EXPLANATION

Very High - Existing landslides (susceptibility category A—see table 1 below); cross hatchure denotes mapped landslides with documented historical movement. High - Areas where the Petrified Forest Member of the Chinle Formation and the overlying Moenave Formation (susceptibility category B) crop out on slopes greater than 12 percent (7°).

Moderate B - Areas where the Petrified Forest Member of the Chinle Formation crops out on slopes less than 12 percent (7°) . **Moderate** C - Areas where susceptibility-category C geologic units crop out on slopes greater than

Low - Areas where susceptibility-category D geologic units crop out on slopes greater than 31

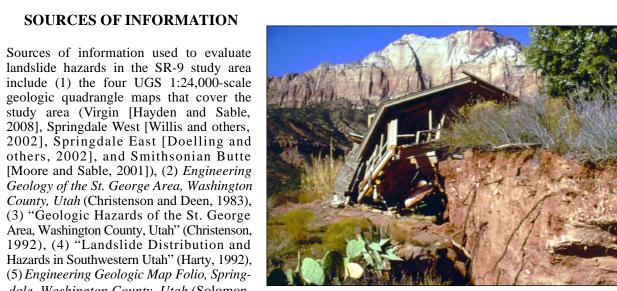
Susceptibility Category	Geologic Units ¹ Existing landslides	Comments	
A		Existing landslides are considered the most likely units in which new landslides may initiate (Ashland, 2003).	
В	Petrified Forest Mbr., Chinle Fm.; Moenave Fm. where above slopes of Petrified Forest Mbr.		
С	Harrisburg Mbr., Kaibab Fm.; Shnabkaib Mbr. and red members, Moenkopi Fm.; Moenave Fm. not above slopes of Petrified Forest Mbr.; Kayenta Fm.		
D	Remaining bedrock and unconsolidated geologic units in the study area.	These geologic units either contain a higher percentage of stronger rock types, crop out on slopes too gentle to generate landslides, or generate landslides that are too small to map at 1:24,000 scale. As a result, they exhibit few or no mapped landslides. Landslides identified within these units typically result from mass movement or erosion in underlying, weaker geologic units.	

INTRODUCTION

Numerous landslides and landslide complexes ranging in age from historical to "old" (based on geomorphic criteria) are present in the State Route 9 Corridor Geologic-Hazard Study Area (SR-9 study area). Landslide is a general term covering a wide variety of mass-movement landforms and processes involving the downslope transport, under gravity, of soil and rock material en masse (Cruden and Varnes, 1996; Neuendorf and others, moisture content of the affected materials at the time of landsliding may range from dry to saturated. Landslides can be both damaging and deadly. The U.S. Geological Survey (USGS) estimated that in the United States, landslides on average cause \$1–2 billion in damage and more than 25 deaths annually (USGS, 2008). The Utah Geological Survey (UGS) landslide compilation Landslide Maps of Utah (Elliott and Harty, 2010) contains more than 22,000 mapped landslides statewide, and demonstrates that landslides are one of Utah's most common geologic hazards.

Landslides, especially landslides highly modified by erosion, can be difficult to recognize, but their stability moves, sometimes with little remains suspect and their identification and proper accommodation in project planning and design is critical if internal disruption. Because of slope-stability problems are to be avoided (Turner and Schuster, 1996). The close correlation of landslides in the study area with weak bedrock units provides ample evidence that development on slopes underlain by landslide-susceptible geologic units must proceed with caution. Historically, landslides have disrupted transportation routes and damaged houses, commercial sites, and public utilities in the study area (figure 1) toward the slide's main scarp. (Black and others, 1995; Lund and Sharrow, 2005; Lund and others, 2007), demonstrating that landslides are an Rotational slide movement may be ongoing concern for existing infrastructure and future development.

