# GEOLOGIC HAZARDS OF THE BULLFROG AND WAHWEAP HIGH-USE AREAS OF GLEN CANYON NATIONAL RECREATION AREA, SAN JUAN, KANE, AND GARFIELD COUNTIES, UTAH, AND COCONINO COUNTY, ARIZONA

by Tyler R. Knudsen, Adam I. Hiscock, William R. Lund, and Steve D. Bowman

**SPECIAL STUDY 166**
**UTAH GEOLOGICAL SURVEY 2020**
UTAH DEPARTMENT OF NATURAL RESOURCES
*in cooperation with the National Park Service*

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***Cover photo:*** *Rounded bluffs of Jurassic Navajo Sandstone envelop Lake Powell at Navajo Canyon near the Utah-Arizona border.*

Suggested citation:

Knudsen, T.R., Hiscock, A.I., Lund, W.R., and Bowman, S.D., 2020, Geologic hazards of the Bullfrog and Wahweap high-use areas of Glen Canyon National Recreation Area, San Juan, Kane, and Garfield Counties, Utah, and Coconino County, Arizona: Utah Geological Survey Special Study 166, 66 p., https://doi.org/10.34191/ss-166.

Mapping available at https://geology.utah.gov/apps/hazards.

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**2020**

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*The Utah Geological Survey and the National Park Service, U.S. Department of the Interior, funded this digital product. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government. These maps and explanatory information are submitted for publication with the understanding that the United States Government is authorized to reproduce and distribute reprints for governmental use.*

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https://geology.utah.gov/apps/hazards

# GEOLOGIC HAZARDS OF THE BULLFROG AND WAHWEAP HIGH-USE AREAS OF GLEN CANYON NATIONAL RECREATION AREA, SAN JUAN, KANE, AND GARFIELD COUNTIES, UTAH, AND COCONINO COUNTY, ARIZONA

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## ABSTRACT

Scenic landscapes and a variety of recreational opportunities centered on Lake Powell attract nearly 4 million visitors annually to the Glen Canyon National Recreation Area. Geologic processes that shaped this rugged landscape are still active today, and can be hazardous to visitors, employees, and infrastructure. To provide the National Park Service with necessary geologic-hazard information for future park management, the Utah Geological Survey conducted a geologic-hazard investigation of two high-use sections of the recreation area. The Bullfrog section encompasses a 297-square-mile area (478 km$^2$) centered on Lake Powell extending from the west end of Good Hope Bay down-lake to Annies Canyon, and includes the popular Bullfrog and Halls Crossing Marinas and nearby bays, canyons, and inlets. The Wahweap section encompasses a 117-square-mile area (188 km$^2$) that includes Wahweap and Antelope Point Marinas, Antelope and Navajo Canyon inlets, Glen Canyon near Glen Canyon Dam, lower Paria Canyon, and Lees Ferry.

On an annual basis, the most widespread and dangerous geologic hazard in the Glen Canyon National Recreation Area geologic-hazard study area is flooding. Flash floods conveyed in narrow slickrock canyons have claimed many lives in and near the recreation area. Additionally, floods and debris flows have repeatedly damaged roads near Lees Ferry. The creation of Lake Powell has accelerated the occurrence of rockfalls and landslides along Glen Canyon's walls. Rockfalls killed four individuals within the recreation area between 1975 and 2007. Landslides are common where the clay-rich Chinle Formation crops out on slopes. Unconsolidated Quaternary deposits are commonly fine grained and may be susceptible to erosion by flowing water, and locally, by wind that can cause sand migration over roads. Large earthquakes are rare events in the Glen Canyon area, and expected levels of ground shaking are relatively low; however, surface faulting and liquefaction are possible.

This investigation included mapping of geologic hazards in the Bullfrog and Wahweap sections, including flooding and debris flows, rockfall, landslides, soil piping and erosion, gypsiferous soil and rock, expansive soil and rock, collapsible soil, surface faulting, liquefaction, and indoor radon potential. The mapping was published in the online Utah Geologic Hazards Portal. This text document describes the geologic hazards and provides background information on data sources, the nature and distribution of the hazards, and possible hazard-reduction measures.

Most visitors to the Glen Canyon area likely lack a full appreciation of the nature of the area's two most deadly geologic hazards: flash floods and rockfall. To help mitigate these hazards, we recommend the increased use of brochures, web-based education materials, and interpretive signage to educate visitors on ways to recognize and avoid flood- and rockfall-prone areas. We recommend a site-specific geotechnical investigation for all new construction in the study area, and a geologic investigation to identify potential geologic hazards at sites within special-study areas shown on the maps accompanying this report.

## INTRODUCTION

Glen Canyon National Recreation Area (GCNRA) comprises approximately a 1940-square-mile region (3122 km$^2$) of deep canyons and broad, cliff-edged mesas carved by the Colorado River and its tributaries in southeastern Utah and north-central Arizona (figure 1). At 1.24 million acres, the GCNRA is the largest National Park Service (NPS)-managed unit in Utah and the sixth largest in the contiguous United States. Lake Powell occupies most of Glen Canyon—a long, narrow canyon carved by the Colorado River—for a distance of about 186 miles (300 km) (at full pool). Several slender arms of the lake extend from Glen Canyon where tributaries enter the Colorado River. The largest of these are the San Juan and Escalante Rivers. GCNRA shares borders with Canyonlands National Park to the northeast, Capitol Reef National Park and Grand Staircase-Escalante National Monument to the west, and Grand Canyon National Park and Rainbow Bridge National Monument to the south. Elevation ranges from about 7600 feet (2300 m) on the Kaiparowits Plateau to about 3100 feet (950 m) where the Colorado River exits the recreation area at Marble Canyon (figure 1).

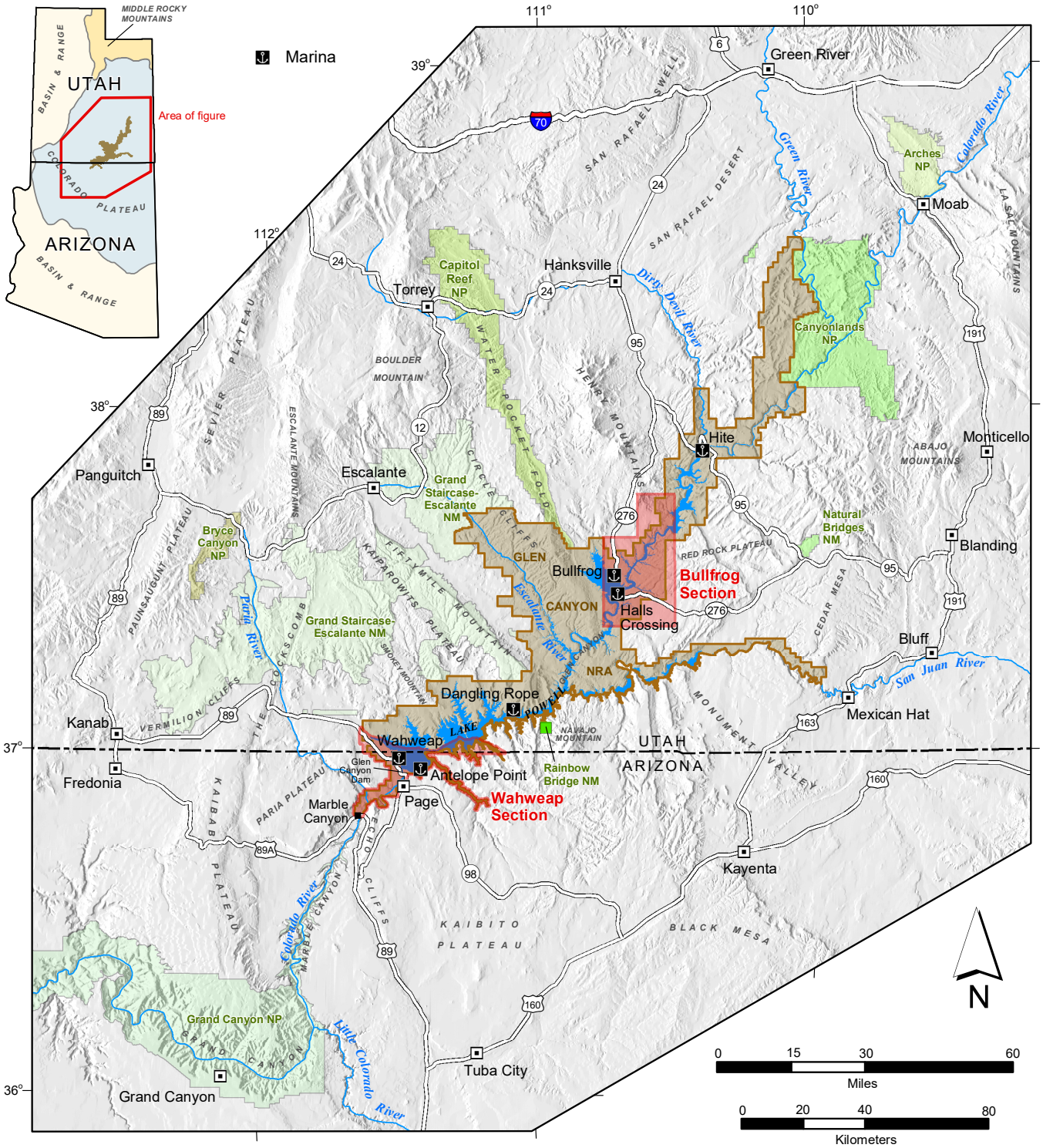


***Figure 1.*** *Glen Canyon National Recreation Area and study-area boundaries, principal developed areas, nearby communities, principal drainages, major transportation corridors, and nearby NPS-managed parks and monuments. Inset shows physiographic provinces. Shaded-relief base map generated from U.S. Geological Survey 90-meter digital elevation model.*

Glen Canyon National Recreation Area was established in 1972, nearly a decade after closure of Glen Canyon Dam and initial filling of Lake Powell in 1963. Lake Powell has a storage capacity of 26,215,000 acre-feet when at full pool (surface elevation 3700 feet [1128 m] above sea level), making it the second-largest reservoir in North America. Full pool was first achieved in 1980. Although Lake Powell covers less than 14 percent of GCNRA, a large portion of the recreation area's 2.5 million annual visitors (average calculated from 1980–2018 NPS [2019] data) recreate on or near the reservoir. Annual visitation has risen in recent years, peaking at 4.6 million visitors in 2017 (NPS, 2019).

The geologic processes that shaped GCNRA's rugged landscape remain active today and can be hazardous to visitors, employees, and infrastructure. Erosional geologic processes dominate the Glen Canyon region. In particular, canyon entrenchment and widening via stream erosion (primarily floods) and mass wasting (landsides, rockfalls, and debris flows) create the principal geologic hazards with which planners, public safety personnel, maintenance workers, and others in GCNRA must contend. Rockfalls and flash floods in GCNRA have caused several fatalities. Floods and debris flows have repeatedly damaged infrastructure (figure 2). With the exception of the effects of an unlikely large earthquake, the remaining geologic hazards considered in this report are typically localized, and while potentially costly when not recognized and properly accommodated in project planning and design, the problems associated with them are rarely life threatening.

***Figure 2.*** *August 18, 1989, flash flood damage to Lees Ferry Road (photograph courtesy of the National Park Service).*

## Purpose

The purpose of this study is to provide the NPS with geographic information system (GIS)-based information on the kind and location of geologic hazards that may affect existing and future development and visitor and employee safety in the Glen Canyon National Recreation Area geologic-hazard study area (Glen Canyon study area). Geologic-hazard-map boundaries extend beyond NPS-administered areas and generally conform to Utah Geological Survey (UGS) 7.5-minute geologic quadrangle map boundaries. The study focuses on two separate high-use sections of GCNRA. The Bullfrog section encompasses 297 square miles (478 km$^2$) centered on Lake Powell and extends from the west end of Good Hope Bay southward to Annies Canyon, and includes the popular Bullfrog and Halls Crossing Marinas and nearby bays, canyons, and inlets (figure 3). The Bullfrog section also includes the Cane Spring Desert and southeast quadrant of Mount Ellsworth in the Henry Mountains. The Wahweap section is a 117-square-mile area (188 km$^2$) that encompasses Wahweap and Antelope Point Marinas, Antelope and Navajo Canyon inlets, Glen Canyon below Glen Canyon Dam, lower Paria Canyon, and Lees Ferry (figure 4). The two sections of the Glen Canyon study area were established in consultation with GCNRA administrative staff, and were chosen based on high visitation rates, reports of geologic-hazard incidents, and availability of recent UGS 1:24,000-scale (1"= 2000') geologic mapping.

We compiled and mapped geologic-hazard data at a scale of 1:24,000 in a GIS database. This mapping can be viewed on the Utah Geologic Hazards Portal (Utah Geological Survey, 2020) (https://geology.utah.gov/apps/hazards). Geologic hazards mapped in the Glen Canyon study area are: (1) flooding and debris flows, (2) rockfall, (3) landslides, (4) soils susceptible to piping and erosion, (5) gypsiferous soil and rock, (6) expansive soil and rock, (7) collapsible soil, (8) surface faulting, (9) liquefaction, and (10) indoor radon potential. This report describes the geologic hazards and provides background information on data sources, the nature and distribution of the hazards, and possible hazard-reduction measures. This report also includes a discussion of earthquake-induced ground shaking, but data are insufficient to prepare a ground-shaking-hazard map. This mapping is designed as an aid for general planning to indicate where detailed, site-specific geologic-hazard investigations are required. The maps are not intended to be enlarged for use at scales larger than the scale at which they were compiled, and are not a substitute for site-specific geotechnical and geologic-hazard investigations.

We recommend a site-specific geotechnical investigation for all new construction in the Glen Canyon study area, and a geologic investigation to identify potential geologic hazards

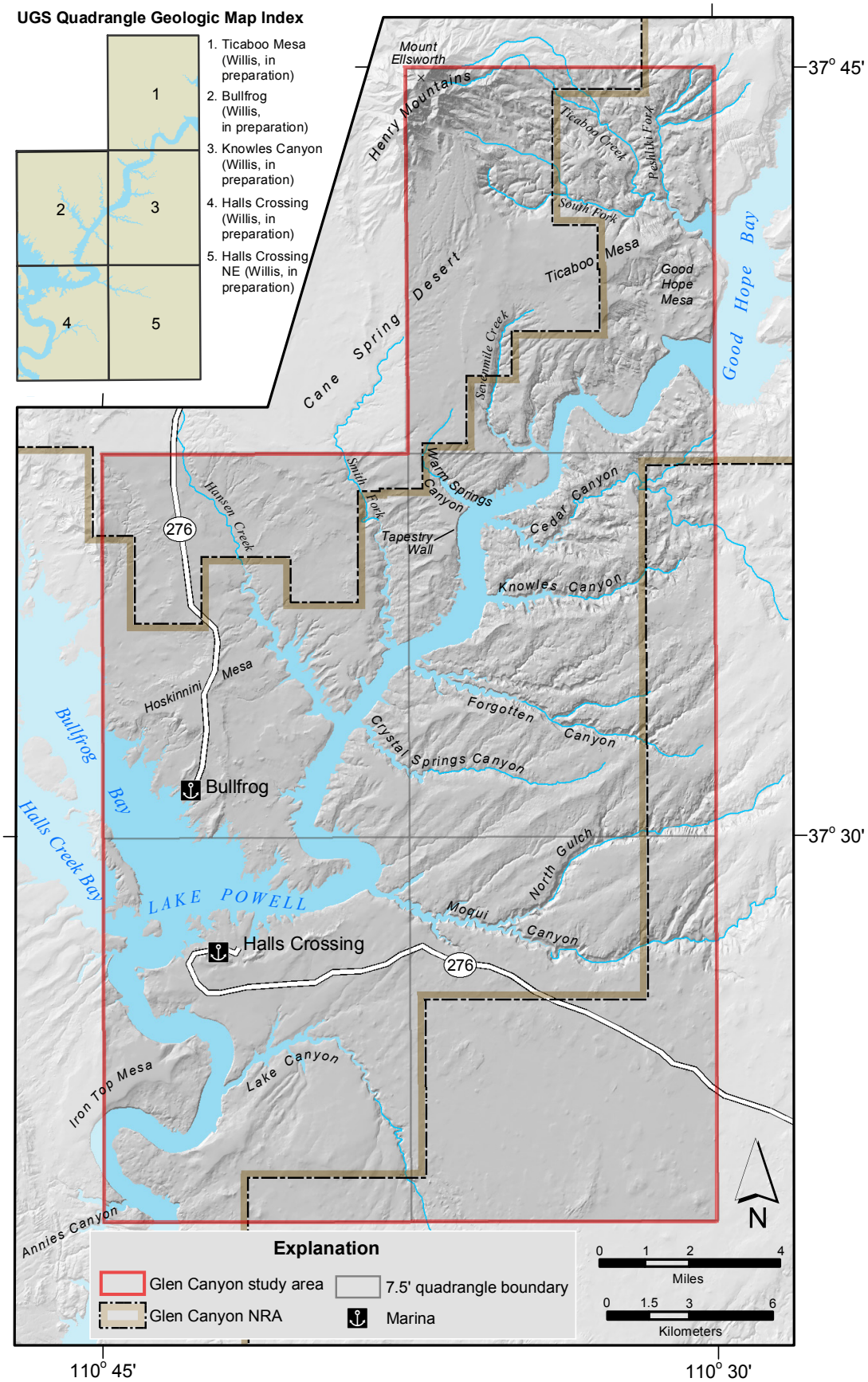


***Figure 3.*** *Boundaries, principal drainages and other physical features, and index to UGS 7.5' geologic quadrangle maps in the Bullfrog section of the Glen Canyon geologic-hazards study area. Shaded-relief base map generated from U.S. Geological Survey 30-meter digital elevation model.*

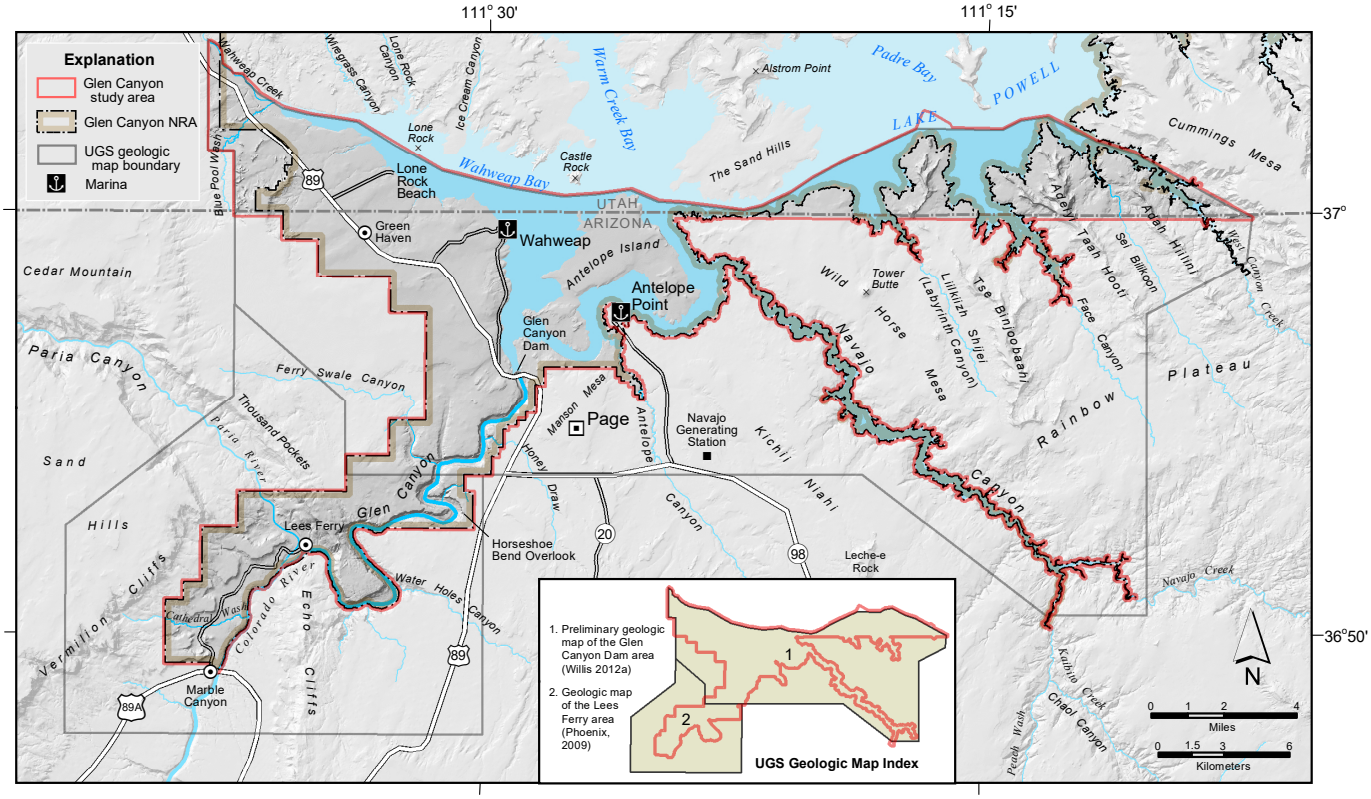


***Figure 4.*** *Boundaries, principal drainages and other physical features, and index to UGS 1:24,000-scale geologic maps in the Wahweap section of the Glen Canyon geologic-hazards study area. Shaded-relief base map generated from U.S. Geological Survey 30-meter digital elevation model.*

at sites within special-study areas shown on the mapping that accompanies this report. Site-specific investigations can resolve uncertainties inherent in these 1:24,000-scale maps, and help increase safety by identifying the need for special engineering design or hazard mitigation. To reduce the potentially deadly rockfall and flood hazard to visitors, we recommend increased distribution of brochures, web-based materials, and signage to educate visitors on how to recognize and avoid these hazardous areas.

## Scope of Work

The hazard maps are derived largely from 1:24,000-scale geologic maps that cover the Glen Canyon study area. The Bullfrog section is covered by five 7.5-minute geologic quadrangles mapped by Willis (in preparation): Bullfrog, Halls Crossing, Halls Crossing NE, Ticaboo Mesa, and Knowles Canyon (figure 3). The Wahweap section is covered by geologic maps of the Glen Canyon Dam area (Willis, 2012a) and the Lees Ferry area (Phoenix, 2009) (figure 4). Unfortunately, existing geologic maps do not extend below the Lake Powell full-pool elevation of 3700 feet (1128 m). Prolonged periods of drought have significantly lowered the reservoir level since the late 1990s. From February 2002 to July 2016, the reservoir had an average surface elevation of 3609 feet (1100 m) and has been below 3650 feet (1113 m) 98 percent of the time (statistics calculated from U.S. Bureau of Reclamation [USBR, 2016] data). Predicted continued drought conditions in the Southwest (e.g., Cayan and others, 2013; Melillo and others, 2014), increasing demands for Colorado River water, and ongoing USBR management plans to promote equal storage between Lake Powell and Lake Mead (U.S. Department of the Interior, 2007) greatly decrease the likelihood of Lake Powell attaining full pool in the near future. Because a large portion of visitors to GCNRA spend substantial time recreating at Lake Powell (Holmes and others, 2008), and spend long periods of time along the reservoir's shoreline, we extended existing geologic mapping to about the 3600-foot (1100 m) level throughout the study area.

The scope of work for this study consisted of:

1. Reviewing and rectifying digital geologic, hydrologic, and soils information; producing digital elevation models; and examining aerial photography available for the study area.

2. Extending existing 1:24,000-scale geologic mapping from an elevation of 3700 feet (1128 m) to approximately 3600 feet (1100 m) near Lake Powell using various sets of aerial photography (chiefly 1940 [Soil Conservation Service, 1940], 1948 [Jack Ammann Photogrammetric Engineers, 1948], 1953 [Army Map Service, 1953], 2014 [Utah AGRC, 2014], and 2015 [Utah AGRC, 2016b] aerial photographs) and field mapping.

3. Collecting the few geotechnical reports available in the Glen Canyon area.
4. Incorporating current road, trail, and land parcel information into a GIS database.
5. Creating GIS-based derivative geologic-hazard maps for the 10 principal geologic hazards affecting the study area.
6. Field checking and mapping as necessary to improve the geologic-hazard maps.
7. Preparing an explanatory report to accompany the geologic-hazard mapping.

Considering the map scale and limited geotechnical data, the special-study area boundaries shown on the maps accompanying this report are considered approximate and subject to change as additional information becomes available. Furthermore, small, unrecognized areas of hazard may exist in the study area, but their identification was precluded by limitations of data availability or map scale.

## Geology

Glen Canyon National Recreation Area lies within the Colorado Plateau physiographic province (figure 1), which is generally characterized as an elevated region with simple "layer-cake" geology. However, in the Glen Canyon region, the geology is locally complicated by folds, faults, joints, igneous intrusions, and erosion. Because of this complexity, the discussion here is limited to a brief description of the geologic units, structures, and conditions pertinent to geologic hazards in the Glen Canyon region. Readers interested in detailed information on the geology of GCNRA can consult Phoenix (2009), Anderson and others (2010), Willis (2012a), and Willis (in preparation).

Exposed bedrock in GCNRA consists of a vertical sequence of sedimentary rock layers ranging in age from Late Pennsylvanian (about 300 million years ago) to Late Cretaceous (about 80 million years ago) (figure 5). The rock units represent an about 10,000-foot (3000 m) section of primarily marine and continental depositional environments; rock types include limestone, mudstone, claystone, shale, sandstone, conglomerate, and evaporite deposits (figure 6). Within the Bullfrog and Wahweap sections of the Glen Canyon study area, the landscape is dominated by slickrock benches, broad mesas, and deep canyons developed on the Jurassic Navajo and Entrada Sandstones. In the northwestern Bullfrog section, Mount Ellsworth of the Henry Mountains exposes diorite porphyry intruded into domed and faulted Triassic and Jurassic sedimentary strata (e.g., Gilbert, 1877; Hunt and others, 1953; Jackson and Pollard, 1988, 1990). Major tributary canyons near Bullfrog/Halls Crossing, including Lake, Moqui, Forgotten, Knowles, Warm Springs, and Smith Fork Canyons, are deeply incised into the 1200-foot-thick (365 m) Navajo Sandstone. Bullfrog Marina facilities are on benches and bluffs formed on pale-orange Entrada Sandstone (figure 7). Halls Crossing Marina rests primarily on gently sloped benches of brick-red mudstone and siltstone of the Jurassic Carmel Formation. In the Wahweap section, major canyons tributary to the Colorado River, including West, Face, Navajo, and Antelope Canyons, are cut into Navajo Sandstone. Glen Canyon, below Glen Canyon Dam, is cut about 1000 feet (300 m) deep into Navajo Sandstone (figure 8). Most of the slickrock benches, bluffs, and buttes surrounding Wahweap Bay, including Lone Rock and Castle Rock, are yellowish-gray, cross-bedded Entrada Sandstone (figure 9) that closely resembles nearby outcrops of Navajo Sandstone. Facilities at Wahweap Marina are primarily on the Carmel Formation. Near Lees Ferry, tall mesas of Triassic Moenkopi Formation mudstone capped by the Shinarump Conglomerate Member of the Triassic Chinle Formation rise above a broad limestone platform of the Permian Kaibab Formation (figure 10).

Some bedrock units in the Glen Canyon study area, such as the mudstone-rich upper members of the Chinle Formation, contain a high percentage of clay and are correspondingly weak and moisture sensitive, making them susceptible to landslides and volumetric change (shrink/swell). Landslides associated with weak rock units are common in the Lees Ferry area and near Good Hope Bay, and commonly coalesce to form landslide complexes. More competent, cliff-forming rock formations, such as the Wingate, Navajo, and Entrada Sandstones, are cut by large, throughgoing joint sets (figure 8), which make many areas of the recreation area susceptible to rockfall.

Quaternary unconsolidated geologic units in the study area are generally of limited aerial extent and thickness due to the dominance of erosive geomorphic processes. Stream alluvium is present in active channels as well as in erosional remnants up to 1600 feet (500 m) above modern drainages (Anderson and others, 2010). Additionally, a few small alluvial fans have formed at the mouths of tributaries draining into Paria Canyon. Thin eolian deposits, predominately derived from the Navajo and Entrada Sandstone, mantle upland areas that are protected from runoff during thunderstorms. Mixed eolian and alluvial deposits are widespread and are composed mostly of fine-grained sand, but also contain subordinate clay, silt, and gravel deposited by fluvial processes. Common mass-wasting deposits in the Glen Canyon study area are landslides, rockfall, and debris flows. Mass wasting has significantly increased along the shores of Lake Powell since its creation (Brokaw, 1974; Grundvig, 1980) (see Rockfall and Landslide Hazard sections below).

