a fire perimeter were considered low, moderate or high burn severity. By 2006 methods had evolved so unburned areas within the fire perimeter could be mapped (pale green areas in the February Fire, Figure 8). Areas of moderate and high severity burn were relatively limited in both fires, and not all of the low severity burned area within the Webber Fire perimeter actually burned.

Bray Creek had a debris flow following the 1990 Bray Fire (Grant Loomis and Mike Johns, personal communication). No post-fire debris flows occurred on Bray Creek during 2006, immediately following the February Fire. However, debris flows occurred on two occasions during 2007, on July 22 and September 22 (Mike Johns, personal communication). This delayed and continued response was also evident in the Webber Fire area. No debris flows have been reported within the developed area of Camp Geronimo, nor were debris flow deposits observed. Post-fire debris flows were observed in the upper watersheds of four canyons above Webber Creek (Figure 8). Deposits indicative of past debris flows were observed all along the east fork of Webber Creek, but recent debris-flow deposits post-dating the 2004 fire were not observed. Responses on East Webber Creek appeared to be limited to flooding, although it is possible debris flows occurred higher in the tributary basins and were deposited closer to the cliffs.

Due to the numerous debris flow deposits observed from canyons along the Mogollon Rim, it is reasonable to assume post-fire debris flows are likely given an appropriate rainfall event. Within the developed areas around Pine and Strawberry, several drainages were noted to have debris flow deposits (Figures 5 - Pine7, Pine 19, Pine20, Pine28, Pine31; Figure 6 - Straw3, Straw4, Straw6), a few drainages appeared to have no debris flow deposits (Figure 5 - Pine3, Pine4, Pine27; Figure 6 - Straw7, Straw8), while many were too disturbed from development to know determine if debris flows had occurred in the past. Several of the basins in Pine and Strawberry were not directly observed due to access limitations.

It should be noted that at least one basin (Figure 5 - Pine8) has an old sediment-filled stock tank located just above two houses on the eastern edge of Pine Creek floodplain. A very small snout-like debris-flow deposit was observed upstream of the stock tank. No other debris flow deposits were observed in this basin but access was limited. This stock tank, while not posing a debris flow hazard could pose an increased post-fire flood hazard if a post-fire flood or debris flow entered and flowed over or breached the stock tank. This is one area where mitigation efforts could have a significant impact.

Models

Models developed by the USGS require extent and degree of burn severity and a likely triggering rainfall intensity and duration. As such, these models may be more appropriate to apply immediately after a wildfire. For the purpose of this study, the USGS models were tested on the 2004 Webber and 2006 February Fires. Three models yielded results that could be evaluated (2a, 7a and 10a). Percent of basin burned at medium and high severity and average rainfall intensity were combined with additional factors such as ruggedness, percent of basin area above 30% slope, clay content, liquid limit, and/or hydrologic soils group.

Models 2a and 7a yielded very high probabilities (>75%) of debris flow occurrence for many basins, most of which have not had debris flows since the fires. Probability of debris flow occurrence is combined with potential debris flow volume to generate a hazard ranking. Models 2a and 7a had 6 and 11 basins, respectively, as moderately high (3) hazard, with all other basins low (1) or moderately low (2) hazards. Moderately high hazard ranked basins did not necessarily reflect basins with observed debris flows. Both of these models incorporated soil parameters for which the available data are not very good, and this may contribute to the poor quality of results.

Model 10a incorporates basin parameters only. Of 31 burned basins, predicted probabilities of debris flow occurrence ranged from 26-66% in five basins, two of which had documented debris flows. Two other basins had very low probability of occurrence, yet debris flows occurred. All remaining basins had low to very low probabilities (<10%). Combining probability of occurrence with potential volume, all basins in model 10a were ranked as low (1) or moderately low (2), even those with documented post-fire responses. The low hazard rankings from this model are due to low probabilities of occurrence combined with small basin size, and hence low potential volumes.

These same models were applied to Pine and Strawberry assuming two burn scenarios, 10% and 30% of the basins burned at medium and high severity. Similar patterns and results were yielded from each model. Considering results from the 30% burn scenario and model 10a, the best performer in Webber Canyon, all basins in Pine and Strawberry had probabilities of debris flow occurrence of less than 11%, and most were in single digits. All basins, except for the two larger ones (Pine15 and Straw5) were ranked as low to moderately low hazard. Due to the mixed results from the burned basins, however, it was not possible to judge how well these models might perform when applied to an unburned area.

During this study it became apparent that complex models, such as the USGS models, require more information than is readily available in Arizona. Two major data deficiencies are soils information and rainfall data. National soil databases do not cover federal lands in Arizona thus specific soil parameters are typically not available. More importantly is the lack of precipitation data. Precipitation in Arizona is extremely variable both spatially and temporally. Rain gages are sparsely located and thus may miss the highest intensity events. In addition, triggering rainfall thresholds for debris flow initiation have not been developed for anywhere in Arizona. Future post-fire studies combined with enhanced Doppler Radar precipitation estimates may help close this information gap, but for now effective precipitation data is unavailable. These information gaps make it necessary to use only basin morphometrics, and possibly lithology, for identifying hazard risks.

To develop a less-complex method for identifying basins likely to have post-fire debris flows, several combinations of basin morphometrics were evaluated to determine if predictive pairings could be found. Cannon and Gartner (2005) identified lithology and basin area plus average basin gradient as important variables for generating post-fire debris flows. Indeed, responses to the Bray, February and Webber Fires indicates lithology and slope, and probably rainfall intensity, may be more important factors than burn severity. Observations made at the top of Bray and Cow Canyons indicate post-fire debris flows were initiated just above and below the top layers of Coconino Sandstone. There was very little contributing area above initiation zones which were classified as low burn severity. Based on field evidence from these recent fires lithology probably does play a key role for two reasons. Outcrops of the Coconino Sandstone form cliffs or steep slopes (Figure 4) providing the necessary gradient for debris-flow initiation. The Coconino Sandstone also provides significant amounts of eroded material to channels for debris flow bulking and propagation.

Along the Mogollon Rim both percent of basin area with slope greater than 30% and average basin gradient seem to reasonably reflect the influence of the Coconino Sandstone on basin morphology. Figures 9 through 20 show basins in the study area based on hazard rankings for the different parings of basin morphometrics. For example, basins were ranked from high to low (4-1) based on area (large = 4) and then basin gradient (steep =4). In this system, basin area is a proxy for debris flow volume, with larger basins potentially generating larger debris flows. The rankings for each basin were combined and re-ranked for a hazard ranking of 4 (highest) to 1 (lowest). Using this system, a small but very steep basin could receive a high hazard ranking as could a larger, lower gradient basin. Additional considerations for final basin selection were whether or not a given basin, or a portion of a basin, was located with developed areas, and the portion of basin already treated for fuel reduction (Figures 21 and

22). Basins within developed areas of Pine and Strawberry present the highest potential mitigation options and benefits.

Results from combining basin area with average basin gradient yielded the best results with ground observations (Figures 9-11). The large basins of Pine15 and Straw5 were ranked high, as expected due to the size of these basins. In Pine Canyon (Figure 9) basins ranked moderately high also had evidence of past debris flows, while debris-flow deposits were not observed in basins ranked low. Basins with moderately low hazard ranking were the most questionable due to either disturbance from development or access limitations. Two exceptions to these results are Pine20 and Pine29 where debris-flow deposits were observed. These two basins should be considered in the moderately-high hazard ranking group when considering mitigation efforts. In general pairing basin area with average basin gradient appeared to have a strong correlation with field evidence in Pine Canyon.

Basins in Strawberry Canyon were not as clearly identified using this combination. All basins in or adjacent to developed areas were ranked as either low or moderately-low. Basins of particular concern are Straw3, Straw11, Straw12, Straws14-17, and Straw20 (Figure 10). Debris-flow deposits were observed in Straw3 but not in any of these other areas. Observations of Straws14-17 were not made directly at the base of the watersheds but farther downstream where deposits may have been destroyed by development. Because none of these basins have received any fuels reduction treatment, and they debouch into developed areas, these basins should be considered for mitigation opportunities.

Results of pairing basin area with basin gradient in Webber Creek were similar to those of Pine Canyon with field observations matching will with hazard rankings (Figure 11).Post-fire basin responses in the small upper watersheds of Bray, Cow, Poison, Geronimo Spring (informal) and TJ's Ravine (informal) were well reflected in the hazard rankings, as were many of the other basins. Moderately-high ranked basins had observed debris-flow deposits, low ranked basins did not, and moderately-low ranked basins yielded mixed results.

Pairings of other basin variables, unfortunately, were not as strong. These combinations included ruggedness with percent of area with slopes greater than 30% (Figures 12-14), ruggedness with relief ratio (Figures 15-17), and ruggedness with planimetric length (Figures 18-20). Of these three combinations, basin ruggedness with percent basin >30% slopes was the most robust. Indeed, this pairing may be a better predictor of basins within Strawberry Canyon than basin area with average gradient. Of the eight basins in Strawberry listed above, this method ranked seven as moderately-high hazard. Strawberry Canyon is not as large or steep as Pine and Webber Canyons. These results may indicate that different combinations of basin morphometrics are more suited to one particular environment over another.

Neither basin ruggedness with relief ratio nor ruggedness with planimetric length was very robust for differentiating hazard ranks in subbasins. Almost all rankings of basins for these methods were low to moderately-low, including the large canyons of Pine15 and Straw5. Wilford and others (2004) found a combination of the ruggedness with planimetric watershed length to be a strong indicator of debris-flow prone basins in Canada. This is not a strongly correlated relationship in this region pairing due to the nature of the Mogollon Rim, which forms short steep basins.

Mitigation Opportunities

Mitigation opportunities to consider, in addition to the forest thinning already occurring in these canyons, could include re-sizing culverts and bridges to pass larger amounts of debris in addition to flood flows, rezoning or acquiring land on terraces along channels in basins with highest or moderately high risks for debris-flow hazards, and identifying and breaching potential dams such as old stock tanks that could be quickly filled with sediment of debris flows occurred.

CONCLUSIONS

This pilot study was conducted to develop a method for identifying and prioritizing areas for mitigation to reduce the threat of post-wildfire debris flows. Two different approaches were evaluated for identifying basins likely to have post-fire debris flows. USGS models developed to assess recently-burned basins for potential risks of post-fire debris flows were tested in recently-burned areas and applied to unburned areas. A GIS method of combining various basin morphometrics to identify basins most likely to have debris flows was assessed by comparing hazard rankings with field evidence in both burned and unburned areas.

Predictive USGS models for post-fire hazard analysis were applied to previously burned basins with mixed results. Two major problems exists for using these models in Arizona. Much of the required soils data is not available for lands most likely to be burned by wildfires. More importantly, the models require a threshold triggering rainfall intensity and duration. Due to the sparseness of rain gages and the spatial variability of rainfall in Arizona, data is not available to determine reasonable triggering thresholds, and thus values have not yet been developed. Due to these factors, it does not appear that the USGS models provide meaningful hazard rankings for pre-wildfire mitigation planning, although they should be considered for post-burn analysis.