SOURCES OF INFORMATION Sources of information used to evaluate landslide hazards in the SR-9 study area include (1) the four UGS 1:24,000-scale geologic quadrangle maps that cover the study area (Virgin [Hayden and Sable, 2008], Springdale West [Willis and others, 2002], Springdale East [Doelling and others, 2002], and Smithsonian Butte [Moore and Sable, 2001]), (2) Engineering Geology of the St. George Area, Washington County, Utah (Christenson and Deen, 1983),



dale, Washington County, Utah (Solomon, Figure 1. Home destroyed by the 1992 Springdale landslide. 1996), (6)Landslide Susceptibility Map of Utah (Giraud and Shaw, 2007), (7) Landslide

Maps of Utah (Elliott and Harty, 2010), (8) Geologic Hazards of the Zion National Park Geologic-Hazard Study Area, Washington and Kane Counties, Utah (Lund and others, 2010), and (9) Geologic Hazards and Adverse Construction Conditions, St. George—Hurricane Metropolitan Area, Washington County, Utah (Lund and others, 2008).

LANDSLIDE CAUSES, TYPES, AND PROCESSES

Three factors acting individually or in combination contribute to all landslides (Varnes, 1978; Wieczorek, 1996) (1) increase in shear stress, (2) low material strength, and (3) reduction of shear strength. Common factors that increase shear stress include removing support from the toe of a slope, adding mass to the top of a slope, adding water to a slope, transitory stresses from earthquakes and explosions, and long-term effects of tectonic uplift or tilting. Additionally, a trigger that initiates landsliding either by increasing stresses or reducing the strength of slope materials is required for slope movement to occur (Varnes, 1978; Cruden and Varnes, 1996). Common triggers include prolonged or extreme periods of above-normal precipitation; a transient snowmelt-induced rise in groundwater levels (Ashland, 2003); irrigation above unstable slopes; leakage from canals, pipes, and other water conveyance structures; erosion; and earthquake ground shaking.

Cruden and Varnes (1996) grouped landslides into specific types based on their mode of movement: fall, topple, slide, spread, and flow (figure 2). In the SR-9 study area, landslides consist almost exclusively of "slides." Due 2005). The term includes both deep-seated and shallow mass movements (Cruden and Varnes, 1996). The to the region's semiarid climate, spreads, creep, and slow-moving flows, which depend on a high water content to mobilize, have not been recognized in the study area and consequently are not considered further here. Debris flows are discussed on the Flood and Debris-Flow Hazards map (plate 1), and rock falls are considered separately on the Rock-Fall Hazard map (plate 3).

> Within the study area, landslide movements are typically rotational or translational (figure 2). Rotational slides have curved, concave rupture surfaces, which may be shallow or deep seated, along which the slide mass continued to move slowly for

the curved rupture surface (figure 3), the head of a rotational slide commonly tilts backward very slow to rapid and take place under dry to wet conditions. Translational slides move along planar or gently undulating shear surfaces

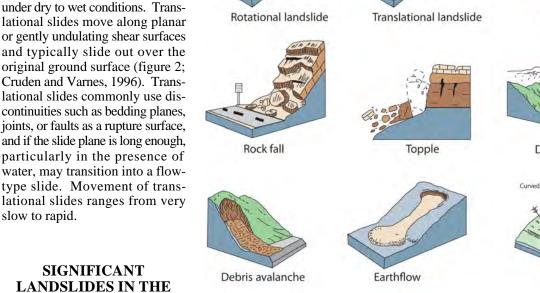
and typically slide out over the original ground surface (figure 2; Cruden and Varnes, 1996). Transational slides commonly use discontinuities such as bedding planes, oints, or faults as a rupture surface, and if the slide plane is long enough, particularly in the presence of water, may transition into a flowtype slide. Movement of translational slides ranges from very

STUDY AREA

North Fork of the Virgin River.

Springdale Landslide

ed the movement, the landslide



Three historical landslides (Spring dale, Paradise Road, and Watchman) in the SR-9 study area have Figure 2. Major types of landslides and their physical characteristics (modified from either damaged infrastructure, *Cruden and Varnes, 1996*). have the potential to do so with additional movement, or may, with