Bedrock strata in GCNRA are typically within a few degrees of horizontal except where locally contorted into relatively narrow folds associated with the 70 to 40 million year old (Ma) Laramide orogeny (Hintze and Kowallis, 2009; Anderson and others, 2010). The folds likely developed over deep reverse faults in Precambrian basement rocks (Davis, 1978). Notable folds within or near the Glen Canyon study area include the northwest-trending Circle Cliffs anticline that ex-

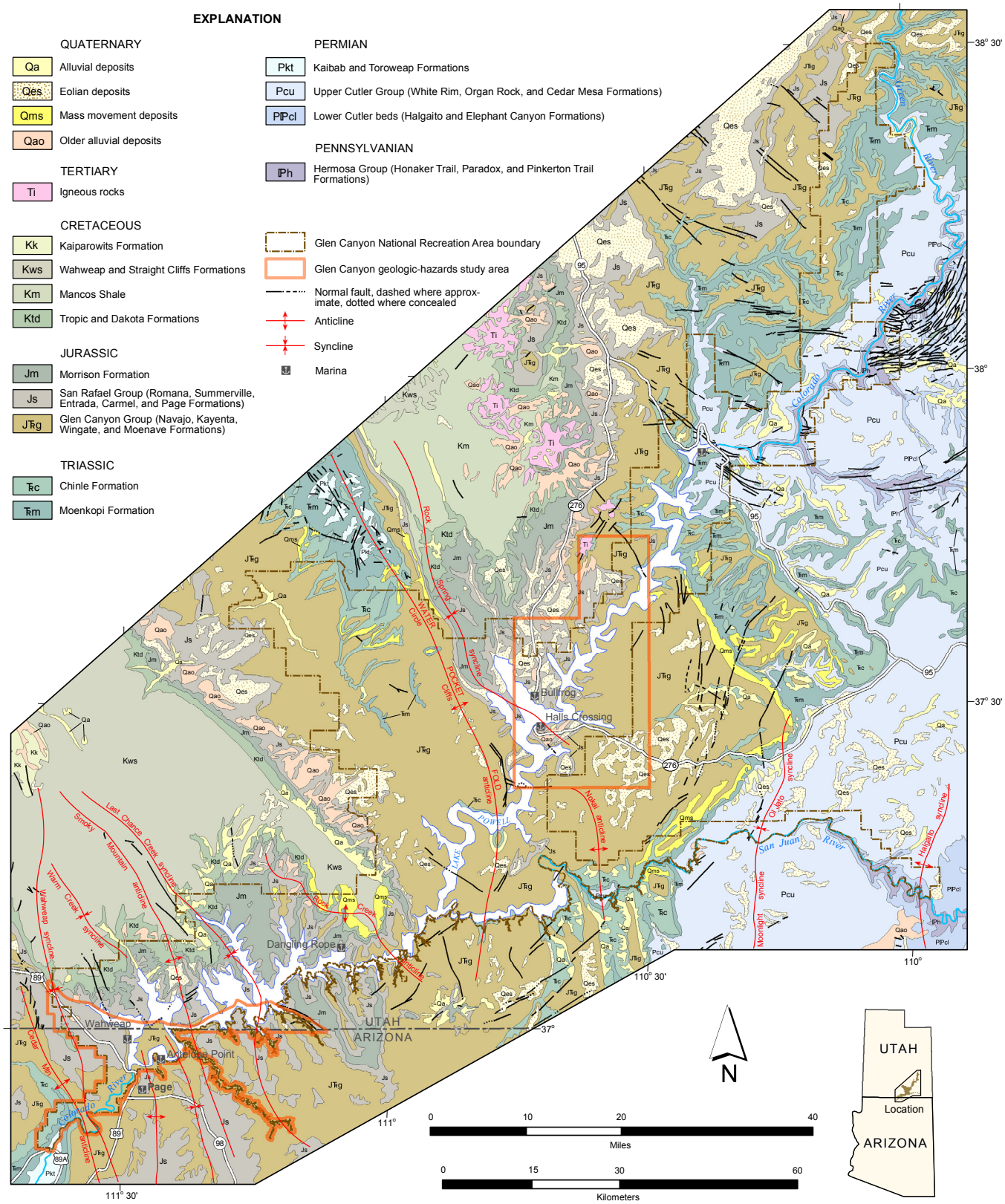


***Figure 5.*** *Simplified geologic map of Glen Canyon National Recreation Area and vicinity. Modified from Wilson and Moore (1969) and Hintze (1980).*

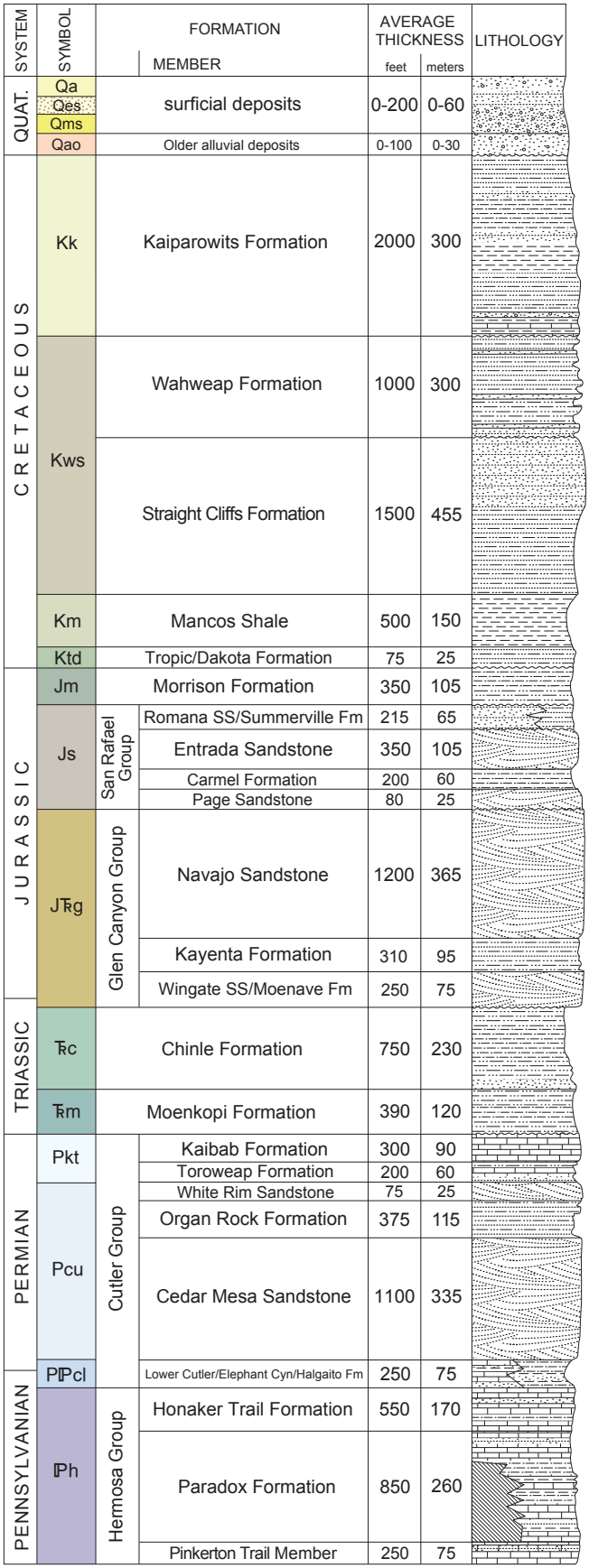


***Figure 6.*** *Lithologic column of geologic units that crop out near Glen Canyon National Recreation Area. Modified from Anderson and others (2010).*

tends more than 100 miles (160 km) through GCNRA (figure 5) and Capitol Reef National Park to the west. The fold's steep east limb is known as the Water Pocket Fold. The Rock Spring syncline is subparallel to the Circle Cliffs anticline and brings Carmel and Entrada strata to the level of Lake Powell near Halls Creek Bay and Halls Crossing. Near Lees Ferry, erosion of the steep east limb of the northwest-trending Cedar Mountain anticline is responsible for the prominent Echo Cliffs.

Uplift of the greater Colorado Plateau region began in the early Tertiary (about 65 Ma) and continues to the present (Hunt, 1956; Lucchitta, 1979; Anderson and others, 2010). This uplift caused the erosion and removal of several thousands of feet of sedimentary rocks by running water and mass wasting. Erosional processes were greatly accelerated after collapse of the Basin and Range starting about 17 Ma (Stewart, 1978), and integration of the upper Colorado River system to the Gulf of California in the past 6 million years (Lucchitta, 1979; Young and Spamer, 2001; Anderson and others 2010; Karlstrom and others, 2014). Sparse, small-displacement, northeast- and northwest-trending normal faults (figure 9) and contemporary seismicity indicate that the interior of the Colorado Plateau near Glen Canyon is under an extensional stress regime (Wong and Humphrey, 1989).

## FLOOD HAZARD

Flooding is the overflow of water onto lands that are normally dry and is the most commonly occurring natural hazard (Keller and Blodgett, 2006). Damage from flooding includes inundation of land and property, erosion, deposition of sediment and debris, and the force of the water itself, which can damage property and take lives (Stauffer, 1992). Historically, flooding is the most prevalent and destructive (on an annual basis) geologic hazard affecting the Glen Canyon study area. The flash-flood hazard to hikers in slot canyons is particularly acute because the sheer canyon walls provide few avenues to escape floodwaters.

The high flood hazard results from the complex interaction of the area's rugged topography and the Colorado Plateau's seasonal weather patterns. Two principal types of floods occur in the study area: riverine (stream) floods and flash floods. Both types are associated with natural climatic fluctuations and may, under certain circumstances, occur simultaneously. Wildfires significantly increase the risk from flooding, because in burn areas, wildfires cause a decrease in water infiltration and an increase in runoff and erosion (Neary and others, 2005). Human activities, such as placing structures and constrictions in floodplains, on active alluvial fans, or in erosion-hazard zones; developing without adequate flood and erosion control; poor watershed management practices (such as overgrazing or allowing indiscriminate off-road vehicle traffic); and the unintentional release of water from an engineered water-retention or conveyance structure (such as a dam or canal) also increase the potential for flooding.

***Figure 7.*** *Facilities near Bullfrog are underlain by a thin mantle of mixed eolian-alluvial sand covering the Entrada Sandstone. Photo taken on August 19, 2015; view is to the northeast.*

***Figure 8.*** *South-directed view of Glen Canyon and the Colorado River below Glen Canyon Dam. Canyon walls are jointed Navajo Sandstone. Talus deposits mantling lower slopes attest to the high rates of rockfall in the canyon. Photo taken on May 11, 2014.*

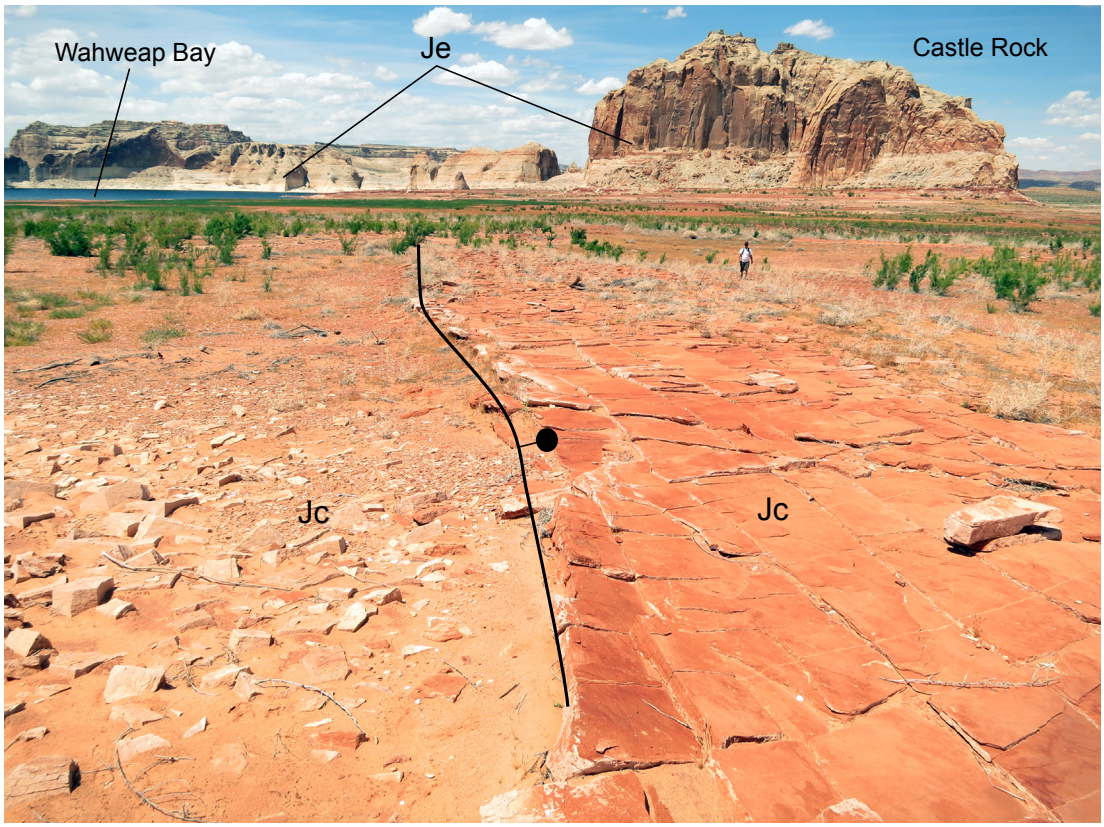


***Figure 9.*** *Foreground: a small-displacement normal fault juxtaposes different strata within the Carmel Formation (Jc) on Antelope Island near the Utah-Arizona border; bar and ball on downthrown side of fault. Distance: tall mesas of Entrada Sandstone (Je) bound the northern margin of Wahweap Bay. Photo taken on May 12, 2015; view is to the north.*

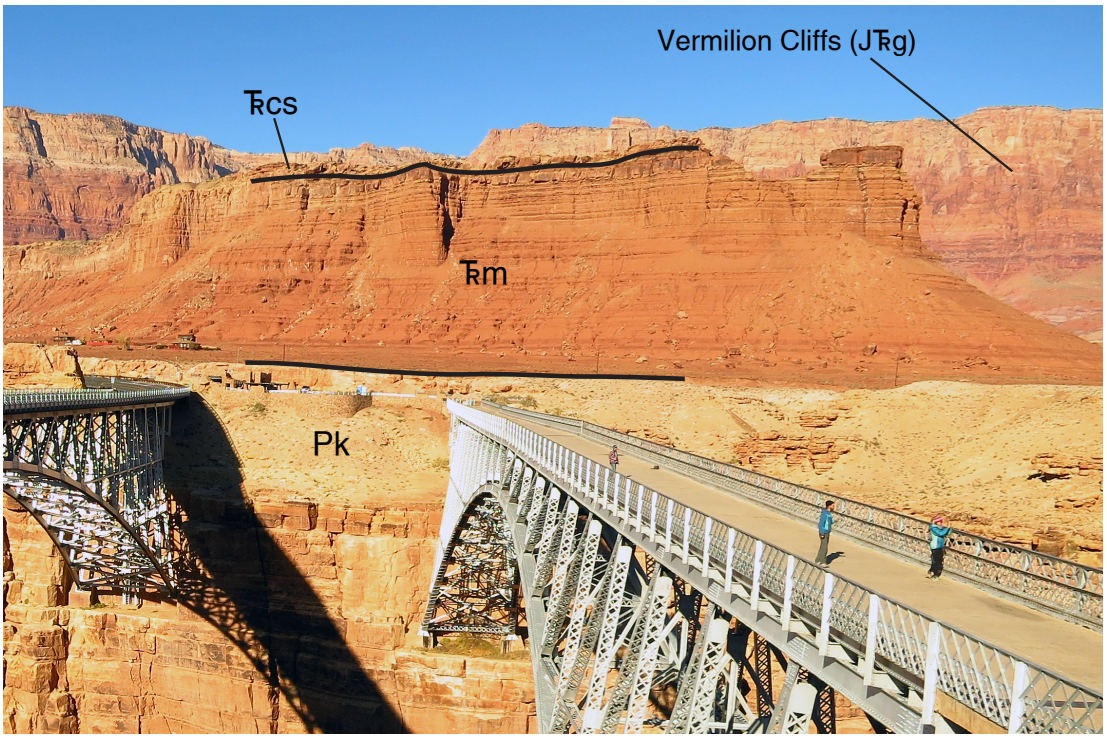


***Figure 10.*** *West-directed view across Navajo Bridge spanning Marble Canyon. Bridge abutments are on Permian Kaibab Formation (Pk). Five Mile Point mesa in mid-distance is composed of Triassic Moenkopi Formation (TRm) capped by the Triassic Shinarump Conglomerate Member of the Chinle Formation (TRcs). Vermilion Cliffs in far distance are primarily composed of Navajo Sandstone of the Glen Canyon Group (JTRg). Photo taken November 17, 2014.*

## Sources of Information

Sources of information used to evaluate flood hazard in the Glen Canyon study area include (1) Federal Emergency Management Agency (FEMA) National Flood Insurance Program Flood Insurance Rate Maps (FIRMs) (FEMA, 2010); (2) the distribution of young, water-deposited geologic units shown on UGS 1:24,000-scale geologic maps that cover the study area (Willis, 2012a; Willis, in preparation); (3) aerial photography interpretation (chiefly 2014 [Utah AGRC, 2014] and 2015 [Utah AGRC, 2016b] aerial photographs); (4) 1:2000-scale *Map Showing Quaternary Geology and Geomorphology of the Lees Ferry Area, Arizona* (Hereford and others, 2000); and (5) 1:5000-scale *Map Showing Quaternary Geology and Geomorphology of the Lonely Dell Reach of the Paria River, Lees Ferry, Arizona, with Comparative Landscape Photographs* (Hereford, 2003; Webb and Hereford, 2003).

## Flood Hazard in the Glen Canyon Study Area

Prior to Glen Canyon Dam closure in 1963, the Colorado River displayed highly variable discharge with large snowmelt-induced spring floods and low winter flows (Topping and others, 2003). Downstream from Glen Canyon Dam, the Colorado River currently reaches flood stage only during releases from the dam, or when there are significant contributions from tributaries during intense or prolonged rainfall.

### Flooding on the Paria River

The Paria River is the largest tributary of the Colorado River within the Glen Canyon study area, having a drainage area of over 1400 square miles (2300 km$^2$). The Paria River has a long history of damaging floods that typically occur in the late summer or early fall in response to monsoonal thunderstorms (Webb and others, 2002), although spring snowmelt floods are also possible. The Paria River stream gage, installed in 1923 near Lees Ferry, has recorded average annual mean discharge ranging from about 11 to 63 cubic feet per second (cfs) (U.S. Geological Survey [USGS], 2016a). However, the average annual peak discharge recorded at the Paria River gage is 4130 cfs. The largest recorded flood on the Paria River occurred in October 1925 with a peak discharge of 16,100 cfs (USGS, 2016a). Larger floods undoubtedly preceded installation of the Paria River stream gage, possibly including historical floods in the winter of 1862, March 1884, and September 1909 (Webb and others, 2002). The latter two floods caused extensive erosion and damage to the newly settled Utah communities of Rockhouse, Adairville, and Paria, that contributed to their abandonment (Gregory, 1945; Chidester and Bruhn, 1949; Carr, 1972; Webb and others, 2002). Using analyses of paleoflood deposits, Webb and others (2002) estimated that several floods in the 42,000 to 85,000 cfs range—about 3 to 5 times larger than the largest gaged floods—have occurred on the Paria River within the past approximately 10,000 years.

Floodplains and other low-lying areas near the mouth of the Paria River are particularly prone to flooding and erosion because the Paria River in this area has historically exhibited abrupt channel avulsions (sudden changes in flow path) during floods. A loss of confinement and a reduction in gradient at the mouth of the Paria River contribute to the alluvial-fan- or delta-like channel dynamics observed there. Thunderstorm-induced floods in the fall of 2013 (5890 cfs) and 2014 (6210 cfs) (USGS, 2016a) caused as much as 100 feet (30 m) of lateral erosion of the Paria River's bank near the NPS maintenance facilities at Lees Ferry (figure 11). Photographs taken in 1873, 1889, 1910, 1915, and 1921 all show different positions of the Paria River where it joins the Colorado River (Hereford and others, 2000; Webb and Hereford, 2003). Comparative photos of the confluence taken in 1910 and 1999 (Webb and Hereford, 2003) show that the mouth of the Paria River was once located at or very near the NPS maintenance facilities (figure 12). Because of the historical volatility of the Paria River in this area, we designate all floodplains and lower terraces adjacent to the river to be in the very high flood-hazard zone (https://geology.utah.gov/apps/hazards).

### Flash Floods

Flash floods are sudden, intense, localized events that occur in response to heavy rainfall that often accompanies convective, monsoonal thunderstorms. Because thunderstorms result from strong convective cells produced by differential atmospheric heating, flash floods are typically a summertime and early fall phenomenon in desert regions. Flash floods in the Glen Canyon study area can affect both perennial and ephemeral drainages and alluvial fans. In the study area, several normally dry streams drain large- to medium-sized areas (≥ 5 mi$^2$ [8 km$^2$]) and can channel damaging and life-threatening floods during thunderstorms. These canyons are included in the very high flood-hazard category and include Ticaboo Creek, Sevenmile Creek, Smith Fork, Hansen Creek, Lake Canyon, Moqui Canyon, Forgotten Canyon, and Cedar Canyon in the Bullfrog section of the study area. Wahweap Creek, Blue Pool Wash, Honey Draw, Ferry Swell, and Cathedral Wash in the Wahweap section of the study area are considered very high hazard, as well as West Canyon, Sei Bilbikooh, Face Canyon, Labyrinth Canyon, Navajo Creek, Kaibito Creek, and Antelope Canyon where not submerged by Lake Powell. The most unpredictable and intense floods in the Glen Canyon study area often take place in smaller drainages (<5 mi$^2$ [8 km$^2$]) that are typically floored by less-permeable bedrock and have relatively steep gradients. Steeper slopes increase the velocity of overland flow and decrease permeability (Costa and Baker, 1981). Hundreds of such drainages are designated as high hazard on the flood-hazard map. Minor (< 2 mi$^2$ [3 km$^2$]) tributary drainages subject to relatively shallow sheetfloods and moderate flash floods (figure 13) are designated as moderate hazard.

Floodwaters typically contain a large amount of sediment ranging in size from clay to boulders. As the proportion of sediment increases, flash floods transform into debris floods

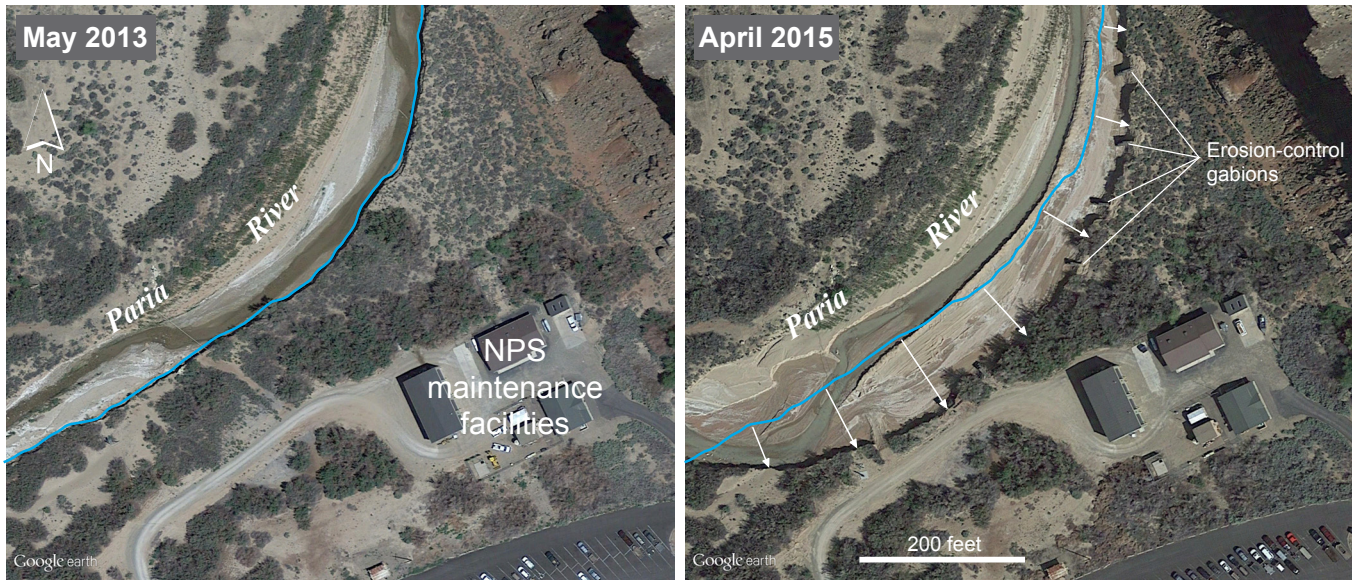


***Figure 11.*** *Comparison of Google Earth aerial imagery acquired in May 2013 and April 2015 showing as much as 100 feet of bank erosion along the Paria River near Lees Ferry. White arrows indicate change in river bank position from 2013 to 2015. Most erosion likely occurred during thunderstorm-induced floods during the fall of 2013 and 2014. Erosion-control gabions were constructed in fall of 2014 in an attempt to protect NPS maintenance facilities.*

and finally debris flows. A debris flow moves as a viscous fluid capable of transporting large boulders, trees, and other heavy debris over long distances. Debris flows on the Colorado Plateau commonly initiate as shallow slope failures in clay-rich bedrock units or colluvial deposits derived from those units (Webb and others, 2008). Like flash floods, debris flows are fast moving and under some conditions can exceed 35 miles per hour (56 km/h) (USGS, 1997). Their greater density and high speed make debris flows particularly dangerous to life and destructive to property. Debris flows can destroy buildings, roads, and bridges, and can deposit thick layers of mud, rock, and other debris. In the Glen Canyon study area, debris floods and flows occur most frequently near Lees Ferry (figure 14), where several short, steep drainages have headwaters in the easily eroded Chinle Formation.

Flash floods resulting from summer and early fall thunderstorms have claimed lives in the extremely narrow, bedrock-floored canyons of the Colorado Plateau in and near GCNRA (figure 15). In the fall of 1961, prior to the establishment of GCNRA, a nine-year-old girl was killed by a flash flood in Wahweap Creek (NPS, unpublished internal documents; Salt Lake Tribune, 1961). On September 5, 1998, a 10-year-old girl died in a flash flood in Ice Cream Canyon—a relatively small drainage (~3 $mi^2$ [5 $km^2$]) just north of the study area (figure 4) near Wahweap Window (NPS, unpublished internal documents; NOAA 2016a). One of the deadliest floods on the Colorado Plateau occurred on August 12, 1997, in lower Antelope Canyon less than 2 miles (3 km) south of the GCNRA boundary. A severe thunderstorm 3 to 5 miles (5–8 km) upstream caused a flash flood that swept 11 tourists and a tour guide down the slot canyon; the tour guide alone survived (NPS, unpublished internal documents; NOAA, 2016b). Of the 11 killed, one body was recovered from inside the canyon; eight bodies were recovered from Lake Powell; and two remain missing. A similar flash flood passed through Antelope Canyon in July 2010 that injured five tourists (NOAA, 2016b).

The increasing popularity of canyoneering—hiking, climbing, and swimming through slot canyons with the aid of technical climbing equipment—will likely cause an increase in flood-related incidents within GCNRA. Slot canyons in the Glen Canyon study area are particularly prone to the effects of flash floods because they commonly lack escape routes, are remotely located, are subject to logjams that present troublesome obstacles, and many can hold cold floodwaters for weeks that can contribute to hypothermic conditions for unprepared canyoneers. In April 2005, two canyoneers died in GCNRA at Choprock Canyon, a tributary of the Escalante River, likely of hypothermia or drowning when they unexpectedly encountered deep, cold water and logjams during a winter-spring period of above-average precipitation (NPS unpublished documents; Salt Lake Tribune, 2005). In addition to the internationally well-known Antelope Canyon, technically more-difficult slot canyons in West Canyon, Blue Pool Wash, and Cathedral Wash in the Wahweap section of the study area, and Ticaboo Creek, Sevenmile Creek, Warm Spring Canyon, and Smith Fork in the Bullfrog section of the study area, have all increased in popularity in the past two decades.

Boaters on Lake Powell should be wary of selecting mooring and campsites near the mouths of tributary canyons entering the lake. Normally dry, many of these ephemeral tributaries are "hanging" with their mouths 10s to 100s of feet above lake level, making them difficult to detect from below (figure 16). Hanging tributaries may be at the head of large alcoves in which boaters may seek shelter during thunderstorms, un-

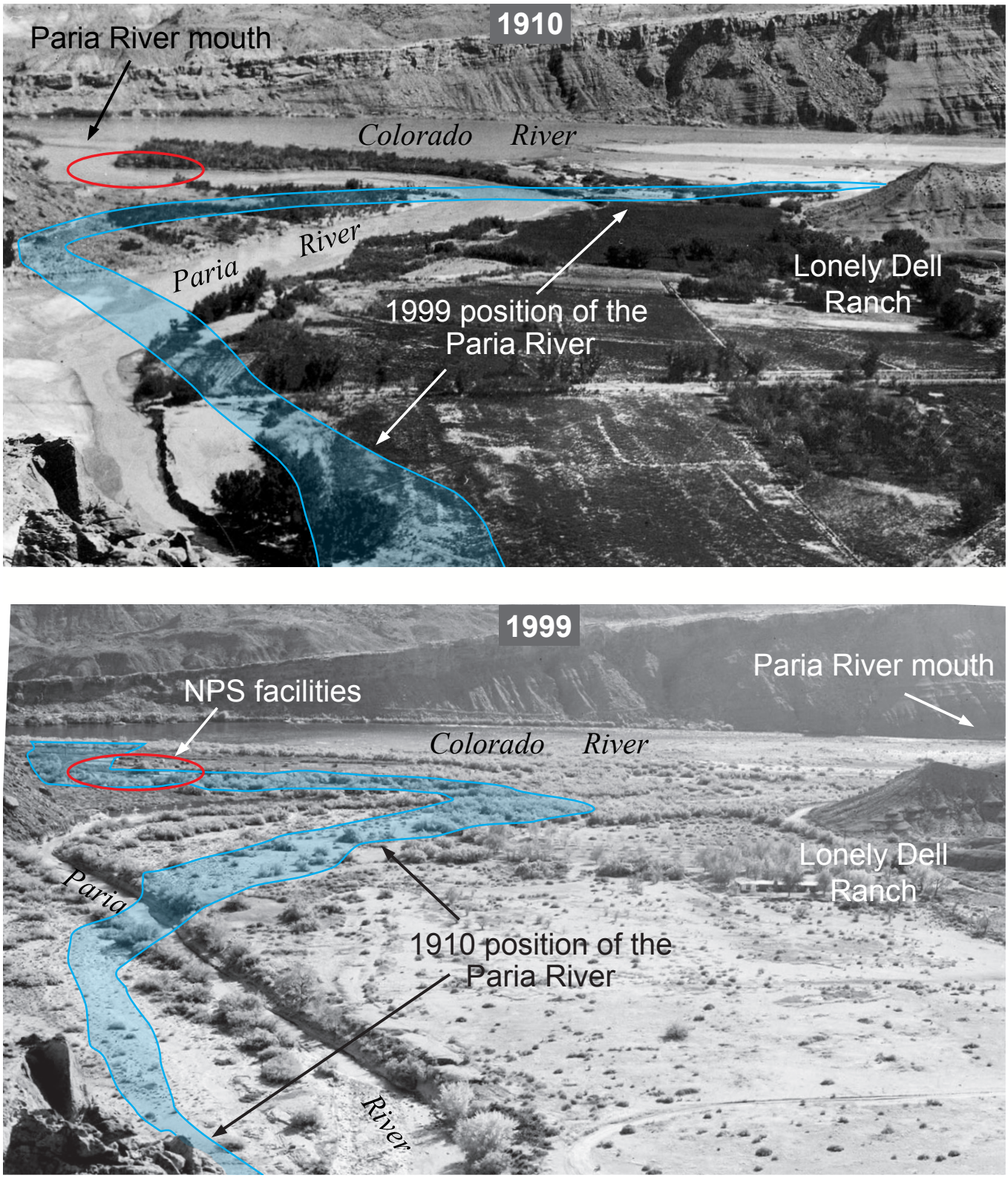


***Figure 12.*** *Photographs taken from the same vantage point of the confluence of the Paria and Colorado River in 1910 and 1999 near Lees Ferry; view is to the southeast. Red ellipse indicates location of the NPS maintenance facilities, which are coincident with the Paria River in 1910. Modified from Webb and Hereford (2003); 1910 photograph is by Albert H. Jones, courtesy of the Cline Library, Northern Arizona University; 1999 photograph by Robert Webb, U.S. Geological Survey.*

***Figure 13.*** *Example of a moderate flood-hazard area, where a small stream channel intersects the Bullfrog Campground. Although minor, such channels can carry substantial water and debris during thunderstorm-induced flash floods which can damage facilities and threaten visitor safety. Photo taken August 20, 2015.*

***Figure 14.*** *September 12, 2013, debris flow that deposited mud and car-sized boulders onto Lees Ferry Road. Photo courtesy of the National Park Service.*

***Figure 15.*** *Short, unnamed slot canyon formed in Entrada Sandstone near the Bullfrog Visitor Center. The closely spaced, near-vertical walls of slot canyons can make it difficult for hikers and canyoneers to see approaching thunderstorms and to escape flash floods. Photo taken August 20, 2016.*

***Figure 16.*** *Flash flood water plunges into Lake Powell from a normally dry hanging tributary on June 6, 2015. Such hanging drainages pose a significant hazard to boaters because they can be difficult to recognize from lake level. Photo courtesy of Valerie Reynolds, National Park Service.*

aware of the potentially high flood hazard. On June 6, 2015, intense rain from a thunderstorm caused a flash flood in an unnamed slightly hanging tributary of Crystal Springs Canyon. A boating group camping near the normally dry tributary's mouth (estimated to be about 15 to 20 feet (5–6 m) above lake level at the time) was stranded for several hours as the plunging floodwaters created a powerful eddy that ripped their three boats from their anchors and tossed them about (NOAA, 2016b; KSL, 2016). One 23-foot boat was hit and submerged by large boulders entrained in the cascading floodwaters and was a total loss.