Basin morphometric data was extracted using a GIS. Various combinations of basin geometry were ranked to provide potential hazards from individual basins. Hazard rankings were compared to responses from previous fires and to observations made in several of the study basins. A pairing of basin area with average basin gradient appeared to yield the most reasonable hazard rankings in Pine and Webber Canyons when considering field evidence. Basin area with percent of basin area with slopes >30% seemed to provide better results for Strawberry Canyon. These methods may provide practical means for prioritizing basin treatments but further work is needed to determine which combinations of basin morphometrics work best in various environments.

Six basins in Pine (Pine6, Pine7, Pine18, Pine19, Pine20, and Pine29) were identified as potential targets for mitigation efforts based on model results and field evidence. No basins in Strawberry were strongly identified as potential targets for mitigation efforts. Debris-flow deposits were observed in basin Straw3 but this in a small basin on the edge of development and mitigation options may be limited. Six basins (Straw11, Straw12, Straws14-17) were identified to consider for mitigation efforts. Although debris-flow deposits were not directly observed in this area, these short, steep basins directly emanate into a developed area, and no treatment has yet occurred in any of these basins.

The goal of this pilot study was to develop a method to identify basins with high potential risks of post-fire debris flows prior to the occurrence of fire. The purpose of this study was to provide local governments, emergency planners and land managers a means to prioritize basins for treatment to reduce risk of post-fire debris flows. It is important to bear in mind two points. First, the method developed here is not intended to replace post-fire hazard analysis. Second, actual basin response after a fire will be strongly influenced by burn severity and, most importantly, rainfall intensity and duration. Precipitation is extremely variable both spatially and temporally, and therefore not predictable. Although post-fire debris-flow hazard analyses which incorporates burn severity should be conducted after a fire to better predict site-specific hazard risks, the occurrence of debris flows will be controlled by precipitation. Due to the nature of precipitation, a model may be considered successful if it accurately predicts half of the basins within a study area.

Results from this pilot project provide local agencies, emergency planners and land managers a tool for prioritizing watershed treatment areas and implementing mitigation measures to alleviate potential impacts and threats from post-fire debris flows. As with most tools, field observations are imperative to test model results. Future work needs to address the lack of data, specifically rainfall triggering thresholds, for Arizona, and to test this method in other environments. Finally, results from any models or method will only be truly tested when a fire and subsequent rainfall occurs.

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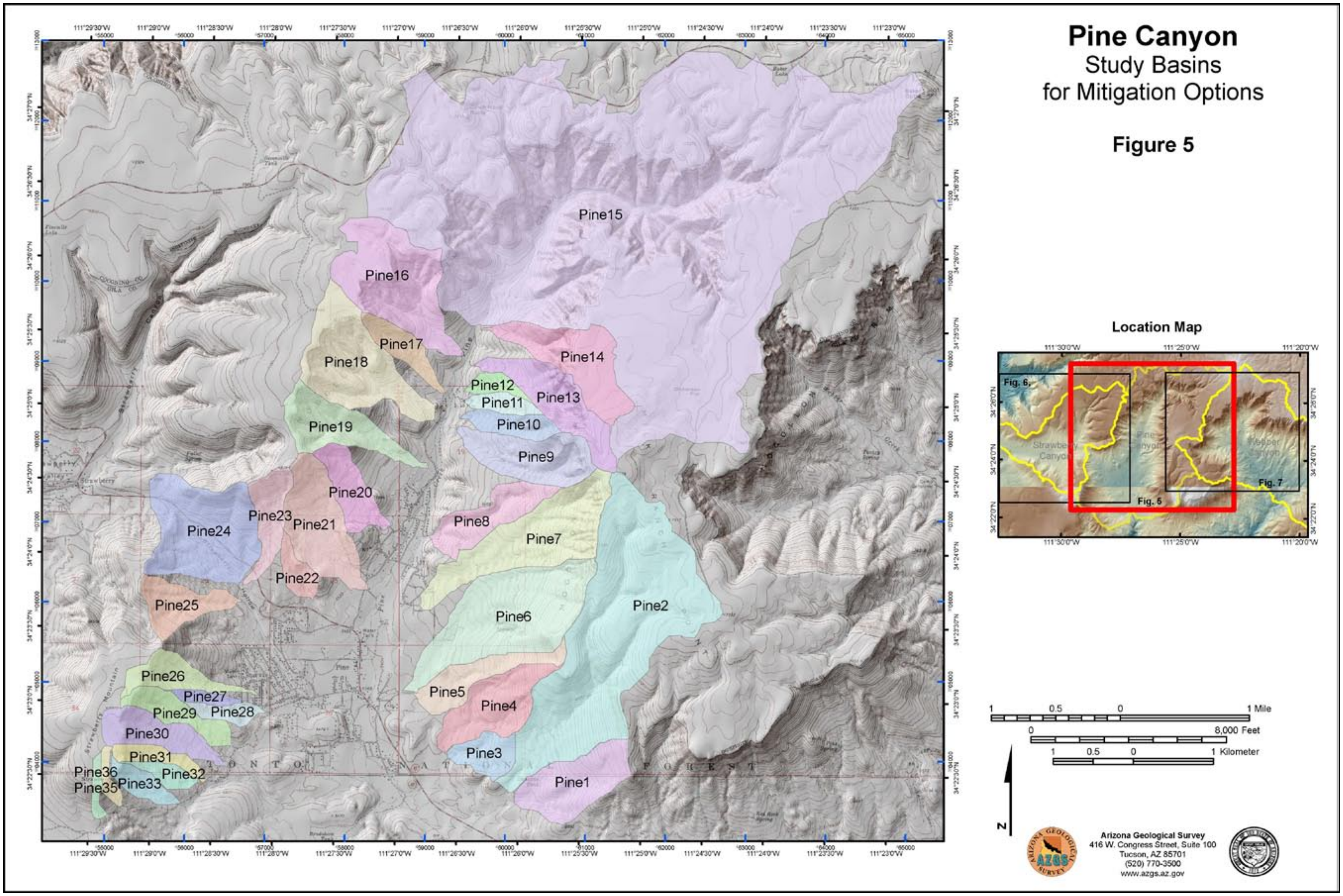
Pine Canyon
Study Basins
for Mitigation Options
Figure 5
Pine1
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Location Map
Fig. 6
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Fig. 7
1 0.5 0 1 Mile
0 8,000 Feet
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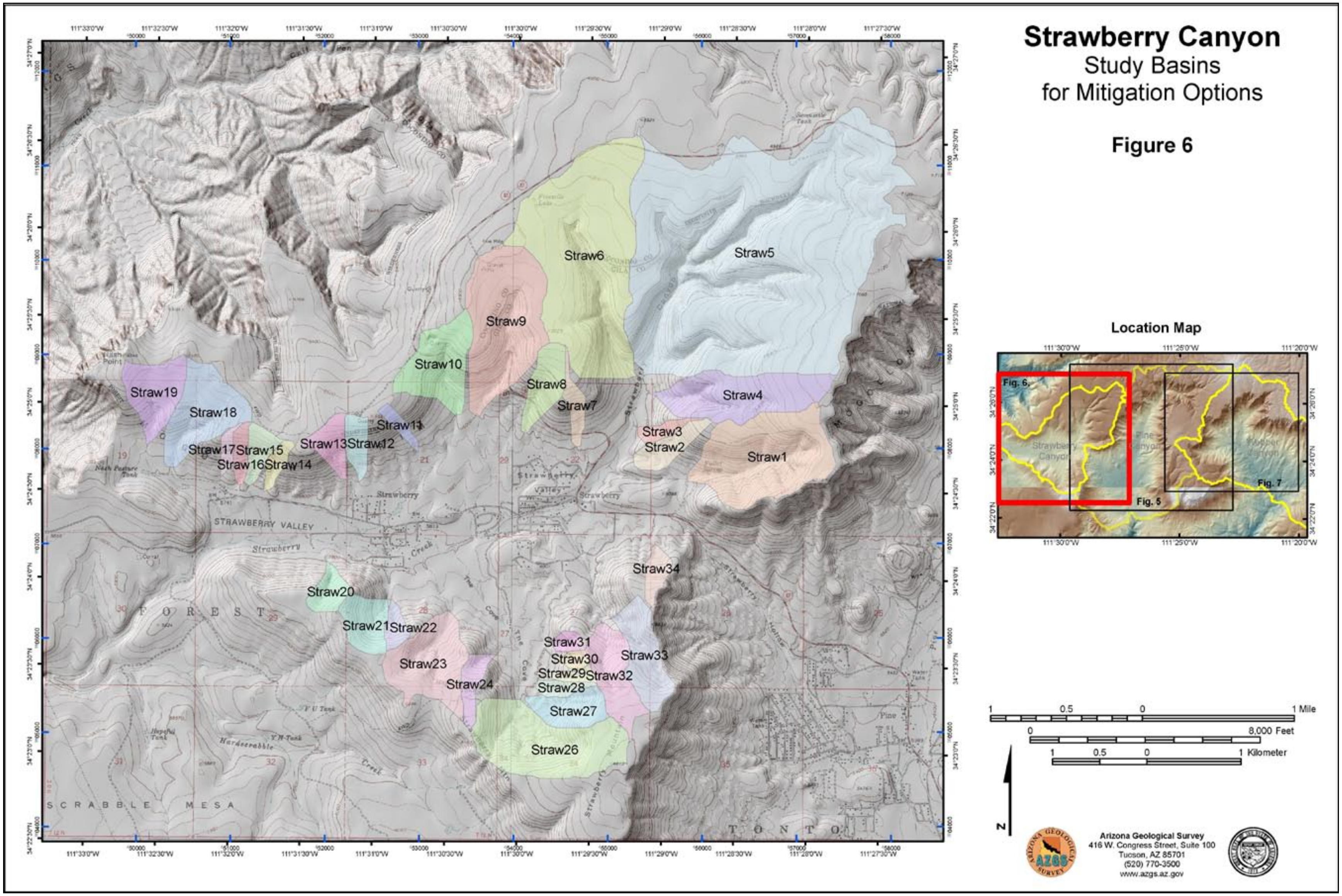