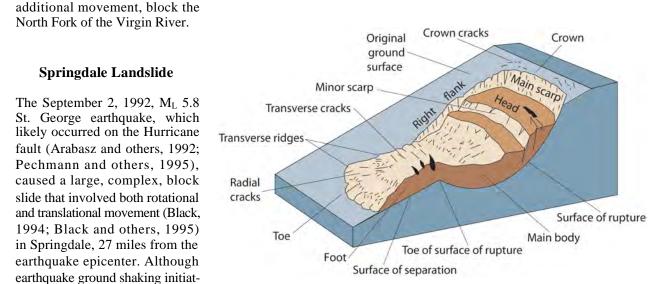
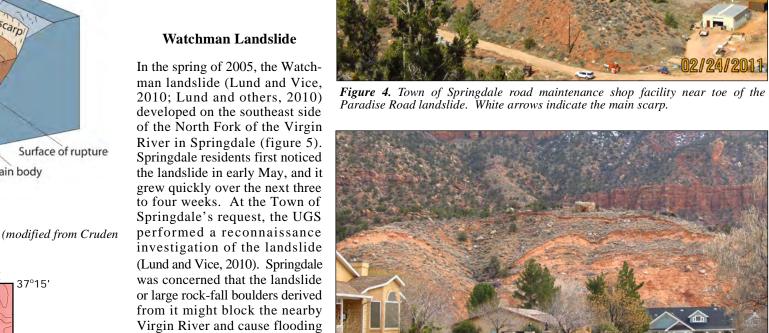


Figure 3. Block diagram of an idealized complex earth slide (modified from Cruden 113°07'30"



the steep east wall of Zion Figure 5. The Watchman landslide in Springdale, Utah.

1996; Doelling and others, 2002), which is likely involved in the landsliding.

Canyon. The landslide toe abuts flat-lying alluvial terrace deposits along the North Fork of the Virgin River. The landslide is a rotational slump with a main scarp up to 6 feet high and numerous internal transverse scarps. The rupture surface appears to be steep and there is no discernable location where the slide plane daylights; a pioneer rock wall at the landslide toe remains undisturbed, except where impacted by rock falls and talus shed from the landslide surface. Where exposed in scarps, the material comprising the landslide has been dry during repeated visits to the site brownish-red fine sand derived from the sandstone formations exposed in the walls of Zion Canyon.

several hours after the earthquake. The landslide measured approximately 1600 feet from the main scarp to the

toe, had a width of about 3600 feet, and a surface area of about 100 acres. The total volume of the landslide is

approximately 18 million cubic yards (Black and others, 1995). The landslide destroyed three houses (figure 1),

two water tanks, and several outbuildings; ruptured both buried and above-ground utility lines; caused a

condominium complex and several businesses at the landslide periphery to be temporarily evacuated; and closed

The landslide basal shear plane is in the Petrified Forest Member of the Chinle Formation, a weak, clay-rich

rock unit. The movement also involved the overlying Moenave Formation and alluvium and colluvium derived

from the Kayenta Formation. Prehistoric landslides in the Petrified Forest Member are common in the

southwestern Utah (Giraud and Shaw, 2007; Elliott and Harty, 2010). Slope-stability analysis indicates that the

static factor of safety for the landslide before the earthquake may have been as low as 1.30 (Jibson and Harp,

1995, 1996). The earthquake apparently triggered only a small amount of coseismic displacement, but enough to

elevate pore-water pressure in the clays of the Petrified Forest Member. The elevated pore-water pressure likely

Paradise Road Landslide

The 1992 St. George earthquake also triggered the smaller (approximately 8.5 acres) Paradise Road landslide

west of the Springdale landslide (Black and others, 1995). A rotational landslide with its basal shear plane also

reduced the factor of safety below 1.0, leading to large-scale slope movement (Jibson and Harp, 1995, 1996).

Springdale area (Solomon, 1996), and this unit is involved in many deep-seated landslides throughout

SR-9 for several days (Black and others, 1995; Jibson and Harp, 1995, 1996).

in the Petrified Forest Member

of the Chinle Formation, the

Paradise Road landslide caused

no significant damage when it

initially moved. However, the

landslide continues to move incre-

mentally and develop fresh ground

cracks and internal scarps. The

landslide threatens a Town of

building, which is close to the

landslide toe (figure 4). The

cement slab foundation of the

shop building shows possible

effects of landslide movement

(cracking and minor slab dis-

placement). Renewed movement

nificant damage to the building

of the landslide could cause sig-

and road.

in Springdale.