## Flood-Hazard Classification

The Federal Emergency Management Agency (FEMA), through its National Flood Insurance Program (NFIP), has prepared Flood Insurance Rate Maps (FIRMs) for a very limited area in the Glen Canyon study area. FIRMs show expected boundaries for 100-year and in some cases 500-year floods (floods having a 1 percent and 0.2 percent annual chance, respectively, of occurring in any given year) along selected drainages. The NFIP uses FIRMs to make federally subsidized flood insurance available in flood-prone areas once required flood-proofing design features are incorporated into building construction. FIRM coverage in the Glen Canyon study area is limited to the Page–Lees Ferry area, where FIRM Community-Panel Numbers 04005C0400G, 04005C0375G, 04005C0725G, and 04005C0750G (FEMA, 2010) show the expected 100-year-flood boundaries along parts of the Colorado River and a few of its larger tributaries including Honey Draw, Ferry Swale Canyon, the Paria River, and Cathedral Wash. Some 500-year-flood boundaries are also mapped along Honey Draw. FEMA now makes their flood-hazard mapping data available to GIS users via a digital database called the National Flood Hazard Layer

(NFHL) (FEMA, 2018). FEMA-designated flood zones from the NFHL are overlain on our geology-based flood-hazard categories shown on the flood-hazard map (https://geology.utah.gov/apps/hazards).

Those parts of the study area not covered by FIRMs contain numerous ephemeral drainages, alluvial fans, and other low-lying areas subject to periodic flooding and debris flows, chiefly resulting from monsoonal thunderstorms. The probability of flooding, particularly flash flooding, at a particular location over a fixed period of time is uncertain; however, relative flood hazard can be estimated from the distribution of evidence of previous flooding in the study area. Where possible, we used the distribution of geologically young alluvial deposits shown on 1:24,000-scale geologic maps (see Sources of Information section) to identify flood-prone areas and their relative susceptibility to flooding throughout the Glen Canyon study area. However, the study area contains large areas of exposed bedrock (chiefly slickrock benches and canyons, badlands, and mesa tops) undergoing active erosion that lack mappable alluvial deposits. Flood hazard in these areas was based primarily on drainage size, drainage gradient, general permeability of geologic substrate, clay content of geologic substrate (for evaluating debris-flow potential), and evidence of past flooding observed on aerial photography or in the field. Due to topographic complexities and scale limitations, flood hazard could not be mapped for some smaller channels, particularly in complexly eroded slickrock and badland areas. It is important to note that a flash flood can occur in, or issue from any drainage, whether depicted or not, on the flood-hazard map.

## Using This Map

Our flood-hazard mapping (https://geology.utah.gov/apps/hazards) shows flood-susceptible areas in the Glen Canyon study area and provides a basis for conducting site-specific flood-, debris-flow-, and erosion-hazard investigations. Site-specific investigations can resolve uncertainties inherent in generalized hazard mapping and help ensure safety by identifying the need for flood-resistant design. However, because intense thunderstorms create a potential for flash floods, debris flows, and sheetfloods anywhere in the Glen Canyon study area, even locations outside identified flood-prone areas could be subject to periodic flooding. The map also shows where existing development lies in flood-prone areas, and therefore, where flood-resistant-design measures may be required. An evaluation of existing flood-mitigation measures and their likely effectiveness is beyond the scope of this study.

## Hazard Reduction

Early recognition and avoidance of areas subject to flooding are the most effective means of flood-hazard reduction. However, avoidance may not always be a viable or cost-effective option, especially for existing development. Other techniques available to reduce flood and debris-flow damage may include, but are not limited to, source-area stabilization, engineered protective structures, flood and debris-flow warning systems, and flood proofing. Some of these techniques can be expensive and their cost-versus-benefit ratio should be carefully evaluated along with effectiveness and reliability. We recommend a flood- and erosion-hazard investigation for new construction in all hazard categories shown on the flood-hazard map, and for debris-flow hazards following the guidelines of Giraud (2016). The first consideration in reducing the hazard from stream flooding and debris flows is the proper identification of hazard areas through detailed mapping, and qualitative assessment of the hazard (Giraud, 2016). The stream-flooding hazard assessment should determine the active flooding area, the frequency of past events, and the potential inundation area and flow depths. The debris-flow hazard assessment should determine active depositional areas, the frequency and volume of past events, and sediment burial depths (Giraud, 2016). The level of detail for a hazard assessment depends on several factors, including (1) the type, nature, and location of the proposed development; (2) the geology and physical characteristics of the drainage basin, channel, and alluvial fan; (3) the history of previous flooding and debris-flow events; and (4) proposed risk-reduction measures.

Where development is proposed in areas identified as having a potential flood hazard, a site-specific investigation should be performed early in the project design phase, and for debris-flow hazards following the guidelines of Giraud (2016). The investigation should clearly establish whether a flood, debris flow, or erosion hazard is present at a site and provide appropriate design recommendations. Additionally, GCNRA visitors often enter areas that are prone to flooding. The risk to visitors is short-term but constitutes a significant threat due to the number of visitors and the fact that most come to the park lacking a full appreciation of the nature of rainfall and flooding in this area. To mitigate this threat, the NPS should continue to inform visitors—particularly hikers, canyoneers, and boaters—of flood hazards via brochures, web-based education materials, and interpretive signage in some high-risk, high-visitation areas.

## Map Limitations

Our flood-hazard mapping is based on limited geological, geotechnical, topographic, and hydrological data; site-specific investigations are required to produce more detailed flood-hazard information. The mapping also depends on the quality of those data, which varies throughout the study area. The mapped boundaries of the flood-hazard categories are approximate and subject to change as new information becomes available. The flood hazard at any particular site may be different than shown because of geological and hydrological variations within a map unit, gradational and approximate map-unit boundaries, the generalized map scale, and topographic

changes along drainages that postdate mapping. Small, localized areas of higher or lower flood hazard may exist within any hazard area, but their identification is precluded because of limitations of the map scale. The mapping is not intended for use at scales other than the target scale of 1:24,000 and is designed for use in general planning to indicate general hazard areas and the need for site-specific investigations.

## ROCKFALL HAZARD

Rockfall is a natural mass-wasting process that involves the dislodging and downslope movement of individual rocks and rock masses (Cruden and Varnes, 1996). Rockfalls pose a threat because falling or rolling boulders can damage property and cause injury or loss of life. Rockfall hazard exists where a source of rock is present above slopes steep enough to allow rapid downslope movement of dislodged rocks by falling, rolling, and bouncing. Most rockfalls originate on slopes steeper than 35 degrees (Wieczorek and others, 1985; Keefer, 1993), although rockfall hazards may be found on less-steep slopes.

Rockfall hazard potential is based on several factors including geology, topography, and climate. Rockfall sources include bedrock outcrops or boulders on steep mountainsides or steep escarpments such as bluffs, cliffs, and terraces. Talus cones and scree-covered slopes are indicators of a high rockfall hazard, although other areas are also vulnerable. Rockfalls may be initiated by frost action, rainfall, weathering and erosion of the rock or surrounding material, and root growth, though in many cases, a specific triggering mechanism is not apparent. Rockfalls may also be initiated by ground shaking. Keefer (1984) indicated earthquakes as small as magnitude 4.0 can trigger rockfalls.

Slope modifications, such as cuts for roads and building pads or clearing of slope vegetation for development, can increase or create a local rockfall hazard. However, in many cases, a specific triggering event is not apparent. Although not well documented, rockfalls in Utah appear to occur more frequently during spring and summer months, likely due to spring snowmelt, summer thunderstorms, and large daily temperature variations (Castleton, 2009).

### Sources of Information

Sources of information used to evaluate rockfall hazard in the Glen Canyon study area include (1) recent UGS 1:24,000-scale geologic mapping that covers the Bullfrog (Willis, in preparation) and Wahweap sections (Phoenix, 2009; Willis, 2012a) of the study area; (2) reconnaissance landslide and rockfall surveys of GCNRA by the Bureau of Reclamation (Mann, 1973; Grundvig, 1980); (3) interpretation of stereo and orthophoto aerial photography including 1940 (Soil Conservation Service, 1940), 1948 (Jack Ammann Photogrammetric Engineers, 1948), 1953 (Army Map Service, 1953), mid-1990s (Utah Automated Geographic Reference Center [AGRC] 2016a), 2014 (Utah AGRC, 2014), and 2015 (Utah AGRC, 2016b) aerial photographs; (4) high-resolution Lake Powell bathymetry data (NPS, unpublished GIS data); and (5) a limited number of unpublished, site-specific geotechnical reports acquired in the Glen Canyon area.

### Rockfall Sources

The geology of the Glen Canyon study area is conducive to widespread rockfall hazard. Rockfalls are particularly prevalent and hazardous where more resistant bedrock formations form ledges above easily eroded bedrock units (figure 17). Four resistant-over-easily-eroded bedrock pairs are particularly susceptible to rockfall in the study area: Shinarump Conglomerate over the Moenkopi Formation, Wingate Sandstone over the upper Chinle Formation, Navajo Sandstone over the Kayenta Formation, and Entrada Sandstone over the Carmel Formation. On a smaller scale, ledges within some slope-forming units can also create a rockfall hazard. Erosion of the underlying units and subsequent undercutting of the more resistant bedrock formations trigger many rockfalls. Talus deposits blanket steep to moderate slopes throughout the study area. These deposits are derived from upslope ledges and cliffs and consist chiefly of accumulations of poorly sorted, coarse, angular rockfall blocks of various sizes. The widespread distribution of talus and the direct relation of talus deposits to the rockfall process attest to the widespread extent of the rockfall hazard in the study area. Along the margins of Lake Powell, talus deposits are commonly submerged and not visible; therefore, the presence of talus alone cannot be used to identify rockfall-prone areas.

Joints are among the most prominent bedrock structures in GCNRA, and jointing is the most significant bedrock discontinuity contributing to rockfall hazard in the study area (Grundvig, 1980; Anderson and others, 2010). There are two basic joint types in the Glen Canyon area: (1) relatively long, primary regional joints that have developed due to regional tectonic stresses such as Laramide-age folding, nearby laccolithic intrusions, and the erosional unloading of thousands of feet of overlying rock; and (2) relatively short, secondary, stress-relief joints that develop parallel to canyon walls in response to lateral unloading due to canyon erosion. The orientation and spacing of primary joints vary throughout the study area. We generally found the most pervasive, closely spaced primary jointing within Navajo Sandstone outcrops in the Wahweap section of the study area—particularly in Glen Canyon below Glen Canyon Dam and along the main channel of Lake Powell. Both vertical and inclined primary regional joints are common throughout the study area. Several northwest-trending Laramide folds crossing the Wahweap section (Cedar Mountain anticline, Wahweap syncline, Smoky Mountain anticline, and Last Chance Creek syncline; figure 5) are

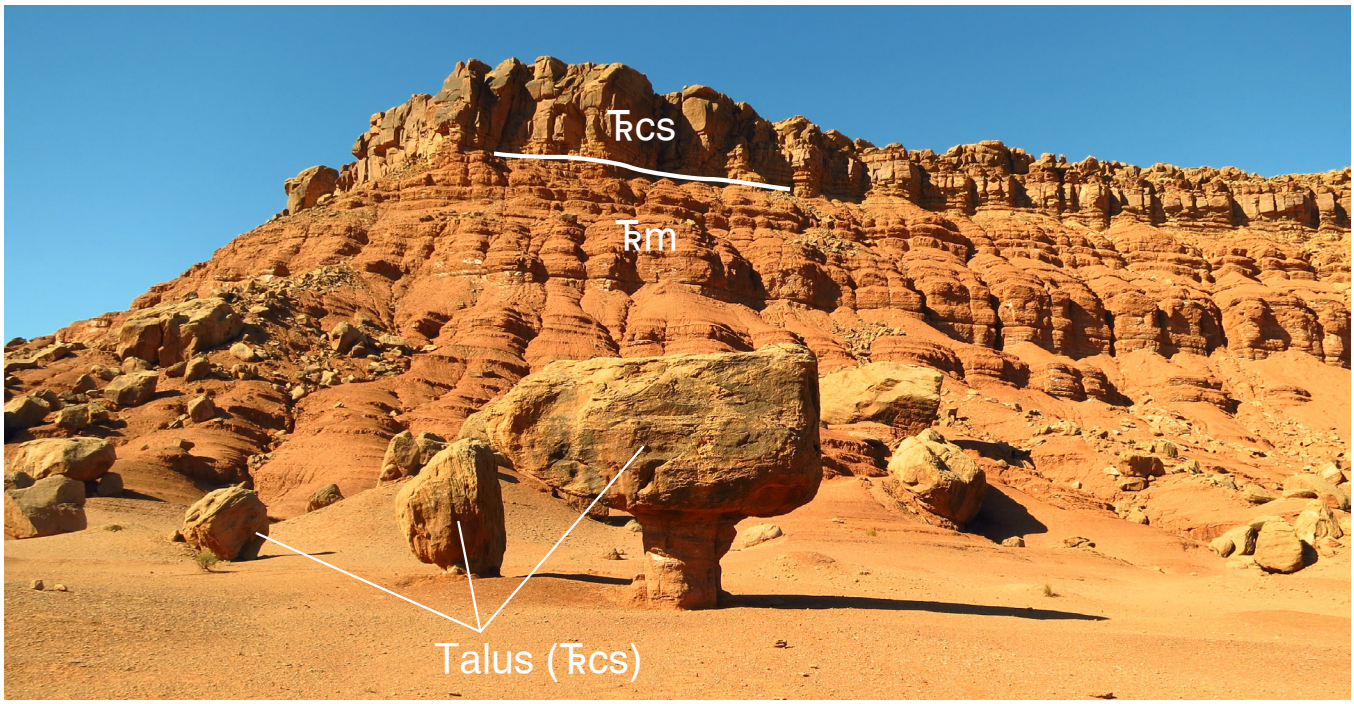


***Figure 17.*** *Very high rockfall-hazard area near Lees Ferry that is typical of many similar areas in the study area where softer bedrock units crop out on slopes below more resistant cliff-forming formations. Erosion of the underlying softer unit undercuts the more resistant unit, producing numerous rockfalls. Photo taken on November 17, 2014. TRcs= Triassic Shinarump Conglomerate, TRm= Triassic Moenkopi Formation.*

likely responsible for the high joint density in this area. The orientation of shorter, secondary stress-relief joints tends to mimic the orientation of the nearby cliff faces and may be vertical, inclined, or curvilinear. Stress-relief joints near Glen Canyon Dam were one of the most important geologic problems encountered during construction of the dam (U.S. Bureau of Reclamation, 1970). Rock bolting and grout injection were used extensively to stabilize stress-relief joints at the dam site prior to and during dam construction. Rock bolting is still periodically employed to stabilize partially detached rock slabs near the dam (figure 18).

A common mode of rockfall observed along the cliff-edged canyons in the study area occurs where primary regional joints intersecting the cliff face at a wide angle are cut by younger stress-relief joints oriented parallel to the canyon wall. The near-orthogonal intersection of primary and secondary joints creates partially detached pillars, slabs, or wedges (depending on whether the joint sets are inclined or vertical) that are prone to topple or slide downslope (figure 19).

Alcoves and other overhanging rock masses along the Lake Powell shoreline make attractive mooring spots and campsites for boaters (figure 20), particularly in the summer when alcoves provide shade, cooler temperatures, and shelter from thunderstorms. Talus deposits beneath alcoves are indicative of prolific rockfall generation. Talus deposits at lake level also offer convenient boat anchoring compared to surrounding vertical or near-vertical sandstone walls. Additionally, submerged rockfall boulders beneath shady overhangs are favored fishing areas. Within the Glen Canyon study area, deep alcoves frequented by boaters are particularly prevalent in Lake, Moqui, Crystal Springs, Forgotten, Knowles, Cedar, and Warm Springs canyons.

Alcoves commonly form in the Navajo Sandstone when percolating groundwater reaches a relatively impermeable layer (clay-rich or limestone interbeds, or underlying Kayenta Formation) that forces groundwater to flow laterally until eventually emerging as springs or seeps. The discharging groundwater weakens and removes the cement between sand grains, which accelerates erosion, and forms a recess or alcove in the cliff face (Anderson and others, 2010). We found the greatest concentration of alcoves in the Bullfrog section of the study area. Many Bullfrog-section canyons are incised into Navajo Sandstone that generally lacks the pervasive regional joint sets common in the Wahweap section. The lack of closely spaced joints results in a more competent rock mass that favors formation of deep alcoves. Other deep alcoves in the Bullfrog section formed by undercutting of rock on the outside bend of meanders of entrenched drainages. Although most alcoves formed in Navajo Sandstone that lacks primary regional joints, many alcoves have developed open, curvilinear secondary joints (figure 21) that promote instability by (1) partially detaching the alcove's roof from the adjoining rock mass, and (2) allowing water infiltration that promotes further erosion of the overhanging rock mass.

The filling of Lake Powell and subsequent water-level fluctuations have greatly contributed to the generation of rockfalls and landslides within GCNRA (Brokaw, 1974; Grundvig, 1980; Anderson and others, 2010). Some reservoir effects that

***Figure 18.*** *Work crew installs rock bolts on September 2, 2015, to help stabilize a large slab of Navajo Sandstone created by a secondary stress-relief joint near Glen Canyon Dam. Photo courtesy of Frank Talbot (franktalbott.net).*

***Figure 19. Left:*** *Secondary stress-relief joints formed parallel to a Navajo Sandstone cliff face in Glen Canyon below Glen Canyon Dam.* ***Right:*** *Closely spaced primary joints (prominent joints in cliff face) intersect secondary stress-relief joints (normal to camera view and therefore not easily seen in this view) to produce abundant column- and wedge-shaped rock masses prone to collapse below the Horseshoe Bend Overlook in Glen Canyon. Large, unvegetated talus slopes below the cliff indicate a high rate of rockfall. Photos taken on August 13, 2015.*

***Figure 20.*** *Houseboat anchored on talus deposits below a large alcove in Moqui Canyon. Although alcoves can provide shelter from sun and storms, they also produce abundant rockfall that can threaten life and property. Photo taken August 18, 2015.*

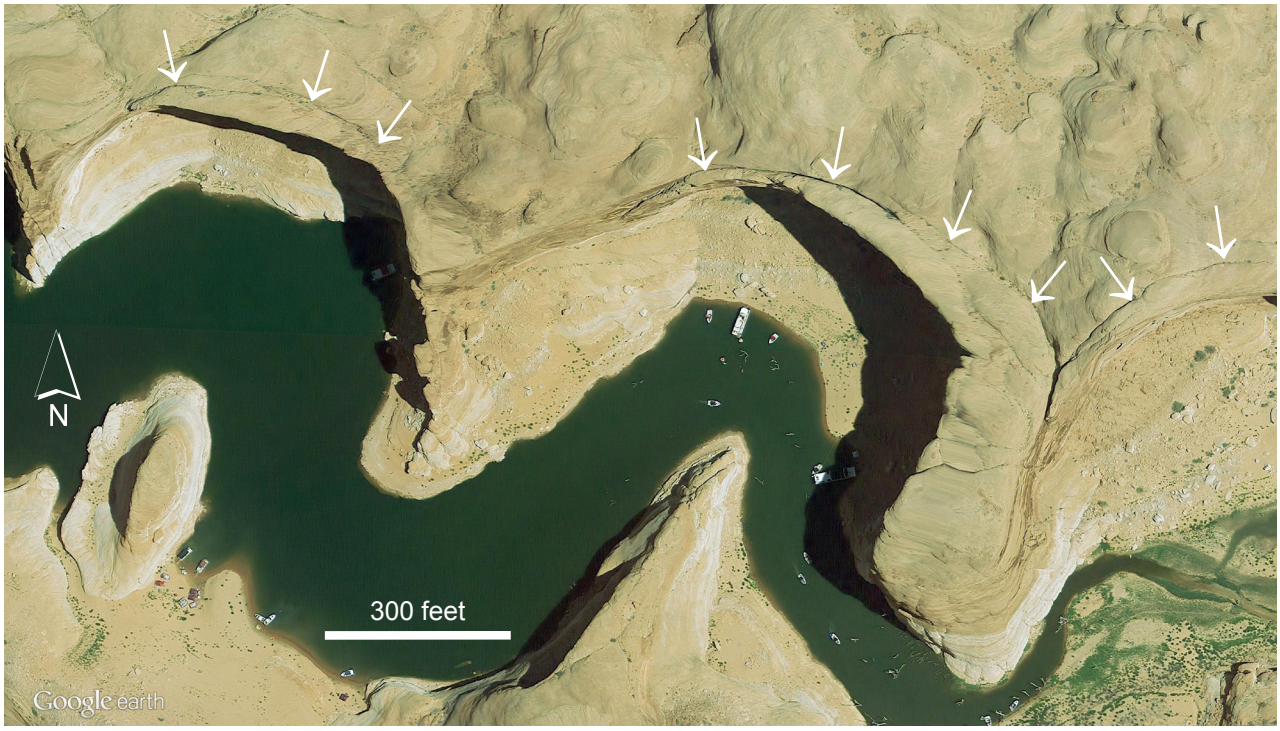


***Figure 21.*** *Curvilinear secondary joints (marked by arrows) developed above alcoves in Forgotten Canyon (June 2013 Google Earth image). Note boats in photo center moored beneath an alcove.*

can accelerate rockfall processes include (1) wave erosion of soft slopes that can destabilize overlying cliffs and ledges, (2) increase in pore-water pressure during periods of drawdown, (3) increased erosion and lubrication along existing joints, and (4) possible weakening of intergranular cementing agents.

## Rockfalls in GCNRA

Four fatalities due to natural rockfall are known within GCNRA. In August 1975, a rock fell from the top of an alcove formed in the Entrada Sandstone near the mouth of Padre Bay and destroyed a boat, killing one person and injuring another (Grundvig, 1980; NPS, unpublished internal documents). In July 1999, a rockfall near the San Juan River upstream from Lake Powell landed on and partially buried the tent of a camper, killing the single occupant inside (NPS, unpublished internal documents). The rockfall was likely sourced from overhanging rock of the Pennsylvanian Paradox Formation, which fell during a heavy rain event. Two people died in Lake Canyon in September 2007 while fishing beneath a small alcove in the Navajo Sandstone. An estimated 25-foot-long (8 m) and 15-foot-thick (5 m) slab of sandstone fell from the roof of the alcove, flipping and damaging the boat and killing both occupants (NPS, unpublished internal documents). At least two additional fatalities in GCNRA occurred when small rock masses upon which people were standing broke loose causing both the rock and the person to fall down near-vertical slopes. The most recent of these incidents occurred at Horseshoe Bend overlook in July 2010 (NPS, unpublished internal documents).

Rockfalls can produce large displacement waves that can greatly extend the hazard beyond the immediate area affected by the falling rock (Roberts and others, 2014). Displacement waves result from the rapid entry of landslides or rockfalls into enclosed water bodies (Hermanns and others, 2013; Roberts and others, 2014). Depending on the size of the mass entering the water, a displacement wave may have the form of a frontal push or a tsunami-like body wave (de Blasio, 2011). Large rockfalls in narrow channels that typify much of Lake Powell can produce sizeable waves capable of swamping boats and running up adjacent shorelines, damaging anchored boats and causing injury or death to campers. In June 1974, a large rock slab released from a Navajo Sandstone cliff in the main channel of Lake Powell near Iceberg Canyon. The resulting displacement wave lifted a boat anchored across the main channel and deposited it 40 feet from the shoreline (Grundvig, 1980). In June 1987, a rockfall in Llewellyn Gulch caused a large wave that grounded a nearby speedboat, injuring the boat operator (figure 22) (NPS, unpublished internal documents).

## Rockfall-Hazard Classification

Our rockfall-hazard mapping (https://geology.utah.gov/apps/hazards) shows areas in the Glen Canyon study area that are susceptible to rockfall. Determining the severity of rockfall hazard requires evaluating the characteristics of three hazard components (figure 23): (1) a rock source, in general defined by bedrock geologic units that exhibit relatively consistent patterns of rockfall susceptibility throughout the study area; (2) an acceleration zone, where rockfall fragments detached from the source gain momentum as they travel downslope—this zone often includes a talus slope, which becomes less apparent with decreasing relative hazard and is typically absent where the hazard is low or may be submerged by Lake Powell; and (3) a runout zone or rockfall shadow, which includes gentler slopes where boulders roll or bounce before coming to rest beyond the base of the slope (Evans and Hungr, 1993; Wieczorek and others, 1998). Where appropriate, we established the boundaries of areas subject to rockfall hazard in the study area by measuring a shadow angle (Evans and Hungr, 1993; Wieczorek and others, 1998), which is the angle formed between a horizontal line and a line extending from the base of the rock source to the outer limit of the runout zone (figure 23). Shadow angles vary based on rock type, boulder shape, slope steepness, slope roughness, and rock source height. We measured shadow angles for dozens of representative rockfall boulders in the Glen Canyon study area. Our investigation showed that a shadow angle of 22 degrees is generally applicable in the study area and defines a hazard zone sufficiently wide to include the limits of rockfall debris that accumulates at the base of cliffs and steep slopes.

We assigned a hazard designation of very high, high, moderate, or low based on the following rockfall-source parameters: rock type, slope angle, orientation and density of discontinuities, presence of alcoves or overhanging rock masses, potential clast size, and mapped talus deposits. We mapped more than 10,000 discontinuities, including regional joint sets, stress-relief joints, and faults along major canyon rims to make simple qualitative assessments of source areas. More densely jointed rock allows more water infiltration into the rock mass where weathering processes, including freeze-thaw and frost wedging, can occur over a larger volume of the slope and accelerate mass wasting. Although we did not perform rigorous analyses of how intersecting joint sets may affect failure mode (i.e., wedge, planar slides, topple), we did assign a higher rockfall hazard to cliff source areas that exhibit a high joint density and/or discontinuities parallel to the cliff face. Similarly, alcoves and other overhanging rock masses were assigned a higher hazard compared to non-overhanging cliffs.

Because reservoir levels fluctuate greatly and may continue to decline due to regional drought conditions, we extended rockfall-hazard zones to the elevation of the former Colorado River beneath Lake Powell. The extension of hazard zones beneath Lake Powell is based on pre-reservoir 1940 (Soil Conservation Service, 1940), 1948 (Jack Ammann Photogrammetric Engineers, 1948), and 1953 (Army Map Service, 1953) aerial photographs and high-resolution bathymetry data (NPS, unpublished GIS data). Due to limited sources of data and the inability to field check, these extended hazard zones are not as accurate as those above about the 3600-foot elevation (2000 m) contour.

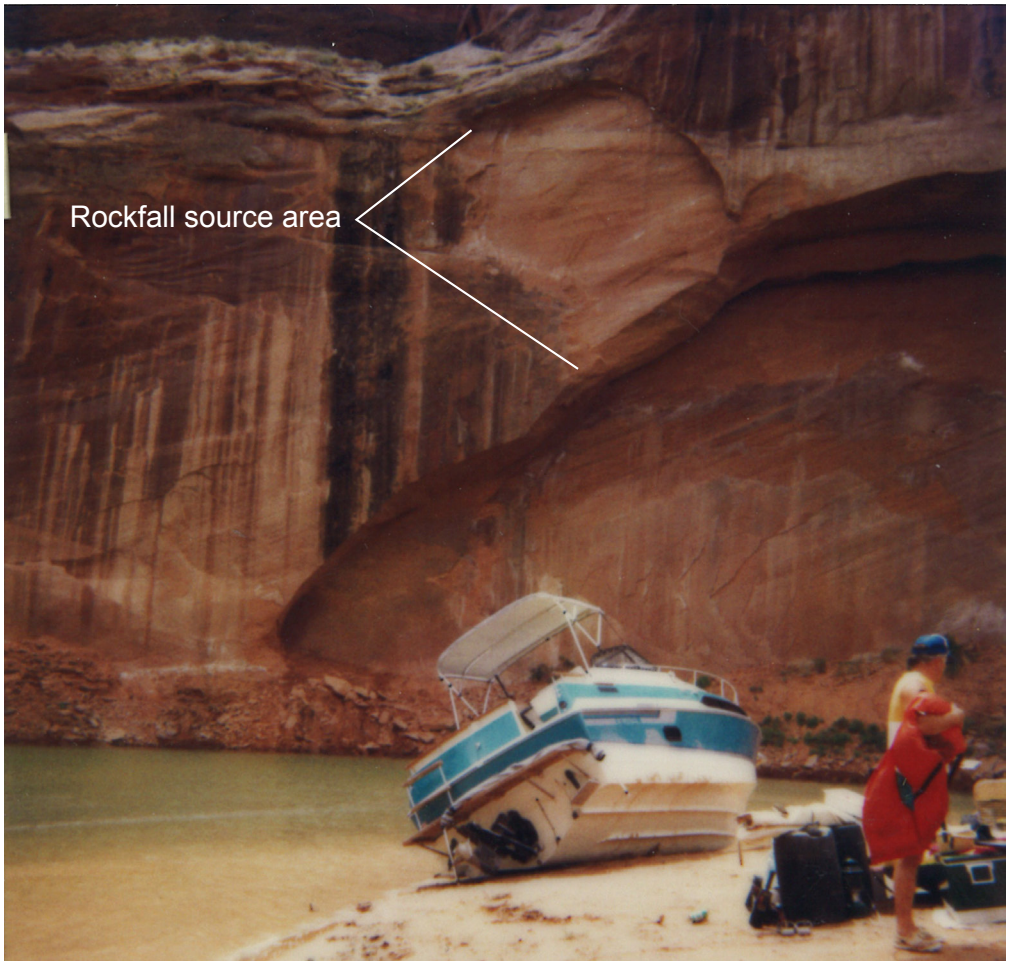


***Figure 22.*** *Speedboat beached by a large displacement wave caused by rockfall in Llewellyn Gulch. National Park Service photo taken June 5, 1987.*

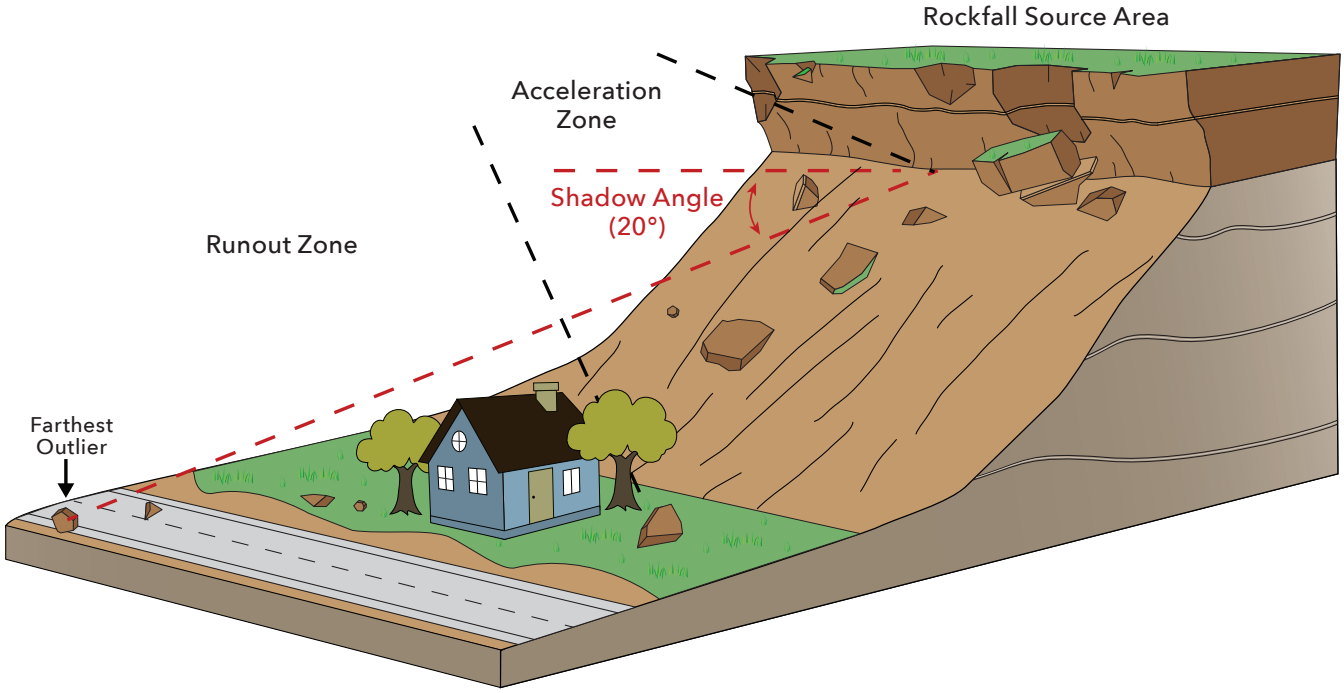


***Figure 23.*** *Components of a characteristic rockfall path profile (modified from Lund and others, 2008b).*

## Using This Map

Our rockfall-hazard mapping (https://geology.utah.gov/apps/hazards) shows areas of relative rockfall hazard in the Glen Canyon study area. The UGS recommends that a rockfall-hazard investigation be made for all new buildings for human occupancy and for modified International Building Code (IBC) Risk Category II(a), II(b), III, and IV facilities (modified from IBC table 1604.5 [International Code Council, 2017a]) that are proposed in mapped rockfall-hazard areas (table 1) (Lund and Knudsen, 2016). The UGS recommends that investigations be conducted for all IBC Risk Category III and IV facilities on or adjacent to areas where bedrock crops out on steep slopes, whether near a mapped rockfall area or not, to ensure that a previously unknown rockfall hazard is not present (Lund and Knudsen, 2016). If a hazard is found, the UGS recommends a comprehensive investigation be conducted. In some instances, an investigation may become necessary when existing infrastructure is discovered to be on or adjacent to a rockfall-susceptible area. An experienced geotechnical engineer should provide design or site preparation recommendations as necessary to reduce the rockfall hazard. These investigations can resolve uncertainties inherent in generalized hazard mapping and help ensure safety by identifying the need for rockfall-resistant design or mitigation.