Strawberry Canyon
Study Basins
for Mitigation Options
Figure 6
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STRAWBERRY VALLEY
Location Map
Fig. 6
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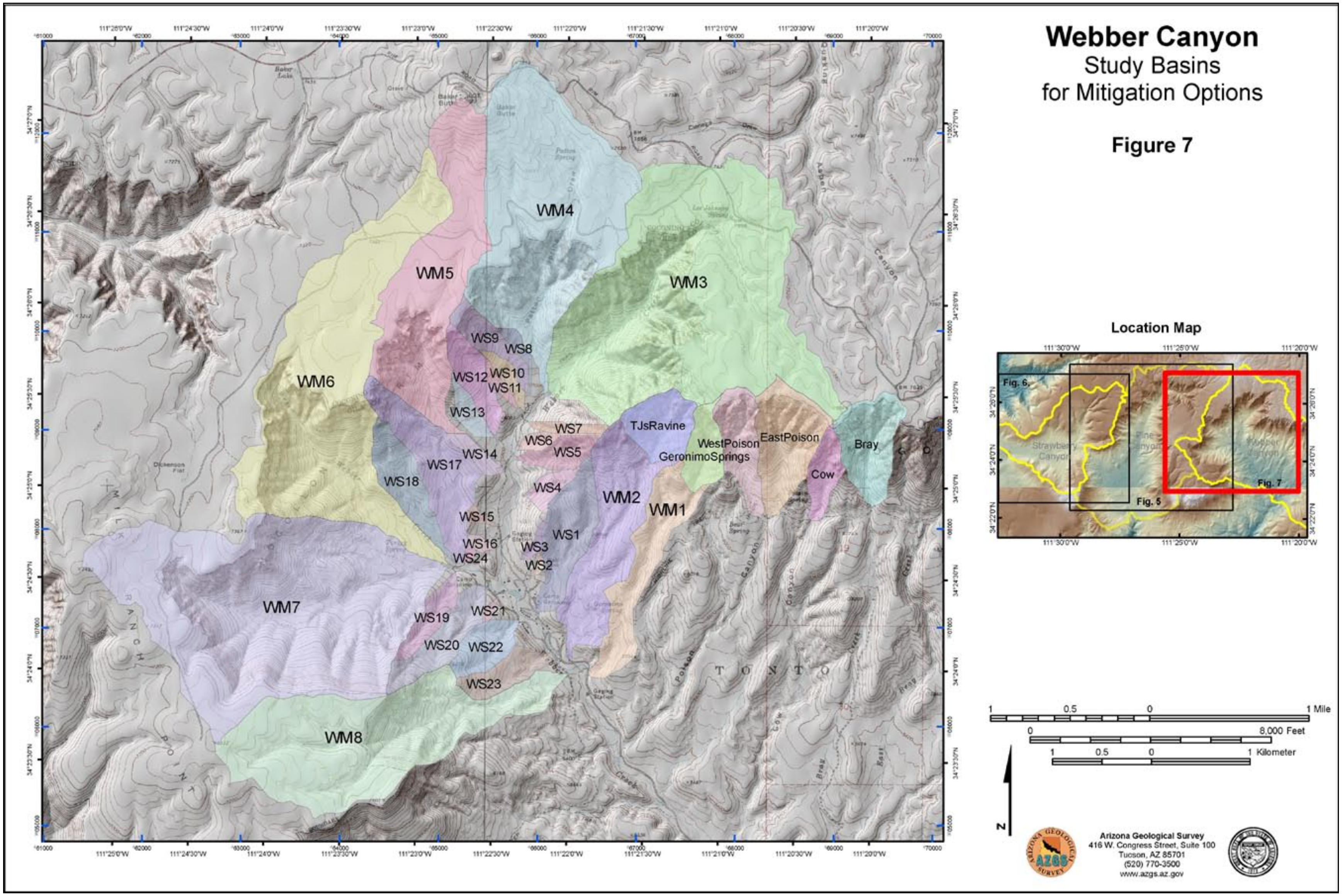
Webber Canyon
Study Basins
for Mitigation Options
Figure 7
Location Map
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WestPoison
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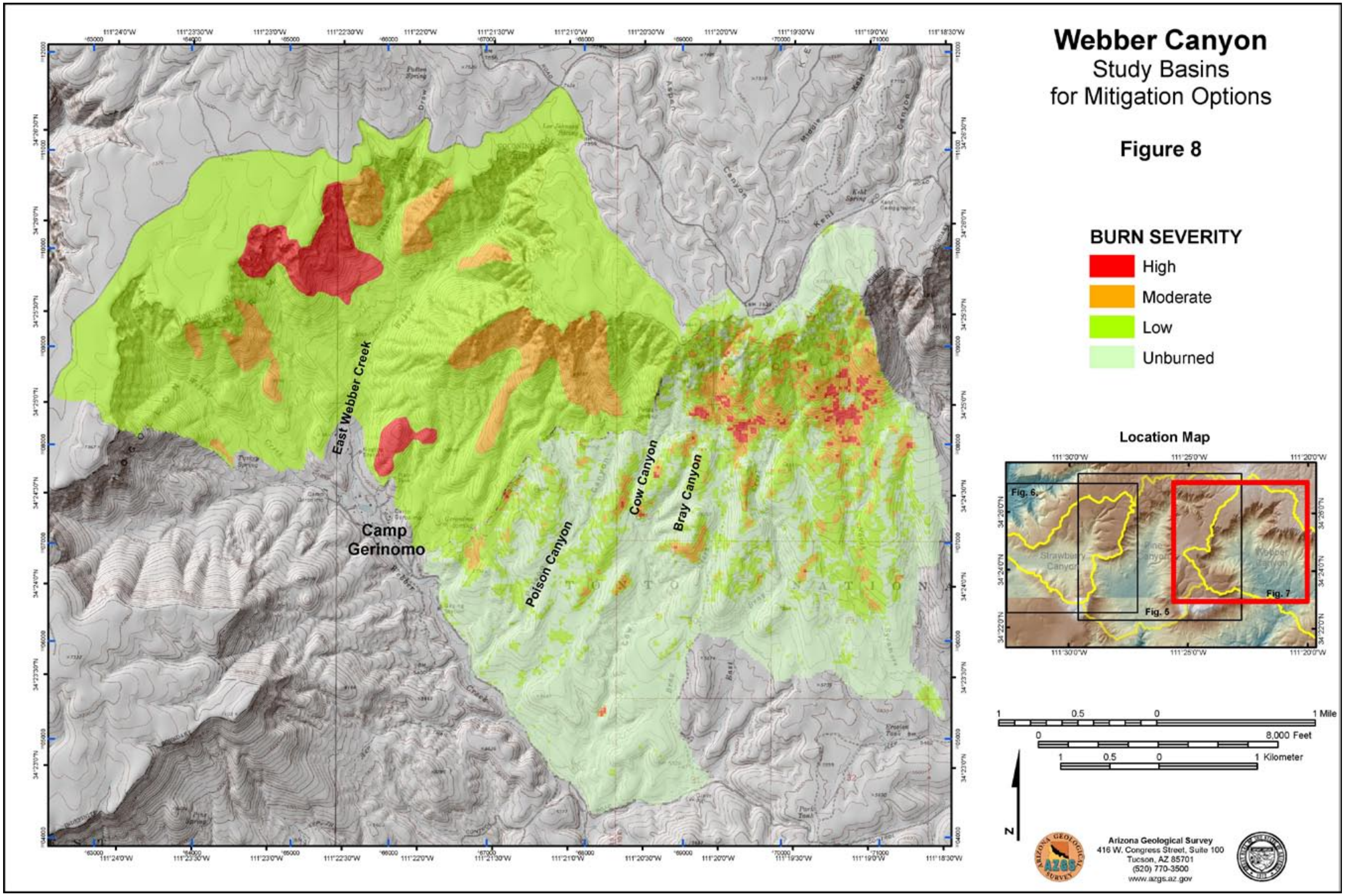
Webber Canyon
Study Basins
for Mitigation Options
Figure 8
BURN SEVERITY
High
Moderate
Low
Unburned
Location Map
East Webber Creek
Camp Gerinomo
Poison Canyon
Cow Canyon
Bray Canyon
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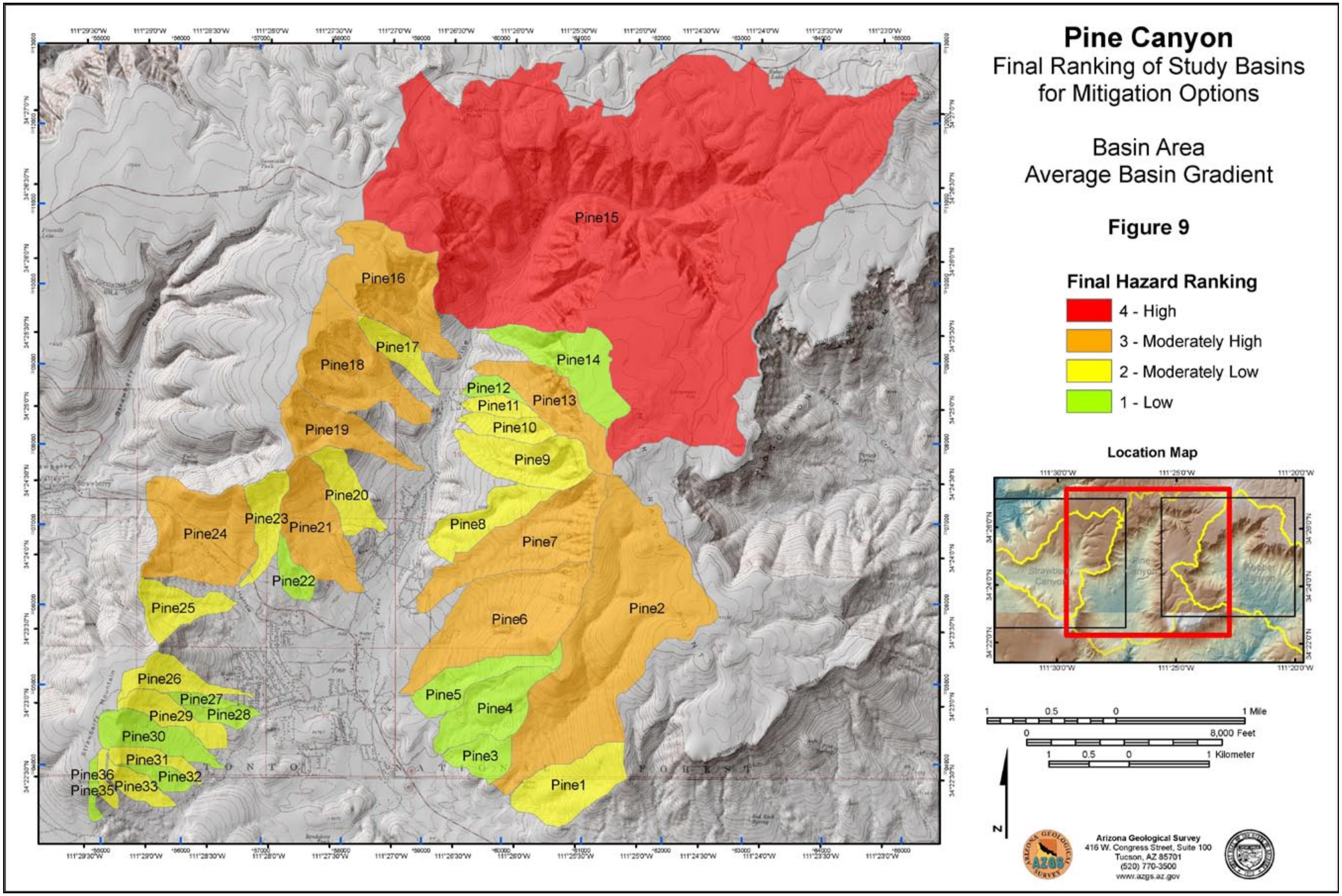
Pine Canyon
Final Ranking of Study Basins for Mitigation Options
Basin Area
Average Basin Gradient
Figure 9
Final Hazard Ranking
4 - High
3 - Moderately High
2 - Moderately Low
1 - Low
Location Map
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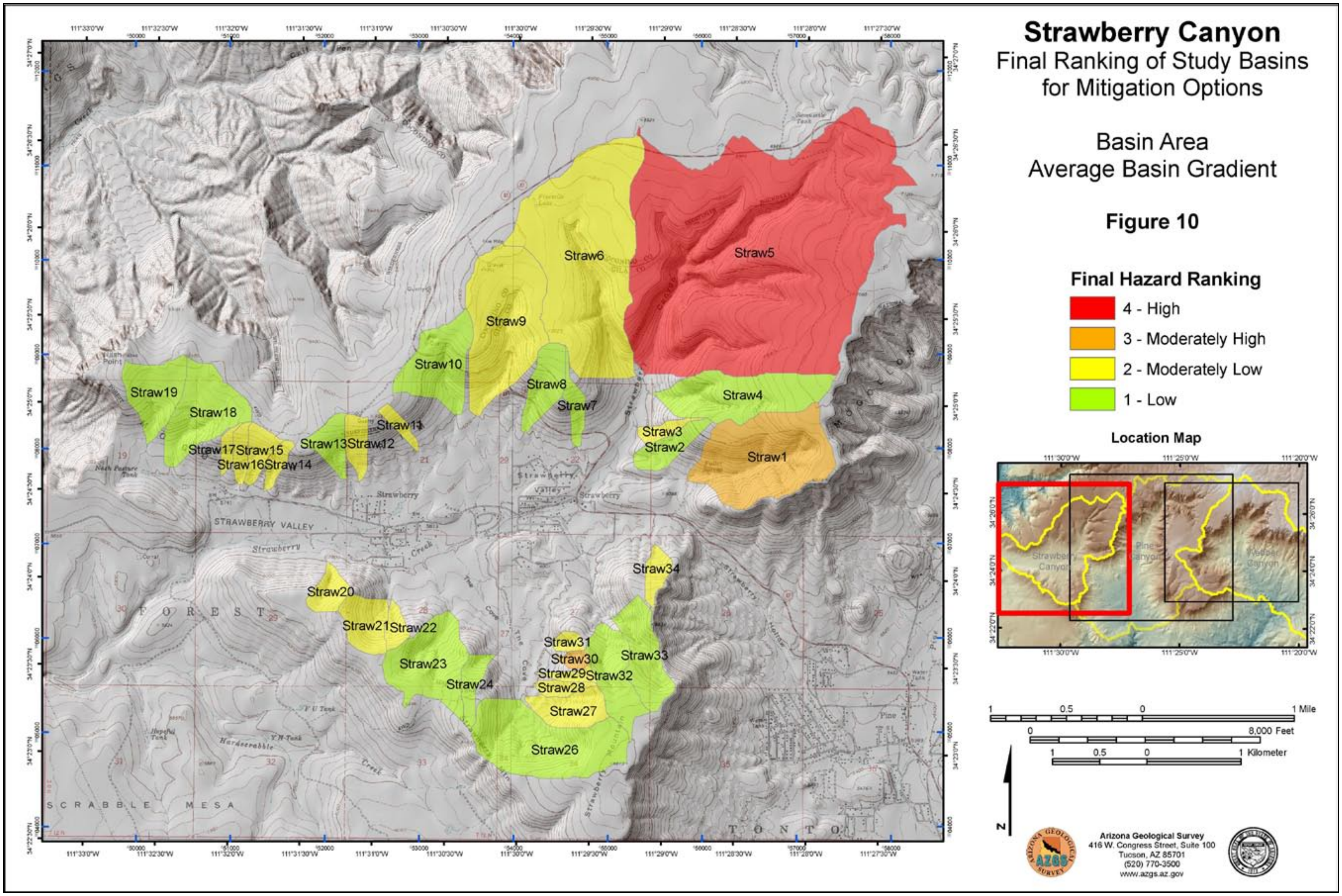
