Natural Hazard Study for the Lake Tahoe Basin Management Unit

Prepared by: ______________________________Date:______________

Tera Curren

Geologist

Eldorado National Forest

Prepared by: ______________________________Date:______________

Thomas E. Koler, Ph.D., P.G.

Geologist

Eldorado National Forest

Reviewed by: ______________________________Date:______________

James Harris

Lake Tahoe Basin Management Unit Hydrologist

Reviewed by: ______________________________Date:_____________

Susan Norman

Lake Tahoe Basin Management Physical Sciences Group Leader

Table of Contents

List of Tables

List of Figures

Executive Summary

This report provides an overview of the geologic risks as natural occurrences within the Lake Tahoe Basin Management Unit (LTBMU). This work included the compilation of information from the available literature and the review of previous geologic work within the LTBMU, including a field verification of previous mapping of the geologic hazards.

Hazard and risk are not synonyms in the risk management sciences. Geologic hazards include a litany of processes. For this study the potentially hazardous geologic processes are landslides (i.e., rockfall, landslides, debris flows and torrents), snow avalanches, seismic activity, lake tsunamis (i.e., seiches), and volcanic activity. In a geologic risk analysis the hazards are evaluated for the likelihood (i.e., chance or probability) that the geologic process will occur. The next step in the risk analysis is to predict what the consequences will be for a particular hazard likelihood. For example in an hypothetical case, an active landslide is located two miles from Highway 50 and 100 feet above a house (i.e., the two resources at risk are the highway and the house). Because this is an active landslide, the likelihood of it continuing to occur is probable and the deposits from the landslide are predicted by geologists to travel 200 feet if a heavy rainfall occurs in the future. In the case of Highway 50, the consequence from this landslide movement is not pertinent (i.e., the landslide and its deposits will remain two miles away) and therefore the risk is very low. However, in the house scenario, the landslide deposit is almost certain to encroach or bury the house and therefore the risk is very high. But how does one determine the likelihood that a geologic hazard will occur? How did we determine that the likelihood in the hypothetical case is probable?

We determined the likelihood by using two approaches in this project. In the first approach, for landslides and snow avalanches, we used the steepness of the hill slope. In the second approach, for seismic activity, seiches and volcanic activity, we used the geologic history of the Lake Tahoe Basin. In the first approach we know from the scientific literature as well as empirical studies on the adjacent Eldorado National Forest, that the hill slopes with gradients of 60% or greater (approximately 58°) are more likely to have landslide movement than the gentle slopes of 59% or less. Therefore the hill slope gradient of 60% was used as a "threshold value" for assigning a high likelihood of landslide movement. For the gentle slopes the hazard was assigned lower likelihoods. In the second approach we know from the geologic history of the Basin that volcanism last occurred sometime between several thousand years ago to a few million years ago. Therefore, in the next ten to fifty years it is unlikely that a volcanic event will occur (if it last occurred several thousand years ago it is unlikely that it will occur again soon). And in a similar vein we did the same with lake tsunamis (seiches). Although seiches do occur on Lake Tahoe, they are not known to occur with any regularity and the most recent is estimated to have occurred several hundred years ago. Therefore seiches were assigned lower probabilities for occurring than for the landslides.

Table 3 on page 18 of this report provides the information that we used in determining the geologic risks within the LTBMU. The likelihood descriptors used in Table 3 are from Table 1 on page 5. The spatial locations of the geologic risks are shown in Figure 4 on page 20. A person who may be interested in finding out what the geologic risk is for a given area would do the following: 1.) locate the site of interest on

the risk map (Figure 4); 2) locate the geomorphic map unit for the site of interest (using Figure 5 on page 21); 3) if the risk rating is "high" for landslide map units, the limiting factor is the steepness of the slope of 60% or greater (please refer to the slope class map in Figure 6 on page 22); 4) if the risk rating is "high" for non-landslide map units, the limiting factor is the nearness to the risk source. For these non-landslide map units the interpretation may not be as obvious because of the age of the volcanic, seismic and seich events.

In summary, the Lake Tahoe Basin is geologically active and therefore geologic risks will continue for millennia to come. To find what the geologic risk is for a given area, one must first determine what the hazard is and its likelihood of occurring, secondly the potential consequence must be assess, and thirdly the risk rating is determined from the combination of the hazard likelihood and predicted consequence.

Introduction

The Lake Tahoe Basin Management Unit (LTBMU) is currently in the process of evaluating areas that need work for updating the Forest Plan. In this regard the LTBMU has identified the need to complete a quality assurance/quality control of the existing geologic hazard mapping and if necessary make appropriate corrections and additions to the existing TEUI[1]. The geologic hazards data are contained in the geomorphology GIS layer and include a litany of processes and landforms: eroding hillslopes; stream channels; colluvial hillslopes and aprons; debris slides and flows; rotational landslides (including translational landslides) rock avalanche sources; frost action; snow avalanche sources; snow runout zones; inner gorges; volcanic plateaus and cones; glacial erosion and deposition areas, glacial cirques, moraines, outwash and terraces. This work was completed by aerial photographic interpretations combined with existing geologic hazard data (e.g., geology maps, previous reports, et cetera) in the late 1990s and early 2000s by Scott Dailey, geologist for AMSAT (an Enterprise Team).

Geologic hazards can be evaluated quantitatively and qualitatively. In quantitative analysis the geologic risk is evaluated by calculating the hazard probability and multiplying this numeric value with the consequence(s) numerical value(s)[2]. In a qualitative analysis the geologic risk is evaluated in which a narrative is provided describing the likelihood of the existing or potential hazard occurring with the measure of consequences that may result (Wu et al., 1996; Koler, 1998 and 2005; Fell et al., 2005). Both the quantitative and qualitative approaches to assessing risk are viable. Although the numerical approach can be difficult to complete it will provide sufficient information to assess the vulnerabilities to loss of life, limb and property as consequences. The numerical approach is, unfortunately, costly and time-consuming. Work for updating the

---

[1] Terra is the U.S. Forest Service's Natural Resource Information System (NRIS) module containing core terrestrial ecology data that includes soils, geology, geomorphology, ecological classification, and potential natural vegetation (R5 Letter to Forest Supervisors, September, 2003). TEUI stands for terrestrial ecologic unit inventory. Terra is not an acronym and simply represents a shortened form of the terrestrial ecological database moniker.

[2] Risk = (hazard probability) * (consequences).

geologic hazards within the LTBMU will therefore entail a qualitative analysis using a modification by Koler of Fell et al. work (2005) as displayed in Table 1.

In 2004 a call for proposals was issued by the Tahoe Regional Planning Agency (TRPA) and the LTBMU responded with a proposal for completing an update to the natural hazards in the Lake Tahoe Basin. The following Project Description section is a summary of the LTBMU proposal to the TRPA as provided by Denise Downie, LTBMU Soil Scientist (modified by Koler).

Table 1: Qualitative terminology for use in assessing geologic risk to property (modified from Fell et al., 2005)

Qualitative measures of likelihood of geologic hazards	
Descriptor	**Description**
Almost certain	The event is expected to occur
Likely	The event will probably occur under adverse conditions
Possible	The event could occur under adverse conditions
Unlikely	The event could occur under very adverse circumstances
Rare	The event is conceivable but only under exceptional circumstances
Not credible	The event is inconceivable or fanciful

Qualitative measures of consequences to the resource	
Catastrophic	Resource is completely destroyed or large scale damage occurs requiring major engineering works for stabilization
Major	Extensive damage to most of the resource, or extending beyond site boundaries requiring significant stabilization
Medium	Moderate damage to some of the resource, or significant part of the site requires large stabilization works
Minor	Limited damage to part of the resource, or part of the site requires some reinstatement/stabilization works
Insignificant	Little damage

Qualitative risk analysis matrix – classes of risk to resource					
	Consequences to the resource				
Likelihood	Catastrophic	Major	Medium	Minor	Insignificant
Almost certain	VH	VH	H	H	H
Likely	VH	H	H	M	L-M
Possible	H	H	M	L-M	VL-L
Unlikely	M-H	M	L-M	VL-L	VL
Rare	M-L	L-M	VL-L	VL	VL
Not credible	VL	VL	VL	VL	VL

Legend – VH: very high risk; H: high risk; M: moderate risk; L: low risk; VL: very low risk

Project Description

- Write a report describing natural hazards in the Lake Tahoe Basin, including but not limited to rockfalls, landslides, snow and rock avalanches, debris flows, volcanic eruption, flooding, and seismic hazards.
- Compile a GIS map from existing sources showing location, nature, and intensity of hazards. Map would meet USFS national standards and would be compatible with the USFS NRIS database.
- Correlate new USFS geomorphic mapping with Robert Bailey's geomorphic mapping
- Compile bibliography of technical guides keyed to hazard types in the report to be used as a reference for making land use planning and permitting decisions.
- Provide all information in digital format that can be made available on the Tahoe Integrated Information Management Systems (TIIMS).
- This project would provide a set of interpretations that would be part of the LTBMU Terrestrial Ecologic Unit Inventory.