## Hazard Reduction

Early recognition and avoiding areas subject to rockfall are the most effective means of reducing rockfall hazard. However,

***Table 1.*** *Recommended requirements for site-specific rockfall-hazard investigations for modified IBC risk category of buildings and other structures (modified from International Code Council [2017a] and IBC table 1604.5).*

| Mapped Hazard Potential | IBC Risk Category[1] | | | | |
|---|---|---|---|---|---|
| | I | II(a) | II(b) | III | IV |
| | Buildings and other structures that represent a low hazard to human life in the event of failure | Single family dwellings, apartment complexes and condominiums (<10 dwelling units), and campgrounds | Buildings and other structures except those listed in I, II(a), III, and IV | Buildings and other structures that represent a substantial hazard to human lives in the event of failure | Buildings and other structures designated as essential facilities |
| Very High, High, Moderate | No[2] | Yes | Yes | Yes | Yes |
| Low | No[2] | Yes | Yes | Yes | Yes |
| None | No | No | No | No[3] | No[3] |

[1] See International Code Council (2017a) chapter 3, Occupancy Classification and Use and chapter 16, Structural Design, table 1604.5 for a complete list of structures/facilities included in each IBC Risk Category. Check table 1604.5 if a question exists regarding which Risk Category a structure falls under. For purposes of these recommendations, Risk Category II has been divided into subcategories II(a) and II(b) to reflect the lower hazard associated with single family dwellings, apartment complexes and condominiums with <10 dwelling units, and campgrounds.

Risk Category I—includes but not limited to agricultural facilities, certain temporary facilities, and minor storage facilities;

Risk Category II(a)—single family dwellings, apartment complexes, condominiums (<10 dwelling units), and campgrounds;

Risk Category II(b)—buildings and other structures except those listed in Risk Categories I, II(a), III, and IV; includes, but not limited to:

a. many business, factory/industrial, and mercantile facilities;
b. public assembly facilities with an occupant load < 300 (e.g., theaters, concert halls, banquet halls, restaurants, community halls);
c. adult education facilities such as colleges and universities with an occupant load < 500;
d. other residential facilities (e.g., boarding houses, hotels, motels, care facilities, dormitories with >10 dwelling units).

Risk Category III—includes, but not limited to:

a. public assembly facilities with an occupant load > 300, schools (elementary, secondary, day care);
b. adult education facilities such as colleges and universities with an occupant load > 500;
c. Group I-2 occupancies (medical facilities without surgery or emergency treatment facilities) with an occupant load > 50;
d. Group I-3 occupancies (detention facilities, for example: jails, prisons, reformatories) with an occupant load > 5;
e. any other occupancy with an occupant load > 5000;
f. power-generating stations, water treatment plants, wastewater treatment facilities, and other public utility functions not included in risk category IV;
g. buildings and other structures not included in risk category IV that contain quantities of toxic or explosive materials.

Risk Category IV—includes, but not limited to:

a. Group I-2 occupancies having surgery or emergency treatment facilities;
b. fire, rescue, ambulance, and police stations, and emergency vehicle garages;
c. designated emergency shelters; emergency preparedness, communication, and operations centers and other facilities required for emergency response;
d. power-generating stations and other public utility facilities required as emergency backup facilities for Risk Category IV structures;
e. buildings and other structures containing quantities of highly toxic materials;
f. aviation control towers, air traffic control centers, and emergency aircraft hangars;
g. buildings and other structures having critical national defense functions;
h. water storage facilities and pump structures required to maintain water pressure for fire suppression.

[2] Property damage possible, but little threat to life safety.

[3] Investigations are recommended if IBC Risk Category III and IV facilities are adjacent to areas where bedrock crops out on steep slopes, even if not near a mapped rockfall-hazard area, to ensure that a previously unknown rockfall hazard is not present. If a hazard is found, a comprehensive investigation is recommended.

avoidance may not always be a viable or cost-effective option, especially for existing development, and other techniques are available to reduce potential rockfall damage. These may include, but are not limited to, rock stabilization, removal of loose rock (scaling), emplacement of engineered structures, and modification of at-risk structures or facilities. Rock-stabilization methods are physical means of reducing the hazard at its source using rock bolts and anchors, steel mesh, or shotcrete on susceptible outcrops. Engineered catchment or deflection structures, such as berms or benches, can be placed below source areas, or at-risk structures themselves could be designed to stop, deflect, retard, or retain falling rocks. Conversely, after careful consideration of the hazard, it may be possible to conclude that the level of risk is acceptable and that no hazard-reduction measures are required (Lund and others, 2010).

Our rockfall-hazard mapping (https://geology.utah.gov/apps/hazards) shows very high and high rockfall hazard is widespread along the shores of Lake Powell. Placing warning signs/barricades and rock stabilization/scaling at high-hazard areas along the shoreline are not practical, especially considering the large fluctuations in reservoir levels. The most effective way to protect visitors to Lake Powell is through the distribution of safety information to educate boaters on potential shoreline hazards. Brochures and web-based education materials should instruct boaters to avoid spending lengthy periods below potentially unstable cliffs or alcoves and to not topple or force rocks down slopes or over cliffs. The materials should include photographic examples to help boaters recognize simple signs of instability, such as obvious fractures in cliff faces and alcoves, fresh rockfall scars and deposits, and precariously balanced or hanging boulders.

Occasionally, isolated, critically hazardous conditions may arise that require appropriate mitigation. Horseshoe Bend Overlook lies on the rim of Glen Canyon southwest of Page, Arizona, 1100 feet (330 m) above the Colorado River. With easy access via a 0.5-mile (0.8 km) trail, the scenic overlook has become increasingly popular and it is not uncommon during busy summer months to see hundreds of visitors spread across the canyon rim at the overlook. Prominent northeast- and northwest-trending closely-spaced joint sets (figure 19), including some that are inclined toward the cliff face, cut the Navajo Sandstone into relatively small pillar- and wedge-shaped rock masses—many of which appear to be partially detached from the surrounding cliff (figure 24). Slopes below the overlook are buried by large, actively accumulating talus deposits that indicate high rates of rockfall. While impractical to stabilize the entire Navajo Sandstone ledge, NPS management may want to consider scaling or fencing off a few small, particularly hazardous blocks that could fall or topple with the additional weight of humans. A fenced viewing deck completed in 2018 offers visitors an option to safely view Horseshoe Bend from the rim without fear of unstable rock. We recommend signage be installed to clearly warn visitors of unstable rock that will likely be encountered if they choose to explore the unfenced rim beyond the viewing deck.

***Figure 24.*** *An open joint (indicated by white arrows) has partially detached a Navajo Sandstone block at Horseshoe Bend Overlook. View is to the north; photo taken May 11, 2015.*

### Map Limitations

The map boundaries between rockfall-hazard categories are approximate and subject to change as new information becomes available. The rockfall hazard at any particular site may be different than shown because of geological variations within a map unit, gradational and approximate map-unit boundaries, and map scale. Small, localized areas of higher or lower rockfall hazard may exist within any given map area, but their identification is precluded because of limitations of the target mapping scale. Our mapping does not consider rockfall hazards caused by cuts, fills, or other alterations to the natural terrain. The mapping is not intended for use at scales other than the target scale and is designed for use in general planning and design to indicate the need for site-specific investigations.

## LANDSLIDE HAZARD

Rock and soil units susceptible to landsliding underlie parts of the Glen Canyon study area. *Landslide* is a general term that refers to the gradual or rapid movement of a mass of rocks, debris, or earth down a slope under the force of gravity (Neuen-

dorf and others, 2011). The term covers a wide variety of mass-movement processes and includes both deep-seated and shallow slope failures. The moisture content of the affected materials when a slope fails can range from dry to saturated. High moisture content reduces the strength of most deposits susceptible to landslides, and is often a contributing factor to landsliding. Landslides can be both damaging and deadly.

## Sources of Information

Sources of information used to evaluate landslide hazard in the Glen Canyon study area include (1) recent UGS 1:24,000-scale geologic mapping that covers the Bullfrog (Willis, in preparation) and Wahweap sections (Phoenix, 2009; Willis, 2012a) of the Glen Canyon study area; (2) reconnaissance landslide and rockfall surveys of GCNRA by the USBR (Mann, 1973; Grundvig, 1980); (3) interpretation of stereo and orthophoto aerial photography including 1940 (Soil Conservation Service, 1940), 1948 (Jack Ammann Photogrammetric Engineers, 1948), 1953 (Army Map Service, 1953), mid-1990s (Utah Automated Geographic Reference Center [AGRC] 2016a), 2014 (Utah AGRC, 2014), and 2015 (Utah AGRC, 2016b) aerial photographs; and (4) a limited number of unpublished, site-specific geotechnical reports completed for projects in the Glen Canyon area.

## Landslide Causes, Types, and Processes

Three factors acting individually or in combination contribute to landsliding (Varnes, 1978; Wieczorek, 1996): (1) an increase in shear stress, (2) low material strength, and (3) a reduction of shear strength. Common factors that increase shear stress include adding mass to the top of a slope, removing support from the toe of a slope, adding water to a slope, transitory stresses from earthquakes and explosions, and long-term effects of tectonic uplift or tilting. Low material strength in rock or soil typically reflects the inherent characteristics of the material or is influenced by discontinuities (joints, faults, bedding planes, and desiccation fissures). Factors that reduce shear strength include both physical and chemical weathering, and the addition of water to a slope, which increases pore-water pressure and reduces the effective intergranular strength within slope materials.

Although one or more of the above causes may make a rock or soil mass susceptible to landsliding, a trigger is required for a landslide to occur (Varnes, 1978; Cruden and Varnes, 1996). A trigger is an external stimulus or event that initiates a landslide either by increasing stresses or reducing the strength of slope materials (Wieczorek, 1996). Landslide triggers may be either static or dynamic. Common triggers include prolonged or extreme periods of above-normal precipitation; a transient snowmelt-induced rise in groundwater levels (Ashland, 2003); added water from reservoirs, irrigation, or improper drainage; 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 25). In the Glen Canyon study area, rotational landslides, rockfall, topple, and debris flows are most common. Due to the region's semiarid climate, slow-moving spreads and creep, 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 in the Flood Hazard section of this report, and rockfalls are considered separately in the Rockfall Hazard section. Within the study area, landslide movements are typically rotational (figure 25). Rotational slides have curved, concave rupture surfaces, which may be shallow or deep seated, along which the slide mass moves, sometimes with little internal disruption. Because of the curved rupture surface (figure 26), the head of a rotational slide commonly tilts backward toward the slide's main scarp. Rotational slide movement may be very slow to rapid and take place under dry to wet conditions. Some prehistoric landslides near Lees Ferry, some of which exceed 1 mile (1.6 km) in length, are complex because they initiated as a rotational slide, but transitioned into earthflows as landslide material progressed downslope (figure 27).

## Landslides in the Glen Canyon Study Area

Most mapped landslides in the Glen Canyon study area are closely correlated with the clay-rich upper part of the Triassic Chinle Formation that includes the Monitor Butte and Petrified Forest Members. Within the study area, these low-shear-strength units crop out near Lees Ferry, along the main channel of Lake Powell near Good Hope Mesa, and along the shores of the Ticaboo Creek inlet. Some of the largest landslides in GCNRA lie a short distance to the northeast of the study area in Good Hope Bay.

The abundance of active, modern landslides where the Chinle Formation is exposed near Lake Powell's shoreline leaves little doubt that infiltrating reservoir water has facilitated landsliding. Reservoir-induced landslides can occur as a result of either filling or drawdown of a reservoir (Schuster, 1979). Filling of Lake Powell during the 1970s raised Glen Canyon's base level hundreds of feet above the position of the former Colorado River. In 1980, Lake Powell first reached full pool (elevation 3700 feet [1100 m]) where reservoir levels remained relatively steady for several years. Consequently, the water table adjacent to the reservoir would have risen to reach equilibrium with the new semi-permanent base level. Deep saturation of formerly dry slopes drives instability by raising pore-water pressure and reducing shear strength. Conversely, declining reservoir levels may also destabilize slopes along a reservoir's rim by removal of lateral confining pressure on lower slopes, loss of buoyancy provided by reservoir water, and residual high pore-water and seepage pressures as perched groundwater drains to equilibrate to a lower base level (Schuster, 1979). The reservoir causes additional slope instability when wave action, created either by wind or motorboats, erodes and undermines lower slopes along the shoreline.

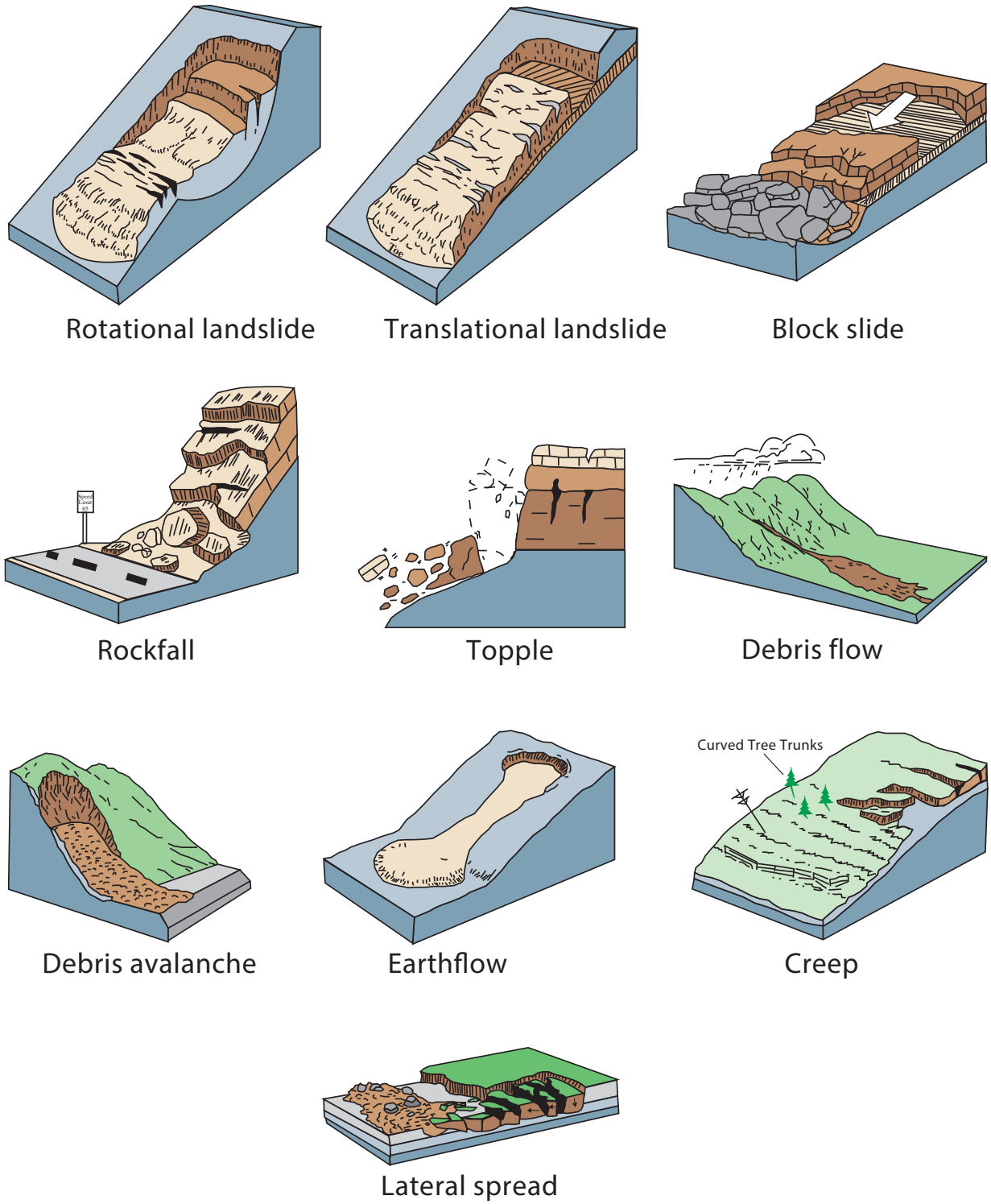


***Figure 25.*** *Major types of landslides and their physical characteristics (modified from Cruden and Varnes, 1996, and Beukelman, 2011).*

Landslides having historical movement along Lake Powell's shoreline below Good Hope Mesa and at Ticaboo Creek inlet have escarpments that exceed 1 mile (1.6 km) in length (figure 28). Recent landsliding is obvious where the reservoir's high-water mark has either been displaced by landslides or obscured by deposition of landslide deposits. Slumping Chinle strata in the Ticaboo Creek inlet has undercut and destabilized the overlying Wingate cliff creating numerous rockfalls and at least one massive rock avalanche since Lake Powell reached full pool in 1980 (figures 29 and 30).

Many of the large landslide complexes rooted in the Chinle Formation exposed throughout GCNRA likely initiated in the Pleistocene when the Southwest's climate was cooler and wetter (Ahnert, 1960; Schumm, 1965; Shroder, 1971; Doelling and Davis, 1989). Some landsides may have initiated

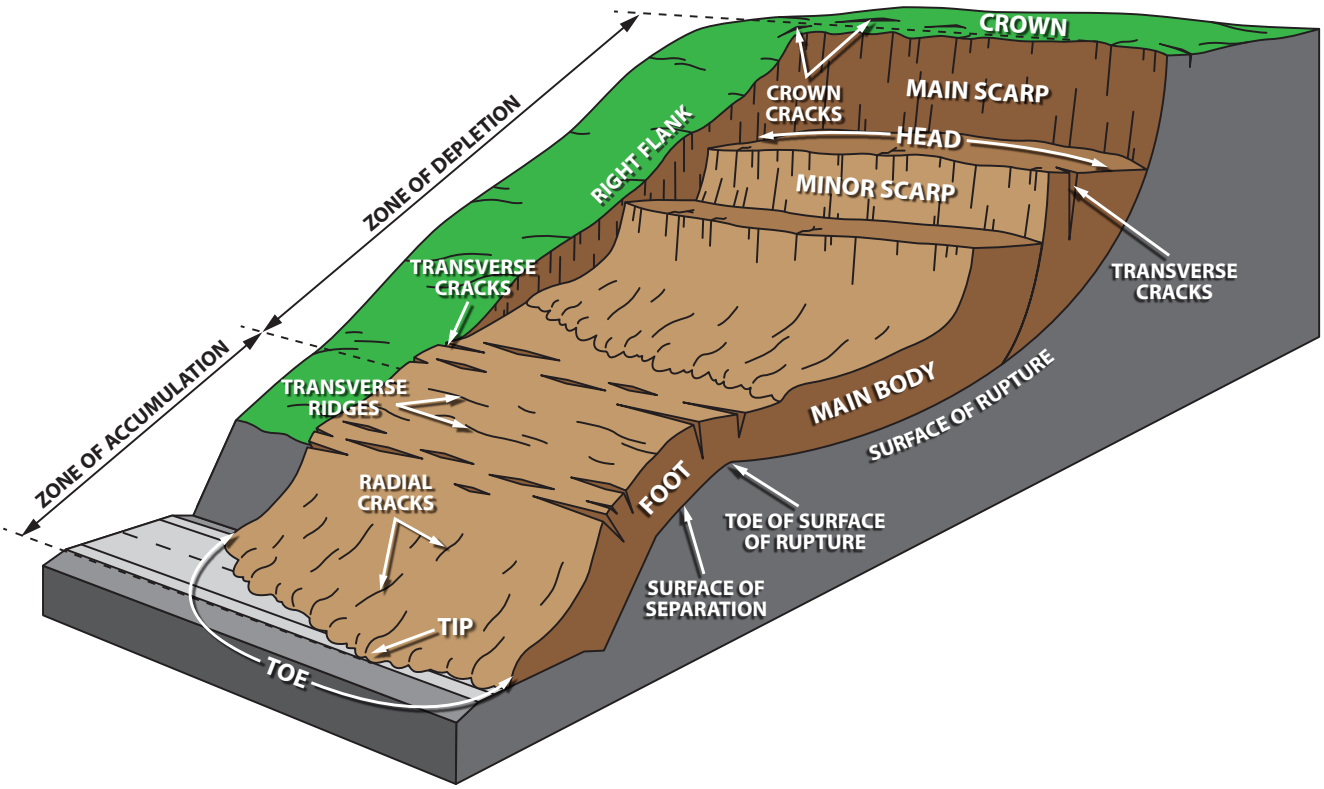


***Figure 26.*** *Diagram of an idealized landslide showing commonly used landslide morphology nomenclature (modified from Cruden and Varnes, 1996).*

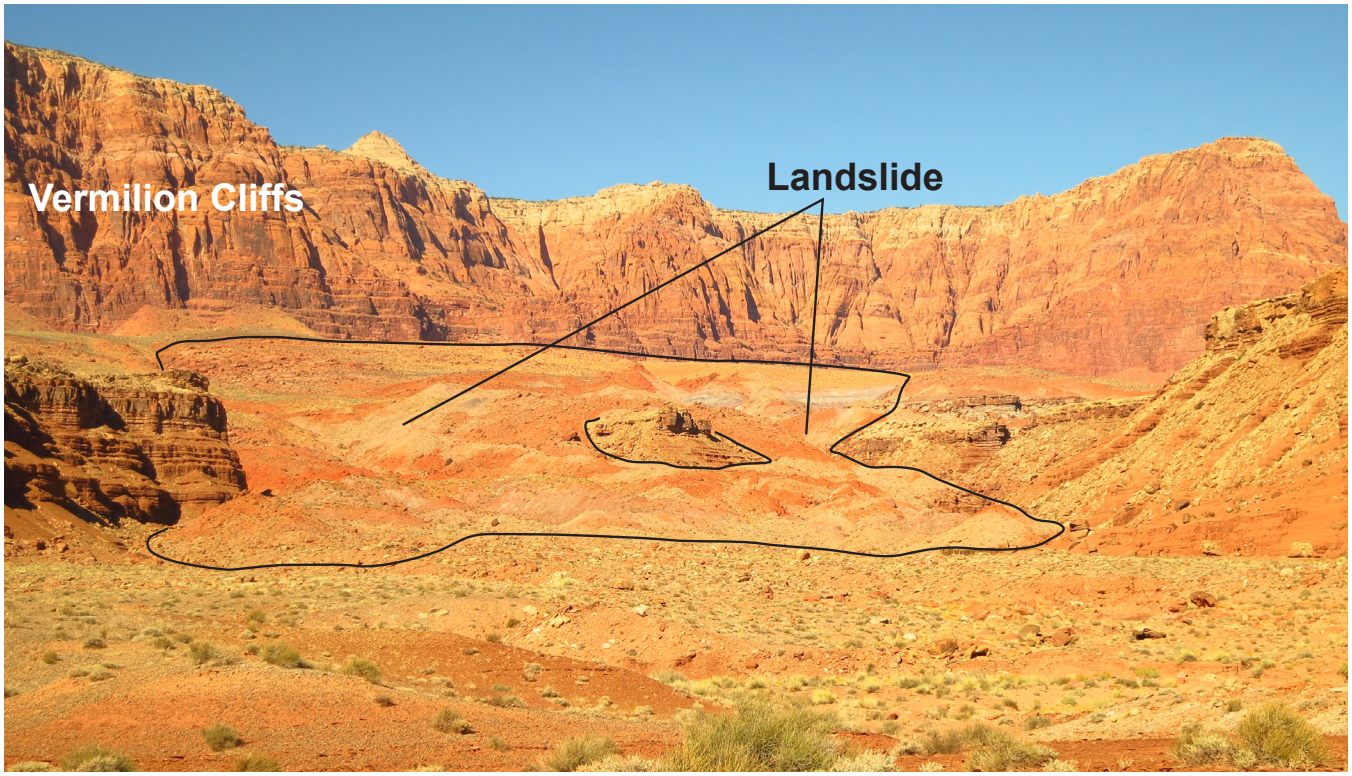


***Figure 27.*** *Nearly 1-mile-long landslide sourced from clay-rich upper Chinle Formation near Lees Ferry. The long, earthflow-type deposit indicates that groundwater was higher at the time of movement than it is today.*

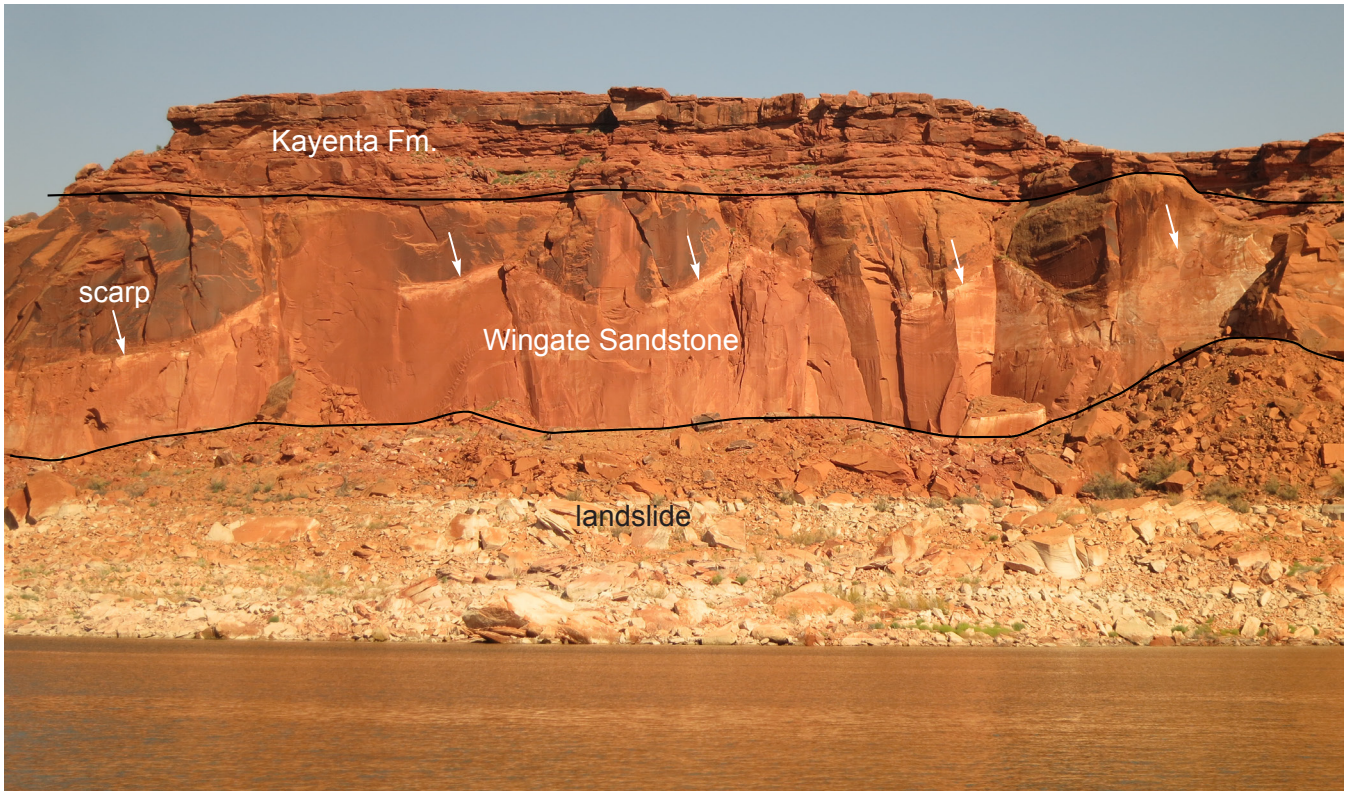


***Figure 28.*** *Talus mantles a landslide rooted in the Chinle Formation on the east side of Lake Powell's main channel near Good Hope Bay. The fresh scarp and a displaced high-water line indicate movement occurred after lake filling. Photo taken August 17, 2015.*

***Figure 29.*** *Massive collapse of Wingate/Kayenta cliff on the south side of the Ticaboo inlet. Photograph courtesy of Douglas Sprinkel, Utah Geological Survey.*

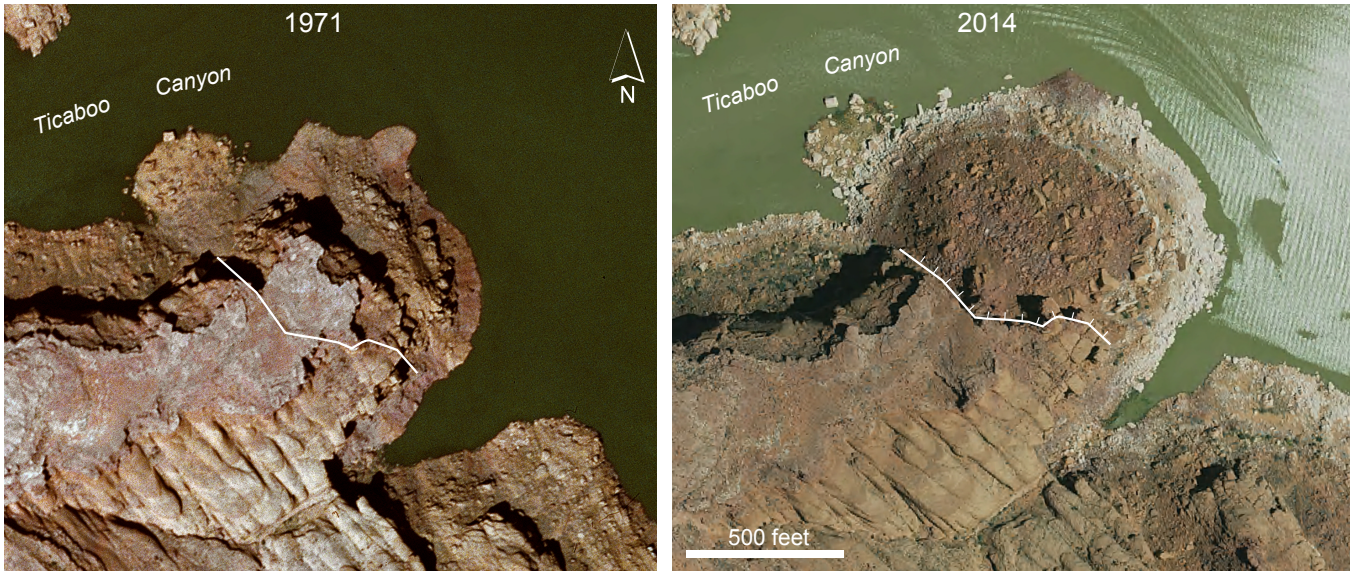


***Figure 30.*** *Sequence aerial photographs showing extent of cliff collapse at Ticaboo Canyon inlet.* ***Left:*** *1971 aerial photograph (Defense Mapping Agency, 1971) shows the Wingate/Kayenta promontory still intact nine years before Lake Powell full pool is achieved. White line is approximate location of future main scarp.* ***Right:*** *Cliff collapse shown in 2014 National Agriculture Imagery Program (NAIP) orthophotography (Utah Automated Geographic Reference Center, 2016a); white line with hachures indicates the main scarp. The collapse likely occurred sometime between Grundvig's 1980 mass-movement reconnaissance—which makes no mention of the obvious collapse—and 1993 when the collapsed cliff appears on U.S. Geological Survey aerial photos (Utah Automated Geographic Reference Center, 2016b).*

when Chinle slopes were saturated by postulated Pleistocene lakes that may have filled much of the Colorado River corridor. Hamblin (1994) described several lava dams created in the western Grand Canyon that impounded the Colorado River and created massive lakes. The Prospect lava dam, emplaced about 600,000 years ago (Pederson and others, 2002; Fenton and others, 2004), was the tallest and may have created a lake with a surface elevation of about 4000 feet (1200 m) above sea level. This lake would have extended up the Colorado River corridor to the site of present-day Moab, Utah, (Hamblin, 1994, 2003)—well above Lake Powell's full-pool elevation of 3700 feet (1100 m). Catastrophic failure of a number of these lava dams (Fenton and others, 2002, 2004, 2006) would have resulted in sudden lake-level declines, elevated pore-water pressures, and steep seepage gradients that may have triggered additional landslides. Other researchers including Kaufman and others (2002) and Crow and others (2008, 2015) have cast doubt on whether the size and stability of these lava dams were sufficient to create massive lakes. Regardless of whether a wetter climate or lava-dam lakes (or a combination of both) caused widespread Pleistocene landslides, these conditions no longer exist in the Lees Ferry area where mapped landslides are deeply dissected and lack evidence of historical movement. As described above, however, the creation of Lake Powell has reactivated numerous landslides near Good Hope Mesa and the Ticaboo inlet. Although no historical landslides have been mapped within the study area near Lees Ferry, sudden movement of the Bitter Springs landslide in the Echo Cliffs near the junction of U.S. Highways 89 and 89A (figure 1) destroyed a 500-foot section (150 m) of Highway 89 in February 2013 (Kleinfelder, 2013), which serves as a costly reminder of how slope modifications can reactivate dormant landslides in this region.