Strawberry Canyon
Final Ranking of Study Basins for Mitigation Options
Basin Area
Average Basin Gradient
Figure 10
Final Hazard Ranking
4 - High
3 - Moderately High
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1 - Low
Location Map
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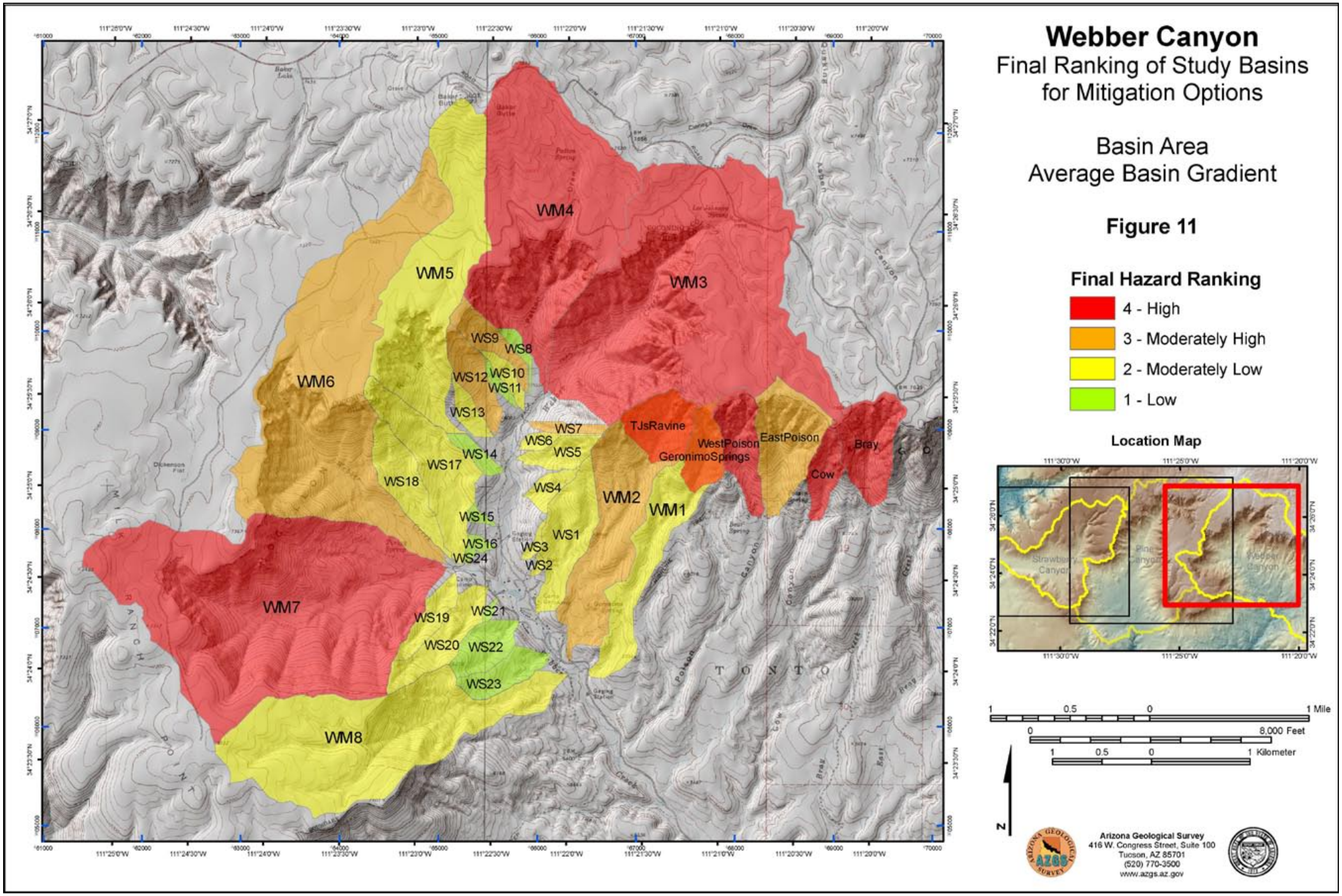
Webber Canyon
Final Ranking of Study Basins for Mitigation Options
Basin Area
Average Basin Gradient
Figure 11
Final Hazard Ranking
4 - High
3 - Moderately High
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Location Map
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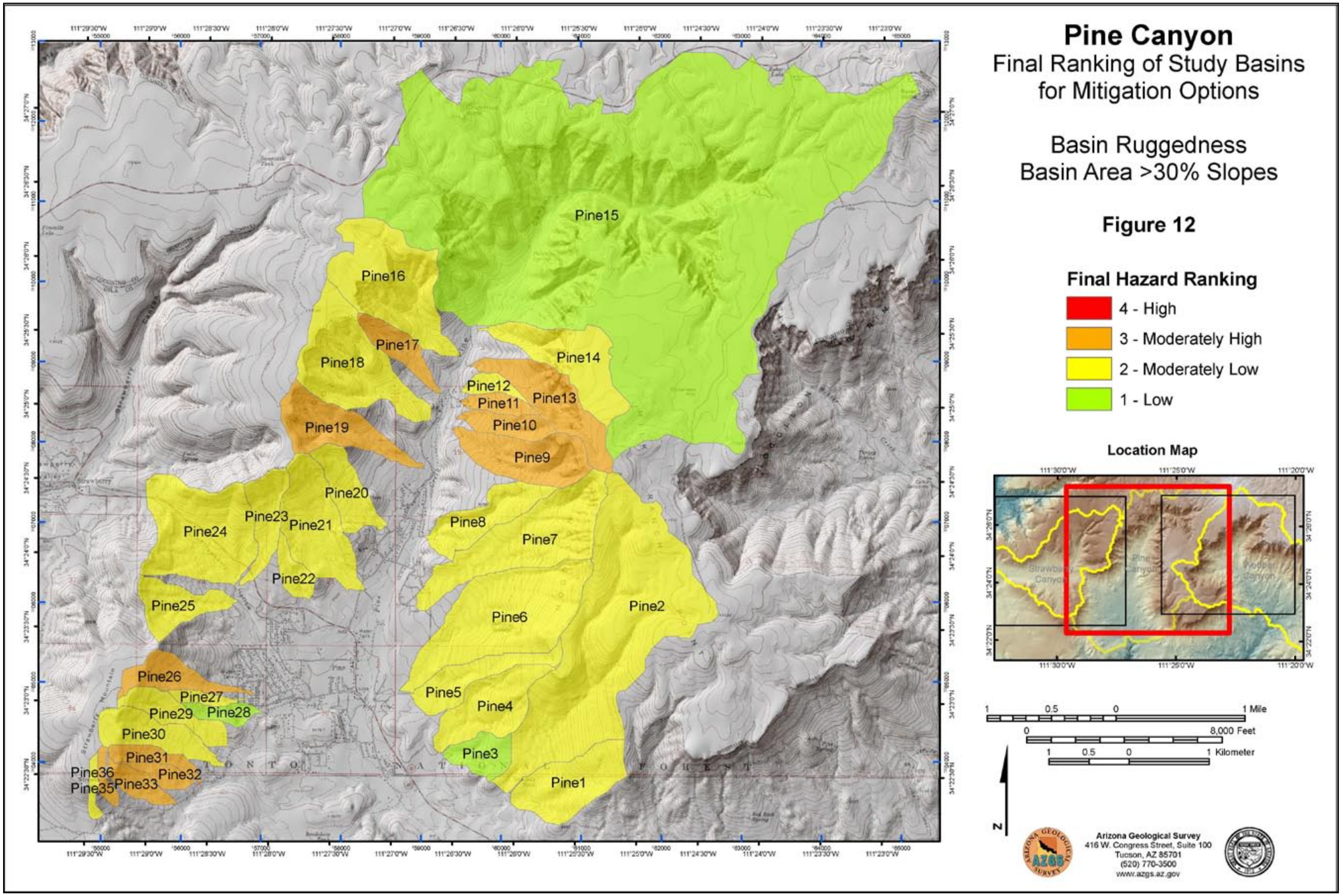
Pine Canyon
Final Ranking of Study Basins for Mitigation Options
Basin Ruggedness
Basin Area >30% Slopes
Figure 12
Final Hazard Ranking
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2 - Moderately Low
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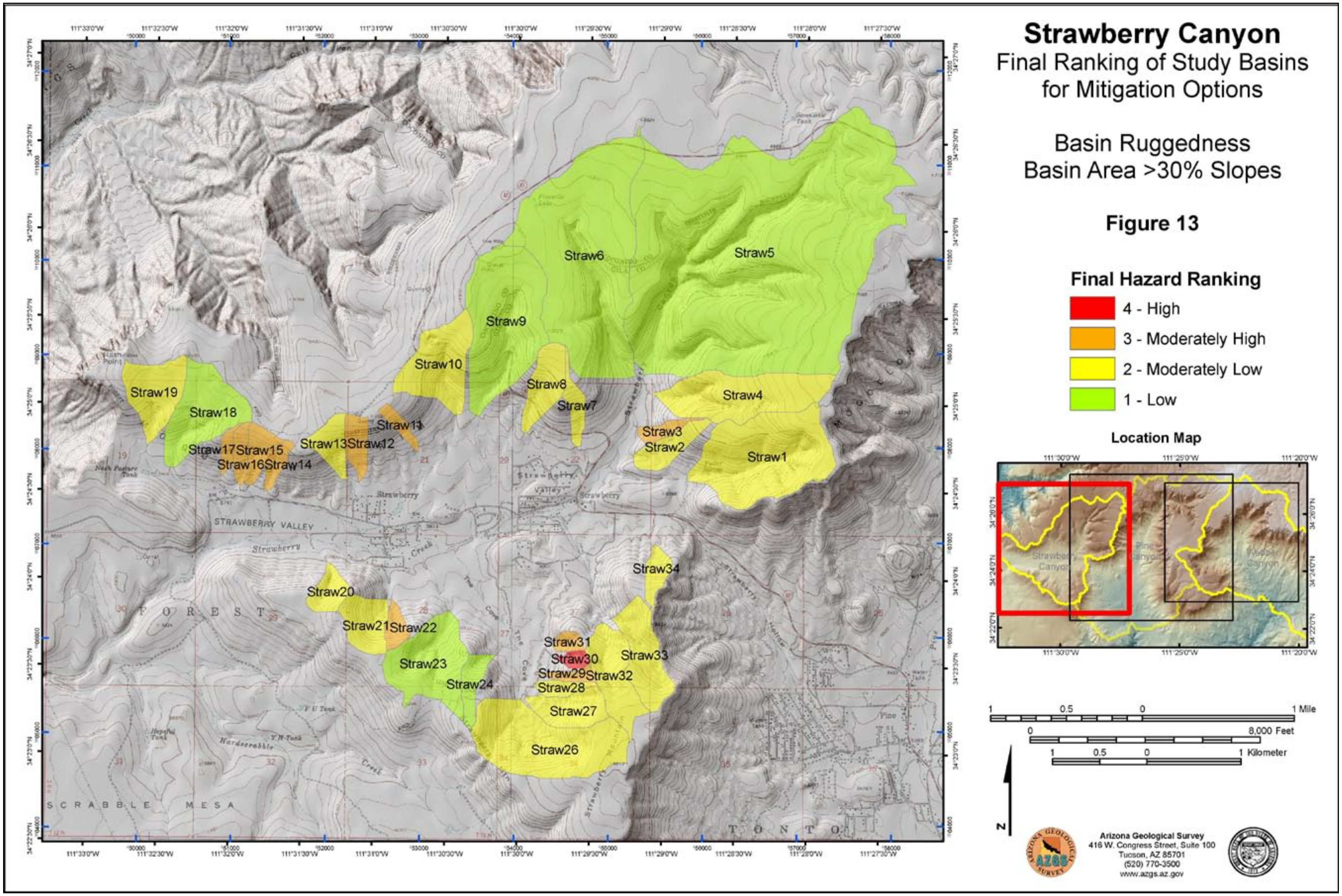