The 4-acre landslide formed in

unconsolidated deposits that

have accumulated at the base of

Springdale road maintenance shop

No water has been observed draining from or near the landslide (Lund and Vice, 2010; Lund and others, 2010; UGS unpublished data). However, the Zion Canyon weather station, which is less than a mile from the landslide, reported 26.59 inches of precipitation at the end of May for the 2005 water year—14.7 inches greater than the average for that time of year, and remains by far the wettest winter/spring season on record for Springdale (Western Regional Climate Center, 2011). The high

However, the landslide is underlain by the Petrified Forest Member of the Chinle Formation (Solomon,

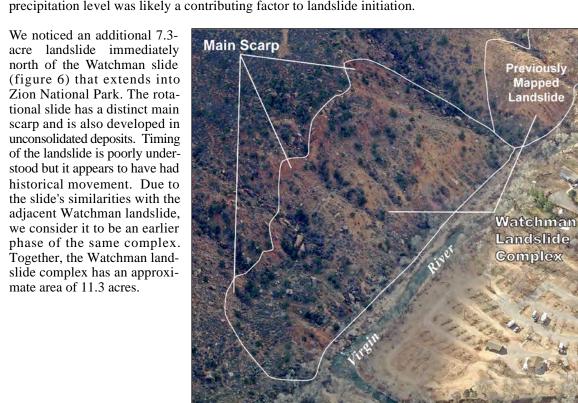


Figure 6. Circa 2008 south-directed, oblique aerial view of the larger, earlier

phase of the Watchman landslide complex. Photo is from Microsoft's Bing

Secondary paved road

Unimproved road

Springdale municipal boundary

Rockville municipal boundary

La Verkin municipal boundary

Apple Valley municipal boundary

Virgin municipal boundary

MAP SYMBOLS

LANDSLIDE-HAZARD CLASSIFICATION

We classified landslide hazards int the SR-9 study area using a three-step procedure:

1. Geologic units on UGS geologic maps were grouped into four relative susceptibility categories based on their lithologic characteristics as they relate to material strength and stability, and on the number of landslides mapped in each unit.

. Average ground-surface slope inclinations (% slope) of representative landslides in the study area were measured to identify the critical slope inclination above which landsliding may initiate in the various susceptibility categories.

3. The results of steps (1) and (2) were integrated to create four Landslide Susceptibility Categories.

Landslide Susceptibility

Bedrock units consisting chiefly of weak rock types (claystone, mudstone, siltstone, and gypsum) are more susceptible to slope instability than rock units consisting of stronger rock types (sandstone, conglomerate, imestone, and basalt). We consider the number of landslides mapped in each geologic unit to be an important, but secondary, indicator of overall landslide susceptibility. Whereas the presence of landslides clearly indicates susceptibility to landsliding, the number of landslides in a geologic unit is, at least in part, a function of the unit's outcrop area. A geologic unit that contains mostly weak rock types, but crops out over a small area may exhibit fewer total landslides than a stronger unit that crops out over a larger area. Additionally, many landslides mapped in relatively strong geologic units are the result of slope movement in an underlying weaker unit that undermined the more competent overlying rocks.

We assigned geologic units in the study area to four broad susceptibility categories ranging from most susceptible to least susceptible (A through D), based on the perceived strength characteristics and relative percentage of strong versus weak lithologies in each unit, and secondarily on the number of landslides present in each unit. Table 1 in the Explanation section summarizes the susceptibility categories.

Landslide Slope Inclination

We measured average ground-surface slope inclinations for representative landslides in each of the susceptibility categories in table 1. Landslide slope inclination is the overall ground-surface slope of the displaced landslide mass, and is calculated by dividing the difference between the landslide head and toe elevations by the horizontal distance from the head to the toe (Hylland and Lowe, 1997), which gives the tangent of the overall slope angle. Multiplying that value by 100 gives percent slope. Hylland and Lowe (1997) considered landslide slope inclinations to represent the approximate maximum quasi-stable slope for a geologic unit under constant conditions of material strength, nature and origin of discontinuities, and groundwater