Steep cones of wind-blown sand accumulate on the lee side of vertical cliffs throughout GCNRA. Along the Lake Powell shoreline, sand piles make attractive campsites for boaters, but also pose a hazard when they are destabilized by increased water levels and/or erosional undermining due to wave action. The sudden failure of sand piles can result in parts of or the entire sand deposit slipping into the lake in a matter of seconds (Brokaw, 1974; Grundvig, 1980). Grundvig (1980) noted that many precarious sand piles reported in earlier mass-movement surveys conducted by the USBR periodically in the 1970s no longer remained at the time of his survey, implying that rising reservoir levels had caused many sand piles to slip into the lake. We observed few oversteepened sand piles during our shoreline reconnaissance within the study area and conclude that fluctuating lake levels over the past three decades have reduced, but not eliminated, the hazard posed by the sand piles. During prolonged periods of low lake levels, new sand cones can quickly form that will be subject to destabilization when lake levels again rise.

Declining lake levels since the late 1990s have created small, localized areas of landslide hazard at the heads of several canyon inlets where streams enter Lake Powell. We observed several locations where loosely consolidated, fine-grained delta deposits exposed by the receding lake are being actively incised by streams that are equilibrating with a lower base level. The streams are predominantly ephemeral and most erosion appears to occur episodically during flash-flood events. The stream incision tends to form a deep channel in the delta deposits with near-vertical walls that are prone to collapse and slumping. In June 2015, over-

steepened delta deposits collapsed during a flash flood near the head of Forgotten Canyon inlet where a trail accessing the Defiance House ruin was damaged (Valerie Reynolds, NPS, written communication, 2015) (figure 31). In the Bullfrog section of the study area, potentially unstable channels cut in lake deposits were also noted in Lake Canyon, Moqui Canyon, Hansen Creek Canyon, and an unnamed inlet immediately west of the boat storage area at Bullfrog Marina. Additionally, we observed deep, potentially unstable channels cut into loose sand deposits at Hobie Cat Beach. In the Wahweap section, we observed oversteepened delta deposits where Wahweap and Antelope Creeks enter Lake Powell. Because these landslide-prone areas are very small and are likely to migrate laterally after large floods, they are not all depicted on the landslide-hazard map (https://geology.utah.gov/apps/hazards).

***Figure 31.*** *Wall of fine-grained delta deposits that suddenly collapsed after being undercut by flash-flood water on June 6, 2015, in Forgotten Canyon. Parts of a user-made trail that accesses the Defiance House ruin were damaged by the slumping. Such deposits are common in many tributary canyons near the mouths of streams entering a receding Lake Powell, and their rapid incision produces unstable vertical-walled channels prone to slumping. Photo courtesy of Valerie Reynolds, National Park Service.*

## Landslide-Hazard Classification

We classified landslide hazard in the Glen Canyon 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.
2. Average ground-surface slope angles of representative landslides in the study area were measured to identify the critical slope angle above which landsliding may initiate in the various susceptibility categories.
3. The results of steps (1) and (2) were integrated to create three Landslide Hazard 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, limestone). 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. Because the outcrop area of many landslide-prone units is limited within the Glen Canyon study area, we expanded our analysis of mapped landslides beyond the study area boundaries and included nearby geologic maps of the Smoky Mountain 30' x 60' quadrangle (Doelling and Willis, 2006), the Glen Canyon Dam 30' x 60' quadrangle (Billingsley and Priest, 2013), the lower Escalante River area (Doelling and Willis, 2007), the White Canyon–Good Hope Bay area (Thaden and others, 2008), and the Hite Crossing–lower Dirty Devil River area (Willis, 2012b).

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 2 summarizes the susceptibility categories.

### Landslide Slope Angle

We measured average ground-surface slope angles for representative landslides in each of the susceptibility categories in table 2. Landslide slope angle 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

***Table 2.*** *Landslide susceptibility categories and their critical slope angle for landslide-susceptible geologic units in the Glen Canyon study area.*

| Susceptibility Category | Geologic Unit | Critical Slope Angle | Comments |
|---|---|---|---|
| A[1] (High) | Existing landslides | Not applicable | Existing landslides are considered the most likely units in which new landslides may initiate (Ashland, 2003). |
| B (High) | Monitor Butte and Petrified Forest Members, and some Owl Rock Member where not mapped separately from Petrified Forest Member, Chinle Formation; Moenave Formation where above slopes of Petrified Forest Member | 8° | The Monitor Butte and Petrified Forest Members consist chiefly of bentonitic clay, which is expansive and has low shear strength. This unit includes the greatest number of landslides in the study area. Landslides may also form in the overlying Moenave Formation where the Petrified Forest crops out on lower slopes. |
| C (Moderate) | Kaibab Formation, Moenkopi Formation, Moenave Formation not above slopes of Chinle Formation, Kayenta Formation, Carmel Formation, Dakota Formation; also includes some lake and eolian sand deposits near Lake Powell | 17° | These units contain varying amounts of gypsum, shale, claystone, mudstone, siltstone, or a combination of these rock types that imparts weak shear strength to the units, at least locally, and makes them susceptible to landsliding. These units contain the second greatest number of landslides in the Glen Canyon region. |
| D (Low) | Remaining bedrock and unconsolidated geologic units exclusive of the Wingate, Navajo, Page, and Entrada Sandstones[2] | 20° | These geologic units either contain a higher percentage of stronger rock types, crop out on slopes too gentle to generate landslides, or generate failures that are too small to map at 1:24,000 scale. As a result, they exhibit few or no mapped landslides. |

[1] Category A is not slope dependent.
[2] Mass wasting in these massive sandstone units is limited to rockfalls and therefore, mass-wasting hazards associated with these units are discussed in the Rockfall Hazard section of this report.

(Hylland and Lowe, 1997), which gives the tangent of the overall slope angle. Hylland and Lowe (1997) considered landslide slope angles to represent the maximum quasi-stable slope for a geologic unit under constant conditions of material strength, nature and origin of discontinuities, and groundwater conditions at a given site.

Considering the broad scale of this study and the intended use of the mapping as a land-use planning tool, we selected the lowest measured landslide slope angle for each susceptibility category as the critical slope angle for that category (table 2). The critical slope angle is the minimum slope above which landsliding typically occurs in a particular susceptibility category, and serves as a conservative guide for initiating site-specific, slope-stability investigations for that susceptibility category.

## Landslide-Hazard Categories

We combined the landslide-susceptibility categories with the critical slope inclinations determined for each of those categories to characterize landslide hazard in the Glen Canyon study area. Since existing landslides are considered the most likely units in which new landslides may initiate (Ashland, 2003), we assigned all mapped landslides to the highest hazard category ($H_{LSS}$) regardless of slope. In addition to mapped landslides, the high landslide-hazard category ($H_{LSS}$) includes highly landslide-prone geologic units (table 2) that crop out on slopes at or above a critical angle of 8 degrees. Moderate landslide hazard ($M_{LSS}$) includes moderately landslide-prone units that crop out on slopes at or above a critical angle of 17 degrees and highly landslide-prone geologic units that crop out on slopes less than 8 degrees. Low landslide hazard ($L_{LSS}$) includes geologic units of low landslide-prone susceptibility that crop out on slopes at or above a critical angle of 20 degrees and moderately landslide-prone geologic units that crop out on slopes less than 17 degrees.

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 together to promote slope failure. For that reason, we recommend that a site-specific investigation be 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

Our landslide-hazard mapping (https://geology.utah.gov/apps/hazards) shows areas of relative landslide susceptibility where site-specific slope-stability conditions (material strength, orientation of discontinuities, groundwater conditions, and erosion or undercutting) should be evaluated prior to development. The UGS recommends that a landslide-hazard investigation be made for all new buildings for human occupancy and for modified IBC Risk Category II(a), II(b), III, and IV facilities (table 1604.5 [International Code Council, 2017a]) that are proposed in mapped landslide-hazard areas (Beukelman and Hylland, 2016). The level of investigation needed at a given site depends on the relative hazard and the nature of the proposed development. Recommendations for site-specific investigations in each landslide-hazard category are given in table 3. The UGS recommends that investigations be conducted for all IBC Risk Category III and IV facilities in slope areas, whether near a mapped landslide-hazard area or not, to ensure that previously unknown landslides are not present (Beukelman and Hylland, 2016). If a hazard is found, the UGS recommends a comprehensive investigation be conducted. In some instances, an investigation may become necessary when existing infrastructure is discovered to be on or adjacent to a landslide. A valid landslide-hazard investigation must address all pertinent conditions that could affect, or be affected by, the proposed development, including earthquake ground shaking, perched or irrigation-induced groundwater, and slope modifications. This can only be accomplished through the proper identification and interpretation of site-specific geologic conditions and processes (Blake and others, 2002; Beukelman and Hylland, 2016).

The analysis of natural and modified slopes for static and/or seismic stability is a challenging geotechnical problem. Blake and others (2002, p. 3) considered accurate characterization of the following as required for a proper static slope stability analysis:

1. surface topography,
2. subsurface stratigraphy,
3. subsurface water levels and possible subsurface flow patterns,
4. shear strength of materials through which the failure surface may pass, and
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.

Blake and others (2002) considered all of the above factors vital for a proper slope stability analysis, but noted that some factors are more easily characterized than others. Two factors—subsurface stratigraphy/geologic structure and soil shear strength—are particularly challenging to accurately characterize.

Accordingly, landslide-hazard investigations must be interdisciplinary in nature and performed by qualified, licensed geotechnical engineers and engineering geologists working as a team. Recommended minimum standards for performing landslide-hazard investigations are presented in *Guidelines for Evaluating Landslide Hazards in Utah* (Beukelman and

***Table 3.*** *Recommendations for landslide-hazard investigations for all new buildings for human occupancy and for modified IBC Risk Category II(a), II(b), III, and IV facilities (see table 1).*

| Landslide-Hazard Category | Recommended Site-Specific Study |
|---|---|
| High | Detailed engineering geologic and geotechnical-engineering investigation necessary. Predevelopment stabilization recommended for historical and geologically young (late Pleistocene or Holocene) landslides. |
| Moderate | Geologic evaluation and reconnaissance-level geotechnical-engineering investigation necessary; detailed engineering geologic and geotechnical-engineering investigation may be necessary. |
| Low | Geologic evaluation and reconnaissance-level geotechnical-engineering investigation necessary; detailed geotechnical-engineering investigation generally not necessary. |
| None | None for IBC Risk Category II(a) and II(b) facilities. Geologic evaluation recommended for Risk Category III and IV facilities near slopes even if not mapped as a landslide-hazard area, to ensure previously unknown landslides are not present. If a hazard is found, a comprehensive investigation is recommended. |

Hylland, 2016). Turner and Schuster (1996) and Blake and others (2002) provided additional guidance for evaluating landslide hazard. Local jurisdictions may adopt more stringent requirements for slope-stability investigations, as they deem necessary, to meet local needs and conditions. Recommendations for site-specific investigations in each landslide-hazard category are given in table 3.

### Hazard Reduction

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).

Where development is proposed in areas identified on the landslide hazard map as having a potential for landsliding, we recommend that a phased site-specific investigation (see Beukelman and Hylland, 2016) 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

Our landslide-hazard mapping is based on 1:24,000-scale UGS geologic mapping, and the inventory of landslides obtained from that mapping reflects that level of mapping detail. Some smaller landslides may not have been detected during UGS mapping or our aerial photograph interpretation, and some may be too small to show at the landslide-hazard map target 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. The mapping is not intended for use at scales other than the target scale and is intended for use in general planning and design to indicate the need for site-specific investigations.

## PIPING, EROSION, AND WIND-BLOWN SAND

### Piping and Erosion

Piping refers to the subsurface erosion of permeable, fine-grained, unconsolidated or poorly consolidated deposits by percolating groundwater (Cooke and Warren, 1973; Costa and Baker, 1981; figure 32). Piping creates narrow, subterranean conduits that enlarge both in diameter and length as increasingly more subsurface material is removed and as the cavities trap greater amounts of groundwater flow. Piping eventually leads to caving and collapse of the overlying surficial materials and is an important process in the headward extension of gullies in the arid southwestern United States (Costa and Baker, 1981).

For piping to take place, the following conditions are required: (1) fine-grained, non-cohesive or poorly consolidated, porous materials, such as some silt and clay; fine sand; poorly consolidated, typically sandy siltstone, mudstone, or claystone; and volcanic ash or tuff; (2) a sufficient thickness of susceptible material in which pipes may form; (3) a sufficiently steep hydraulic gradient to cause groundwater to percolate through the subsurface materials; and (4) a free face that intersects the permeable, water-bearing horizon and from which the water can exit the eroding deposit. The walls of an incised stream channel commonly provide the necessary free face, but human-made excavations, such as canal banks or road cuts, may also contribute to piping. Parker and Jenne (1967, in Costa and Baker, 1981) described extensive damage to U.S. Highway 140 where it traverses dissected and extensively piped valley fill along Aztec Wash in southwestern Colorado.

The characteristics that make soil or rock susceptible to piping (fine-grained texture, little or no internal cohesion, and loose or poor consolidation) are also typical of highly erodible materials. Consequently, piping often develops in and is an indicator of otherwise highly erodible deposits. On the Colorado Plateau, most erosion occurs during thunderstorms and is caused by sheetwash and eventual channelization of runoff. If disturbed, highly erodible soil or rock become even more susceptible to erosion, particularly when stabilizing vegetation and/or desert pavement is removed or disturbed.

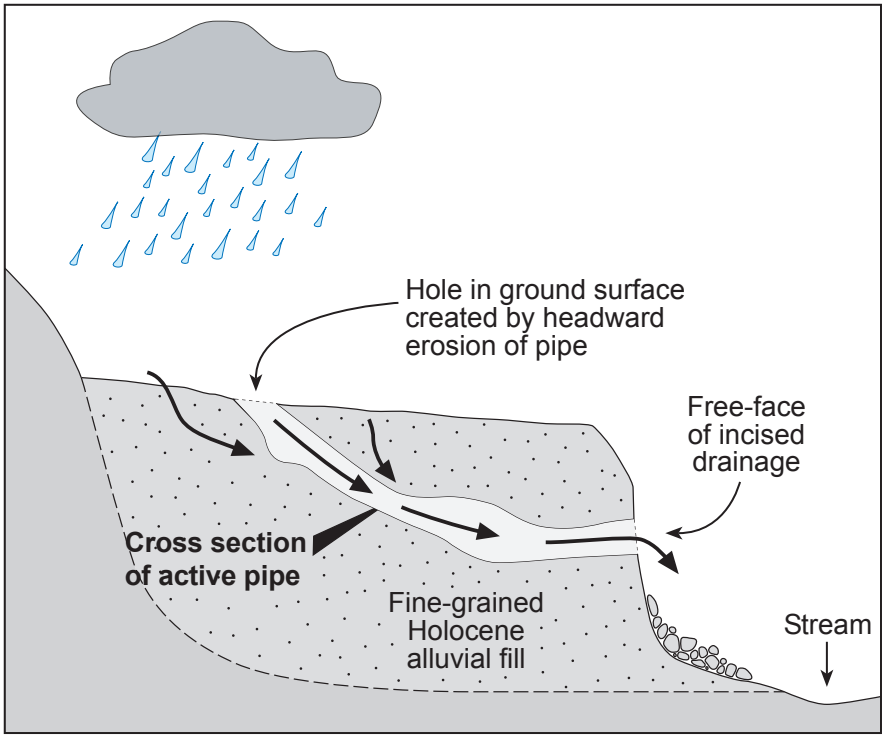


***Figure 32.*** *Cross section of a pipe in fine-grained Holocene alluvium (after Black and others, 1999).*

## Wind-Blown Sand

Unless stabilized by natural vegetation or by artificial means, loose sand will move in response to high-velocity and long-duration wind. Wind transport (e.g., saltation) (deBlij and Muller, 1996) winnows the sand, producing a well-sorted (poorly graded) deposit that typically consists of subrounded to rounded sand grains with diameters ranging from very fine to coarse (0.1 to 1.0 mm; Neuendorf and others, 2011). The fines content (silt and clay fraction) in wind-blown sand is generally less than 10 percent. Depending on topography, wind characteristics, and sand availability, blowing sand may accumulate in dunes or sand sheets, both of which may cover large areas. If development encroaches into areas with predominantly sandy soil and disturbs the natural vegetative cover and/or desert pavement, the wind may mobilize the disturbed material leading to erosion and redeposition of the sand. Stabilized sand dunes and sand sheets may react in the same manner when disturbed. High winds can move fines by suspension and produce sand and dust storms that reduce visibility to near zero and sandblast vehicles and structures. Additionally, steep cones of wind-blown sand near Lake Powell's shoreline can pose a landslide hazard when destabilized by increased water levels and/or erosional undermining due to wave action (see Landslide Hazard section).

## Sources of Information

Sources of information used to evaluate piping, erosion, and wind-blown-sand susceptibility in the Glen Canyon study area include (1) recent UGS 1:24,000-scale geologic mapping that covers the Bullfrog (Willis, in preparation) and Wahweap sections (Phoenix, 2009; Willis, 2012a) of the study area**,** (2) the U.S. Department of Agriculture (USDA) National Resources Conservation Service (NRCS) *Soil Survey of Glen Canyon National Recreation Area, Arizona and Utah* (USDA, 2010a, 2010b), and (3) a limited number of unpublished, site-specific geotechnical reports completed for projects in the Glen Canyon area.

## Erodible Soil and Rock in the Glen Canyon Study Area

### Piping and Erosion

UGS geologic maps show that fine-grained, non-cohesive, loose sand and silt deposits are present in many areas of the Glen Canyon study area (figure 33). They include eolian, alluvial, lacustrine, and mixed-unit geologic deposits that contain a high percentage of wind-blown sand derived from the weathering and erosion of sandstone bedrock that crops out in the study area. Poorly consolidated, often highly weathered, fine-grained bedrock units also crop out over parts of the study area.

### Wind-Blown Sand

Several sandstone formations crop out extensively within the Glen Canyon study area. Sand eroded from those bedrock units is the principal source of wind-blown sand in the study area. Chief among the sandstone formations is the Navajo Sandstone, which consists of a thick (~1200 ft [360 m]) sequence

***Figure 33.*** *Headward erosion of fine-grained material near a boat storage yard at Bullfrog Marina. Photo taken on August 19, 2015.*

of lithified, mostly wind-blown sand of Jurassic age. The sand released by weathering and erosion of the Navajo Sandstone is in effect recycled "fossil" dune sand that has the same size, sorting, and grain-shape characteristics of sand comprising modern sand dunes and sand sheets. Other bedrock formations that are less prolific, but still important sources of sand include the Wingate, Entrada, and Page Sandstones, and the Kayenta Formation.

UGS geologic maps show that loose sand deposits are widely distributed throughout the study area. The UGS mapping encompasses what are chiefly geologically young, active or partially stabilized, windblown or mixed-unit sand deposits characterized by well-sorted, loose, sandy soil texture having few or no fines.

## Hazard Classification

### Piping and Erosion

Our piping-and-erosion mapping (https://geology.utah.gov/apps/hazards) shows the location of highly erodible soil and bedrock deposits susceptible to piping in the study area. We grouped geologic deposits considered susceptible to piping and erosion into two susceptibility categories, one for unconsolidated deposits (soil) and the other for bedrock. Unconsolidated geologic units susceptible to piping and erosion include eolian, alluvial, lacustrine, and mixed-unit deposits that contain a high percentage of fine-grained, non-cohesive, loose to poorly consolidated sand or silt. Bedrock units susceptible to piping and erosion contain abundant fine-grained, poorly consolidated siltstone, mudstone, or claystone, and include the Moenkopi Formation, the clay-rich members of the upper Chinle Formation, the Dinosaur Canyon Member of the Moenave Formation, the Carmel Formation, and the Dakota Formation. Because piping occurs only where susceptible soil and rock exist in the presence of a free face and percolating groundwater, the presence of these units in and of themselves does not create a piping hazard. Conversely, a change in conditions brought about either naturally or through human activity can create the conditions necessary for piping to occur. While susceptible to erosion, these units are generally stable in their natural, undisturbed state, but can quickly erode if disturbed or if drainage conditions change in an uncontrolled manner.

### Wind-Blown Sand

Where disturbed, sandy soils may migrate across roads and bury structures (Mulvey, 1992; Hayden, 2004; Lund and others, 2008b) (figure 34), and wind erosion may expose foundations and underground utilities (figure 35). During high wind events, blowing sand and dust may become a serious safety

***Figure 34.*** *Migrating sand partially buries Bureau of Land Management Road 531 north of Bullfrog Marina. Photo taken on November 20, 2014.*

***Figure 35.*** *Exposed fence foundation near Halls Crossing due to wind erosion of sandy soils. Photo taken November 19, 2014.*

hazard to driving. We grouped wind-blown sand deposits and mixed-unit geologic deposits containing a high sand component into a single susceptibility category ($S_{WSS}$) that is shown on the wind-blown-sand susceptibility map (https://geology.utah.gov/apps/hazards).

### Using This Map

Our piping-and-erosion and wind-blown-sand mapping (https://geology.utah.gov/apps/hazards) shows the location of geologic units in the Glen Canyon study area that are potentially susceptible to piping and erosion and/or reactivation by wind if disturbed. This mapping is intended for general planning and design purposes to indicate where susceptible soil and rock exist and where special investigations should be required. Site-specific investigations can resolve uncertainties inherent in generalized mapping and help identify the need for special design or mitigation techniques. The presence of soil or rock susceptible to erosion along with other geologic hazards should be addressed in these investigations. If a potential for piping and erosion and/or wind-blown sand is present at a site, appropriate design and construction recommendations should be provided.

### Hazard Reduction

Although potentially costly when not recognized and properly accommodated in project design and construction, problems associated with piping and erosion and/or wind-blown sand rarely are life threatening. As with most geologic hazards, early recognition and avoidance are the most effective ways to mitigate potential problems. However, geologic units susceptible to piping and erosion and/or wind-blown sand are widespread in the study area, and avoidance may not always be a viable or cost-effective option. Where the presence of soil or rock susceptible to piping or rapid erosion and/or wind-blown sand is confirmed, possible mitigation techniques include minimizing disturbance of vegetated areas, controlling the flow of shallow groundwater, use of erosion-control products, and managing surface drainage onsite in a controlled manner.

### Map Limitations

Our mapping is based on limited geologic and geotechnical data; site-specific investigations are required to produce more detailed geotechnical information. The mapping also depends on the quality of those data, which may vary throughout the study area. The boundaries of the areas shown as susceptible to piping, erosion, and wind-blown sand are approximate and subject to change as new information becomes available. The susceptibility may be different than shown at any particular site because of variations in the physical properties of geologic deposits within a map unit, gradational and approximate map-unit boundaries, and the small map scale. Localized areas of piping, erosion, and wind-blown-sand susceptibility may exist throughout the study area, but their identification is precluded because of limitations of map scale. The mapping is not intended for use at scales other than the target scale and is designed for use in general planning and design to indicate the need for site-specific investigations.

## GYPSIFEROUS SOIL AND ROCK

Gypsum-bearing soil and rock are subject to dissolution of the gypsum ($CaSO_4 \cdot 2H_2O$), which causes a loss of internal structure and volume. Where the amount of gypsum is ≥10 percent, dissolution can result in localized land subsidence and sinkhole formation (Mulvey, 1992; Muckel, 2004; Santi, 2005). Dissolution of gypsum may lead to foundation collapse problems and may affect roads, dikes, underground utilities, and other infrastructure. Gypsum dissolution has resulted in sinkhole formation and has damaged infrastructure near Hurricane and St. George in southwestern Utah (Gourly, 1992; Everitt and Einert, 1994; Lund, 1997; Lund and others, 2008b). In September 2015, hazardous sinkholes attributed to gypsum dissolution were discovered in a Moab, Utah, subdivision (UGS internal documents). Gypsum dissolution can be greatly accelerated by application of water, such as that provided by reservoirs; septic-tank drain fields; street, roof, or parking lot runoff; and irrigation (Martinez and others, 1998).

Gypsum is also a weak material having low bearing strength and is not well suited as a foundation material. Additionally, when gypsum weathers it forms dilute sulfuric acid and sulfate, which can corrode and weaken unprotected concrete and metals. Type V or other sulfate-resistant cement is typically required in areas having abundant gypsum, as is corrosion protection for metals.

### Sources of Information

Sources of information used to evaluate gypsiferous soil and rock in the Glen Canyon study area include (1) recent UGS 1:24,000-scale geologic mapping that covers the Bullfrog (Willis, in preparation) and Wahweap sections (Phoenix, 2009; Willis, 2012a) of the Glen Canyon study area**,** (2) the NRCS *Soil Survey of Glen Canyon National Recreation Area, Arizona and Utah* (USDA, 2010a, 2010b), and (3) a limited number of unpublished, site-specific geotechnical reports completed for projects in the Glen Canyon area.

### Gypsum in the Glen Canyon Study Area

In the Glen Canyon study area, the locally gypsum-rich Kaibab, Moenkopi, and Carmel Formations generally lack thick, laterally continuous gypsum horizons that may be common in those units elsewhere in southern Utah and northern Arizona. More commonly, rich concentrations of gypsum are found in these units as thin veins (figure 36) or as a cementing agent of gypsum-rich siltstone and sandstone beds (Billingsley and

Priest, 2013). Locally, gypsum-rich horizons may also be encountered in the Toroweap, Chinle, and Dakota Formations. Additionally, residual and colluvial soils derived from these bedrock units may contain locally significant pedogenic gypsum (formed by dissolution and re-precipitation at depth during the soil-forming process). However, because gypsum is typically concentrated in subsurface horizons by soil-forming processes, problem soils may be difficult to recognize in the absence of subsurface exploration.

## Corrosive Soil and Rock

Gypsum is the most common sulfate mineral in soils in the western United States (Muckel, 2004). Gypsum is soluble and along with associated sulfates, such as sodium sulfate and magnesium sulfate, can dissolve in water to form a weak acid solution that is corrosive to concrete and metals in areas where the amount of soil gypsum is one percent or greater (Muckel, 2004). The ions within the acid react chemically with the cement (a base) in the concrete. Gypsum-induced corrosion of unprotected concrete slabs, walls, and masonry blocks is widespread in parts of southern Utah and northern Arizona (figure 37), and damage can become severe after just a few years of exposure (Lund and others, 2008b; Knudsen and Lund, 2013).