Strawberry Canyon
Final Ranking of Study Basins for Mitigation Options
Basin Ruggedness
Basin Area >30% Slopes
Figure 13
Final Hazard Ranking
4 - High
3 - Moderately High
2 - Moderately Low
1 - Low
Location Map
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Straw27
Straw28
Straw29
Straw30
Straw31
Straw32
Straw33
Straw34
STRAWBERRY VALLEY
F O R E S T
S C R A B B L E M E S A
T O N T O
1 0.5 0 1 Mile
0 8,000 Feet
1 0.5 0 1 Kilometer
N
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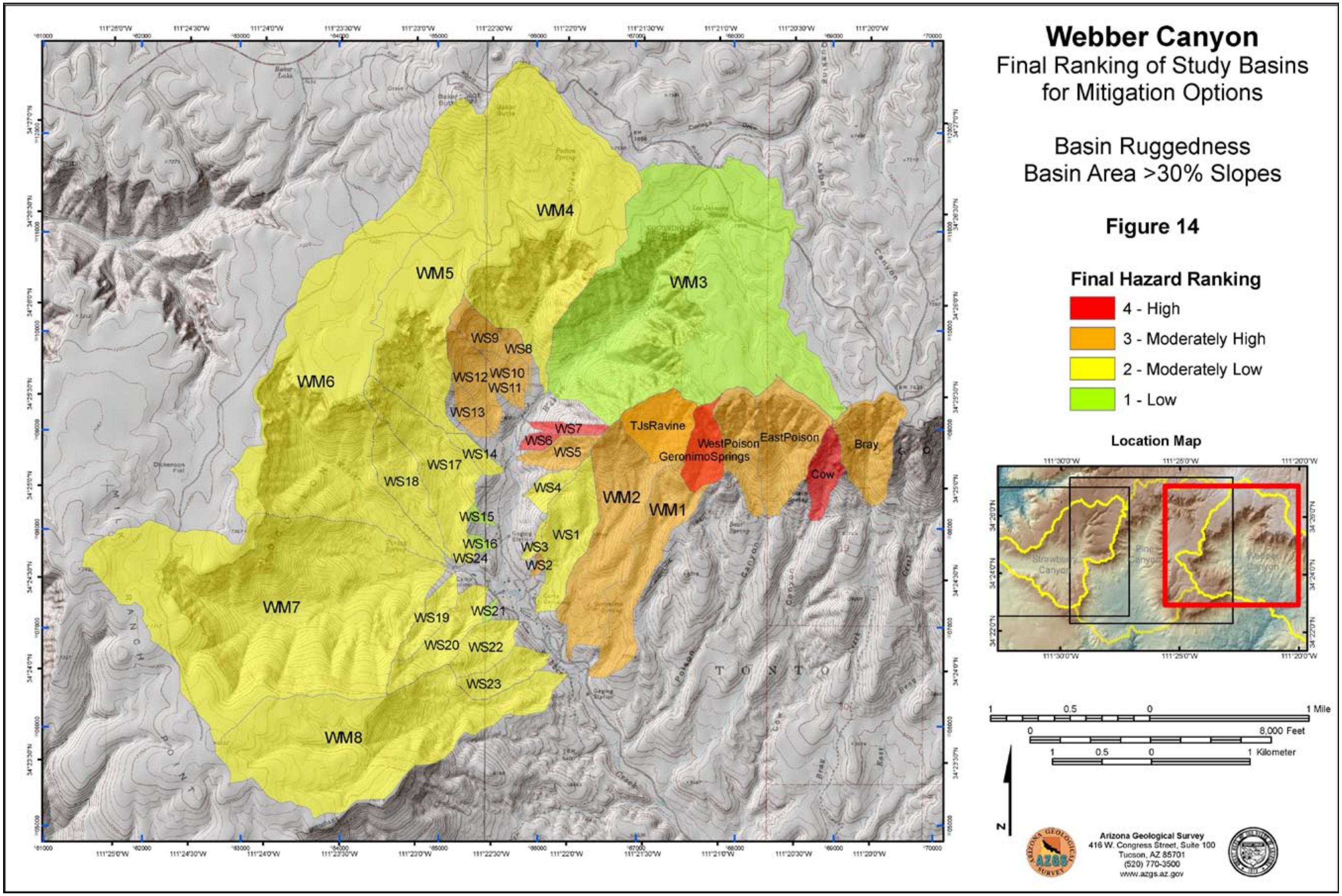
Webber Canyon
Final Ranking of Study Basins for Mitigation Options
Basin Ruggedness
Basin Area >30% Slopes
Figure 14
Final Hazard Ranking
4 - High
3 - Moderately High
2 - Moderately Low
1 - Low
Location Map
WM1
WM2
WM3
WM4
WM5
WM6
WM7
WM8
WS1
WS2
WS3
WS4
WS5
WS6
WS7
WS8
WS9
WS10
WS11
WS12
WS13
WS14
WS15
WS16
WS17
WS18
WS19
WS20
WS21
WS22
WS23
WS24
TJsRavine
WestPoison
EastPoison
GeronimoSprings
Cow
Bray
1 Mile
8,000 Feet
1 Kilometer
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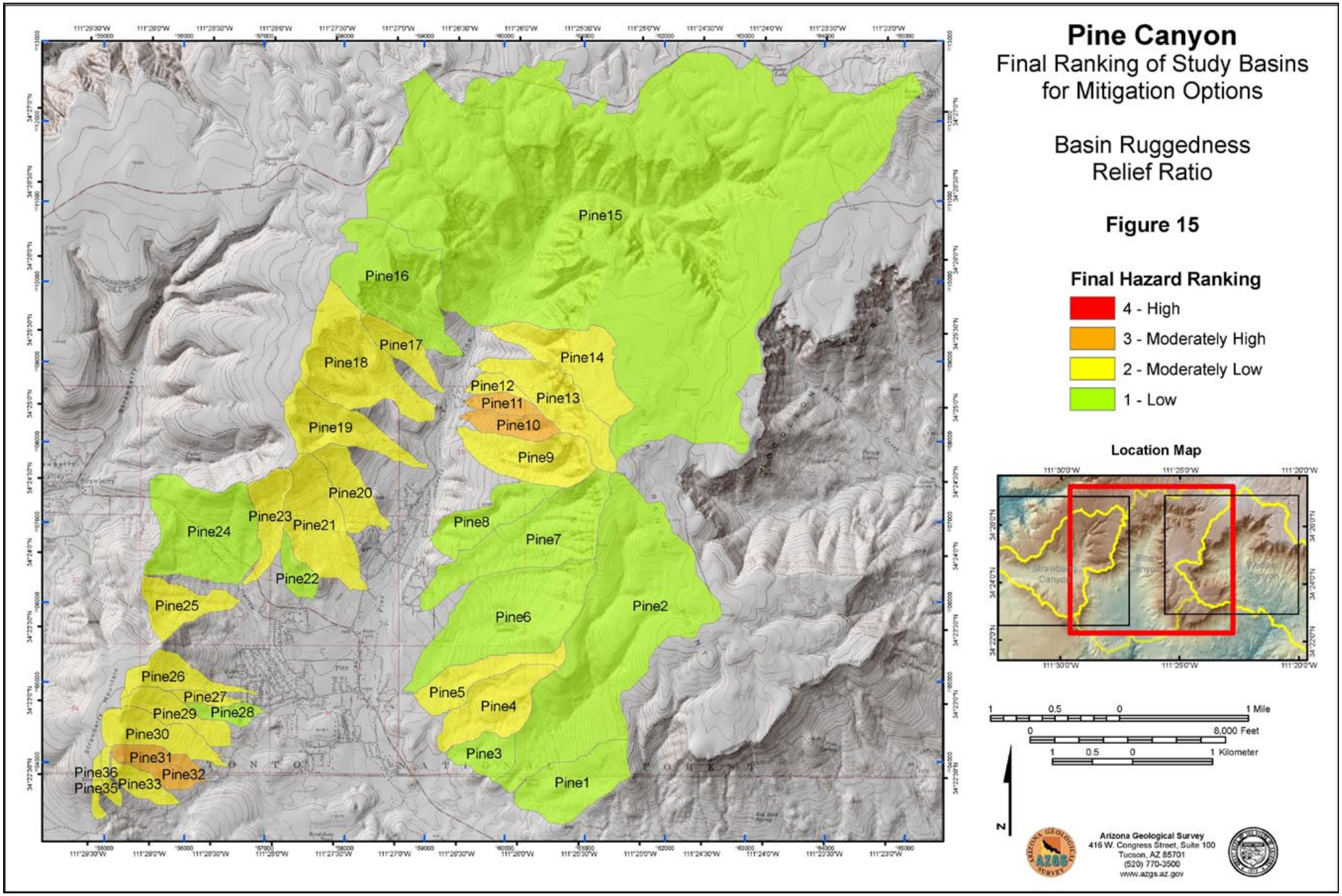
Pine Canyon
Final Ranking of Study Basins for Mitigation Options
Basin Ruggedness Relief Ratio
Figure 15
Final Hazard Ranking
4 - High
3 - Moderately High
2 - Moderately Low
1 - Low
Location Map
Pine15
Pine16
Pine17
Pine18
Pine19
Pine14
Pine12
Pine11
Pine13
Pine10
Pine9
Pine20
Pine23
Pine21
Pine24
Pine22
Pine8
Pine7
Pine25
Pine6
Pine2
Pine26
Pine27
Pine29
Pine28
Pine30
Pine31
Pine32
Pine36
Pine35
Pine33
Pine5
Pine4
Pine3
Pine1
1 Mile
8,000 Feet
1 Kilometer
N
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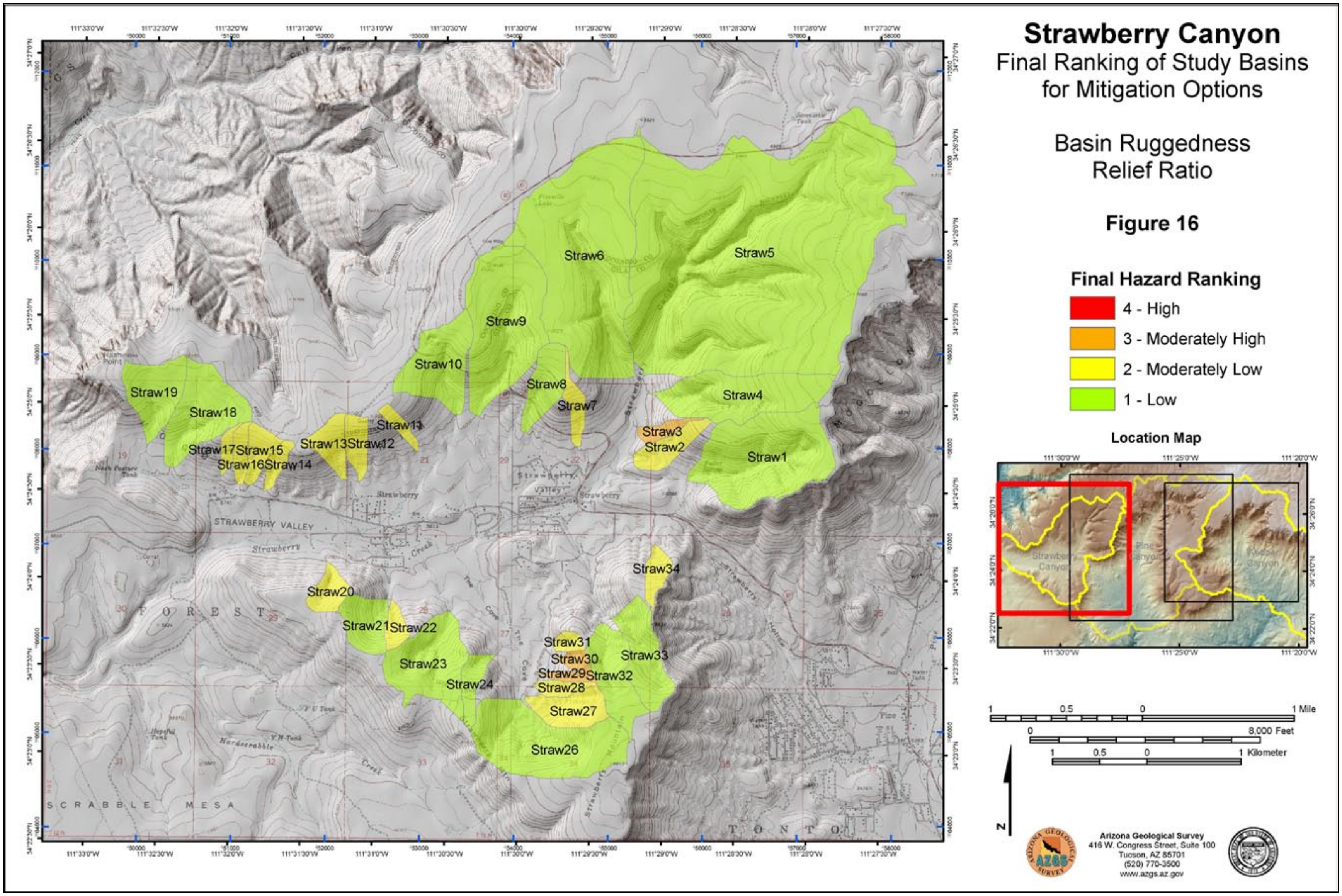
Strawberry Canyon
Final Ranking of Study Basins for Mitigation Options
Basin Ruggedness Relief Ratio
Figure 16
Final Hazard Ranking
4 - High
3 - Moderately High
2 - Moderately Low
1 - Low
Location Map
Straw1
Straw2
Straw3
Straw4
Straw5
Straw6
Straw7
Straw8
Straw9
Straw10
Straw11
Straw12
Straw13
Straw14
Straw15
Straw16
Straw17
Straw18
Straw19
Straw20
Straw21
Straw22
Straw23
Straw24
Straw26
Straw27
Straw28
Straw29
Straw30
Straw31
Straw32
Straw33
Straw34
1 Mile
8,000 Feet
1 Kilometer
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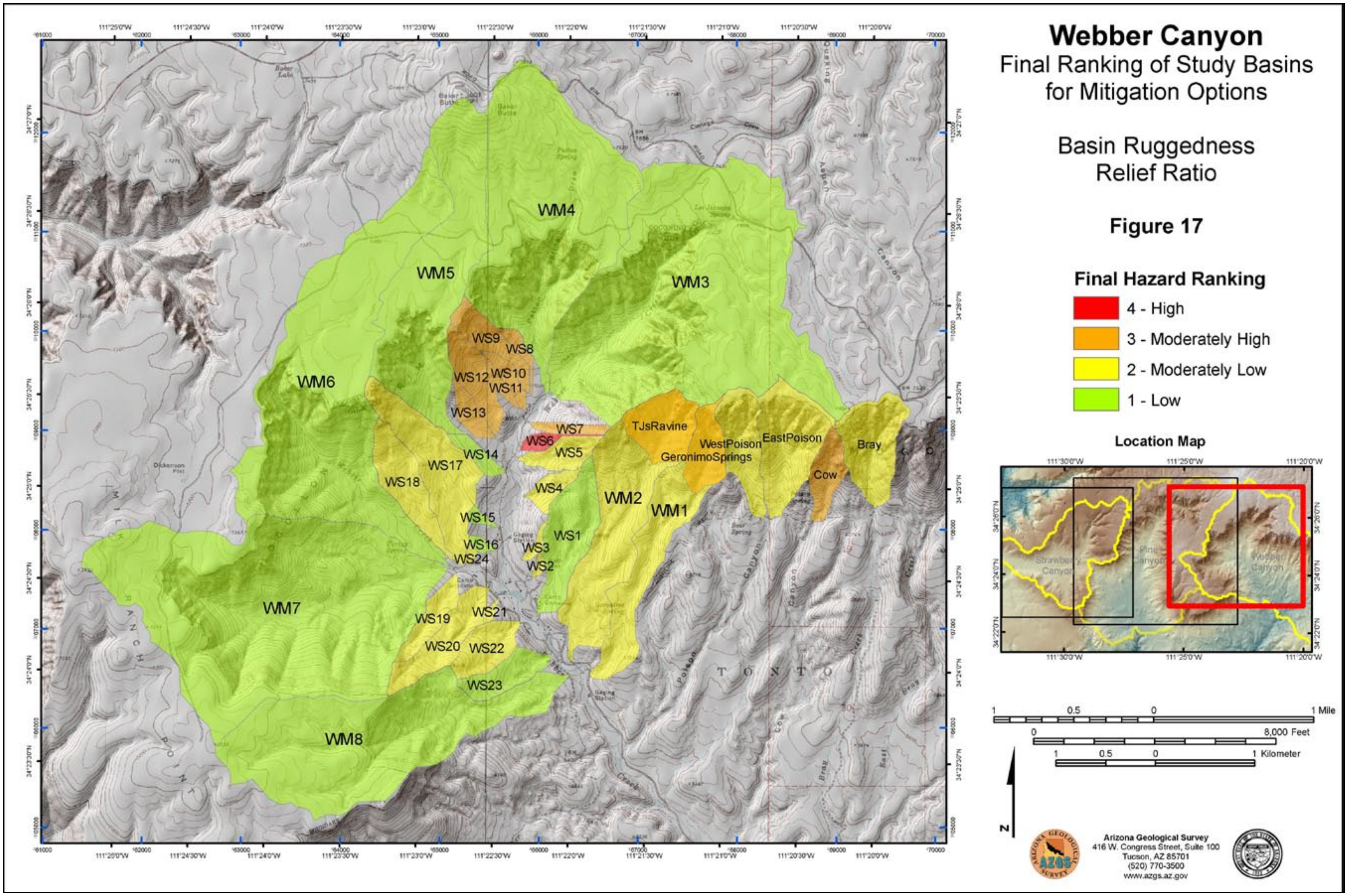