Considering the broad scale of this study and the intended use of the maps as land-use planning tools to indicate where site-specific investigations are needed, we selected the lowest measured landslide slope inclination, or lowest proxy estimate from nearby well-studied areas, for each susceptibility category as the critical slope

inclination for that category. Table 2 shows representative landslide slope inclinations measured for geologic units comprising the different susceptibility categories in the study		entative landslide and critical s ceptible geologic units in the SI	
area, or where measuring reliable post-failure angles was not possible, angles for those same	Susceptibility Category	Representative Landslide Slope Inclinations	Critical Slope Inclination
geologic units were used as determined by	A^1	Not applicable	Not applicable
Lund and others (2008) in the St. George—	В	12-42% (7°-23°)	12% (7°)
Hurricane metropolitan area. The critical slope inclination is the minimum slope above which	С	25-84% (14°-40°)	25% (14°)
landsliding typically occurs in a particular	D^2		31% (17°)
susceptibility category, and serves as a conservative guide for initiating site-specific, slope-stability investigations for that	¹ Category A is not slope dependent. ² Discrete landslides not related to undercutti by underlying weak units were not identified in category D, so we adopted critical slope inclination of 17°, which was the angle used for low-susceptibili units in the St. George—Hurricane metropolitan area (Lund and others, 2008).		

Landslide-Hazard Categories

We combined the four landslide-susceptibility categories in table 1 with the critical slope inclinations determined for each of those categories in table 2 to characterize landslide hazard in the SR-9 study area. The four resulting levels of landslide hazard are described in the Explanation. Due to the highly landslide-prone nature of the clay-rich Petrified Forest Member of the Chinle Formation (landslide-susceptibility category B, table 1), we included areas where the Petrified Forest Member crops out on slopes less than 12 percent (the critical slope for susceptibility category B) in the Moderate Hazard category (see hazard category Moderate B in Hylland, M.D., and Lowe, M., 1997, Regional landslide-hazard evaluation using landslide slopes, western Wasatch County, Utah: Environmental the Explanation) to indicate the hazard posed by this unit even in gently sloping areas. While it is possible to classify relative landslide hazard in a general way on the basis of material characteristics

and critical slope inclinations, landslides ultimately result from the effects of site-specific conditions acting conducted to evaluate the effect of development on slope stability for all development in areas of sloping terrain where modifications to natural slopes are planned, and where landscape irrigation, onsite wastewater disposal systems, or infiltration basins may cause groundwater levels to rise (see, for example, Keaton and Beckwith, 1996: Ashland and others, 2005).

USING THIS MAP

This map shows areas of relative landslide hazard, and provides a basis for requiring site-specific hazard investigations. Site-specific investigations can resolve uncertainties inherent in generalized geologic-hazard mapping and help ensure safety by identifying the need for hazard mitigation.

This map identifies areas, based on previous landslide history, material characteristics, and slope, where sitespecific slope-stability conditions (such as material strength, orientation of bedding or fractures, groundwater conditions, erosion, or undercutting) should be evaluated prior to development. The level of investigation needed at a given site depends on the relative hazard and the nature of the proposed development (structure type, size, use, and placement; required cuts and fills; and changes in groundwater conditions). A valid landslide-hazard investigation must address all pertinent conditions that could affect, or be affected by, the proposed development, including earthquake ground shaking. This can only be accomplished through the proper identification and interpretation of site-specific geologic conditions and processes (Blake and others, 2002). Nearby conditions that may affect the site must also be considered.

The analysis of natural and modified slopes for static and/or seismic stability is a challenging geotechnical problem. Blake and others (2002, p. 3) consider the following steps necessary for a proper static and seismic

'Accurate characterization of:

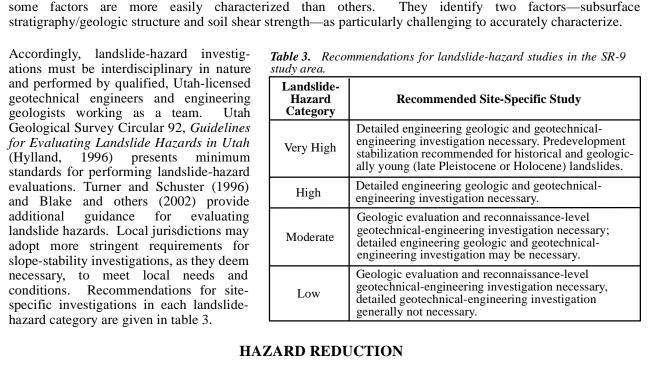
1. surface topography 2. subsurface stratigraphy,

conditions at a given site.

susceptibility category.