A similar report was prepared by the Tahoe Regional Planning Agency in cooperation with an engineering geology firm (O'Rourke and Cooper, 1974), but the associated map has been lost. Some of the information is still current, but much needs updating, particularly seismic hazards, which have been the subject of several recent research efforts. A new geomorphic map has been completed by the Forest Service; a new geologic map has been compiled by the California Geological Survey (Saucedo, 2005); additional geologic maps of several quadrangles have been recently completed, and new and ongoing seismic mapping and research are changing the perception of seismic hazard in the Tahoe Basin.

The US Forest Service addressed natural hazards in its 1988 Land and Resource Management Plan, and the Tahoe Regional Planning Agency addresses natural hazards in its Code of Ordinances. Work in the late 1900s and early 2000s was completed by Scott Dailey, geologist with AMSAT (an Enterprise Team) to map and develop a GIS geomorphic layer meeting USFS GIS requirements. The product from this work is an inventory and GIS layer portraying geomorphic polygons, an example of which is shown in a photo in Figure 1.

All of this information needs to be updated for the current Pathway 2007 plan revision effort, but neither agency currently has staff able to undertake this task. Therefore the LTBMU has released this work to the Eldorado National Forest geology staff. Anticipated uses for the product are described below.

Response to Natural Disasters

If a major earthquake occurs, it will be necessary to rescue hikers and bikers who may be trapped by rockfalls, rockslides, and other major slope failures. Knowing where these are most likely to occur would facilitate finding and rescuing people. At present, this information could not be assembled quickly enough to be useful in an emergency. In the event of a large wildfire, it will be useful to know where major slope failures are likely to occur in order to keep firefighters from being injured or stranded. After a wildfire, it will be useful to know where slope failures and flooding are likely to occur in order to prescribe emergency restoration treatments to protect life and property.

Figure 1: View north across Big Meadow mapped as Polygon #37, a fluvial/glacial deposit map unit.

Land Use Planning

Both the Tahoe Regional Planning Agency and the US Forest Service would use these products to inform land use planning decisions. Knowledge about the location and nature of natural hazards is necessary for effectively locating many types of construction projects and identifying the geotechnical issues that may be involved with such projects.

Land Use Permitting

The Tahoe Regional Planning Agency would use these products to aid in land use permitting decisions. When permits are requested in an area with a known hazard, the technical references in this document would guide decisions about permit requirements.

Project Products

The products produced in this project will help in making management decisions and some of which will contribute to public safety and welfare. These products can also serve as a comprehensive source of public information on natural geologic hazards in the Lake Tahoe Basin that could be used by local agencies and governments as well as by the general public.

Literature Review

General Background

A great deal of geological work has been completed within the Lake Tahoe Basin over the past one-hundred plus years. Lindgren (1897) was the first geologist to recognize that the lake sits in a graben (please refer to glossary for geologic definitions). Important works by Birkeland (1963, 1964, 1966 and 1968) updated this previous work and provided the origin and evolution of the Lake Tahoe area. His work included descriptions of lava and glacial dams along the Truckee River as well as the glacial activity of Lake Tahoe during the Donner Lake and Tahoe glaciations. Early seismic profile work of the lake bottom was completed by Hyne (1969) and Hyne et al. (1972 and 1973) and Court et al. (1972). These researchers were able to document evidence for active faults and landslides along the lake floor. Subsequent work by Henyey and Palmer (1974) concluded that the lake bottom mounds are of nonvolcanic origin. Geologic hazards were comprehensively studied by Cooper and O'Rourke (1974). And recent work by Schweickert et al. (1999a, 1999b, 2000a, 2000b, and 2000c) updated the information concerning geologic hazards within the basin.

Granodiorite of the Sierra Nevada batholith underlies most of the Lake Tahoe Basin (Burnett, 1968). Within the northern and northwestern sections of the basin the area is covered with andesitic volcanic rocks. Quaternary glacial deposits blanket the southwestern and southern part of the lake. Immediately to the west of the lake the geomorphology is heavily influenced by glaciation during the Pleistocene. To the east this appears to not be the case within the Carson Range.

Numerous geologic maps have been completed in parts of the basin. These include Wahrhaftig and Curtis (1965), Matthews (1968), Tabor and Ellen (1975), Bonham and Burnett (1976), Trexler (1977), Pease (1980), Loomis (1981), Wagner et al. (1981), Harwood (1981 and 1992), Armin and John (1983), Latham (1985), Grose (1985 and 1986), Lewis (1988), Fisher (1989 and 1992), Sabine (1992), Saucedo and Wagner (1992), and most recently Saucedo (2005).

Structural Geology and Tectonics

There continues to be a debate concerning the timing of the Lake Tahoe graben, but the initial work by Wahrhaftig and Curtis (1965) is still considered a reasonable interpretation. These researchers have proposed that the basin was formed after andesitic volcanism and deformation between 7.4- and 2.6-Ma (million years ago). Lake Tahoe is considered to be the westernmost graben of the Basin and Range physiographic province. The western faults of the graben have been mapped as normal faults (Le Conte, 1875; Lindgren, 1897; Lauderback, 1924; Hudson, 1948 and 1951; Pakiser, 1960; and, Burnett, 1968). The faults along the eastern boundary have been identified by Burnett (1968) through inference from the shape of the basin.

The graben was not initially closed in its present form and three hypotheses provide interpretations for the formation of the lake:

1) Birkeland (1964) suggests that a blockage of the northern end of the graben was formed by a buried fault block.

2) Lauderback (1911) inferred that a buildup of andesitic mudflow breccias from the Martis Peak area created the closure of the basin.

3) Blackwelder (1933) proposed that north end was uplifted through a combination of bedrock warping and faulting.

The exact timing of the partial closure of the northern part of the basin still continues to be debated, but work by Burnett (1968) has dated the volcanics overlying the earliest lake deposits have been dated to 1.9 ± 0.1 Ma. Therefore, a latest Pliocene-earliest Pleistocene age has been suggested for the initial filling of the lake.

On-going studies indicate that the Sierra Nevada did not exist as a topographic high before Miocene time (e.g., Bateman and Warhraftig, 1966; and Unruh, 1991). A date of 9-Ma for initiation of tectonic uplift on the eastern front of the Sierra Nevada has been proposed by several researchers (e.g., Dalrymple, 1964; and Huber, 1981). However, a paleontological study provides a hypothesis that uplift did not start until 5-Ma. This work suggests that flora preserved in the Miocene Coal Valley Formation of western Nevada could not have lived in the rain shadow of a mountain range like the present Sierra Nevada (Axelrod, 1958). Later paleontological studies by Wolfe (1994) and Wolfe et al. (1997) pose a different hypothesis that the ancestral Basin and Range province was a broad topographic high that collapsed behind the Sierra approximately 12-Ma. Other research suggests that uplift did not start until 3- to 4-Ma based on the ancestral drainage patterns of western Sierran rivers (Huber, 1981) or 8.4- to 3.4-Ma based on tectonic block tilting (Unruh, 1991). The tilt and uplift may have been enhanced by the unroofing of the Sierra Nevada and sediment loading in the Great Valley to the west (Small and Anderson, 1995). Therefore the exact timing of the creation of the Sierra Nevada Mountain Range remains controversial.

Seismic Activity

Seismotectonic analyses of the basin area have been completed by Hawkins et al. (1986), and Schweickert et al. (2000c). The work published in 1986 concluded that Magnitude 7 earthquakes are possible on faults such as the West Tahoe fault and the

North Tahoe fault. Schweickert et al. (2000c) found that there are three major fault zones within the basin: (1) the North Tahoe-Incline Village fault zone trending northeast-southwest; (2) West Tahoe-Dollar Point fault zone trending north-south; and, (3) Tahoe-Sierra frontal fault zone trending northwest. Currently the initiation of faulting along the eastern boundary of the Sierra Nevada is thought to have occurred 9-Ma (Dalrymple, 1964; and Huber, 1981). Schweickert et al. (1999a and b, 2000a and b) and Lahren et al. (1999) produced preliminary maps and interpretations of active faults and landslides associated with faulting within the Lake Tahoe Basin. Ichinose et al. (1999 and 2000) provided reports on recent earthquakes and model results of seiches on Lake Tahoe.

Bathymetry, Lake Sediments and Landslides

Prior to the work completed by Schweickert et al. (2000c) there have been very few bathymetric studies of the lake floor for better understanding geologic hazards within the basin area (Gardner et al., 1999). Only a few depth measurements were made before 1923 and these were made by fishermen or by Charles Burckhalter of the U.S. Naval Observatory (McGlasham and McGlasham, 1986). In 1923 the U.S. Coast and Geodetic Survey surveyed Lake Tahoe using a leadline-sounding technique (U.S. Coast and Geodetic Survey, 1923). Research completed by Gardner et al. (1998, 1999 and 2000) showed that numerous landslide deposits cover the lake floor. A 1999 manuscript by Moore et al. reported preliminary results of dredge haul samples from large landslide blocks on the floor of the lake. In addition to the landslide deposits there is also a volcanic ash layer that has been identified near the bottom of the sediment strata composed of Mazama Ash from Crater Lake (Hyne, 1969; and Bacon, 1983). From radiocarbon dating of the sediments the rate of average sedimentation has been calculated to be approximately 15-cm/ky (centimeters per thousand years) for the past 10 ky (Hyne et al., 1972). The great size of the landslide deposits on the lake floor is interpreted by Gardner et al. (1999) to indicate that one consequence from landslides entering the lake is seiches. From their work they have estimated that a large landslide entering Lake Tahoe will produce a seiche wave 101-m high (308-feet high). Work by Schweickert et al. (2000c) provides similar interpretations. They pose the possibility that the large landslide deposits are from landslides occurring along the West Tahoe-Dollar Point fault zone. Although it is circumstantial the evidence seems to point towards the landslide initiations being controlled by seismicity.