Webber Canyon
Final Ranking of Study Basins for Mitigation Options
Basin Ruggedness Relief Ratio
Figure 17
Final Hazard Ranking
4 - High
3 - Moderately High
2 - Moderately Low
1 - Low
Location Map
WM1
WM2
WM3
WM4
WM5
WM6
WM7
WM8
WS1
WS2
WS3
WS4
WS5
WS6
WS7
WS8
WS9
WS10
WS11
WS12
WS13
WS14
WS15
WS16
WS17
WS18
WS19
WS20
WS21
WS22
WS23
WS24
TJsRavine
WestPoison
EastPoison
GeronimoSprings
Cow
Bray
1 Mile
8,000 Feet
1 Kilometer
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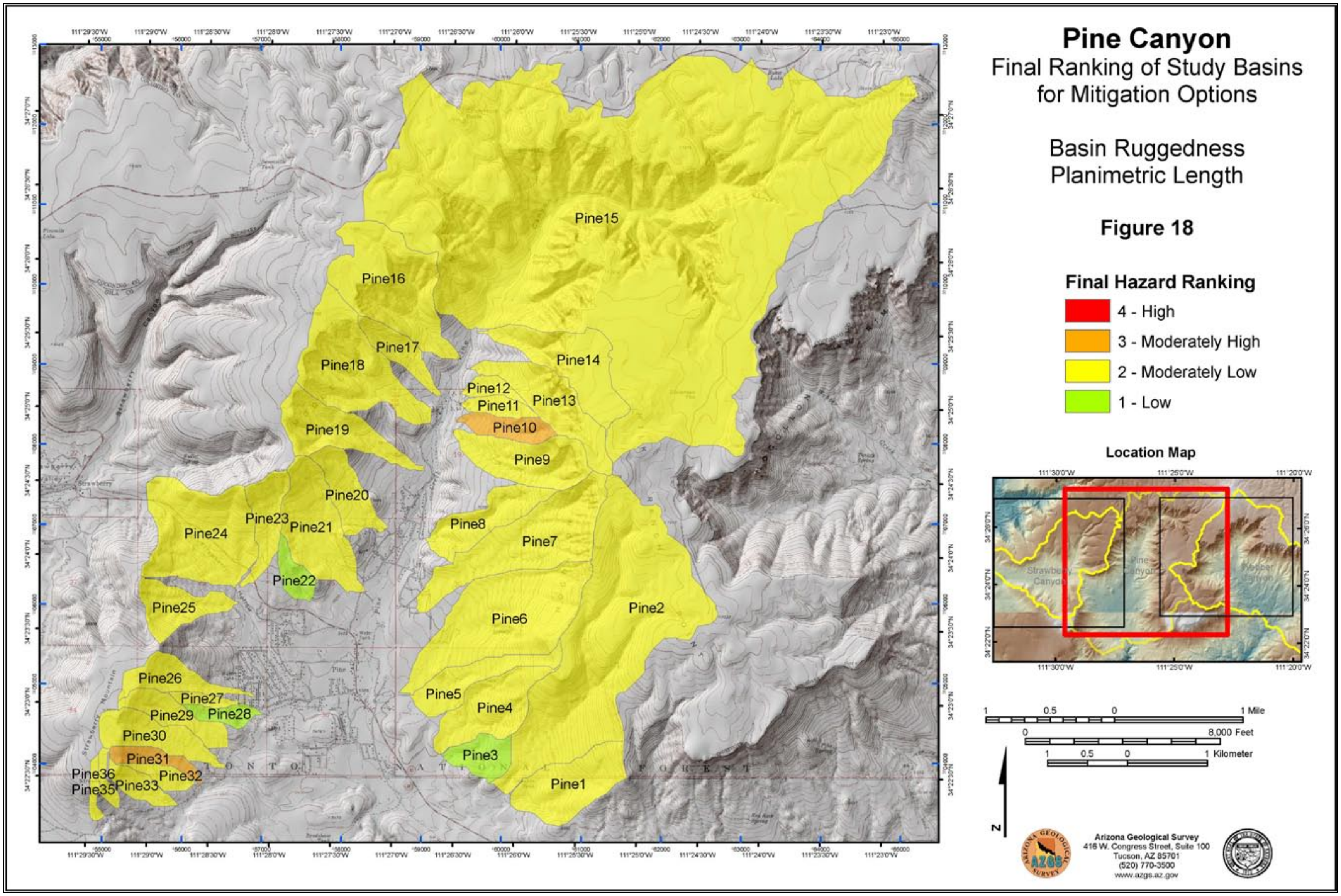
Pine Canyon
Final Ranking of Study Basins for Mitigation Options
Basin Ruggedness
Planimetric Length
Figure 18
Final Hazard Ranking
4 - High
3 - Moderately High
2 - Moderately Low
1 - Low
Location Map
Pine15
Pine16
Pine17
Pine18
Pine14
Pine12
Pine11
Pine13
Pine19
Pine10
Pine9
Pine20
Pine23
Pine21
Pine24
Pine8
Pine7
Pine22
Pine25
Pine6
Pine2
Pine26
Pine27
Pine29
Pine28
Pine5
Pine4
Pine30
Pine31
Pine3
Pine36
Pine32
Pine35
Pine33
Pine1
1 Mile
8,000 Feet
1 Kilometer
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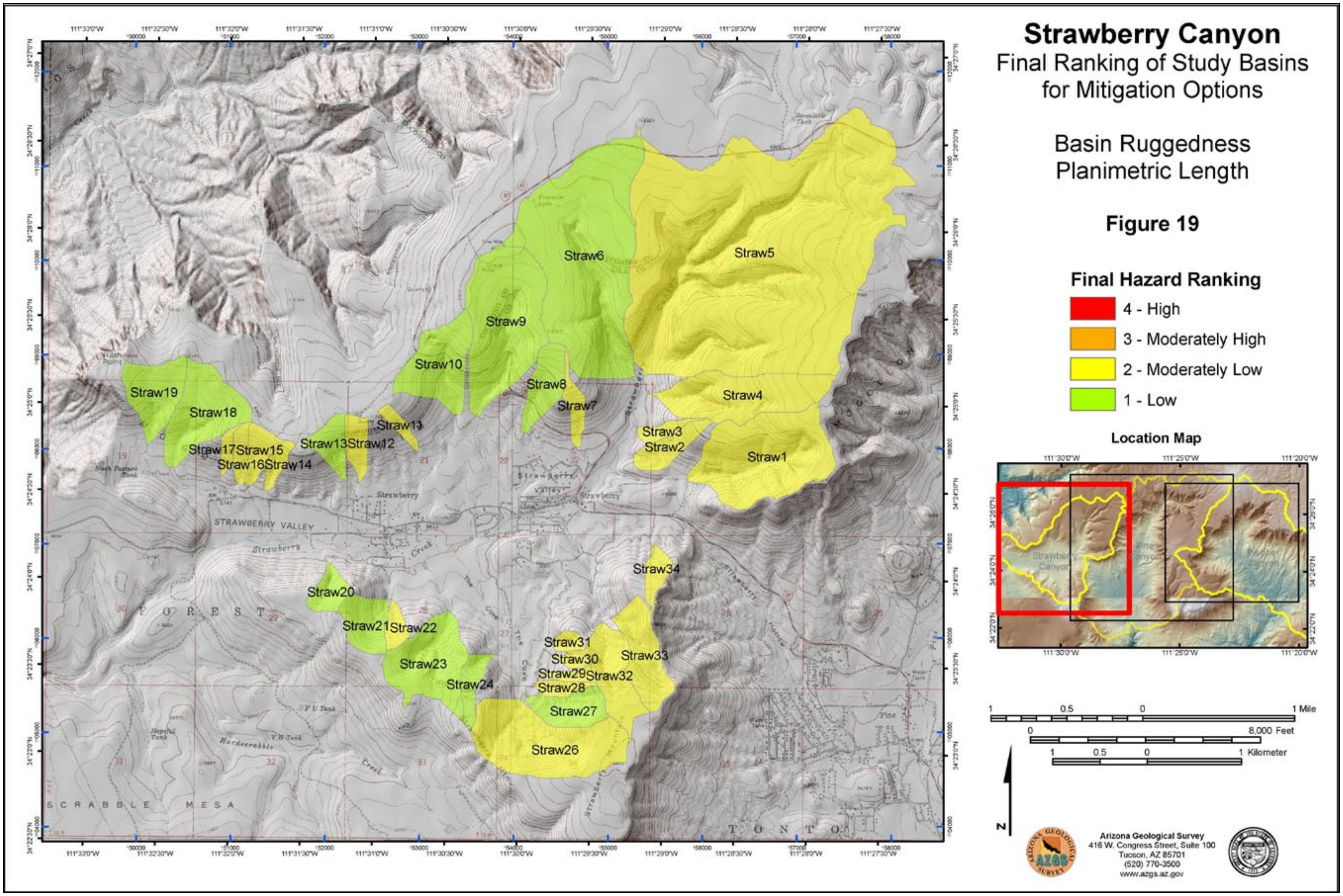
Strawberry Canyon
Final Ranking of Study Basins for Mitigation Options
Basin Ruggedness
Planimetric Length
Figure 19
Final Hazard Ranking
4 - High
3 - Moderately High
2 - Moderately Low
1 - Low
Location Map
Straw1
Straw2
Straw3
Straw4
Straw5
Straw6
Straw7
Straw8
Straw9
Straw10
Straw11
Straw12
Straw13
Straw14
Straw15
Straw16
Straw17
Straw18
Straw19
Straw20
Straw21
Straw22
Straw23
Straw24
Straw26
Straw27
Straw28
Straw29
Straw30
Straw31
Straw32
Straw33
Straw34
STRAWBERRY VALLEY
SCRABBLE MESA
1 Mile
8,000 Feet
1 Kilometer
Arizona Geological Survey
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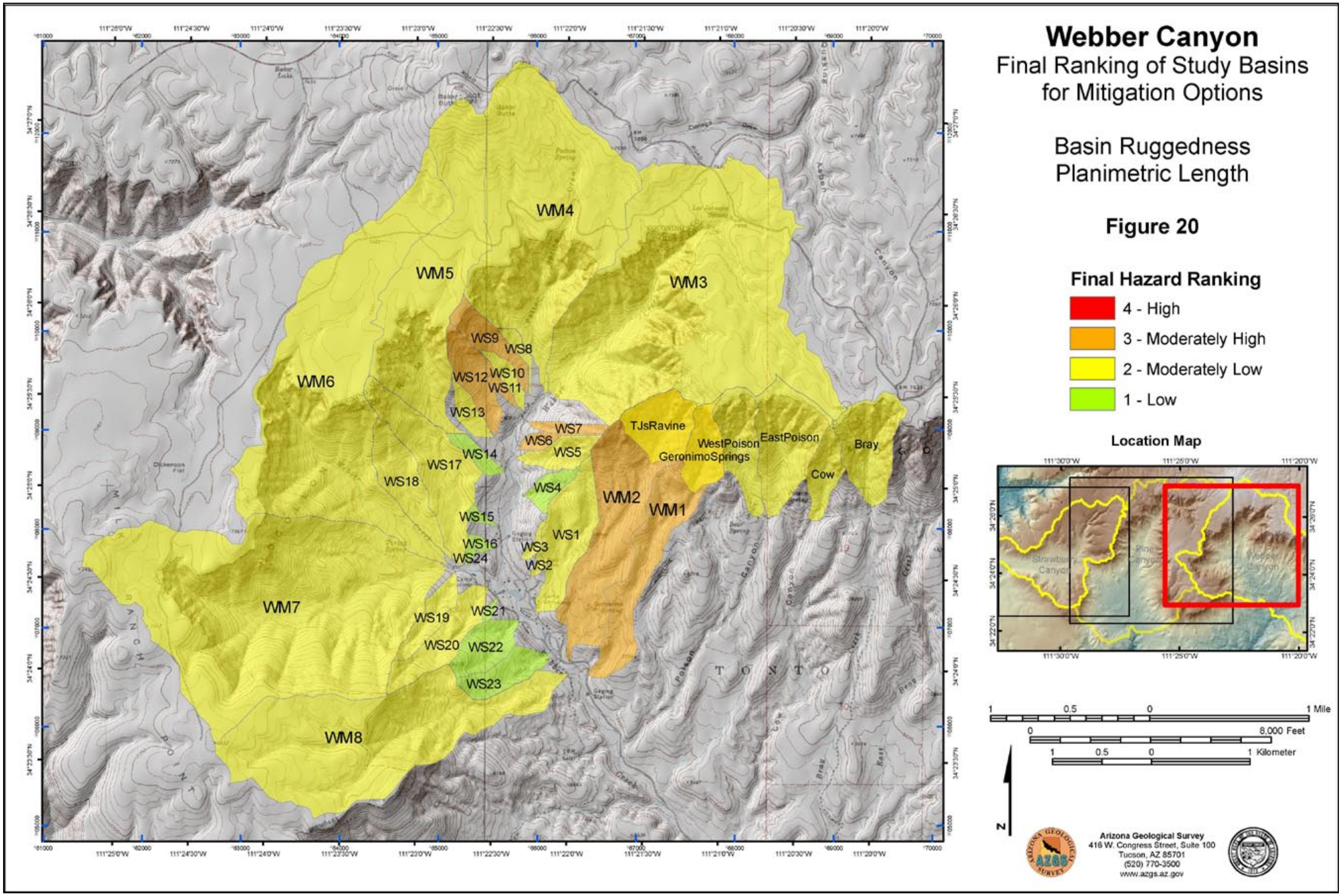