- 3. subsurface water levels and possible subsurface flow patterns, 4. shear strength of materials through which the failure surface may pass,
- 5. unit weight of the materials overlying potential failure planes. The stability calculations are then carried out using an appropriate analysis method for the potential failure surface being analyzed. A seismic slope-stability analysis requires consideration of each of the above factors for static stability, as well as characterization of:
- 1. design-basis earthquake ground motions at the site, and

2. earthquake shaking effects on the strength and stress-deformation behavior of the soil, including pore pressure generation and rate effects."



As with most geologic hazards, early recognition and avoidance are the most effective ways to mitigate landslide hazards. However, avoidance may not always be a viable or cost-effective option, especially for existing developments, and engineering techniques are available to reduce potential landslide hazards. Techniques for mitigating landslide hazards include, but are not limited to, care in site grading; proper engineering, construction, and compaction of cut-and-fill slopes; careful attention to site drainage and dewatering of shallow or perched groundwater; construction of retaining structures within the toe of slopes; and

use of mechanical stabilization including tiebacks or other means that penetrate the landslide mass to anchor it to underlying stable material. Other techniques used to reduce landslide hazards include benching, bridging, weighting, or buttressing slopes with compacted earth fills, and installation of landslide warning systems (Keller and Blodgett, 2006). However, some geologic units, for example the Petrified Forest Member of the Chinle Formation, may be too weak to buttress, and may continue to move upslope of the buttress (Francis Ashland, UGS, written communication, 2007).

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Where development is proposed in areas identified on this map as having a potential for landsliding, we recommend that a phased site-specific investigation (see Hylland, 1996) be performed early in the project design phase. A site-specific investigation can establish whether the necessary conditions for landsliding are present at a site; if they are, appropriate design and construction recommendations should be provided.

MAP LIMITATIONS

This map is based on 1:24,000-scale UGS geologic mapping, and the inventory of landslides obtained from that mapping and shown on this map reflects that level of mapping detail. Some smaller landslides may not have been detected during the mapping or are too small to show at that scale. Therefore, site-specific geotechnical and geologic-hazard investigations should be preceded by a careful field evaluation of the site to identify any landslides present. The mapped boundaries of the landslide-hazard categories are approximate and subject to change as new information becomes available. The landslide hazard at any particular site may be different than shown because of variations in the physical properties of geologic units, groundwater conditions within a map unit, gradational and approximate map-unit boundaries, and the generalized map scale. Small, localized areas of higher or lower landslide hazard may exist within any given map area, but their identification is precluded by limitations of map scale. This map is not intended for use at scales other than the published scale, and is

intended for use in general planning and design to indicate the need for site-specific investigations.