Geologic Hazards

Work completed by Cooper and O'Rourke (1974) was a benchmark paper that has been available for the last three decades for planners and policy makers in the Lake Tahoe Basin. Although the document is dated, the geological discussion and conclusions derived from this work remain remarkably similar to today's on-going research. These authors approached this work with a geotechnical perspective by inventorying and characterizing the geologic hazards in a broad sense of risk. This was before risk was recognized in the scientific literature as a function of hazard probability multiplied by predicted consequences. The products from this work include a geotechnical report with accompanying hazard maps. A final product (discussed in the 1974 document) was to be a natural hazards planning guide to be completed in cooperation with the Tahoe Regional Planning Agency.

Risk in this report is frequently substituted for the word hazard which in today's geologic literature is not accepted. Table 2 provides a list of geologic risks (sic) and the various ratings of low (L) to moderate (M) to high (H) are hazards in the sense that there is some likelihood or probability that the hazard event will occur. The information in the table was compiled by Mathews and Burnett (1971) and later modified by Cooper and O'Rourke (1974).

These authors identified several areas within the Lake Tahoe Basin that had undergone slope instability. They document that in 1953 a rockslide occurred along the road-cut of Emerald Bay. During the winter of 1955-1956, a second slide occurred at this location and at least 200,000-cy of material slid onto the road and into Emerald Bay. The authors cite Glancy (1969) who evaluated a 1967 mudflow (sic, probably more correct to label as a debris flow) estimated to be more than 50,000-cy of material that occurred in response to storm water flowing across poorly indurated volcanic rocks adjacent to Second Creek near Incline Village. Cooper and O'Rourke use the term mass-wasting as an umbrella term to cover all types of landslides. They identified a large deep-seated landslide that was active in 1852 at Slide Mountain, just northeast of the Lake Tahoe Basin, in which 125,000,000-cy of material moved in response to the 1852 earthquake.

In addition to slope instability Cooper and O'Rourke (1974) described several other natural hazards including erosion, snow avalanches, frozen ground, expansive soils, flooding, volcanic, and seismic hazards. The authors describe most of these hazards in broad terms. Erosion is identified as commonly found associated with granitic and volcanic rock. Snow avalanches were identified as a potential concern within only the western side of the Lake Tahoe Basin documenting the regular avalanches that occur along Highway 89 near Emerald Bay and along Highway 50 at Meyers Grade. Frozen ground, as noted by the authors, can cause problems with road pavements and building foundations through the freeze/thaw process. Expansive soils were not labeled as a major concern and the more susceptible soils were found associated with volcanic rocks that produce montmorillonite (now more commonly referred to in the geologic literature as smectite). Flooding was assigned as a minor hazard with the possible exception of flash flooding associated within developed areas with large surface areas covered in concrete or asphalt. Although volcanic activity has occurred in recent geologic history (several thousands of years ago to a few million years ago) the authors assigned a low probability of volcanic activity. And lastly, their coverage of seismic hazards was rudimentary at best.

Table 2: Potential environmental problems related to geologic units in the Lake Tahoe Drainage Basin (modified after Mathews and Burnett, 1971, by Cooper and O'Rourke (1974).

Geologic Map Symbol	Geologic Unit	Degree of Consolidation	Stream Channel Stability	Erosion Siltation Potential	Soil Creep	Natural Landslide Potential	Disturbed Landslide Potential	Seismic Hazard Potential
Qal	Alluvium	L – M	M – H	M – H	L	L	M	M - H
Ql	Recent Lake Sediments	L – M	L – M	H	L – M	L – M	H	L - M
Qlo	Older Lake Sediments	L – M	M	M – H	L	L – M	M	L – M
Qta	Talus	L	L	L – M	M – H	L – M	H	M – H
Qls	Landslide Deposits	L	L	H	H	H	H	H
Qg	Glacial Outwash	L	M	M – H	L	L – M	M	M – H
Qm	Moraines	L – M	L – M	M – H	L – M	M	M – H	M
Qv	Intrusive Volcanic Rocks	H	H	L	L	L	L	L
Tv	Volcanic Rocks	H	H	L – H	L	L	L – M	L
Tvp	Pyroclastic Rocks	L – M	L – M	M – H	M	M	M – H	M
gr	Granitic Rocks	H	H	L	L	L	L – M	L
grd	Decomposed Granitic Rocks	L	L	H	H	M	H	L – M
di	Intrusive Rocks (Diorite)	H	H	L	L	L	L – M	L
ms	Meta-sedimentary Rocks	H	H	L	L	L	M – H	L – M
mv	Meta-volcanic Rocks	H	H	L	L	L	M – H	L – M
m	Undifferentiated Metamorphic Rocks	H	H	L	L	L	M – H	L – M

Figure 2: View south looking at Polygon #24, a fluvial/glacially eroded map unit.

Findings

All TEUI geomorphic polygons that were field-verified were determined to be accurate for planning scale applications. Some modifications may be made for boundaries based on professional judgment on a case-by-case basis; however, the current quality of the data is very high. Therefore there are no recommendations to make any major changes to the current TEUI. One suggestion for consideration is to provide a narrative for each polygon that outlines the characteristics of geomorphic features within the polygons as well as the potential hazards, consequences and risks. This can be accomplished on a project-by-project basis and stored in the GIS library. Although there are 716 polygons (excluding the 88 labeled as “water”), this task can probably be accomplished over the next few fiscal years. The usefulness of the narratives would be to help the non-geologist better understand characteristics and conditions within the polygons.

Without question the Lake Tahoe area, including the Lake Tahoe Basin Management Unit (LTBMU), is geologically active with the potential for a variety of geologic hazards to occur. The presence of geologic hazards or the potential for them to occur does not necessarily imply that this area is swathed with high geologic risks. Geologic risks are by definition the multiplication of the likelihood that a geologic hazard will occur by the consequences resulting from that movement. For example, a hazard with a “possible” descriptor in Table 1 (i.e., the event could occur under adverse conditions) is only high if the consequences are “major” or “catastrophic.” Conversely, an “almost certain” likelihood will result in high to very high risk characterizations for any consequences, even for the “insignificant” (i.e., little damage) consequence. Therefore, it is critical for the scientist or engineer responsible for the qualitative risk assessment to be careful in his/her evaluation of not only the geologic hazard but also of the consequences.

Interested individuals may retrieve information concerning an area of interest by the following steps: 1) locate the area of interest on the risk map (Figure 4); 2) locate the geomorphic map unit for the site of interest (using Figure 5); and, using the slope class map (Figure 6) locate whether or not the site of interest is on gentle slopes (60% or less) or steep slopes (greater than 60%). This information, in combination with the information in Table 1, will provide the individual with materials for determining the geologic risk for the area of interest. However, for areas where there is a high geologic risk, we recommend that this determination be confirmed by a licensed professional geologist.

The following findings provide a narrative for each of the geologic hazards identified by previous workers as well as a summary of the existing and potential geologic hazards recorded within the LTBMU's GIS geomorphology layer. Estimated risk values for each of these hazards are provided in Table 3. These values are suitable only for preliminary planning purposes and should not be used beyond this level without field verification.

Several geomorphic processes and landforms have been identified within the LTBMU TEUI; however, only three processes were identified by previous workers as the dominant geomorphic processes. These are fluvial (F), lacustrine (L) and mass-wasting (MW). Subordinate to these dominant processes are a litany including eroding hillslopes, stream channels, colluvial hillslopes, debris slides and flows, landslides, rock avalanche sources, and so on. This delineation by previous workers makes sense for the LTBMU. The LTBMU is only some 200,000-acres within a geologically constrained setting. The constraint comes from the structural geology (i.e., hinged graben) with a strong glacial and volcanic overprint. The glacial and volcanic processes are now relict and hence can not be identified as dominant geomorphic processes (i.e., by agency convention we only use the current dominant process in mapping TEUI units). Therefore the hazard/risk assessment in this report is focused on solely the fluvial, lacustrine and mass-wasting processes.

Previous work within the Eldorado National Forest (Prellwitz and Koler, 2003) indicates that soils in this part of the Sierras have shear strength properties with angles of internal friction averaging 30°. Since most of these soils are cohesionless an assumption can be made that the friction angle approximates an angle of repose[3]. Any slope with a gradient greater than 30° (i.e., 58% or roughly 60%) is above the angle of repose. Therefore a "threshold" value for slopes greater than 60% were deemed to be potentially more unstable than the gentler slopes as displayed in Tables 3. Table 4 provides a summary of risk values for low, moderate and high risk that can be used with Figure 4 (or Plate I in the back cover jacket) in locating areas of interest.