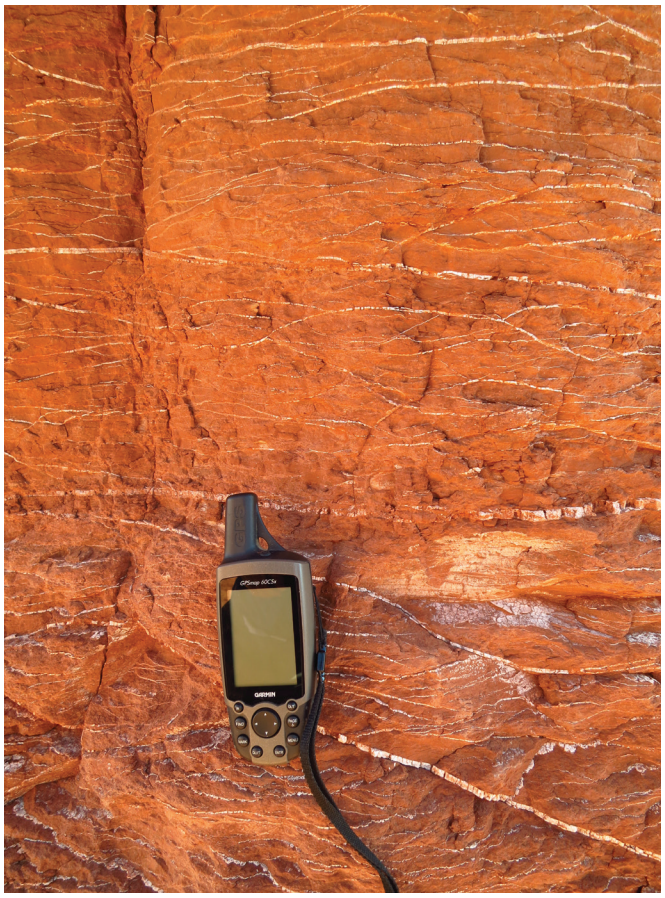

***Figure 36.*** *Gypsum veins in lower red member of the Moenkopi Formation near Lees Ferry. Handheld GPS unit is about 6 inches long.*

## Hazard Classification

### Soil

Information on gypsiferous soil in the study area is limited. The NRCS *Soil Survey of Glen Canyon National Recreation Area, Arizona and Utah* (USDA, 2010a, 2010b) reports visible gypsum in many of their soil profiles. Table 23 in the soil survey (USDA, 2010b) reports a soil's chemical properties including percentage of gypsum, and table 25, "Soil Features," reports the general risk of soil corroding both concrete and uncoated steel. NRCS soil map units described as gypsiferous are the Farb-Pagina-Rock outcrop complex, the Juanalo family-Rock outcrop complex, the Moenkopie-Rock outcrop complex, the Myton very gravelly sandy loam, the Redhouse-Epikom families complex, the Somorent family-Rock outcrop complex, and the Torriorthents-Rock outcrop-Badland complex. We used geologic-map unit descriptions of unconsolidated units and field observations to identify additional gypsiferous soils. We grouped unconsolidated gypsiferous deposits into a single susceptibility category on the soluble-soil-and-rock and corrosive-soil-and-rock maps (https://geology.utah.gov/apps/hazards).

### Rock

Based on geologic-map unit descriptions and field observations, we grouped gypsum-bearing bedrock units (see Gypsum in the Glen Canyon Study Area section above) into a single susceptibility category on the soluble-soil-and-rock and corrosive-soil-and-rock maps (https://geology.utah.gov/apps/hazards).

## Using This Map

Our mapping (https://geology.utah.gov/apps/hazards) shows the location of suspected gypsiferous soil and rock in the study area. The mapping is intended for general planning and design purposes to indicate where gypsiferous soil or rock conditions may exist and special investigations, including sodium sulfate testing to determine the presence of corrosive soil or rock, should be required. Site-specific investigations can resolve uncertainties inherent in generalized mapping and help identify the need for special design or mitigation techniques. The presence and severity of gypsiferous rock units and gypsum-rich soils derived from them, along with other geologic hazards, should be addressed in these investigations. If gypsiferous soil or rock is present at a site, appropriate design and construction recommendations should be provided.

## Hazard Reduction

Although potentially costly when not recognized and properly accommodated in project design and construction, problems associated with gypsiferous soil and rock rarely are life threatening. As with most geologic hazards, early recognition and avoidance are the most effective ways to mitigate potential

***Figure 37.*** *High-sulfate soils corrode a masonry block wall in Page, Arizona. Photo taken November16, 2014.*

problems. However, avoidance may not always be a viable or cost-effective option. Where the presence of gypsiferous soil or rock is confirmed, possible hazard-reduction techniques include, but are not limited to, use of Type V or other sulfate-resistant cement for concrete; corrosion protection for metals; soil removal and replacement with non-cohesive, compacted, non-gypsum-bearing backfill; and careful site landscape and drainage design to keep moisture away from concrete and gypsum-bearing deposits (Keller and Blodgett, 2006). Where gypsum problems are particularly acute, design recommendations should be provided by a qualified corrosion engineer.

### Map Limitations

Our mapping is based on limited geologic and geotechnical data; site-specific investigations are required to produce more detailed geotechnical information. The mapping also depends on the quality of those data, which may vary throughout the study area. The mapped boundaries between susceptibility categories are approximate and subject to change as new information becomes available. The susceptibility may be different than shown at any particular site because of variations in the physical properties of geologic deposits within a map unit, gradational and approximate map-unit boundaries, and the small map scale. Additionally, gypsum-bearing bedrock units are locally covered by a thin veneer of unconsolidated deposits. Such areas may be susceptible to sinkhole development or collapse; however, because subsurface information is generally unavailable, those areas are not identified on this map. The mapping is not intended for use at scales other than the target scale and is designed for use in general planning and design to indicate the need for site-specific investigations.

## EXPANSIVE SOIL AND ROCK

Expansive soil and rock increase in volume (swell) as they get wet and decrease in volume (shrink) as they dry out. Expansive soil and rock contain a significant percentage of clay minerals that can absorb water directly into their crystal structure when wetted. Sodium-montmorillonite clay can swell as much as 2000 percent upon wetting (Costa and Baker, 1981). The resulting expansion forces can be greater than 20,000 pounds per square foot (Shelton and Prouty, 1979) and can easily exceed the load imposed by most structures, resulting in cracked foundations and pavement, structural damage, and other building distress (figure 38).

### Sources of Information

Sources of information used to evaluate expansive soil and rock in the Glen Canyon study area include (1) recent UGS 1:24,000-scale geologic mapping that covers the Bullfrog (Willis, in preparation) and Wahweap sections (Phoenix, 2009; Willis, 2012a) of the Glen Canyon study area**,** (2) the NRCS *Soil Survey of Glen Canyon National Recreation Area, Arizona and Utah* (USDA, 2010a, 2010b), (3) an analysis of expansive soil and rock in Kane County by Doelling and Davis (1989), and (4) a limited number of unpublished, site-specific geotechnical reports completed for projects in the Glen Canyon area.

### Expansive Soil and Rock in the Glen Canyon Study Area

Several bedrock formations in the Glen Canyon study area consist in whole or part of shale, claystone, or mudstone con-

taining expansive clay minerals. These rock units and the expansive soils derived from them are capable of significant expansion and contraction when wetted and dried, causing structural damage to buildings; cracked roads and driveways; damage to curbs, gutters, and sidewalks; and heaving of roads and canals. Expansive soils are chiefly derived from the weathering of clay-bearing rock formations (figure 39) and may be residual (formed in place) or transported (usually a short distance) and deposited in a new location. The principal transporting mechanisms are water or wind, but soil creep and mass-wasting processes may play important roles locally.

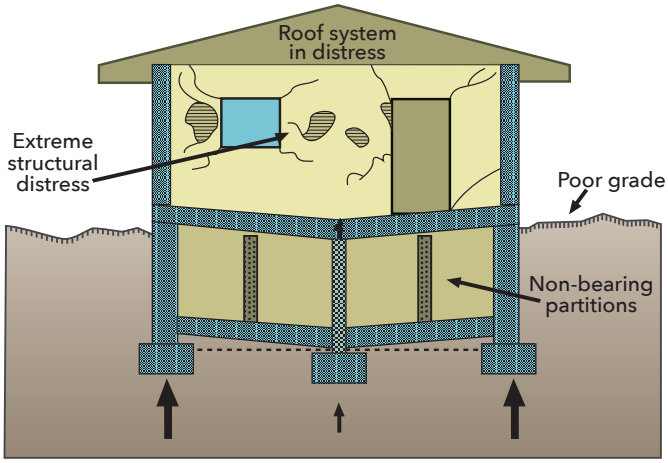


***Figure 38.*** *Typical structural damage to a building from expansive soil (modified from Black and others, 1999).*

## Hazard Classification

### Soil

We classified unconsolidated geologic units as having low or moderate swell potential based primarily on NRCS soils data. The NRCS (USDA, 2010a, 2010b) reported a linear extensibility value that can be used to determine the shrink-swell potential of soils. Linear extensibility is an expression of volume change that represents the change in length of an unconfined clod as moisture content is decreased from a moist to a dry state (USDA, 2010b). The NRCS considered a soil with a linear extensibility of less than 3 percent to have a low shrink-swell potential, moderate if 3 to 6 percent, high if 6 to 9 percent, and very high if greater than 9 percent. Within the Glen Canyon study area, the NRCS (USDA, 2010b) reported only low to moderate potential shrink-swell soils.

### Rock

We also grouped bedrock units in the study area into three shrink/swell-hazard categories on the basis of relative abundance of expansive clay minerals, abundance and thickness of fine-grained strata in mixed bedrock units, and past knowledge and experience with expansive rock units in southwestern Utah (Lund and others, 2008b, 2010; Knudsen and Lund, 2013). Bedrock units with high shrink/swell hazard include the upper members of the Chinle Formation (includ-

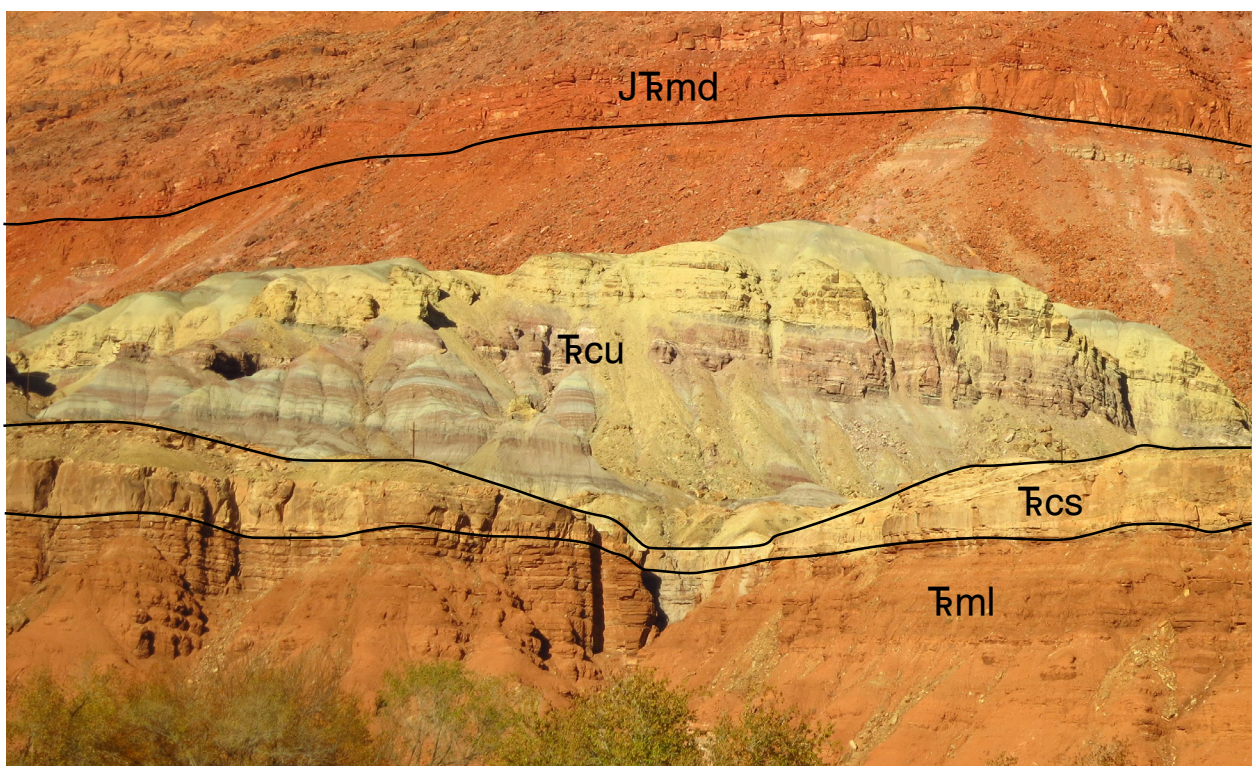


***Figure 39.*** *Outcrop of the expansive, clay-rich upper Chinle Formation (Ŧcu) near Lees Ferry. Such clay-bearing units are also the source rock for expansive soils.* JŦmd*=Dinosaur Canyon Member of the Jurassic-Triassic Moenave Formation,* Ŧcs*=Shinarump Conglomerate of the Triassic Chinle Formation,* Ŧml*=middle red member of the Triassic Moenkopi Formation.*

ing the Monitor Butte, Petrified Forest, and Owl Rock members, where mapped separately) and the Dakota Formation. These bedrock units contain an abundance of expansive clay minerals and are commonly associated with expansive rock problems throughout southern Utah and northern Arizona. Bedrock units with moderate shrink/swell hazard include the lower and upper red members of the Moenkopi Formation and the Dinosaur Canyon Member of the Moenave Formation. These rock units are chiefly fine grained and contain alternating strata of shale, claystone, mudstone, siltstone, sandstone, and limestone. Bedrock units with low shrink/swell potential include the Kayenta and Carmel Formations; these units contain sparse fine-grained, clay-rich strata that may cause local shrink/swell problems. We did not classify bedrock formations possessing little or no potential for volumetric change.

### Concealed Highly Expansive Soil or Rock

Our expansive-soil-and-rock mapping (https://geology.utah.gov/apps/hazards) shows several locations where highly expansive soil or rock may be present in the shallow subsurface (≤20 feet [6 m]), with little or no evidence of such materials at the ground surface. The likely presence of highly expansive materials in the shallow subsurface is based on the outcrop pattern of the upper members of the Chinle Formation, which indicates that the Chinle likely underlies thin unconsolidated deposits in those areas. Past experience in southern Utah has shown that when wetted, highly expansive soil or rock can cause damaging differential displacements at the ground surface even when overlain by as much as 20 feet (6 m) of non-expansive material (Lund and others, 2008b). Therefore, we consider areas where the upper members of the Chinle Formation may be present in the shallow subsurface as having a potential for highly expansive soil and rock problems, despite the lack of surface evidence of such materials.

### Using This Map

Our mapping (https://geology.utah.gov/apps/hazards) shows the location of known or suspected expansive soil and rock in the Glen Canyon study area. The mapping is intended for general planning and design purposes to indicate where expansive soil and rock may exist and special investigations should be required. Site-specific investigations can resolve uncertainties inherent in generalized mapping and help identify the need for special foundation designs, site grading and soil placement, or mitigation techniques. The presence and severity of expansive soil and rock, along with other geologic hazards should be addressed in these investigations. If expansive soil or rock is present at a site, appropriate design and construction recommendations should be provided.

### Hazard Reduction

Although costly when not recognized and properly accommodated in project design and construction, problems associated with expansive soil and rock rarely are life threatening. As with most geologic hazards, early recognition and avoidance are the most effective ways to mitigate potential problems. However, avoidance may not always be a viable or cost-effective option. Where the presence of expansive soil or rock is confirmed, possible mitigation techniques include soil removal and replacement with non-expansive, compacted backfill; use of special foundation designs, such as drilled pier deep foundations; moisture barriers; chemical stabilization of expansive clays; and careful site landscape and drainage design to keep moisture away from buildings and expansive soils (Nelson and Miller, 1992; Keller and Blodgett, 2006).

### Map Limitations

Our mapping is based on limited geologic and geotechnical data; site-specific investigations are required to produce more detailed geotechnical information. The mapping also depends on the quality of those data, which may vary throughout the study area. The mapped boundaries between hazard categories are approximate and subject to change as new information becomes available. The hazard from expansive soil and rock may be different than shown at any particular site because of variations in the physical properties of geologic deposits within a map unit, gradational and approximate map-unit boundaries, and the small map scale. The mapping is not intended for use at scales other than the target scale and is designed for use in general planning and design to indicate the need for site-specific investigations.

## COLLAPSIBLE SOIL

Collapsible (hydrocompactible) soils are relatively dry, low-density soils that decrease in volume or collapse under the load of a structure when they become wet. Collapsible soils may have considerable strength and stiffness in their dry natural state, but can settle up to 10 percent of the susceptible deposit thickness when they become wet for the first time following deposition (Costa and Baker, 1981; Rollins and Rogers, 1994; Keaton, 2005) causing damage to property, structures, pavements, and underground utilities (figure 40). Collapsible soils are common throughout the arid southwestern United States and are commonly geologically young materials, chiefly debris-flow deposits in Holocene-age (past 11,700 years; considered geologically young) alluvial fans, and some wind-blown, lacustrine, and colluvial deposits (Owens and Rollins, 1990; Mulvey, 1992; Santi, 2005).

Collapsible soils typically have a high void ratio and corresponding low unit weight (Costa and Baker, 1981) and relatively low moisture content (Owens and Rollins, 1990), all characteristics that result from the initial rapid deposition and drying of the sediments. Intergranular bonds form between the larger grains (sand and gravel) of a collapsible soil; these bonds develop through capillary tension or a binding agent

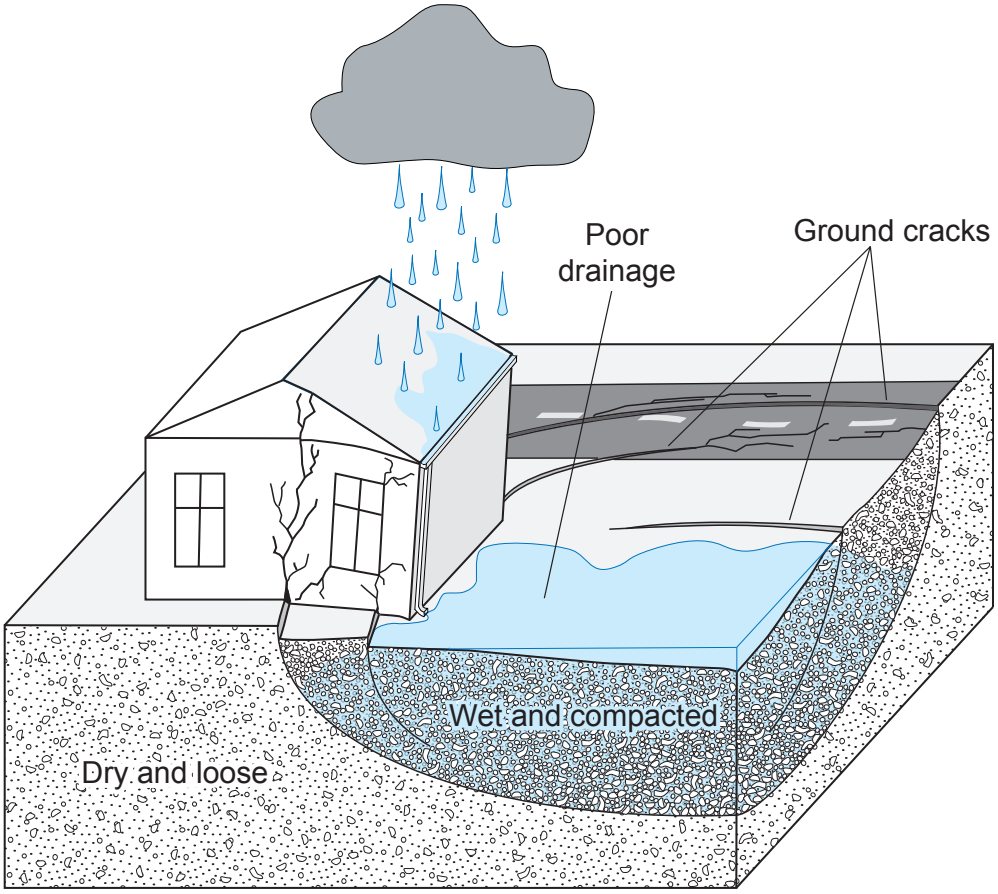


***Figure 40.*** *Diagram of differential settlement and resulting structural damage due to the addition of excess water to collapsible soils (modified from Love, 2001).*

such as silt, clay, or salt. Later wetting of the soil results in a loss of capillary tension or the softening, weakening, or dissolving of the bonding agent, allowing the larger particles to slip past one another into a denser structure (Williams and Rollins, 1991). Abundant small tubular voids or "pin holes" are also known to characterize low-density and collapse-prone soils in the southwestern United States (Lommler, 2012).

Generally, collapsible alluvial-fan and colluvial soils are associated with drainage basins dominated by soft, clay-rich sedimentary rocks such as shale, mudstone, claystone, and siltstone (Bull, 1964; Owens and Rollins, 1990). Bull (1964) found that the maximum collapse of alluvial fan soils in Fresno County, California, coincided with a clay content of approximately 12 percent. Alluvial-fan deposits exhibiting dramatic collapse behavior in Nephi, Utah, typically contain 10 to 15 percent clay-size material (Rollins and Rogers, 1994). At clay contents greater than about 12 to 15 percent, the expansive nature of the clay begins to dominate and the soil is subject to swell rather than collapse (Rollins and Rogers, 1994). Soil composition is the primary indicator of collapse potential in alluvial-fan and colluvial soils. Characteristically, collapsible soils consist chiefly of silty sands, sandy silts, and clayey sands (Williams and Rollins, 1991), although Rollins and others (1994) identified collapse-prone gravels containing as little as 5 to 20 percent fines at several locations in the southwestern United States.

Naturally occurring deep percolation of water into collapsible deposits is uncommon after deposition due to the arid conditions in which the deposits typically form, and the steep gradient of many alluvial-fan and colluvial surfaces. Therefore, soil collapse is usually triggered by human activity such as irrigation, urbanization, and/or wastewater disposal. Kaliser (1978) reported serious damage (estimated $3 million) to public and private structures in Cedar City, Utah, from collapsible soils. Rollins and others (1994) documented more than $20 million in required remedial measures to a cement plant near Leamington, Utah, and Smith and Deal (1988) reported damage to a large flood-control structure near Monroe, Utah. In 2001, collapsible soils damaged the Zion National Park greenhouse soon after its construction (figure 41) as soils below and around the building were wetted by excess irrigation water (Lund and others, 2010). Although we found no conclusive evidence of damage to facilities in the Glen Canyon study area due to collapsible soils, several unconsolidated geologic units within the study area have physical characteristics indicative of potentially collapsible soils.

## Sources of Information

Sources of information used to evaluate collapsible soil in the Glen Canyon study area include (1) recent UGS 1:24,000-scale geologic mapping that covers the Bullfrog (Willis, in prepara-

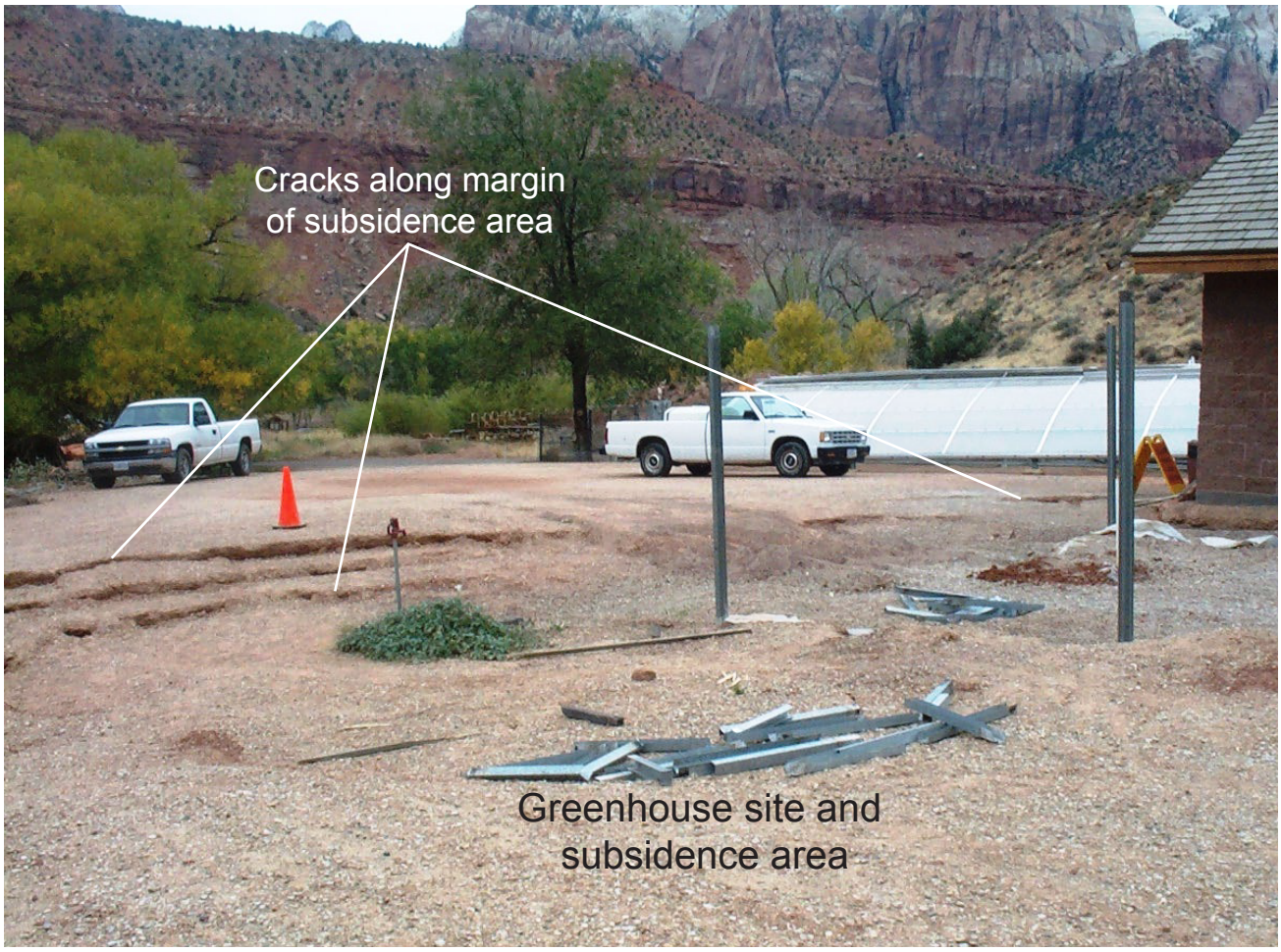


***Figure 41.*** *Site of Zion National Park greenhouse damaged by collapsible soils in 2001. Photo courtesy of the National Park Service.*

tion) and Wahweap sections (Phoenix, 2009; Willis, 2012a) of the Glen Canyon study area**,** (2) the NRCS *Soil Survey of Glen Canyon National Recreation Area, Arizona and Utah* (USDA, 2010a, 2010b), and (3) a limited number of unpublished, site-specific geotechnical reports completed for projects in the Glen Canyon area.

## Hazard Classification

We grouped unconsolidated geologic units that may be prone to collapse into three susceptibility categories. The categories are based on limited geotechnical data, and whether the deposit genesis or texture is permissive of collapse. Due to the lack of geotechnical information in the study area, the classification system presented here employs a relative susceptibility ranking as opposed to a hazard-severity ranking.

Common soil characteristics measured by geotechnical engineers to identify collapsible soils include swell/collapse test (SCT) data, density, and moisture content. With an absence of geotechnical data available in the Glen Canyon study area, we relied on geologic unit descriptions and NRCS soils analyses and descriptions. The unconsolidated geologic units on UGS geologic maps are defined by geomorphology (landform), genesis, age, and to a lesser extent texture. Rapidly deposited, Holocene-age alluvial units with reported low densities (<85 lbs/ft$^3$), abundant fine-grained material in the clay to fine-sand range (Unified Soil Classification System classes SC [clayey sand], SM [silty sands], and GC [clayey gravel-sand mixtures]), and abundant tubular pores as described by the NRCS, are the most likely units to collapse (hazard-map unit $SU2_{CSS}$). Holocene-age alluvial units with a genesis and texture permissive of collapse, but lacking corresponding NRSC data, are mapped as $SU3_{CSS}$ on the collapsible-soil susceptibility map. Pleistocene (~11.7 ka–2.6 Ma) unconsolidated deposits with a genesis and texture permissive of collapse are mapped as $SU4_{CSS}$; because of their older age, they have had greater exposure to natural wetting and collapse may have already occurred, and/or the deposits may be cemented by secondary calcium carbonate or other soluble minerals.

## Using This Map

Our mapping (https://geology.utah.gov/apps/hazards) shows the location of known and suspected collapsible-soil conditions in the Glen Canyon study area. The mapping is intended for general planning and design purposes to indicate where collapsible soil conditions may exist and where special investigations

are required. Site-specific investigations can resolve uncertainties inherent in generalized mapping and help identify the need for special design, site grading and soil placement, and/or mitigation techniques. The presence and severity of collapsible soil along with other geologic hazards should be addressed in these investigations. If collapsible soil is present at a site, appropriate design and construction recommendations should be provided.

### Hazard Reduction

Although costly when not recognized and properly accommodated in project design and construction, problems associated with collapsible soil rarely are life threatening. As with most geologic hazards, early recognition and avoidance are the most effective ways to mitigate potential problems. However, avoidance may not always be a viable or cost-effective option. Where the presence of collapsible soil is confirmed, possible mitigation techniques include soil removal and replacement with non-cohesive, compacted backfill; use of special foundation designs such as drilled pier deep foundations, grade beam foundations, or stiffened slab-on-grade construction; moisture barriers; and careful site landscape and drainage design to keep moisture away from buildings and collapse-prone soils (Nelson and Miller, 1992; Pawlak, 1998; Keller and Blodgett, 2006).

### Map Limitations

Our mapping is based on limited geologic and geotechnical data; site-specific investigations are required to produce more detailed geotechnical information. The mapping also depends on the quality of those data, which may vary throughout the study area. The mapped boundaries between susceptibility categories are approximate and subject to change as new information becomes available. The susceptibility may be different than shown at any particular site because of variations in the physical properties of geologic deposits within a map unit, gradational and approximate map-unit boundaries, and the small map scale. The mapping is not intended for use at scales other than the target scale and is designed for use in general planning and design to indicate the need for site-specific investigations.

## EARTHQUAKE GROUND-SHAKING HAZARD

Ground shaking is the most widespread and typically the most costly earthquake hazard in terms of property damage, injury, and death (Yeats and others, 1997). Earthquakes occur on faults where bedrock on one side of the fault slips in relation to bedrock on the other side of the fault. Ground shaking is caused by seismic waves that originate at the source of the earthquake and radiate outward in all directions. The strength of ground shaking generally decreases with increasing distance from the earthquake epicenter because the earthquake's energy scatters and dissipates as it travels through the Earth (attenuation). However, in certain cases earthquake ground motions can be amplified and shaking duration prolonged by local site conditions (Hays and King, 1982; Wong and others, 2002). The degree of amplification depends on factors such as soil thickness and the characteristics of geologic materials.

The extent of property damage and loss of life due to ground shaking depends on specific factors, such as (1) the strength and duration of the earthquake; (2) the proximity of the earthquake to an affected location; (3) the amplitude, duration, and frequency of earthquake ground motions; (4) the nature of the geologic materials through which the seismic waves travel; and (5) the design of engineered structures (Costa and Baker, 1981; Reiter, 1990). In general, earthquakes in the Glen Canyon area are infrequent and of small to moderate magnitude (Wong and Humphrey, 1989; Wong and others, 1996). If a significant earthquake were to occur in the Glen Canyon study area, potential geologic hazards would include ground shaking and possibly surface fault rupture, liquefaction, landslides, rockfalls, and the production of standing waves (seiches) on Lake Powell. As discussed below, however, the possibility of a strong earthquake capable of causing appreciable damage in the study area is low.