Webber Canyon
Final Ranking of Study Basins for Mitigation Options
Basin Ruggedness
Planimetric Length
Figure 20
Final Hazard Ranking
4 - High
3 - Moderately High
2 - Moderately Low
1 - Low
Location Map
WM1
WM2
WM3
WM4
WM5
WM6
WM7
WM8
WS1
WS2
WS3
WS4
WS5
WS6
WS7
WS8
WS9
WS10
WS11
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WS22
WS23
WS24
TJsRavine
WestPoison
EastPoison
GeronimoSprings
Bray
Cow
1 Mile
8,000 Feet
1 Kilometer
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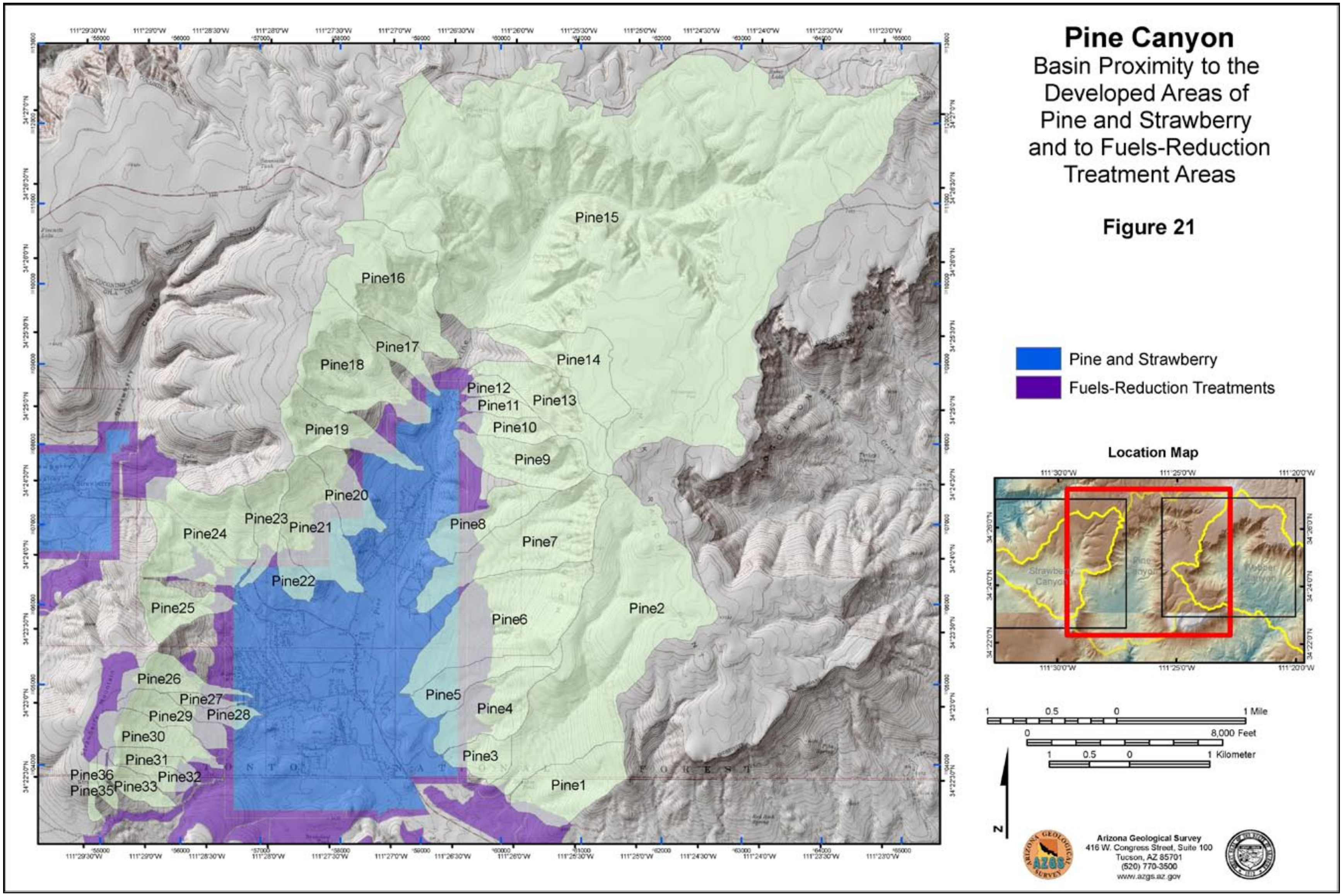