Known Geologic Hazards

Avalanche Chutes

Snow avalanches have been identified by geologists and engineers as a potential concern within the western side of the Lake Tahoe Basin. Past avalanches have occurred

[3] Angle of repose is only comparable to cohesionless soils.

along Highway 89 near Emerald Bay and along Highway 50 at Meyers Grade. The shorthand designator for snow avalanche source areas in the TEUI layer is “SAS.” None of the polygons within the geomorphology layer have been designated SAS as the dominate geomorphic process/landform. However, they are contained within the “GE” (glacial – erosional) map unit as a map inclusion and documented as such in Table 3. Estimated risk values for avalanche chutes in Table 3 vary from low to high for steep slopes and very low to low for the gentler slopes.

Rockfall

Potential rockfall occurs where bedrock joints, fractures and other types of planar features are exposed in a rock face with the features dipping out of the slope. Rockfall can also occur where large, steep-sloped, glacial deposits of boulder-size materials have been made such as moraines. Rockfall potential exists across the LTBMU, especially on the western side of the basin. In the geomorphology layer rockfall is characterized within the mass-wasting category with the shorthand “MW.” In the basin the most common area for locating rockfall hazards are within the MW/GE map units. Rockfall has a wide range of risk values in Table 3. For hill slopes greater than 60% gradient, the risk values are low to very high whereas for gentler slopes, 0% to 60%, the risk values are much lower – very low to moderate.

In a rockfall analysis for the Geology BAER Report for the Angora Wildfire (Koler, 2007), the computer simulation of unvegetated hill slopes of the glacial moraine located above Fallen Leaf Lake showed that some rockfall is possible but the likelihood was assigned a “rare” value. However, the consequences were assigned a “medium” value in recognition that when the rare rockfall event occurs it has the potential of resulting in some damage to structures. Therefore the estimated risk value was given a very low to low rating. Later this summer this observation was given some credence with the unfortunate damage to a private residence from rockfall occurring near Fallen Leaf Lake. Although the damage was unfortunate, it was not widespread and catastrophic to merit an increase in the risk rating.

Landslides

There are a wide variety of landslides within the LTBMU, all of which have been categorized in the geomorphic layer under the designation of “MW.” Landslides can be initiated from a variety of geological materials but in all cases the two controlling parameters for slope instability are the hill slope gradient and the amount of ground water within the slide mass for non-seismically induced failures. In rare situations it is possible that the only controlling parameter is ground water, for example saturated, gentle gradient hill slopes can be unstable. Seismically induced failures, those near active fault zones for example, will fail due to accelerated forces acting on the slide masses. In worst case situations a combination of steep, saturated slopes undergoing a seismic event will result in failure.

Large landslide events in the basin have been documented by several geologists. Some of these have deposited their materials along the floor of Lake Tahoe leaving a hummocky bathymetry. The source areas for these deposits are the hill slopes above the western side of Lake Tahoe. For example, numerous landslides have occurred within the Emerald Bay area in 1953, and in the winter of 1955-1956. The second event deposited at least 200,000-cy of material onto Highway 89. The large landslide deposits on the floor of the lake are probably from landslides induced by large magnitude earthquakes, although this hypothesis remains untested. On the eastern side of the lake the hill slopes within US Forest System lands are gentler and appear to be more stable than the western side.

Estimated risk values for landslide hazards are low to very high for the steep slopes and very low to high for the gentle slopes. As stated above, most of the high risk landslide areas are located within the hill slopes above the western side of Lake Tahoe. Figure 3 shows an example from this area in which the source materials are glacial (till in this case). The landslide is inactive and probably will not be re-activated unless some combination of heavy rainfall and/or seismic event occurs.

Figure 3: Geomorphic Polygon #335, a mass-wasting/glacially-deposited map unit. This area is mapped as Quaternary till materials by Saucedo (2005).

Debris Flows/Torrents

Debris flows are landslides according to landslide nomenclature (e.g., Cruden and Varnes, 1996) with a gradation from landslides to flows based on water content, mobility and evolution of the movement. If the water content increases significantly the debris flow then becomes a debris torrent sometimes referred to as a hyperconcentrated flow. Debris flows can occur within stream channels and from hill slopes. Stream channel-initiated debris flows occur where large landslide deposits form part of the stream channel geometry or from a deep terrace deposit adjacent to the channel. Here the debris flows fail in response to a rise in the stream flow as well as increases in ground water levels. On hill slopes the common source areas are in stream head areas sometimes referred to as zero-order basins or colluvial-filled bedrock hollows.

Glancy (1969) evaluated a 1967 debris flow estimated to be more than 50,000-cy of material that occurred in response to storm water flowing across poorly indurated volcanic rocks adjacent to Second Creek near Incline Village. Other debris flow areas include the deposits located along Angora Creek mapped and evaluated in the Geology BAER Report for the Angora Wildfire (Koler, 2007). Estimated risk values for debris flows from steep slopes range from moderate to very high and for gentler slopes the risk values range from very low to high.

Seismic

The Lake Tahoe area is a seismically active area with estimates of possible earthquake magnitudes as high as 7 along faults such as the West Tahoe fault and the North Tahoe fault. The results from large magnitude earthquakes may include large, deep-seated landslide movement possibly similar to the enormous landslide in 1852 at Slide Mountain in which 125 million-cy of material that failed in response to the 1852 earthquake. The California Geological Survey is conducting an on-going analysis of the seismic risk within the basin and the information will be available in the near future. In the meantime, it is safe to make some broad generalizations about the seismic risk within US Forest Service System lands.

Earthquakes will occur along one of several Holocene-age faults within the basin in the future. Of note, the West Tahoe Fault Zone, the North Tahoe Fault Zone, and the Incline Village Fault Zone are all Holocene in age and researchers have documented recent movement within these fault zone. Unfortunately these fault zones lie under some of the most populated areas of the Lake Tahoe Basin, and as previously discussed, large landslide movements have occurred in the recent geologic past as indicated by the hummocky bathymetry created by landslide deposits on the lake floor. Therefore, the risk value assigned to this geologic hazard ranges within the full spectrum from very low to very high. These risk values will, hopefully, be re-fined after the work by the California Geological Survey is completed.

Seiches

Seiches are a form of "tidal wave" initiated from severe windstorms blowing across the lake's surface, large landslides entering the lake, and seismic activity from which the lake basin geometry changes suddenly. Researchers have estimated that in a worst case scenario, a seiche with a water height of 308-feet can result from a large landslide entering the lake. Therefore, the risk value for this geologic risk is given a range of very low to high. In a majority of the time this risk value will remain very low to low; for rare winter/spring storms the risk value probably increases from low to moderate and for the very rare seismic and/or landslide event the value increases to high.

Table 3: Estimated geologic hazards, consequences and risks within the LTBMU. Delineation between slopes with greater than 60% and those with 60% or less is based on a shear strength study by Prellwitz and Koler (2003).

Hazard	GIS Geomorphic Map Unit	Estimated Hazard Rating		Possible Consequences	Estimated Risk Rating		Possible Mitigation Options
		> 60% Hill Slope Gradient	≤ 60% Hill Slope Gradient		> 60% Hill Slope Gradient	≤ 60% Hill Slope Gradient	
Snow Avalanche Chutes	GE[1]	Possible to Almost Certain	Rare	Some damage to Highway 50 (Minor to Medium)	Low to High	Very Low to Low	Caltrans currently provides mitigation for minimizing avalanche hazards from occurring
Rockfall	MW[2] MW/GE and MW/GD[3]	Unlikely to Almost Certain	Rare	Medium to Catastrophic	Low to Very High	Very Low to Moderate	Warning systems, deflection walls, and nets
Landslides	MW[4]	Unlikely to Almost Certain	Rare to Possible	Medium to Catastrophic	Low to Very High	Very Low to High	Warning systems, retaining structures, dewatering of landslide mass
Debris Flows and Torrents	MW	Possible to Almost Certain	Rare to Possible	Medium to Catastrophic	Moderate to Very High	Very Low to High	Warning systems and deflection structures
Seismic	----	Rare to Almost Certain		Minor to Catastrophic	Very Low to Very High		All structures meet seismic design criteria under the Unified Building Code
Seiches	----	Rare to Possible		Minor to Catastrophic	Very Low to High		Warning systems
Volcanic	----	Rare		Minor to Catastrophic	Very Low to Moderate		----

[1] Although there are no mapped avalanche chutes mapped within the LTMBU GIS geomorphic layer, they are included as inclusions within the glacial erosional map unit (GE).
[2] MW represents mass-wasting which not only includes rockfall but also landslides and debris flows.
[3] MW/GD represents mass-wasting within glacial deposits (GD).
[4] MW may also include secondary geomorphic processes such as fluvial (F), glacial erosional and depositional processes (GE and GD). For the polygons that have a fluvial dominate process with mass-wasting as a secondary process (F/MW), the mass-wasting is usually stream bank failure or the materials through which the stream is cutting its course may be mass-wasting deposits.