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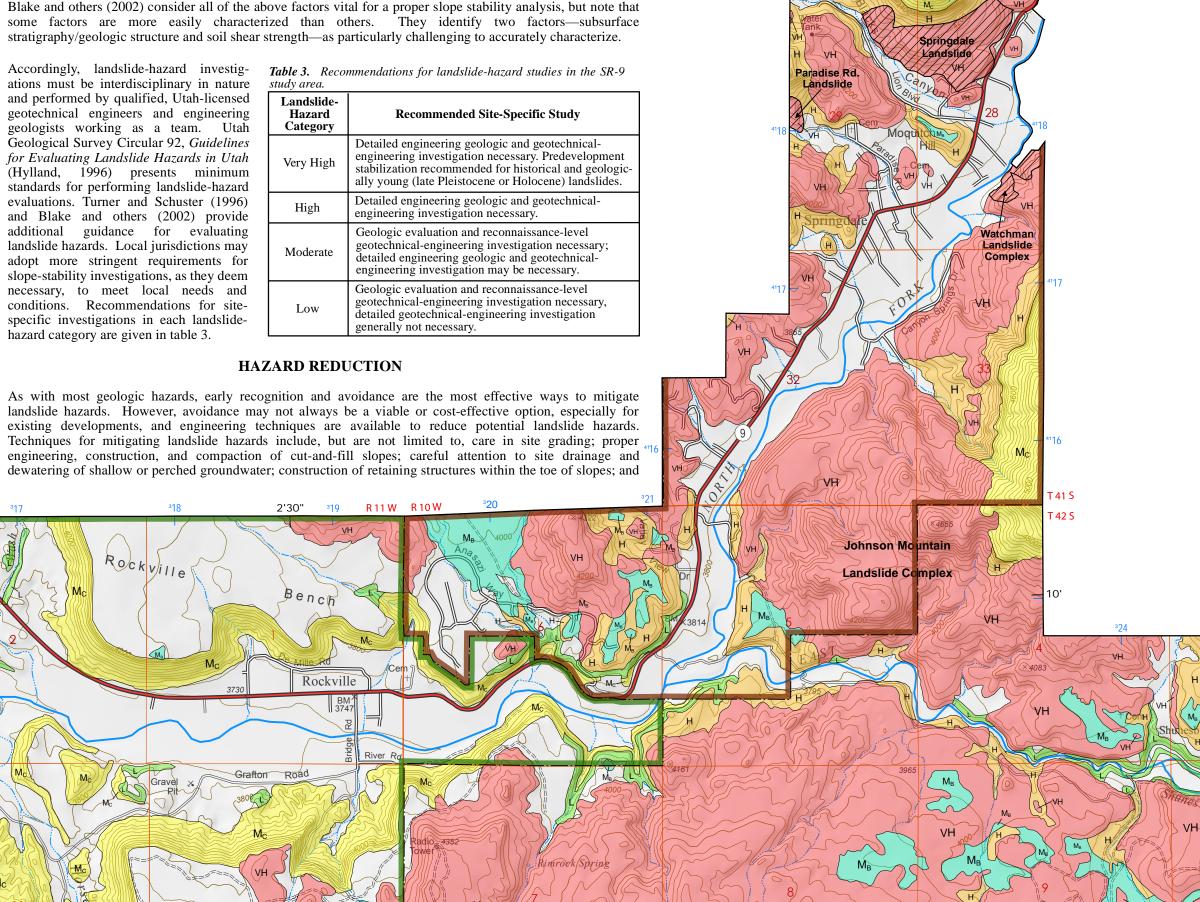
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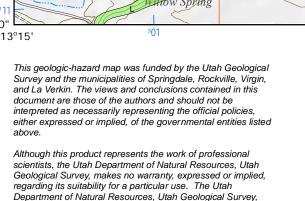
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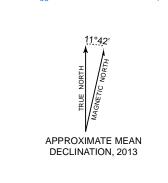


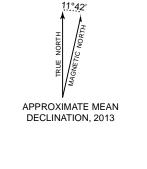
shall not be liable under any circumstances for any direct

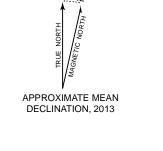
indirect, special, incidental, or consequential damages with

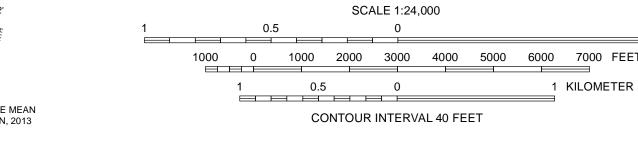
respect to claims by users of this product

For use at 1:24,000 scale only.







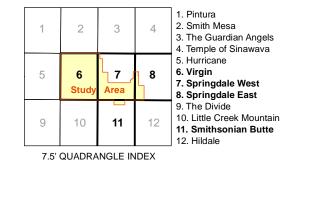




1 KILOMETER

STATE ROUTE 9 CORRIDOR GEOLOGIC-HAZARD STUDY AREA, WASHINGTON COUNTY, UTAH Tyler R. Knudsen and William R. Lund

LANDSLIDE HAZARD



Base-map topographic contours and shaded relief derived from 10 meter U.S. Geological Survey National Elevation Dataset. Geographic labels from U.S. Geological Survey 7.5-minute quadrangle maps acquired from the Utah Automated Geographic Reference Center. Projection: UTM Zone 12 Ellipsoid: GRS 80 GIS and Cartography: Tyler R. Knudsen Utah Geological Survey 1594 West North Temple, Suite 3110 P.O. Box 146100, Salt Lake City, UT 84114-6100 (801) 537-3300 geology.utah.gov