### Sources of Information

Sources of information used to evaluate the earthquake-ground-shaking hazard in the Glen Canyon study area include (1) recent UGS 1:24,000-scale geologic mapping that covers the Bullfrog (Willis, in preparation) and Wahweap sections (Phoenix, 2009; Willis, 2012a) of the Glen Canyon study area; (2) information on historical earthquakes in southern Utah and northwestern Arizona, chiefly from the University of Utah Seismograph Stations (UUSS) earthquake catalog (UUSS, 2020), and the Arizona Earthquake Information Center (AEIC) earthquake catalog (AEIC, 2016); (3) the *Quaternary Fault and Fold Database of the United States* (USGS, 2016b); (4) the *Utah Quaternary Fault and Fold Database* (UGS, 2016); (5) a limited number of unpublished, site-specific geotechnical reports completed for projects in the Glen Canyon area; (6) the USGS National Seismic Hazard Maps (USGS, 2016c); (7) a probabilistic seismic hazard analysis for the Glen Canyon Dam by URS Greiner Woodward Clyde (2000); (8) the 2018 *International Building Code* (IBC) (International Code Council, 2017a); and (9) the 2018 *International Residential Code for One- and Two-Family Dwellings* (IRC) (International Code Council, 2017b).

### Earthquakes in the Glen Canyon Region

The Glen Canyon region is within the interior of the Colorado Plateau—a region characterized by generally low to moderate levels of historical earthquake activity. The more seismically active Intermountain Seismic Belt (ISB) (Smith and Sbar, 1974; Smith and Arabasz, 1991) and the Northern Arizona Seismic Belt (NASB) (Brumbaugh, 1987) lie to the west (figure 42). Earthquakes in the Glen Canyon region are chiefly

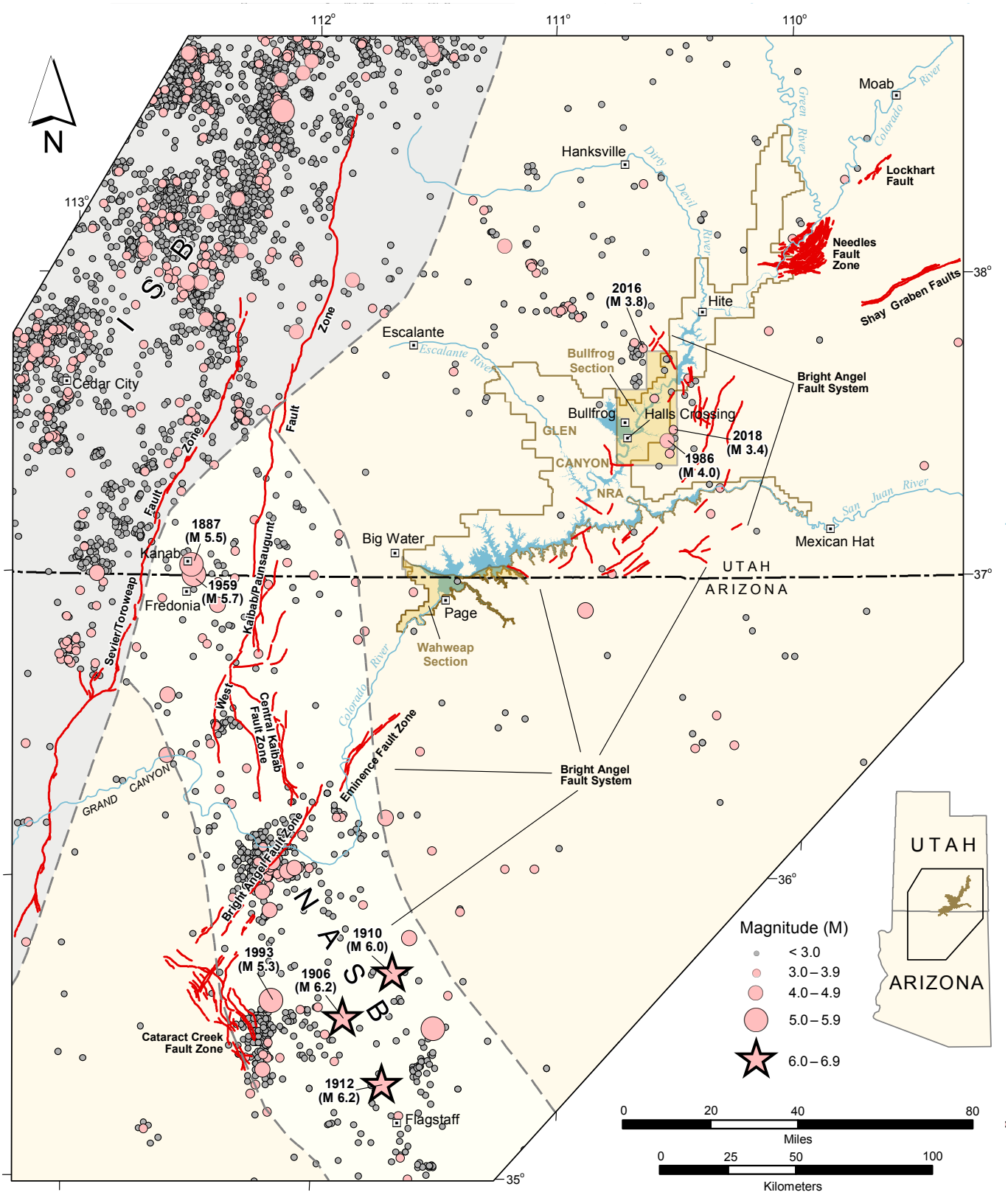


***Figure 42.*** *Earthquake epicenters, major Quaternary faults (red lines), Intermountain Seismic Belt (ISB), and Northern Arizona Seismic Belt (NASB) in relation to the Glen Canyon study area. Epicenter locations from the Arizona Earthquake Information Center (2016) and University of Utah Seismograph Stations (2020) earthquake catalogs.*

associated with normal-slip faults. Normal-slip faults form in response to tensional (pulling apart) stresses, typically dip 50° ± 15°, and place younger rock on older rock (see Surface-Fault-Rupture Hazard section below).

Since 1962, when the first regional seismic network was installed to record earthquakes in Utah, approximately 12 earthquakes have been recorded within the Glen Canyon study area (UUSS, 2020; AEIC, 2016). All except four were smaller than magnitude (M) 3.0. The largest known earthquake in the study area (M 4.0) occurred on August 22, 1986, near Halls Crossing (figure 42). On March 1, 2016, a M 3.8 tremor occurred about 2 miles northwest of the study area near the Henry Mountains and was felt at Bullfrog. More recently, on October 27, 2018, a M 3.4 earthquake occurred 10 miles east of Halls crossing (figure 42). The few earthquakes recorded in and near the study area have not been attributed to mapped faults.

Regionally, larger earthquakes have occurred in the NASB—a narrow region of elevated seismicity that extends southeast from the ISB in southwestern Utah through the Kanab-Fredonia area, intersects the eastern Grand Canyon, and dies out south of Flagstaff (Brumbaugh, 1987) (figure 42). Seven earthquakes of M 5.0 or larger have occurred in the NASB since 1887. The largest instrumentally recorded earthquake in Arizona (M 5.7) occurred on July 21, 1959, about 50 miles west of the Glen Canyon study area near Fredonia (DuBois and others, 1982) (figure 42). Damaged chimneys, cracked walls, and broken windows reported in Fredonia and Kanab, and a large rockfall in the Grand Canyon were all attributed to the quake (Stover and Coffman, 1993). A similarly sized damaging earthquake was reported near Kanab in 1887 (Stover and Coffman, 1993). Strong NASB earthquakes in 1906, 1910, and 1912 within the San Francisco volcanic field, approximately 80 miles southwest of the study area, caused moderate damage to structures in Flagstaff and are estimated to have been in the M 6.0–6.2 range (Bausch and Brumbaugh, 1997). Bausch and Brumbaugh (1997) estimated the maximum credible earthquake possible for the Flagstaff area is a M 7.3. However, the GCNRA is nearly 100 miles (160 km) from Flagstaff, and the ground-shaking hazard produced from an earthquake at that distance is uncertain in the study area. For comparison, a 1993 M 5.3 earthquake northwest of Flagstaff was felt more than 100 miles (160 km) away in the Lake Powell area and reportedly caused minor damage at Big Water, Utah, just west of the study area (USGS, 2016d). The continuous and generally unfaulted bedrock of the Colorado Plateau may decrease earthquake attenuation and facilitate ground shaking over larger areas. This affect was demonstrated during the 1988 M 5.2 San Rafael Swell earthquake near Castle Dale, Utah, when ground shaking was felt as far away as Golden, Colorado, 295 miles (475 km) to the east across the Colorado Plateau, but only as far as Delta, Utah, 97 miles (156 km) to the west across the densely faulted Basin and Range Province (Case, 1988).

Earthquakes of about magnitude 4.5–5.0 or greater can trigger translational or rotational landslides (Keefer, 1984). Ground shaking can also produce standing waves or seiches that oscillate the water surface of lakes. Large seiches could be destructive to facilities along Lake Powell's shorelines. Abundant rockfalls should be expected during moderate to strong earthquakes as demonstrated by the hundreds of rockfalls triggered by the 1988 M 5.2 earthquake in the San Rafael Swell (figure 43)—an area with similar geology/topography as the GCNRA. Areas most prone to earthquake-triggered rockfalls are shown on the rockfall-hazard map (https://geology.utah.gov/apps/hazards) and are discussed in the Rockfall Hazard section above.

## Potential Sources of Strong Earthquake Ground Shaking

Ground shaking could result from an earthquake generated by movement on a mapped fault, or from an earthquake not attributable to a mapped fault. Most earthquakes on the Colorado Plateau cannot be attributed to movement on known faults (Wong and Humphrey, 1989; Wong and others, 1996). Although the maximum magnitude of these background earthquakes could theoretically approach M 6.5 (lower limit of surface-fault rupture on the Colorado Plateau), historical earthquakes in GCNRA have been much smaller. However, the greater southwestern Colorado Plateau region near GCNRA has several faults that have been active during Quaternary time (the past 2.6 million years) (Hecker, 1993; UGS, 2016; USGS, 2016b), and the region has experienced several moderately strong earthquakes (M 5.0–6.2; see Earthquakes in the Glen Canyon Region section above).

Several relatively short, northwest- and northeast-trending normal-slip faults in the Glen Canyon study area are part of the regional Bright Angel fault system (Shoemaker and others, 1978; Menges and Pearthree, 1983; Hecker, 1993; UGS, 2016) that extends from the Lake Powell area into north-central Arizona (figure 42). Bright Angel faults in the Glen Canyon area have relatively small displacements of tens to hundreds of feet (figure 44), and likely have low rates of activity. Due to a general lack of Quaternary-age deposits overlying the faults, constraints on the timing of most recent fault movement are lacking. However, based on similarities with larger Quaternary-active strands of the Bright Angel fault system in north-central Arizona, including the Eminence fault, Bright Angel fault, and Cataract Creek fault zone (figure 42), the smaller Glen Canyon-area faults are also suspected to be Quaternary-active (Menges and Pearthree, 1983; Hecker, 1993; UGS, 2016). Additional major regional Quaternary faults within 60 miles (97 km) of the Glen Canyon study area that could produce strong ground shaking include the West Kaibab/Paunsaugunt and Central Kaibab fault zones (Bowers, 1991; Brumbaugh, 2008; USGS, 2016b) and the Sevier/Toroweap fault (Lund and others, 2008a) about 25 and 55 miles (40 and 90 km) west of the study area, respectively (figure 42). While these sources could potentially produce strong ground shaking, they are suspected to have generally low rates of activity and are unlikely to produce strong ground

***Figure 43.*** *Dust clouds from numerous rockfalls triggered by the 1988 M 5.2 San Rafael Swell earthquake in central Utah. The Glen Canyon area has similar canyon and mesa topography and can expect similar rockfall activity during moderate to strong earthquakes (> M 4.5). Photo courtesy of Terry Humphrey, Bureau of Land Management.*

***Figure 44.*** *North-directed view of a small-displacement normal fault exposed in the walls of the Castle Rock cut. Fault displaces Carmel Formation strata about 4 feet. Photo taken May 12, 2015.*

shaking in the study area. A moderate-magnitude background earthquake below the threshold required for surface rupture (~ M 6.5) in or near the study area is also a possibility that must be considered in the planning process. Other nearby potentially Quaternary-active faults including the Needles fault zone, Shay Graben faults, and the Lockhart fault (figure 42), appear to be related to gravitational collapse and/or dissolution of buried salt (Baker, 1933; McGill and Stromquist, 1974; Huntoon, 1988; Crider and others, 2002). Because these faults only extend to relatively shallow depths in the crust, they are not considered capable of producing significant earthquakes or strong ground shaking.

## Hazard Reduction

Geotechnical data available are insufficient to prepare a ground-shaking-hazard map for the Glen Canyon study area. However, risk to public safety due to earthquake ground shaking can be reduced by incorporating building-code-based earthquake-resistant construction requirements in new construction and when retrofitting existing structures. Earthquake-resistant design requirements are specified in the seismic provisions of the IBC (International Code Council, 2017a) and the IRC (International Code Council, 2017b). We recommend that the NPS adopt current IBC and IRC codes for all new construction in the study area.

A building need only withstand the vertical force of gravity to support its own weight. However, during an earthquake a building is also subjected to horizontal forces. Horizontal ground motion is typically the most damaging type of earthquake ground shaking, and is expressed in decimal fractions of the acceleration due to gravity (1 *g*). In general, the greater the acceleration or "*g*" force, the stronger the ground shaking and the more damaging the earthquake. Horizontal ground motion as small as 0.1 *g* may cause damage to weak structures (buildings not designed to modern building codes incorporating seismic design) (Richter, 1958), and in a large earthquake, horizontal motion may reach values greater than that of gravity. Consequently, the type and quality of construction play critical roles in determining the damage caused by strong ground shaking. Locally, ground motion can be amplified (more severe shaking) or deamplified (less severe shaking) depending on particular geologic conditions at the site (site class). The degree of amplification depends on factors such as soil thickness and the characteristics of geologic materials.

Probabilistic ground motion for the Glen Canyon study area is shown on the National Seismic Hazard Maps (NSHMs) developed by the USGS (2016c). Maximum considered earthquake ground motion (mapped spectral accelerations) for rock sites (IBC Site Class B) can be calculated for any point using the USGS U.S. Seismic Design Maps web application (https://earthquake.usgs.gov/ws/designmaps/). The different values are used by engineers for earthquake design of structures, based in part on the height and intended use of the structure. Different structures are affected by different frequencies of ground motion which, when matching the natural frequency of vibration of a structure (a function of building height and construction type), may cause resonance resulting in severe damage or collapse. Therefore, the IBC and USGS provide maximum considered earthquake ground motion for two periods (0.2 s and 1.0 s), which together are appropriate for a wide range of building types. The 0.2 s mapped spectral acceleration is appropriate when evaluating the effect of short-period (high-frequency) ground motion, which typically affects short buildings (one to two stories). The 1.0 s mapped spectral acceleration is appropriate when evaluating the effect of long-period (low-frequency) ground motion, which typically affects tall buildings (more than two stories). Table 4 summarizes probabilistic 0.2 and 1.0 s spectral accelerations derived from the NSHMs applicable to rock sites at Bullfrog, Wahweap, and Navajo Bridge. These values are presented solely to illustrate examples of predicted ground motion, and how ground motion increases slightly to the southwest across the study area. However, ground motion overall is expected to be low and is likely to cause only slight to moderate damage to well-built structures. As noted above, earthquake-triggered rockfalls are likely to be the greatest earthquake hazard in the Glen Canyon study area.

For building design, mapped maximum considered earthquake ground motion for a rock site (Site Class B) is adjusted for amplification or deamplification of ground motion, depending on site-specific soil and rock conditions. These effects may be particularly severe in areas subject to amplified ground motions. In general, site class is determined by conducting a geotechnical investigation during the project design phase prior to construction. For construction in areas underlain by rock subject to deamplification (Site Class A) or no amplification (Site Class B), site geological and geotechnical investigations are needed to confirm the mapped site class based on rock type. However, as amplification increases in Site Classes C, D, and E, more detailed subsurface investigations should be conducted for all types of development intended for human occupancy, and for critical facilities regardless of occupancy category. For construction in areas underlain by soil of Site

***Table 4.*** *Spectral response acceleration (SA) in g, generally applicable to rock sites (IBC site class B) in the Glen Canyon study area determined using USGS U.S. Seismic Design Maps web application (https://earthquake.usgs.gov/ws/designmaps/). These data are for informational purposes only; values for use in design must be derived from IBC seismic-hazard maps and corrected for geologic site conditions (site class) as required in the IBC seismic provisions.*

| Location | 0.2 s SA | 1.0 s SA | Latitude | Longitude |
|---|---|---|---|---|
| Bullfrog | 0.256 | 0.075 | 37.523° N | 110.722° W |
| Wahweap | 0.289 | 0.093 | 36.997° N | 111.490° W |
| Navajo Bridge | 0.298 | 0.095 | 36.818° N | 111.633° W |

Class C, D, or E, a geotechnical investigation is needed to characterize site soil conditions. The IBC requires that both site-specific geotechnical investigations and dynamic site-response analyses be performed in areas underlain by Site Class F materials. Site Class F includes collapse-prone soils that may be common locally in the Glen Canyon study area. In some cases, as a default option, the IBC allows use of Site Class D, except where the local building official determines that Site Class E or F is likely to be present. We recommend that IBC or IRC site classes be determined on a site-specific basis for all new construction in the Glen Canyon study area.

## SURFACE-FAULT-RUPTURE HAZARD

Earthquakes occur without warning and can cause injury and death, major economic loss, and social disruption (Utah Seismic Safety Commission, 1995). An earthquake is the abrupt, rapid shaking of the ground caused by sudden slippage of bedrock deep beneath the Earth's surface. The rocks break and slip when accumulated stress exceeds the rock's strength. Strong earthquakes (>M 6.5) in the western U.S. are commonly accompanied by surface faulting. The rupture may affect a zone tens to hundreds of feet wide and tens of miles long. Surface faulting on normal faults produces ground cracking and typically one or more fault scarps (figure 45). When originally formed, fault scarps have near-vertical slopes and, depending on the size of the earthquake, can range from a few inches to many feet high. Local ground tilting and graben formation by secondary (antithetic) faulting may accompany surface faulting, resulting in a zone of deformation along the fault trace tens to hundreds of feet wide (figure 45). Surface faulting, while of limited aerial extent when compared to other earthquake-related hazards, such as ground shaking (see Earthquake Ground-Shaking Hazard section) and liquefaction (see Liquefaction Hazard section), can have serious consequences for structures or other facilities that lie along or cross the fault rupture path (Bonilla, 1970). Buildings, bridges, dams, tunnels, canals, and pipelines have all been severely damaged by surface faulting (see for example, Lawson, 1908; Ambraseys, 1960, 1963; Duke, 1960; California Department of Water Resources, 1967; Christenson and Bryant, 1998; USGS, 2000).

The hazard due to surface faulting is directly related to the activity of the fault—that is, how often the fault ruptures the ground surface and how likely it is to rupture in the future (Christenson and Bryant, 1998). Fault-related surface rupture has not occurred on the Colorado Plateau historically; however, geologic data for faults in the region indicate a low to moderate rate of Quaternary surface-faulting activity.

### Sources of Information

Sources of information used to evaluate surface-fault-rupture hazard in the Glen Canyon study area include (1) recent UGS 1:24,000-scale geologic mapping that covers the Bullfrog (Willis, in preparation) and Wahweap sections (Phoenix, 2009; Willis, 2012a) of the study area, (2) the *Quaternary Fault and Fold Database of the United States* (USGS, 2016b), and (3) the *Utah Quaternary Fault and Fold Database* (UGS, 2016).

### Active Faults in the Intermountain West

Because earthquakes result from slippage on faults, from an earthquake-hazard perspective, faults are commonly classified as (1) active, capable of generating damaging earthquakes, or (2) inactive, not capable of generating earthquakes. The term "active fault" is frequently incorporated into regulations pertaining to earthquake hazards, and over time, the term has been defined differently for different regulatory and legal purposes. In nature, faults possess a wide range of activity levels. Some, such as the San Andreas fault in California, produce large earthquakes and associated surface faulting every hundred years or so, while others, like the Wasatch fault and other faults in the Basin and Range Province, produce large earthquakes and surface faulting every few hundred to tens of thousands of years. Therefore, depending on the area of interest or the intended purpose, the definition of "active fault" may vary. The time period over which faulting activity is assessed is critical because it determines which faults are ultimately classified as hazardous, and therefore, subject to regulatory hazard mitigation (Allen, 1986).

#### Activity Classes

In California, the Alquist-Priolo Earthquake Fault Zoning Act (Bryant and Hart, 2007), which regulates development along known active faults, defines an "active" fault as one that has had "surface displacement within Holocene time (about the past 11,700 years)." Because California has a well-recognized earthquake hazard and was the first state to implement regulations designed to mitigate those hazards, the California "Holocene" standard has found its way into many regulations in other parts of the country, even in areas where the Holocene is not the best time frame against which to measure surface-faulting recurrence. DePolo and Slemmons (1998) argued that in the Basin and Range Province, a time period longer than the Holocene is more appropriate for defining active faults, because most faults there have surface-faulting recurrence intervals (average repeat times) that approach or exceed 10,000 years. They advocated a late Pleistocene-age criterion, specifically 130,000 years, to define active faults in the Basin and Range Province. They based their recommendation on the observation that six to eight (greater than 50 percent) of the 11 historical surface-faulting earthquakes in that region were on faults that lacked evidence of Holocene activity but had evidence of late Pleistocene activity.

Because of the difficulties in using a single "active" fault definition, the Western States Seismic Policy Council (WSSPC) has defined the following fault activity classes (WSSPC Policy

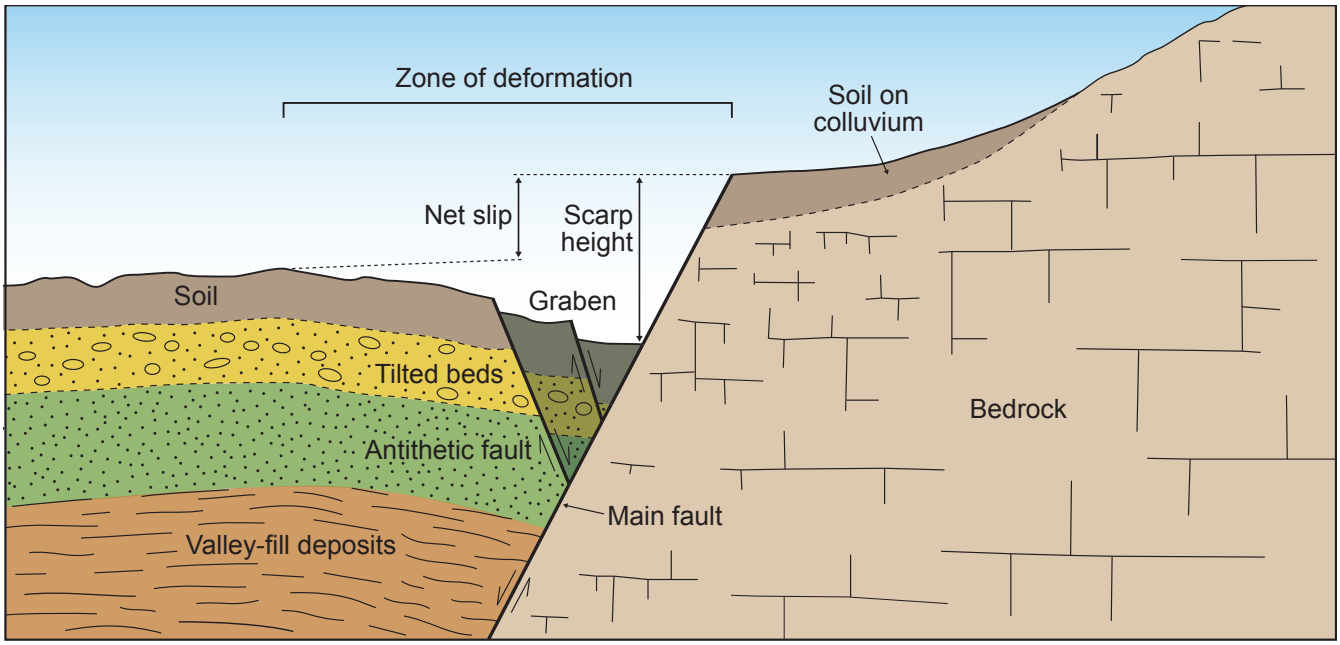


***Figure 45.*** *Schematic cross section of a typical normal fault and associated deformation zone (modified from Robison, 1993).*

Recommendation 11-2, 2011; first adopted in 1997 as WSSPC Policy Recommendation 97-1, and revised and readopted in 2002, 2005, 2008, 2011, and 2015 [WSSPC, 2015]). WSSPC Policy 15-3 recommends that the following definitions of fault activity be used to categorize potentially hazardous faults in the Basin and Range Province:

> **Late Pleistocene-Holocene fault** – a fault that has moved within the past 15,000 years and has been large enough to break the ground surface.
>
> **Late Quaternary fault** – a fault that has moved within the past 130,000 years and has been large enough to break the ground surface.
>
> **Quaternary fault** – a fault that has moved within the past 2.6 million years and has been large enough to break the ground surface.

Lund and others (2016) recommended adopting the WSSPC fault activity-class definitions in Utah, and we follow that recommendation in this study.

## Evaluating Fault Activity

Because both the instrumental and historical records of seismicity on the Colorado Plateau are short (less than 200 years), geologists must use other means to assess fault activity levels, including evaluating the prehistoric record of surface faulting. Paleoseismology is the study of prehistoric surface-faulting earthquakes (Solonenko, 1973; Wallace, 1981; McCalpin, 2009).

Paleoseismic investigations can provide information on the timing of the most recent surface-faulting earthquake (MRE) and earlier events, the average recurrence interval between surface-faulting earthquakes, net displacement per event, slip rate (net displacement averaged over time), and other faulting-related parameters (Allen, 1986; McCalpin, 2009; DuRoss, 2015). Determining the timing of the MRE establishes the fault's activity class (see above). Paleoseismic data from multiple sites can show if a fault ruptures as a single entity, or if it is subdivided into smaller segments that are each independently capable of generating earthquakes. Importantly, paleoseismic investigations can establish the relation between the elapsed time since the MRE and the average recurrence interval between surface-faulting earthquakes. Once that relation is known, the likelihood of surface faulting in a time frame of significance to most engineered structures can be estimated.

## Faults in the Glen Canyon Area

The UGS geologic maps used as the basis for this study (see the Sources of Information section above) show only a few relatively short normal faults in the Glen Canyon study area. Normal-slip faulting occurs when the fault hanging wall moves downward relative to the fault footwall (figure 46). Normal faults form in response to tensional (pulling apart) forces, typically dip 50° ± 15°, and place younger rock on older rock.

Although the Colorado Plateau has historically been considered a seismically inactive region, a denser regional seismograph network installed in the past few decades has revealed that small- to moderate-magnitude single events and small-magnitude earthquake swarms are relatively common and occur widely over the interior of the plateau (e.g., Wong and Simon, 1981; Kruger-Knuepfer and others, 1985; Wong and others, 1987; Wong and Humphrey, 1989). Seismic-data analyses indicate that much of the Colorado Plateau interior,

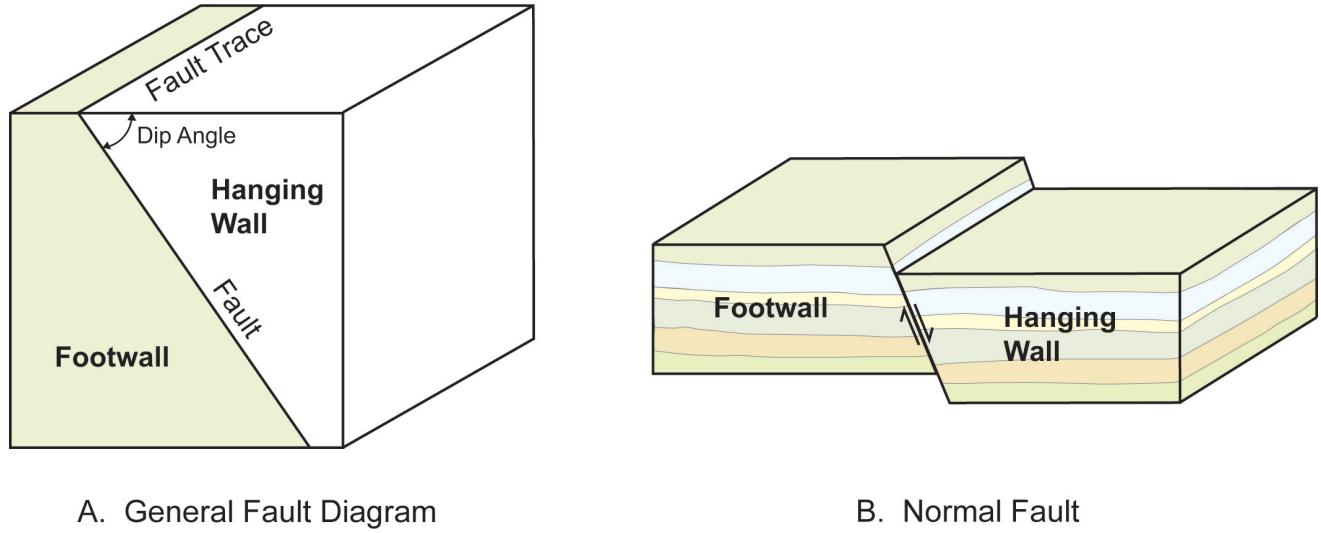


***Figure 46.*** *Characteristics of a typical normal fault in the Glen Canyon study area.*

including the Glen Canyon area, is in a state of northeast-directed tectonic extension (Wong and Humphrey, 1989). Although seismic events on the Colorado Plateau are rarely associated with recognizable faults (Wong and Humphrey, 1989), nodal plane solutions indicate that northeast-directed extensional stress is being accommodated predominantly by normal faulting on northwest-trending faults (Wright and others, 1987; Wong and Humphrey, 1989). Many northeast- and northwest-trending faults exposed at the surface of the Colorado Plateau may result from reactivation of pre-existing Precambrian structures with similar orientations (Hodgson, 1961; Hite, 1975; Shoemaker and others, 1978; Wong and Humphrey, 1989; Brumbaugh, 2005).

The short (< ~5 miles [8 km] long), northwest- and northeast-trending normal-slip faults mapped within the Glen Canyon study area (figure 42) are considered part of the regional Bright Angel fault system (Shoemaker and others, 1978; Menges and Pearthree, 1983; Hecker, 1993; UGS, 2016) that extends into north-central Arizona (see Earthquake Ground-Shaking Hazard section above). The Bright Angel faults in the study area have relatively small displacements of tens to hundreds of feet and, in outcrop, commonly involve only a single geologic formation (figure 44). No detailed paleoseismic investigations have been conducted on normal faults in the Glen Canyon area. UGS geologic mapping shows sparse eolian and alluvial unconsolidated Quaternary deposits along Glen Canyon normal faults, and that those deposits are not displaced. An approximately 2-mile-long (3 km) northeast-trending fault spanning Wahweap Bay south of Wahweap Marina is overlain by and does not displace an upper-level alluvial terrace deposit estimated to be 430,000 to 530,000 years old (Willis, 2012a), indicating the fault has not moved since the middle Pleistocene.

Despite the apparent very low level of activity, the study area faults are considered potentially active and capable of producing infrequent future earthquakes because (1) the faults are normal-slip faults, and as such, are related to the current regional extensional tectonic regime, and (2) the faults share similar geometries and orientations with larger, known Quaternary-active members of the Bright Angel fault system in north-central Arizona. In the absence of information to the contrary, the UGS recommends all Quaternary faults be classified as Holocene active unless there are adequate data to assign them to the Late Quaternary or Quaternary activity class (Lund and others, 2016).