Volcanic

Volcanism, to some peoples' surprise, remains as a potential geologic risk in the basin. The volcanic activity ceased several hundreds of thousands of years ago, this time frame is considered "recent" in geological terms. All of these hazards are located within the northern area of the LTBMU and basin. Little work has been completed in evaluating the potential for future eruptions and flows from volcanic activity, therefore it is difficult to provide a reasonable estimate for the risk from volcanic activities. Therefore, the risk value was given a range of very low to moderate.

Table 4: Geomorphic map unit risk value summary. Please note that these values exclude polygons labeled as "water."

Low Risk (acres)	Percent of LTBMU	Moderate Risk (acres)	Percent of LTBMU	High Risk (acres)	Percent of LTBMU	Summation (acres)
45,407.85	22.13	145,385.64	70.87	14,364.94	7.00	205,158.44

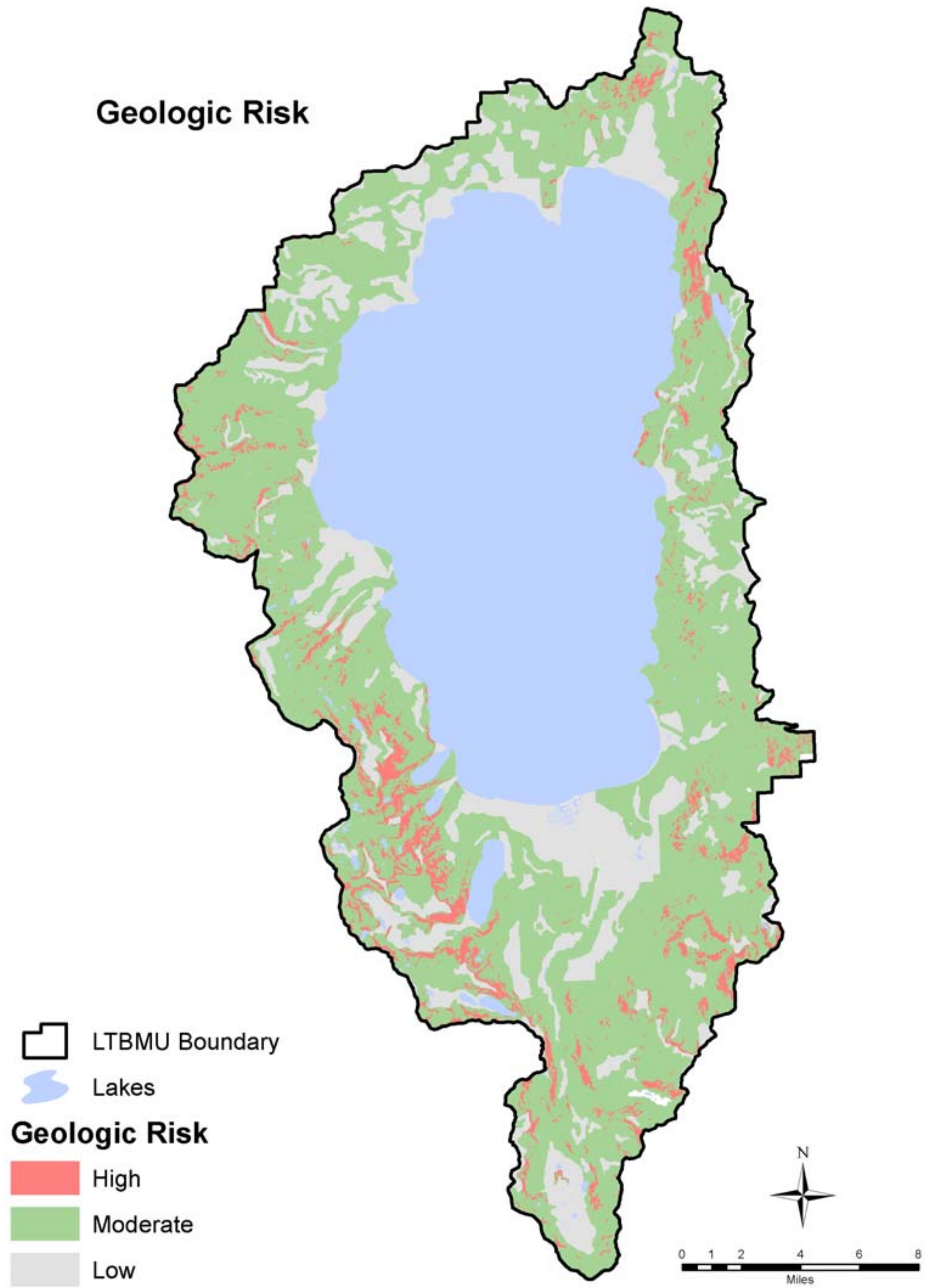

Figure 4: Geologic risk map of the LTBMU.

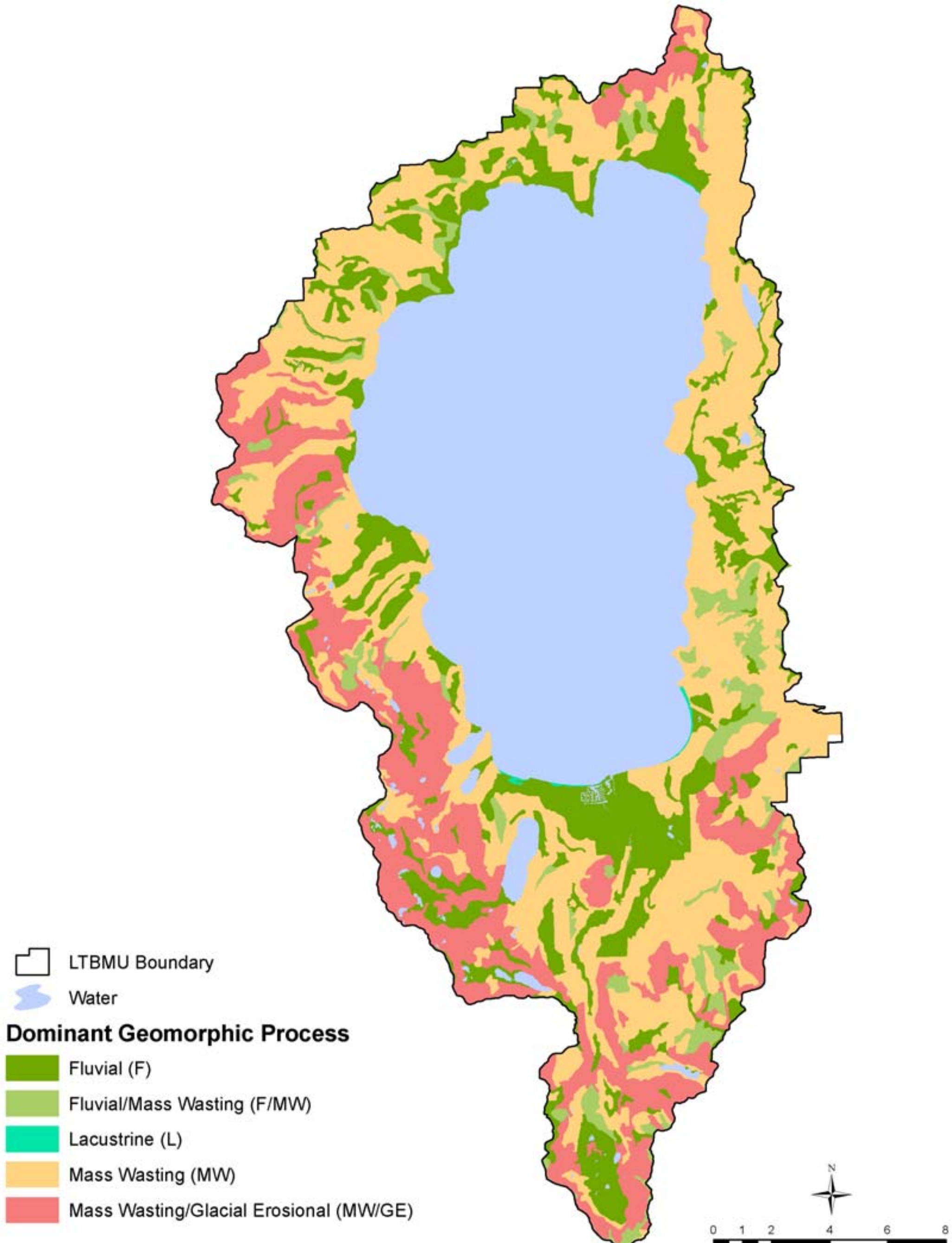

Figure 5: Modified geomorphology map showing map units discussed in the text and shown in Table 3.