Pine Canyon
Basin Proximity to the Developed Areas of Pine and Strawberry and to Fuels-Reduction Treatment Areas
Figure 21
Pine and Strawberry
Fuels-Reduction Treatments
Location Map
Pine1
Pine2
Pine3
Pine4
Pine5
Pine6
Pine7
Pine8
Pine9
Pine10
Pine11
Pine12
Pine13
Pine14
Pine15
Pine16
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Pine28
Pine29
Pine30
Pine31
Pine32
Pine33
Pine35
Pine36
1 Mile
8,000 Feet
1 Kilometer
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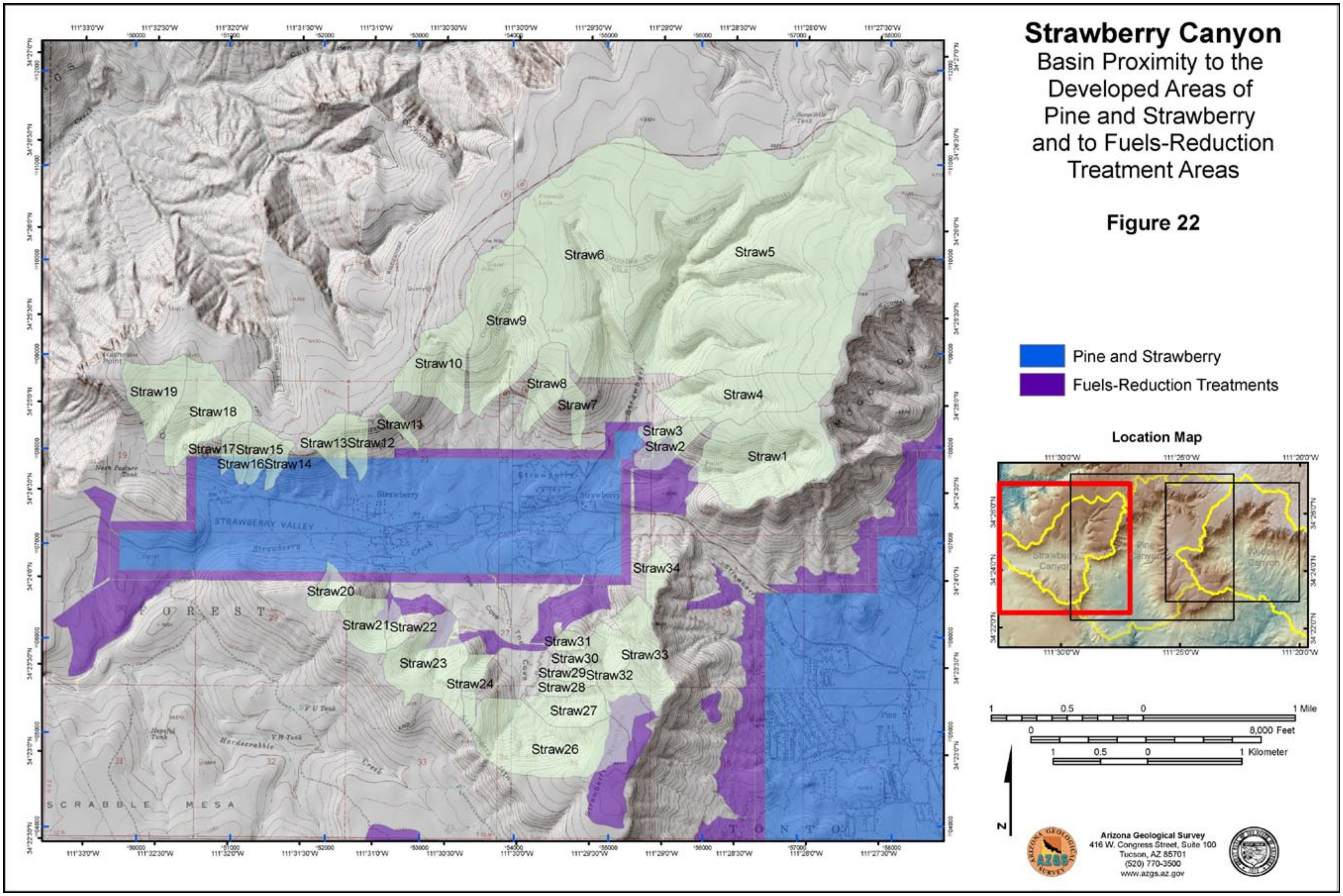

Strawberry Canyon
Basin Proximity to the Developed Areas of Pine and Strawberry and to Fuels-Reduction Treatment Areas
Figure 22
Pine and Strawberry
Fuels-Reduction Treatments
Location Map
Straw1
Straw2
Straw3
Straw4
Straw5
Straw6
Straw7
Straw8
Straw9
Straw10
Straw11
Straw12
Straw13
Straw14
Straw15
Straw16
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Straw18
Straw19
Straw20
Straw21
Straw22
Straw23
Straw24
Straw26
Straw27
Straw28
Straw29
Straw30
Straw31
Straw32
Straw33
Straw34
1 0.5 0 1 Mile
0 8,000 Feet
1 0.5 0 1 Kilometer
N
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