## Surface-Fault-Rupture-Hazard Classification

Our surface-fault-rupture hazard mapping (https://geology.utah.gov/apps/hazards) shows the normal faults in the Glen Canyon study area mapped by the UGS. Because of the prevailing regional extensional tectonic regime, we consider all normal faults in the study area as potentially active until proven otherwise.

### Special Study Areas

Based on UGS geologic mapping, we categorized the normal faults in the Glen Canyon study area as either "well defined," "approximately located," or "buried," and establish surface-fault-rupture-hazard special-study areas (e.g., Lund and others, 2008b; Hiscock and Hylland, 2015; Lund and others, 2016) for each fault category.

**Well-defined faults:** We consider a fault well defined if its trace is clearly detectable by a trained geologist as a physical feature at the ground surface (Bryant and Hart, 2007). We classified normal faults in the study area as well defined if UGS 1:24,000-scale mapping shows them as solid lines, indicating that they are recognizable as faults at the ground surface. The surface-fault-rupture-hazard special-study areas established for well-defined faults extend for 500 feet (150 m) on the downthrown side and 250 feet (75 m) on the upthrown side of each fault.

**Approximately located and buried faults:** The UGS mapped some normal faults in the Glen Canyon study area as approximately located (dashed lines) or buried (dotted lines) because the traces of those faults are not evident at the ground surface. The reasons for the lack of clear surface evidence for these faults are varied, but are chiefly related to one or more of the following causes: (1) long earthquake recurrence intervals combined with a long elapsed time since the MRE allow evidence for the faults to be obscured by subsequent erosion and deposition, (2) rapid deposition occurs in some areas that quickly obscures faults, even those with comparatively short recurrence intervals, (3) the faults generate earthquakes that produce relatively small scarps (<3 feet [1 m]) that are quickly obscured, or (4) faulting occurs at or above the bedrock/alluvium contact in relatively steep terrain and is difficult to identify.

Although not evident at the surface, these faults may still represent a surface-fault-rupture hazard and should be evaluated prior to development in areas where they may rupture to the ground surface. Because of fault-location uncertainty, the surface-fault-rupture-hazard special-study areas around these faults are broader, extending 1000 feet (300 m) on each side of the suspected trace of the faults.

## Using This Map

Our mapping (https://geology.utah.gov/apps/hazards) shows potentially active faults along which surface faulting may occur. A special-study area is shown around each fault, within which we recommend that a site-specific, surface-fault-rupture-hazard investigation be performed prior to development. These investigations can resolve uncertainties inherent in generalized hazard mapping and help ensure safety by identifying the need for setbacks from the fault trace.

Given the scarcity of paleoseismic data for suspected Quaternary faults in the Glen Canyon study area, we consider fault setback and avoidance the safest and most effective surface-faulting-mitigation option for development proposed near study-area faults. The UGS *Guidelines for Evaluating Surface-Fault-Rupture Hazards in Utah* (Lund and others, 2016) includes a detailed rationale for performing surface-fault-rupture-hazard investigations, minimum technical requirements for conducting and reporting those investigations, recommendations regarding when surface-fault-rupture-hazard investigations should be conducted based on fault activity class and the type of facility proposed, and procedures for establishing safe setback distances from active faults. We recommend that National Park Service officials, planners, and consultants refer to the UGS guidelines regarding the details of conducting and reviewing surface-fault-rupture-hazard investigations.

Because approximately located and buried faults lack a clearly identifiable surface trace, they are not amenable to trenching, which is the standard surface-fault-rupture-hazard investigation technique used to study well-defined faults (McCalpin, 2009; Lund and others, 2016). Where development is proposed in a special-study area for a buried or approximately located fault, we recommend that, at a minimum, the following tasks be performed to better define the surface-fault-rupture hazard in those areas:

1. Review published and unpublished maps, literature, and records concerning geologic units, faults, surface water, groundwater, previous subsurface investigations, previous geotechnical and geophysical investigations, and other relevant factors.
2. Use stereoscopic interpretation of aerial photographs to detect any subtle fault-related features expressed in the site topography, vegetation or soil contrasts, and any lineaments of possible fault origin.
3. Perform a field evaluation of the proposed site and surrounding area to observe pertinent surface evidence for faulting, including mapping of geologic units as necessary to define critical geologic relations; evaluation of geomorphic features such as springs or seeps (aligned or not), sand blows or lateral spreads, or other evidence of earthquake-induced features; and excavation of test pits to evaluate the age of the deposits onsite to constrain the time of most recent surface faulting.

If the results of these investigations reveal evidence of possible surface-faulting-related features, those features should be trenched in accordance with the UGS *Guidelines for Evaluating Surface-Fault-Rupture Hazards in Utah* (Lund and others, 2016). Following the above-recommended tasks, if no evidence of surface faulting is found, development at the site can proceed as planned. However, we recommend that construction excavations and cut slopes be carefully examined for evidence of faulting as development proceeds.

## Hazard Reduction

Because surface faulting is typically confined to relatively narrow zones along the surface trace of a fault, early recognition and avoidance are the most effective strategies for mitigating this hazard. Once the activity class of the fault is determined (see Activity Classes section above), we recommend that setbacks from the fault trace and any associated zone of deformation be established in accordance with UGS *Guidelines for Evaluating Surface-Fault-Rupture Hazards in Utah* (Lund and others, 2016). Carefully locating all potentially active fault traces at a site, assessing their level of activity and amount of displacement, establishing an appropriate setback distance from the fault, and proper facility and site design remain the most reliable procedures for mitigating damage and injury due to surface faulting.

Earthquake-resistant design requirements for construction are specified in the seismic provisions of the 2018 IBC (International Code Council, 2017a) and IRC (International Code Council, 2017b). IBC Section 1803.5.11 requires that an in-

vestigation be conducted for all structures in Seismic Design Categories C, D, E, or F (see Earthquake Ground-Shaking Hazard section above) to evaluate the potential for surface rupture due to faulting.

### Map Limitations

Our mapping is based on 1:24,000-scale geologic mapping and the potentially active faults obtained from that mapping are shown on the surface-fault-rupture-hazard map (https://geology.utah.gov/apps/hazards) at that level of detail. Some smaller faults may not have been detected during the mapping or faults may be concealed beneath young geologic deposits. Additionally, approximately located and buried faults lack a clearly identifiable surface trace, and therefore their location is less well known. Site-specific fault-trenching investigations should be preceded by a careful field evaluation of the site to identify the surface trace of the fault, other faults not evident at 1:24,000 scale, or other fault-related features at a site-specific scale.

## LIQUEFACTION

Liquefaction and liquefaction-induced ground failure are major causes of earthquake damage (Keller and Blodgett, 2006). During liquefaction, a soil loses its strength and ability to support the weight of overlying structures or sediment. Soil liquefaction is caused by strong earthquake ground shaking where saturated, cohesionless, granular soil is transformed from a solid to a nearly liquid state. Soil liquefaction generally occurs in sand, silty sand, and sandy silt soils (Youd and Idriss, 1997). Liquefaction typically occurs within approximately 50 feet (15 m) of the ground surface (Seed, 1979), but the likelihood of liquefaction occurring in most deposits is very low when groundwater is deeper than about 30 feet (10 m) (Youd and Perkins, 1978; Youd and Gilstrap, 1999). However, perched groundwater, locally saturated soils, and changes in local and regional water management patterns, along with seasonal variations of the water table, must also be considered when evaluating liquefaction hazard (Martin and Lew, 1999; California Geological Survey, 2008). In general, an earthquake of M 5 or greater is necessary to induce liquefaction. However, liquefaction features, including sand boils along the Bear River, were caused by the April 15, 2010, M 4.5 Randolph, Utah, earthquake (DuRoss, 2011). Larger earthquakes are more likely to cause liquefaction and may result in liquefaction at greater distances from the earthquake epicenter. The following conditions are required for liquefaction to occur:

1. The soils must be below the water table.
2. The soils must be loose to moderately dense.
3. The ground shaking must be intense.
4. The duration of ground shaking must be sufficient for the soils to lose their shearing resistance.

Plastic or clay-rich soils having either a clay content greater than 15 percent, a liquid limit greater than 35 percent, or a moisture content less than 90 percent of the liquid limit are generally immune to liquefaction (Seed and Idriss, 1982; Youd and Gilstrap, 1999).

Four types of ground failure commonly result from liquefaction: (1) loss of bearing capacity, (2) ground oscillation and subsidence, (3) lateral spreading, and (4) flow failure (Youd, 1978, 1984; Tinsley and others, 1985) (figure 47). The expected mode of ground failure at a given site largely depends upon the ground-surface slope. Where slope inclination is less than approximately 0.5 percent, liquefaction may cause damage in one of two ways. The first is the loss of bearing capacity and resulting deformation of soil beneath a structure, which causes the structure to settle or tilt. Differential settlement is commonly accompanied by cracking of foundations and damage to structures. Buoyant buried structures, such as underground storage or septic tanks, may also float upward under these conditions. The second type of damage results from liquefaction at depths below soil layers that do not liquefy. Under these conditions, blocks of the surficial, non-liquefied soil detach and oscillate back and forth on the liquefied layer. Damage to structures is caused by subsidence of the blocks, opening and closing of fissures between and within the blocks, and formation of sand blows as liquefied sand is ejected through the fissures from the underlying pressurized liquefied layer.

Lateral spreading may occur where the ground surface slopes from approximately 0.5 to 5 percent, particularly near a “free face” such as a stream bank or cut slope. Lateral spreads are characterized by surficial soil blocks that are displaced laterally downslope as a result of liquefaction in a subsurface layer. Lateral spreading can cause significant damage to structures and may be particularly destructive to pipelines, utilities, bridges, roadways, and structures with shallow foundations.

Flow failures may occur where the ground surface slopes more than about 5 percent. Flow failures are composed chiefly of liquefied soil or blocks of intact material riding on a liquefied layer. Flow failures can cause soil masses to be displaced several miles and are the most catastrophic mode of liquefaction-induced ground failure.

Liquefiable units in the Glen Canyon study area are not widespread due to an arid desert climate and widespread distribution of bedrock. Potentially liquefiable areas are generally confined to sandy alluvial and eolian deposits along perennial streams and adjacent to springs, seeps, and Lake Powell. Other normally dry soils can become temporarily saturated with perched groundwater when water from prolonged precipitation events or excess water associated with development (reservoirs, irrigation, septic tanks, urban runoff, etc.) percolates through thin, permeable, unconsolidated surface deposits and ponds on less permeable underlying bedrock. Shallow groundwater conditions can remain until the water application stops and the soil has drained.

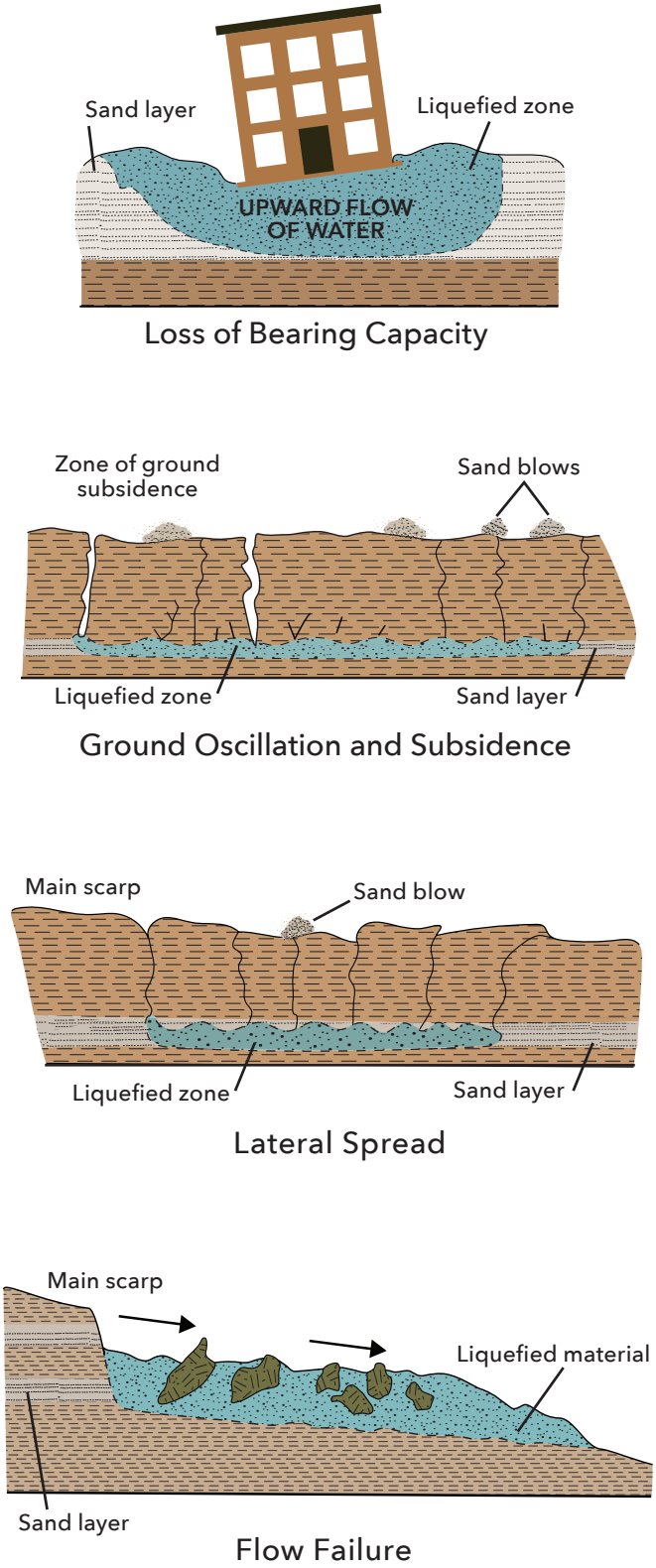


***Figure 47.*** *Four principal types of liquefaction-induced ground failure; arrows indicate direction of movement (modified from Youd, 1984; Harty and Lowe, 2003).*

## Sources of Information

To evaluate liquefaction susceptibility, we used four main sources of data: (1) recent UGS 1:24,000-scale geologic mapping that covers the Bullfrog (Willis, in preparation) and Wahweap sections (Phoenix, 2009; Willis, 2012a) of the study area, (2) the NRCS *Soil Survey of Glen Canyon National Recreation Area, Arizona and Utah* (USDA, 2010a; 2010b), (3) a limited number of unpublished, site-specific geotechnical reports completed for projects in the Glen Canyon area, (4) interpretation of stereo and orthophoto aerial photography including mid-1990s (Utah Automated Geographic Reference Center [AGRC] 2016a), 2014 (Utah AGRC, 2014), and 2015 (Utah AGRC, 2016b) aerial photographs, and (5) *Ground-Water Conditions in the Lake Powell Area* (Blanchard, 1986).

## Sources of Earthquake Ground Shaking

Potential sources of strong earthquake ground shaking in the Glen Canyon study area are shown on figure 42 and include (1) the comparatively short normal-slip faults with very long recurrence intervals within or close to the study area (see Surface-Fault-Rupture Hazard section above), (2) the Eminence fault zone about 20 miles (30 km) south of the study area (USGS, 2016b), (3) the West and Central Kaibab fault zones about 25 miles (40 km) west of the study area (USGS, 2016b), (4) the Bright Angel fault zone about 40 miles (65 km) southwest of the study area (USGS, 2016b), (5) the Sevier fault about 60 miles (95 km) west of the study area (Lund and others, 2008a), and (6) random background earthquakes having a magnitude below that required to produce surface rupture (~M 6.5) that occur either within or near the study area on an unrecognized fault. While all of these sources could potentially produce ground shaking, they have low rates of activity, and generally have a low likelihood to produce ground shaking strong enough to cause liquefaction in the study area. URS Greiner Woodward Clyde (2000) completed a probabilistic seismic hazard analysis for the Glen Canyon Dam site that included predicted ground motions at return periods of 10,000 and 50,000 years. They concluded that since the dam site is not near any faults with a relatively high slip rate (and correspondingly short recurrence interval), a random background earthquake (~M 5–6.5) is most likely to contribute to the peak horizontal acceleration hazard at all return periods. Although unlikely, a moderate to large earthquake is possible and may liquefy loose, saturated unconsolidated deposits along perennial streams and in wet areas within the study area.

## Liquefaction-Hazard Classification

As first determining factors, we considered the age, textural characteristics (grain size and sorting), and cementation of unconsolidated geologic units as characterized by UGS mappers to classify unconsolidated geologic units as potentially liquefiable. Age is an important consideration for liquefaction hazard because the older the unit, generally the more consoli-

dated or cemented it is and the less susceptible it becomes to liquefaction. We then identified where potentially liquefiable units likely contain shallow groundwater (≤ 50 feet [15 m]). NRCS soils data, spring and seep locations, presence of phreatophytes (typically cottonwood, willow, or tamarisk with roots extending to the capillary fringe above the water table), and aerial photo interpretation were used to identify areas of potentially shallow groundwater. We classified potentially liquefiable units with shallow groundwater (≤ 50 feet [15 m]) as having high liquefaction susceptibility. Note that liquefaction susceptibility differs from liquefaction *potential*, which combines susceptibility with consideration of the probability of a sufficiently high earthquake ground-motion acceleration occurring within some specified time interval.

Unclassified areas on the liquefaction-hazard map (https://geology.utah.gov/apps/hazards) include areas of exposed or shallow (≤ 5 feet [1.5 m]) bedrock, unconsolidated geologic deposits with textural or cementation characteristics that generally preclude liquefaction, and areas where depth to groundwater is estimated to be greater than 50 feet (15 m). Unclassified areas are considered to have no liquefaction susceptibility; however, areas of liquefaction susceptibility too small to show at the scale of the map prepared for this study may exist locally within unclassified areas, particularly near springs and seeps.

## Using This Map

Our mapping (https://geology.utah.gov/apps/hazards) shows areas where liquefaction may be possible in the Glen Canyon study area. The mapping is based on limited information about the textural characteristics of unconsolidated geologic units and the distribution and depth of groundwater in the study area. The mapping does not integrate earthquake ground motion with material characteristics and depth to groundwater, which is required to determine relative liquefaction potential in susceptible deposits. Consequently, the mapping does not differentiate ground-failure types or amounts, which are needed to fully assess the hazard and evaluate possible mitigation techniques.

Our mapping is intended for general planning and design purposes to indicate where a liquefaction hazard may exist and to assist in liquefaction-hazard investigations. Soil-test requirements are specified in chapter 18 (Soils and Foundations) of the 2018 IBC (International Code Council, 2017a) and chapter 4 (Foundations) of the 2018 IRC (International Code Council, 2017b). IBC Section 1803.2 requires a geotechnical investigation be performed in accordance with IBC sections 1803.3 through 1803.5. Section 1803.3 requires an investigation to evaluate liquefaction, and Section 1803.5.11 requires a liquefaction evaluation for structures in Seismic Design Categories C, D, E, or F. In general, seismic design categories in the study area for structures built on unconsolidated materials fall into Seismic Design Categories C and D, thus triggering the IBC requirement for a liquefaction investigation. Although the IRC does not specifically mention liquefaction, IRC Section R401.4 states that the local building official determines whether to require soil tests in areas likely to have expansive, compressive, shifting, or other unknown soil characteristics, such as liquefiable soils.

International Building Code seismic design categories are determined on a site-specific basis and vary throughout the study area depending on IBC site class, maximum considered earthquake ground motion, and the IBC risk category of the proposed structure. Because the risk to human life and the requirement that certain essential structures remain functional during natural or other disasters varies by occupancy category, we recommend the following levels of liquefaction-hazard investigation for the different IBC risk categories (table 5) in areas identified on the map as susceptible or potentially susceptible. Detailed (quantitative) subsurface investigations should be performed for modified Risk Category II(a), II(b), III, and IV facilities (modified from IBC table 1604.5 [International Code Council, 2017a]), and reconnaissance (screening) investigations for Risk Category I facilities. Additionally, a reconnaissance investigation should be performed for Risk Category II(a), II(b), III, and IV structures in areas mapped as not susceptible to liquefaction followed by a detailed investigation if a liquefaction hazard is determined to be present. Investigations are not recommended for Risk Category I structures in non-susceptible areas. Martin and Lew (1999) provided guidelines for conducting both reconnaissance and detailed liquefaction investigations.

## Hazard Reduction

Although potentially costly when not recognized and properly accommodated in project design, problems associated with liquefaction rarely are life threatening, unless the unlikely event of building collapse occurs. As with most geologic hazards, early recognition and avoidance are the most effective ways to mitigate this hazard. However, avoidance may not always be a viable or cost-effective option and other techniques are available to reduce liquefaction hazards (National Research Council, 1985).

Liquefaction damage may be reduced either by using ground improvement methods to lower the liquefaction hazard (for example, compacting or replacing soil; installing drains or pumps to dissipate or lower the water table) or by designing structures to withstand liquefaction effects (using deep foundations or structural reinforcement). Existing structures threatened by liquefaction may be retrofitted to reduce the potential for damage. Because the cost of reducing liquefaction hazards for existing structures may be high relative to their value, and because liquefaction is generally not a life-threatening hazard, we consider it prudent, although not essential, to reduce liquefaction hazards for existing structures, unless sig-

***Table 5.*** *Recommended requirements for liquefaction-hazard investigations for modified IBC risk category of buildings and other structures (see table 1; modified from International Code Council [2017a] and IBC table 1604.5).*

| Mapped Susceptibility | IBC Risk Category1 | | | | |
|---|---|---|---|---|---|
| | I | II(a) | II(b) | III | IV |
| | Buildings and other structures that represent a low hazard to human life in the event of failure | Single family dwellings, apartment complexes and condominiums (<10 dwelling units), and campgrounds | Buildings and other structures except those listed in I, II(a), III, and IV | Buildings and other structures that represent a substantial hazard to human life in the event of failure | Buildings and other structures designated as essential facilities |
| High | Reconnaissance | Detailed[2] | Detailed[2] | Detailed[2] | Detailed[2] |
| None | None | Reconnaissance[3] | Reconnaissance[3] | Reconnaissance[3] | Reconnaissance[3] |

[1] See International Code Council (2017a) chapter 3—Use and Occupancy Classification, and chapter 16—Structural Design, table 1604.5 for a complete list of structures/facilities included in each IBC Risk Category. Check table 1604.5 if a question exists regarding which Risk Category a structure falls under.
[2] Detailed evaluation necessary; a detailed liquefaction investigation should be interdisciplinary in nature and performed by qualified experienced geotechnical engineers and engineering geologists working as a team.
[3] A reconnaissance investigation should be followed by a detailed investigation if a liquefaction hazard is determined to be present.

nificant ground deformation (lateral spreading) is anticipated and the structures fall into IBC Occupancy Categories III or IV, in which case retrofitting is recommended.

### Map Limitations

Our mapping is based on limited geological, geotechnical, and hydrological data; a site-specific investigation is required to produce more detailed information. The mapping also depends on the quality of those data, which varies throughout the Glen Canyon study area. The mapped boundaries of the liquefaction-susceptibility zones are approximate and subject to change as new information becomes available. Liquefaction susceptibility at any particular site may be different than shown because of geologic and hydrologic variations within a map unit, gradational and approximate map-unit boundaries, and the map scale. Small, localized areas of liquefaction susceptibility may exist anywhere within the study area, but their identification is precluded because of limitations of either data or map scale. Seasonal and long-term fluctuations in groundwater levels can affect liquefaction hazard at a site. This map is not intended for use at scales other than the target scale and is intended for use in general planning and design to indicate the need for site-specific investigations.

## RADON HAZARD

Radon is an odorless, tasteless, and colorless radioactive gas that is highly mobile and can enter buildings through small foundation cracks and other openings, such as utility pipes. The most common type of radon is naturally occurring and results from the radioactive decay of uranium, which is found in small concentrations in nearly all soil and rock. Air movement and open space dissipates radon gas outdoors, but indoor radon concentration may reach hazardous levels because of confinement and poor air circulation in buildings. Breathing any level of radon over time increases the risk of lung cancer, but long-term exposure to low radon levels is generally considered a small health risk. Smoking greatly increases the health risk due to radon because radon decay products attach to smoke particles and are inhaled into the lungs, greatly increasing the risk of lung cancer. The U.S. Environmental Protection Agency (U.S. EPA, 2009) recommends that action be taken to reduce indoor radon levels exceeding 4 picocuries per liter of air (pCi/L) and cautions that indoor radon levels less than 4 pCi/L still pose a health risk. In many cases radon hazard risk can be reduced.

Indoor radon levels are affected by several geologic factors including uranium content in soil and rock, soil permeability, and groundwater. Granite, metamorphic rocks, some volcanic rocks and shale, and soils derived from these rocks are generally associated with elevated uranium content contributing to high indoor radon levels.

Soil permeability and groundwater affect the mobility of radon from its source. If a radon source is present, the ability of radon to move upward through the soil into overlying buildings is facilitated by high soil permeability. Conversely, radon movement is impaired in soils having low permeability. Saturation of soil by groundwater inhibits radon movement by dissolving radon in the water and reducing its ability to migrate upward through the soil (Black, 1996).

Along with geologic factors, several non-geologic factors also influence radon levels in a building. Although the influence of geologic factors can be estimated, the influence of non-geologic factors, such as occupant lifestyle and home construction, are highly variable. As a result, indoor radon levels fluctuate and can vary in different structures built on the same geologic unit; therefore, the radon level must be measured in each building to determine if a problem exists. Testing is easy, inexpensive, and may often be conducted by the building occupant, but professional assistance is available (for more information, visit https://radon.utah.gov). Evaluation of actual indoor radon levels in the study area was beyond the scope of this investigation.

## Sources of Information

To evaluate the radon-hazard potential, we used five main sources of data to identify areas where underlying geologic conditions may contribute to elevated radon levels: (1) recent UGS 1:24,000-scale geologic mapping that covers the Bullfrog (Willis, in preparation) and Wahweap sections (Phoenix, 2009; Willis, 2012a) of the Glen Canyon study area**,** (2) soil permeability data from the NRCS *Soil Survey of Glen Canyon National Recreation Area, Arizona and Utah* (USDA, 2010a, 2010b), (3) USGS National Uranium Resource Evaluation (NURE) program data including the Hydrogeochemical and Stream Sediment Reconnaissance (HSSR) dataset (USGS, 2004) and the airborne radiometric map of the U.S. (Duval and others, 1989; USGS, 2009), (4) the Arizona Geological Survey's map of *Areas in Arizona With Elevated Concentrations of Uranium* (Spencer and others, 1993), and (5) *Ground-Water Conditions in the Lake Powell Area* (Blanchard, 1986).

## Potential Radon Sources in the Glen Canyon Study Area

Geologic mapping is important for identifying geologic units having high uranium content, particularly outside of areas covered by previous investigations where radiometric data are limited. The most uranium-rich bedrock units that crop out in the Glen Canyon area are the Shinarump (Witkind and Thadden, 1963; Willis, 2004; Thaden and others, 2008), Monitor Butte (Finch, 1959; Thaden and others, 1964), and Petrified Forest (Billingsley and Priest, 2013) Members of the Triassic Chinle Formation and the Jurassic Morrison Formation (e.g., Doelling, 1967; Peterson, 1980). The Triassic Moenkopi Formation (Black, 1993) and the Cretaceous Dakota Formation (Doelling and Davis, 1989) have local uranium occurrences elsewhere on the Colorado Plateau, and we include intrusive igneous rocks of Mount Ellsworth because granitic rocks have been associated with uranium in Utah (Sprinkel, 1987). All alluvium and colluvium locally derived from uranium-bearing bedrock units, and alluvial terrace deposits mapped along the Colorado River that contain abundant granitic, metamorphic, and volcanic rocks (Willis, 2012a), are also potential radon sources. Any areas where uranium ore or waste products have been stored warrant a detailed site-specific study; these areas can emit very high concentrations of radon, even in open air.

## Radon-Hazard-Potential Classification

Using the geologic factors of uranium content, soil permeability, and depth to groundwater, we classified soil and rock units using a three-point system (table 6) into high (3 points), moderate (2 points), and low (1 point) hazard categories based on their potential to generate radon gas and the ability of the gas to migrate upward through the overlying soil and rock (after Black and Solomon, 1996). Points were assigned based on limited groundwater depth data (see Liquefaction-Hazard Classification section), permeability, and relative uranium content of mapped bedrock units in the study area. Alluvium and colluvium sourced from bedrock units mapped as potentially uranium-bearing are assigned to the same hazard-potential category as their parent unit.

## Using This Map

Our radon-hazard-potential mapping (https://geology.utah.gov/apps/hazards) is intended to provide an estimate of the underlying geologic conditions that may contribute to the radon hazard. The mapping does not characterize indoor radon levels because they are also affected by highly variable non-geologic factors. The mapping can be used to indicate the need for testing indoor radon levels; however, we recommend testing in all existing structures. If professional assistance is required to test for radon or reduce the indoor radon hazard, a qualified contractor should be selected. The EPA provides guidelines for choosing a contractor and a listing of state radon offices in *Consumer's Guide to Radon Reduction* (U.S. EPA, 2010). The radon-hazard potential map is not intended to indicate absolute indoor radon levels in specific buildings. Although geologic factors contribute to elevated indoor-radon-hazard potential, other highly variable factors, such as building materials and foundation openings, affect indoor radon levels; therefore, indoor radon levels can vary greatly between structures located in the same hazard category. Additionally, the guidelines within the IRC, Appendix F (International Code Council, 2017b), concerning radon control methods, should be followed for new construction.

## Map Limitations

The hazard-potential categories shown on the map are approximate and mapped boundaries are gradational. Localized areas

***Table 6.*** *Radon-hazard-potential classifications based on geologic factors affecting the ability of radon gas to migrate upward through the overlying soil and rock.*

| Geologic Factors | Radon Hazard Category[1] | | |
|---|---|---|---|
| | **Low** | **Moderate** | **High** |
| Uranium (ppm) | <2 | 2–3 | >3 |
| Soil permeability[2] | Impermeable (hydraulic conductivity <0.6 in/hr) | Moderately permeable (0.6–6 in/hr) | Highly permeable (>6 in/hr) |
| Depth to groundwater | <10 feet | 10–30 feet | >30 feet |

[1]After Black and Solomon (1996)
[2]USDA (2010a, 2010b)

of higher or lower radon potential are likely to exist within any given map area, but their identification is precluded because of the generalized map scale, relatively sparse data, and non-geologic factors such as variability in building construction. The use of imported fill for foundation material can also affect radon potential in small areas, because the imported material may have different geologic characteristics than native soil.

## ACKNOWLEDGMENTS

This study was performed under a cooperative agreement between the U.S. Department of the Interior, National Park Service, Glen Canyon National Recreation Area, and the Utah Department of Natural Resources, Utah Geological Survey (Task Agreement P14AC01288 under Cooperative Agreement P13AC00601). We thank Kimm Harty and Grant Willis of the Utah Geological Survey for their careful and timely reviews of this report. Sarah Doyle (National Park Service, now with Bureau of Land Management) helped collect various digital datasets and historical, geology-related incident data, and facilitated fieldwork, including boat transportation on Lake Powell and the Colorado River. We also thank Carl Elleard (National Park Service) for his insights into geologic hazards in the Glen Canyon area. Valerie Reynolds (National Park Service) provided valuable information and photos of flooding events near Bullfrog. Eric Bilderback, Mark Miller, and Lisa Norby facilitated NPS funding and support for this study.

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