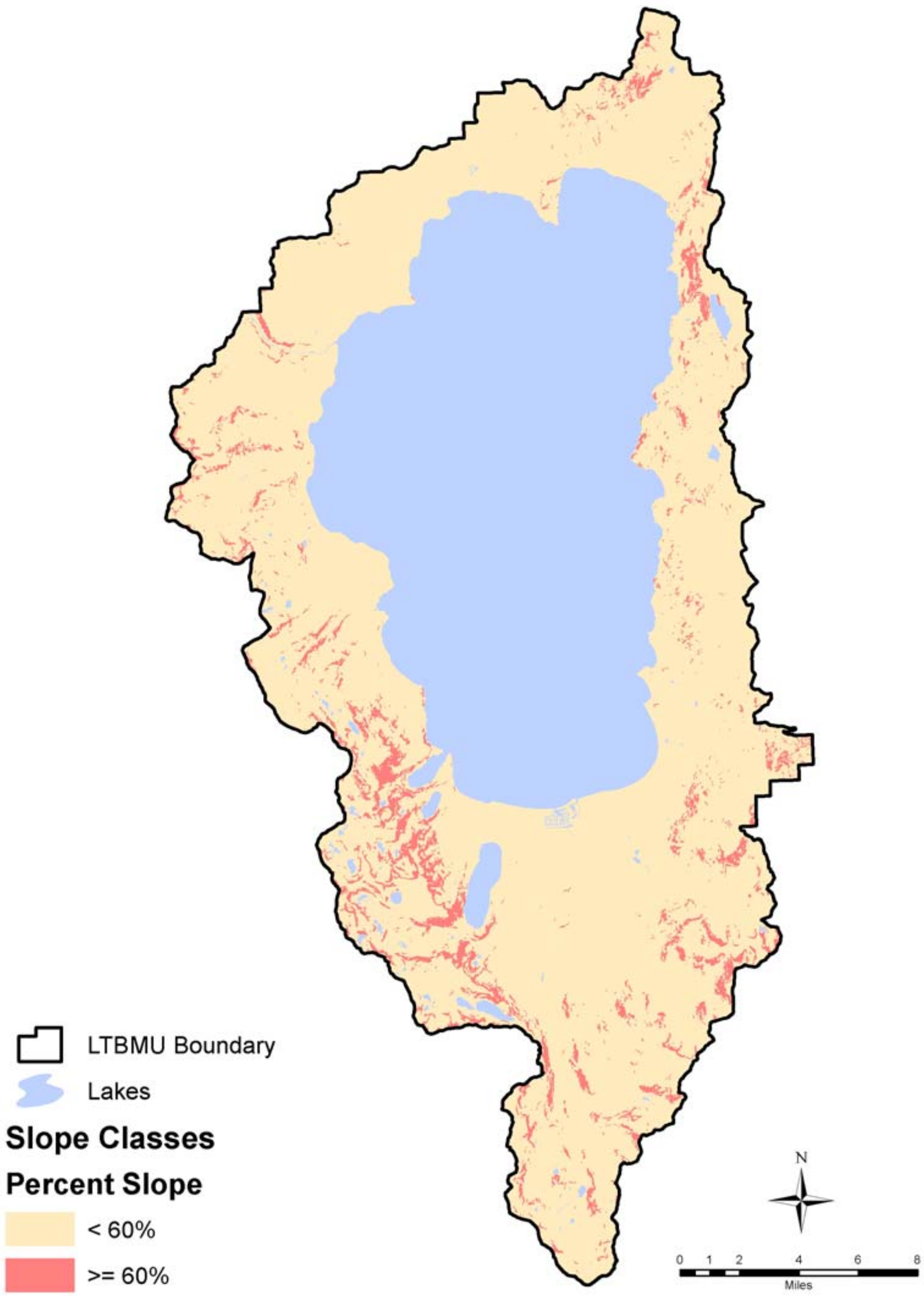

Figure 6: Slope class map.

Response to Natural Disasters

Data from the TEUI and this hazard/risk assessment can be incorporated into a venue for responding to natural disasters. In July, 2007, a wildfire was ignited and burned a little over 3,000-acres along the southeast flank of Angora ridge along the southern boundary of Fallen Leaf Lake. From the field and office analyses the risk assessment for rockfall was summarized as:

> "All of these rockfall simulations resulted in an extremely low number of rockfall reaching more than a few tens of feet from potential initiation sites. Therefore it is extremely unlikely that rockfall will result in any resource damage directly related to the vegetation mortality from the Angora Fire. However, in the event of a large seismic event (probably M 5 or greater) there is a likelihood that rockfall may occur. Therefore rockfall is assigned a very low to low risk value (i.e., rare likelihood and medium consequence equal a very low to low risk in Table 1)."

Although the risk is low, there still is the likelihood that a rockfall event can occur and result in deleterious effects. For example, later in the summer of 2007, a rockfall event occurred near but not within the wildfire area. Unfortunately damage resulted to a private residence. Because there was not widespread damage and the damage that did occur was limited to a single structure, the predicted consequence in the rockfall risk assessment was correct (i.e., medium consequence = moderate damage to some of the structure, or significant part of the site requires large stabilization works).

The other geologic hazard identified and evaluated in the Angora Geology Report (Koler, 2007) was debris flows. From the field and office analyses the risk assessment for debris flows was summarized as:

> "The most significant difference between the four resources at risk is the runout distance. As discussed above, the runout distance is defined as the slope length at which the slope gradient becomes more gentle (usually 10° or less) and the distance is several hundred feet long. Of the four resources at risk only the second (i.e., water tank and Elk Lookout Circle neighborhood) has the shortest runout distance…even this potential runout distance is several hundred feet and therefore the predicted consequence was characterized as "medium." The other three predicted consequences were characterized as "minor." Fortunately there are no areas above this resource and the other three that have a 60% and greater slope class...Therefore, the only resource at risk with a risk rating of low to moderate was the water tank and the Elk Lookout Circle neighborhood. The other resources at risk were assigned lower risk ratings."

Here the major discriminator was the break between slopes less than and greater than 60% due to the estimated shear strength values of the soils (i.e., field classified as gravels and sands, Unified Soil Classification). From several field transects and reconnaissance work there were no slopes 60% or greater within the wildfire area, and therefore the risk values were constrained to slopes less than 60% as documented above.

From the TEUI we know that the geomorphic map units within and adjacent to the Angora Ridge area are mass-wasting/glacially-deposited (MW/GD), mass-wasting/glacial outwash (MW/GO), fluvial/glacially-deposited (F/GD), and fluvial/mass-wasting/glacially-deposited (F/MW/GD). The missing element in these map units is the risk value. Based on the field and office analyses completed for the BAER report, a risk range from very low to moderate can be assigned to these polygons. For example, a numerical value of 3 can be assigned as a modifier for low to very low risk and a value of 5 can be assigned as a modifier for very low to moderate risk and a value of 7 for high to very high risk. In all cases for the sake of being conservative the highest risk value should be assigned to the polygons; therefore our map units should now be designated MW_5/GD, MW_5/GO, and F/MW_5/GD. The modifier can then be used in later projects such as in land use planning and permitting. Interestingly, when referring to Table 2 developed by Cooper and O'Rourke (1974), the risk values for materials found in glacial outwash (Qg in the table) and moraines (Qm) range from low to moderate for natural landslide potential. This provides us with some affirmation that several geologists are recognizing similar risk values over the past 30 some years.

Land Use Planning and Permitting

The current TEUI information is certainly adequate for land use planning and permitting by both the USFS and the Tahoe Regional Planning Agency. The next step is to assign a risk modifier to the individual map units as explained above. This can certainly be done on a case-by-case basis; a competent geologist can provide a risk assessment with the methods described in this document in a matter of a few days depending on the complexity and size of the map polygon. In the meantime, it is reasonable to assign risk modifiers with the information summarized in Table 3. For example for any slopes greater than 60% should have a default to high (i.e., MW_7) whereas the gentler slopes will default to moderate to high (i.e., MW_5, MW_5/GE, MW_5/GD for rockfall; and MW_{5-7}, MW_{5-7}/GE, MW_{5-7}/GD for landslides and debris flows). Field verification will be required in order to change the defaulted risk values.

Conclusions

Without question the Lake Tahoe Basin is a geologically active area and will remain so for millennia to come. However, management activities can certainly proceed with the caveat that geologic risks within management areas are addressed and mitigation alternatives provided. Information provided in this document will help in the initial evaluation of proposed management activities. It is important to note that the risk values in this report are not inviolate and absolute. This is because geologic risks are not static and the mapping of the risk areas is general and not site-specific. Therefore high risk areas may be reduced to a moderate or low risk through site-specific mapping and assessment.

Cited References

Adams, W.C., Prellwitz, R.W., and Koler, T.E., 2003, An economical approach to supplement investigations of soil relative density in forest engineering geology: SARA 2003, 12th Panamerican Conference on Soil Mechanics and Geotechnical Engineering/39th U.S. Rock Mechanics Symposium, Massachusetts Institute of Technology, June 26.

Armin, R.A., and John, D.A., 1983, Geologic map of the Freel Peak 15' quadrangle, California and Nevada: U.S. Geological Survey Miscellaneous Investigations Map I-1424, scale 1:62,500.

Axelrod, D.I., 1958, The Pliocene Verdi flora of western Nevada: University of California Publications in Geological Sciences, v. 34, no. 2, pp. 91-160.

Bacon, C.R., 1983, Eruptive history of Mount Mazama and Crater Lake caldera, Cascade Range, U.S.A.: Journal of Volcanology and Geothermal Research, v. 18, pp. 57-115.

Bateman, P.C., and Wahrhaftig, C., 1966, Geology of the Sierra Nevada: California Division of Mines and Geology Bulletin, v. 190, pp. 107-172.

Birkeland, P.W., 1963, Pleistocene volcanism and deformation of the Truckee area, north of Lake Tahoe, California: Geological Society of America Bulletin, v. 74, pp. 1453-1474.

Birkeland, P.W., 1964, Pleistocene glaciation of the northern Sierra Nevada north of Lake Tahoe, California: Journal of Geology, v. 72, pp. 810-825.

Birkeland, P.W., 1966, Tertiary and Quaternary geology along the Truckee River with emphasis on the correlation of Sierra Nevada glaciations with fluctuations of Lake Lahontan. In: Lintz, J., and Abdullah, S.K.M., (eds.), Geological Society of America Guidebook to Field Trip Excursions in Northern Nevada: University of Nevada, Reno, pp. D1-D24.

Birkeland, P.W., 1968, Correlation of Quaternary stratigraphy of the Sierra Nevada with that of Lake Lahotan area, in Morrison, R.B., and Wright, H.E., Jr., (eds.), INQUA Congress, 7th, Boulder, CO, 1965: Salt Lake City, University of Utah Press, 631 p.

Bonham, H.F., Jr., and Burnett, J.L., 1976, South Lake Tahoe folio geologic map: Nevada Bureau of Mines and Geology, scale 1:24,000.

Burnett, J.L., 1968, Geology of the south half of the Lake Tahoe Basin: California Geology, v. 24, pp. 119-127.

Cooper, R.A., and O'Rourke, J.T., 1974, Natural hazards of the Lake Tahoe Basin California-Nevada: prepared for the Tahoe Regional Planning Agency through a grant with the U.S. Department of Housing and Urban Development under provisions of Section 701 of the Housing Act of 1954; 23 p. with appendices A-E.

Court, J.E., Goldman, C.R., and Hyne, N.J., 1972, Surface sediments in Lake Tahoe – Nevada: Journal of Sedimentary Petrology, v. 42, pp. 359-377.

Cruden, D.M., and Varnes, D.J., 1996, Landslide types and processes. In: Turner, A.K., and Schuster, R.L, (eds.), Landslides Investigation and Mitigation: Transportation Research Board national Research Council Special Report 247, pp. 36-75.

Dalyrymple, G.B., 1964, Cenozoic chronology of the Sierra Nevada, California: University of California Publications in Geological Sciences, v. 46, pp. 1-41.

Fell, R., Ho, K.K.S., Lacasse, S., and Leroi, E., 2005, A framework for landslide risk assessment and management. In: Hungr, O., Fell, R., Couture, R., and Eberhardt, E., (eds.), Landslide Risk Management: Balkema Publishers, New York, pp. 3-25.

Fisher, G.R., 1989, Geologic map of the Mount Tallac roof pendant, El Dorado County, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1943, scale 1:24,000.

Fisher, G.R., 1992, The Mount Tallac roof pendant and its implications for the role of the Sailor Canyon Formation in Jurassic cordilleran tectonics [Ph.D. dissertation]: University of Nevada, Reno, 265 p.

Freese, F., 1974, Elementary Statistical Methods for Foresters: USDA Forest Service Washington Office Agricultural Handbook 317, 87 p.

Gardner, J.V., Mayer, L.A., and Hughes-Clarke, J.E., 1998, The bathymetry of Lake Tahoe, California-Nevada: U.S. Department of the Interior Geological Survey Open-File Report OF-98-509.

Gardner, J.V., Dartnell, P., Mayer, L.A., and Hughes-Clarke, J.E., 1999, Bathymetry and selected perspective views of Lake Tahoe, California and Nevada: U.S. Geological Survey Water Resources Investigations Report 99-4043, 2 sheets, scale 1:250,000.

Gardner, J.V., Mayer, L.A., and Hughes, J.E., 2000, Morphology and processes in Lake Tahoe (California-Nevada): Geological Society of America Bulletin, v. 112, pp. 736-746.

Glancy, P.A., 1969, A Mudflow in the Second Creek Drainage, Lake Tahoe, Nevada, and Its Relation to Sedimentation and Urbanization: U.S. Geological Survey Professional Paper 650-C, pp. C195-C200.

Grose, T.L.T., 1985, Glenbrook quadrangle: Nevada Bureau of Mines and Geology Map 2Bg, scale 1:24,000.

Grose, T.L.T., 1986, Marlette Lake quadrangle: Nevada Bureau of Mines and geology Map 2Cg, scale 1:24,000.

Hawkins, F.F., LaForge, R., and Hansen, R.A., 1986, Seismotectonic study of the Truckee-Lake Tahoe area, northeastern Sierra Nevada, California: U.S. Department of the Interior Bureau of Reclamation Seismotectonic Report No. 85-4, 210 p.

Harwood, D.S., 1981, Geologic map of the Granite Chief Wilderness study area and adjacent parts of the Sierra Nevada, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1273-A, scale 1:62,500.

Harwood, D.S., 1992, Stratigraphy of Paleozoic and lower Mesozoic rocks in the northern Sierra Terrane, California: U.S. Geological Survey Bulletin 1957, 78 p.

Henyey, T.L., and Parmer, D.F., 1974, Magnetic studies on Lake Tahoe, California – Nevada: Geological Society of America Bulletin, v. 85, pp. 1907-1912.

Huber, N.K., 1981, Amount and timing of late Cenozoic uplift and tilt of the central Sierra Nevada, California: Evidence from the upper San Joaquin River basin: U.S. Geological Survey, Professional Paper, v. 1197.

Hudson, F.S., 1948, Donner Pass zone of deformation, Sierra Nevada, California: Geological Society of America Bulletin, v. 59, pp. 795-800.

Hudson, F.S., 1951, Mount Lincoln-Castle Peak area, Sierra Nevada California: Geological Society of America Bulletin, v. 62, pp. 931-952.

Hyne, N.J., 1969, Sedimentology and Pleistocene geology of Lake Tahoe, California – Nevada [Ph.D. dissertation]: Los Angeles, University of Southern California, 121 p.

Hyne, N.J., Chelminski, P., Court, J.E., Gorsline, D.S., and Goldman, C.R., 1972 Quaternary history of Lake Tahoe, California – Nevada: Geological Society of America Bulletin, v. 83, pp. 1435-1448.

Hyne, N.J., Goldman, C.R., and Court, J.E., 1973, Mounds in Lake Tahoe, California – Nevada: A model for landslide topography in the subaqueous environment: Journal of Geology, v. 81, pp. 176-188.

Ichinose, G., Anderson, J., Smith, K., dePolo, D., Anooshehpoor, R., Schweickert, R.A., and Lahren, M.M., 1999, the seismotectonics of the 30 October 1998 Incline Village, Nevada, earthquake and its effects: Seismological Research Letters, v. 70, pp. 297-305.

Ichinose, G., Anderson, J., Satake, K., Schweickert, R.A., and Lahren, M.M., 2000, The potential hazard from tsunami and seiche waves generated by large earthquakes with Lake Tahoe, California-Nevada: Geophysical Research Letters, v. 27, pp. 1203-1206.

Koler, T.E., 2007, Geology BAER Report for the Angora Wildfire: USDA Forest Service document, 11 p.

Koler, T.E., 2005, Business decision-making and utility economics of large landslides within national forest system lands in the United States. In: Hungr, O., Fell, R., Couture R., and Eberhardt, E. (eds.), Landslide Risk Management: Proceedings of the International Conference on Landslide Risk Management, Vancouver, Canada, 31 May – 3 June, 2005, University of British Columbia, pp. 391- 400.

Koler, T.E., 2000, Landslide and roadway stability watershed analyses on industrial forestlands: American Society of Civil Engineers Watershed Management 2000, Colorado State University, Fort Collins.

Koler, T.E., 1998, Evaluating slope stability in forest uplands with deterministic and probabilistic models: Environmental and Engineering Geosciences Vol. IV, No. 2, pp. 185-194.

Koler T.E.,and Rollerson, T., 1999, PALCO approach to watershed analysis: Coastal Forest Site Rehabilitation Workshop, Nanaimo British Columbia, November 17.

Lahren, M.M., Schweickert, R.A., Smith, K.D., Karlin, R.D., and Howle, J.F., 1999, Active faults of the Lake Tahoe Basin, California and Nevada: Implications: Geological Society of America Abstracts and Programs, v. 31, p. A-72.

Latham, T.S., 1985, Stratigraphy, structure, and geochemistry of Plio-Pleistocene volcanic rocks of the western Basin and Range province, near Truckee, California [Ph.D. dissertation]: Davis, University of California, 341 p.

Le Conte, J., 1875, On some ancient glaciers of the Sierra: American Journal of Science, 3rd Series, v. 10, pp. 126-139.

Lewis, R.L., 1988, Geology, neotectonics, and geologic hazards of the Mount Rose 7.5' quadrangle, northern Tahoe basin, Nevada [M.S. thesis]: Golden, Colorado School of Mines.

Lindgren, E., 1897, Geologic atlas of the United States, Truckee Folio, U.S. Geological Survey Folio 39, 10 p., scale 1:125,000.

Loomis, A.A., 1981, Geologic map and sections of the Fallen Leaf quadrangle, El Dorado County, California: California Division of Mines and Geology, Map sheet 32, scale 1:62,500.

Lauderback, G.D., 1911, Lake Tahoe, California-Nevada: Journal of Geography, v. 9, pp. 277-279.

Lauderback, G.D., 1924, Period of scarp production in the Great Basin: University of California Publications in Geological Sciences, v. 15, pp. 1-44.

Matthews, R.A., 1968, Geology of the north half of the Lake Tahoe Basin: California and Nevada. In: Burnett, J.L., 1971, Geology of the Lake Tahoe Basin: California Geology, v. 24, pp. 119-127.

Matthews, R.A., and Burnett, J.L., 1971, Geology and Geomorphology of the Lake Tahoe Region, A Guide for Planning: Tahoe Regional Planning Agency.

McGlasham, M.N., and McGlasham, B.H., (eds.), 1986, From the desk of Turckee's C.F. McGlasham: The Arthur H. Clark Company, Spokane, Washington, 242 p.

Moore, J.G., Champion, D.E., and Starratt, S.W., 1999, Giant landslide blocks in Lake Tahoe: Eos, Transactions of the American Geophysical Union, v. 80, p. F443.

Pakiser, L.C., 1960, Volcanism in eastern California – A proposed eruption mechanism: U.S. Geological Survey Professional Paper 400-B, pp. B411-B414.

Pease, R.C., 1980, Genoa quadrangle: Nevada Bureau of Mines and Geology Map 1 Cg, scale 1:24,000.

Prellwitz, R.W., and Koler, T.E., 2003, Eldorado National Forest Pilot Soil Shear Strength Project: USDA Forest Service internal document.

Rollerson, M.T., Koler, T.E., and Coyle, J.M., 2000, Combining empirical and deterministic approaches for landslide hazard assessment in Northern California watersheds: Association of Engineering Geologists 43rd Annual Meeting Program with Abstracts, San Jose, California, pp. 108.

Sabine, C., 1992, Magmatic interaction in the Crystal Range suite, northern Sierra Nevada batholith, California [Ph.D. dissertation]: Reno, University of Nevada, 163 p.

Saucedo, G.J., 2005, Geologic Map of the Lake Tahoe Basin California and Nevada: California Department of Conservation Geological Survey Regional Geological Map Series 1:100,000 scale Map 4.

Saucedo, G.J., and Wagner, D.L., 1992, Geologic map of the Chico quadrangle, California: California Division of Mines and Geology, scale 1:250,000.

Schweickert, R.A., Lahren, M.M., Smith, K.D., and Karlin, R.D., 1999a, Preliminary map of active faults of the Lake Tahoe Basin: Seismological Research Letters, v. 70, pp. 306-312.

Schweickert, R.A., Lahren, M.M., Smith, K.D., and Karlin, R.D., 1999b, Holocene megalandslides in Lake Tahoe triggered by earthquake along active faults: Geological Society of America Abstracts with Programs, v. 31, p. 1-93.

Schweickert, R.A., Lahren, M.M., Karlin, R., Smith, K., and Howle, J., 2000a, Lake Tahoe Basin: Asymmetric half-graben with active faults, megalandslides, and tsunamis: Geological Society of America Abstracts with Programs, v. 32, no. 6, p. A-67

Schweickert, R.A., Lahren, M.M., Karlin, R., Smith, K., and Howle, J., 2000b, Preliminary map of active faults of the Lake Tahoe Basin, California and Nevada: Nevada Bureau of Mines and Geology Open-file Report.

Schweickert, R.A., Lahren, M.M. Karlin, R., Howle, J., and Smith, K., 2000c, Lake Tahoe active faults, landslides, and tsunamis. In: Lageson, D.R., Peters, S.G., and Lahren, M.M., (eds.), Great Basin and Sierra Nevada: Geological Society of America Field Guide 2, pp. 1-21.

Small, E.E., and Anderson, R.S., 1995, Geomorphically driven late Cenozoic rock uplift in the Sierra Nevada, California: Science, v. 270, pp. 277-280.

Tabor, R.W., and Ellen, S., 1975, Washoe City folio Geologic Map: Nevada Bureau of Mines and Geology, scale 1:24,000.

Trexler, D.T., 1977, Carson City folio geologic map: Nevada Bureau of Mines and Geology, scale 1:24,000.

U.S. Coast and Geodetic Survey, 1923, Lake Tahoe, Chart 5001, reissued as National Oceanic and Atmospheric Administration, Lake Tahoe, Chart 18665 (1992), scale 1:40,000.

Unruh, J.R., 1991, The uplift of the Sierra Nevada and implications for the late Cenozoic epeirogeny in the western Cordillera: Geological Society of America Bulletin, v. 103, pp. 1395-1404.

Wagner, D.L., Jennings, C.W., Bedrossian, T.L., and Bortugno, E.J., 1981, Geologi map of the Sacramento quadrangle, California: California Division of Mines and Geology, scale 1:250,000.

Wahrhaftig, C., and Curtis, G.H., 1965, Tahoe City to Hope Valley. In: Morrison, R.B., and Wahrhaftig, C., (eds.), Guidebook for field conference I, Northern Great Basin and California, INQUA, pp. 59-71.

Wolfe, J.A., 1994, Fossil floras indicate high altitude for west-central Nevada at 16 Ma and collapse to about present altitudes by 12 Ma (abstract): Geological Society of America Abstracts with Programs, v. 26, no. 7, p. A-521.

Wolfe, J.A., Schorn, H.E., Forest, C.E., and Molnar, P., Paleobotanical evidence for high altitudes in Nevada during the Miocene: Science, v. 276, pp. 1672-1675.

Wu, T.H., Tang, W.H., and Einstein, H.H., 1996, Landslide hazard and risk assessment. In: Turner, A.K., and Schuster, R.L., (eds.), Landslides Investigation and Mitigation: Transportation Research Board, National Research Council Special Paper 247, pp. 106-120.

Glossary

Andesitic Mudflow Breccias

A sedimentary-volcanic rock composed of angular fragments of andesite, a volcanic rock composed of sodium, iron and magnesium rich minerals. Andesite is named after the Andes Mountain Range.

Andesitic Volcanism

A volcanic rock composed of sodium, iron and magnesium rich minerals. Andesite is named after the Andes Mountain Range.

Basin and Range Physiographic Province

A large landscape within the Great Basin formed by a series of tilted fault blocks forming longitudinal, asymmetric ridges or mountains and broad, intervening basins.

Batholith

A large intrusive igneous rock that has more than 40-square miles of surface exposure.

Bedrock Warping

The slight flexing or bending of the Earth's crust on a broad or regional scale.

Graben.

An elongated topographical depression bounded by faults on the long sides. From the German word for valley.

Granodiorite

An intrusive igneous rock composed quartz and calcium and sodium feldspar.

Miocene

A geologic epoch dated from 23.8-Ma to 5.3-Ma.

Pleistocene

A geologic epoch that has been dated from 1.8-million to 8-thousand years ago.

Pliocene

A geologic epoch that has been dated from 5.3- to 1.8-million years ago.

Province

Any large area or region considered to be as a whole, all parts of which are characterized by similar features or by a geologic history differing significantly from that of adjacent areas.

Quaternary

A geologic period that dates from 1.8-Ma to the present.

Seiche

A wave produced within an enclosed basin such as lakes and reservoirs. The wave can be produced from wind, seismic activity and landslides.

Structural Geology

The study of geologic structures: faults, folds, etc., and the mechanics of how these features are formed. Structural geology is commonly applied in the study of tectonics.

Tectonics

Tectonics is the study of the structural and deformation features of the outer part of the Earth.

APPENDIX A – Statistical Sampling Calculations

Within the study area there are 523 polygons mapped by Scott Daley. Of these there are 88 polygons labeled as "water." This study was not concerned about the accuracy of the water polygons so these were dropped from the population. The strata within the population of 435 polygons included fluvial, mass wasting and lacustrine statistical strata. From Freese (1974) for calculating the sampling sizes for these strata we used the equation:

$$n = \frac{t^2 s^2}{E^2}$$

Where n = number of samples needed for 95% confidence interval
t = Student's t
s^2 = variance
E = t * standard error

Univariate statistics were completed for the population and the strata for determining Student's t, variance and standard error. The sample number calculated for the lacustrine stratum was less than one and therefore it was rounded up to one sample to be collected. The following calculations are for the fluvial and mass wasting strata.

Fluvial:

Number of polygons = 215
Student's t = 6.210
variance = 199.767
standard error = 5.770

$$E = t * SE = 6.210 * 5.770 = 35.882$$

$$n = \frac{t^2 s^2}{E^2} \cong 6$$

Six fluvial polygons samples were needed for reaching the 95% confidence interval.

Mass wasting:

Number of polygons = 215
Student's t = 5.413
variance = 262.967
standard error = 5.770

$$E = t * SE = 5.413 * 6.620 = 35.834$$

$$n = \frac{t^2 s^2}{E^2} \cong 6$$

Six mass wasting polygon samples were needed for reaching 95% confidence interval.

The final step was to randomly pick the 13 samples using a random number generator.